



2nd International Forum on Water and Food

Addis Ababa Ethiopia
November 10 -14 2008



Volume II

Increasing rainwater productivity

- Increasing crop water productivity through optimising the use of scarce irrigation water resources
- Increasing livestock water productivity
- Integration of germplasm and management for sustainable water productivity improvement in rainfed cropping systems

Multi-purpose water systems

- Catalysing collective action in water management and scaling up and out in multiple use systems
- Collective approaches to fish production
- Tools for understanding collective action around water management

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CGIAR Challenge Program on Water and Food

2nd International Forum on Water and Food

Fighting Poverty Through Sustainable Water Use: Volumes I, II, III and IV.

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Note on cover design: The Amharic lettering in the lower right hand corner translates as “International Program and Water and Food”. The colours in the keyline at the bottom of the page are those of the Ethiopian flag, and the obelisk is a famous landmark of Axum – a historic city of Ethiopia and a world treasure. Their inclusion on the cover and use in other Forum print materials is recognition of the wonderful hospitality of the Ethiopian people and a thank you for being such a generous host country for the 2nd International Forum on Water and Food.

Foreword

Every two years the CGIAR Challenge Program on Water and Food holds an International Forum on Water and Food, during which we present our research results, debate these, and consider ways in which we can better deliver these into impact. Another important function of this second Forum is to consolidate CPWF research priorities for our second 5-year phase starting in 2009.

We are particularly glad to introduce these four volumes of papers and posters originating from CPWF phase one projects. All papers were peer-reviewed, and a total of 154 papers selected for publication in these proceedings. They include papers from all 9 Basin Focal Projects, 30 of the 1st competitive call projects, 3 of the Small Grants projects for innovation, and 2 Themes.

We wish to congratulate all of you who contributed papers to these proceedings, and thank you for the tremendous enthusiasm and cooperation enabling us to meet very tight publication deadlines so that all papers could be available, in hard copy, at the Forum. All this was achieved in less than 9 months, from the time of the call for Abstracts to release at the Forum.

We are also proud of the excellent teamwork of the CPWF Theme Leaders and Basin Focal Project Leadership teams, who worked very hard reviewing abstracts, reviewing and editing papers, checking revised papers, and who designed and selected the papers for the sessions, based on your submissions.

The publication of these proceedings is the result of a truly CPWF global community effort. We also thank Reg and Ida MacIntyre for their careful editing to tight deadlines.

The papers and posters are provided in 4 volumes as follows:

Volume I – 4 invited **Key Concept Papers** from the Phase 1 projects, and 1 invited **Keynote Paper** from Dr Carlos Sere, DG of ILRI entitled 'Swimming upstream' – the water and livestock nexus, and 36 papers on **Cross-cutting topics**: Agriculture, water and health; Governance: linking communities across boundaries; Innovative modelling tools; Participatory modelling and knowledge integration; and Resilience to climate change

Volume II – 44 papers from Phase 1 projects directly relevant to the CPWF Phase 2 Topic 1 **Increasing rainwater productivity** and 21 papers relevant to Topic 2 **Multi-purpose water systems**

Volume III – 23 papers from Phase 1 projects directly relevant to CPWF Phase 2 Topic 3 **Water benefits sharing for poverty alleviation and conflict resolution**, and 25 papers relevant to Topic 4 **Drivers and processes of change**

Volume IV – 40 Project Posters by Phase 1 Projects of the Challenge Program on Water and Food

Five years is at the same time long from an outside perspective, but short for multi-disciplinary projects including partners from different horizons, backgrounds, and often river basins. These Proceedings present many, but not all, of the fine achievements and outcomes of the CPWF Phase 1 projects.

Dr. Jonathan Woolley
Program Coordinator

Dr. Alain Vidal, Cemagref
Forum Convener, Chair Organising Committee

CGIAR Challenge Program on Water and Food

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Increasing crop water productivity through optimizing the use of scarce irrigation water resources

Assessing water supply and demand for dry season rice in coastal polders of Bangladesh

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Abstract

Salinity intrusion prohibits the use of river water for irrigation of dry season (boro) rice in the coastal zone of Bangladesh. This can be overcome by using water stored in the canal networks within the polders for irrigation when river water becomes saline. It is not yet known, however, whether this technology can be adapted on a large scale. By using systems approaches, this study compared the water demand of boro rice with the storage capacity of the canal networks to assess the area of boro rice that can be grown in the polders. A two-season field experiment was carried out in a typical coastal polder to quantify responses of crop growth, yield, and irrigation water demand to different planting dates. Experimental results were used to calibrate and evaluate the model ORYZA2000, which was then used to quantify the probabilistic yields and water demand of boro rice over a 20-year period. Rice crops planted in October suffered from cold temperature, resulting in low harvest index (HI). Delaying the planting after 10 November did not result in yield gain but increased the water requirement from the canal storage substantially. Oryza2000 simulated satisfactorily the total rice biomass, and water requirement, but needed some modifications to take into account the effects of low temperature on HI to enable it to satisfactorily simulate yields of boro rice. The optimum planting time for highest productivity with respect to storage water was from 1 to 10 November. The area of boro rice that can be irrigated from water storage was about 15% of the rice area of the polder in at least 50% of years. This can be increased to 40% of the area if the canals are dredged according to the plan by the Bangladesh Water Development Board. The potential of large-scale adaptation of boro rice warrants the investment to increase the water storage capacity of the polder. Development of cold-tolerant rice varieties can further increase the potential area because they can be planted earlier and hence reduce water requirements.

Media grab

Up to 40% of rice land in the coastal polder areas of Bangladesh can be planted with dry season (boro) rice.

Introduction

Bangladesh faces an enormous challenge in trying to achieve food self-sufficiency for its growing population. The coastal zone of Bangladesh, covering an area of 2.83 million ha, is the least productive agricultural zone. Because of salinity intrusion in the dry season, rice cultivation is limited to a single rainy season crop (aman rice). The area, however, has potential for development. Mondal et al. (2006) showed that with proper water management an additional rice crop could be grown in the dry period after the aman rice in the coastal polder areas. Growing dry season (boro) rice in the area involves two distinct stages of irrigation. The first stage (when river water salinity is low, with electrical conductivity $EC < 4$ dS/m, usually before mid February) is gravity irrigation by letting river water in through sluices at high tides. The second stage starts when the river water $EC > 4$ dS/m. Just before the river water becomes saline, it could be taken into and stored in the on-farm canal networks. The stored water could be used to irrigate the dry season rice by pumping onto the fields until shortly before harvest time. The possibility of out-scaling the technology, i.e. for wide scale adoption of boro rice cropping, has not been systematically investigated. This is hampered by: (1) the lack of data on the water requirement of the boro rice crop; (2) the optimal planting time for high yield and water productivity with respect to the amount of water pumped from the canal network; (3) the storage capacity of the internal canal networks of polders; and (4) the time when river water becomes too saline for irrigation.

The main objective of the study was to determine the potential for increasing boro rice production in the polder areas in the coastal zones of Bangladesh through effective utilization of the available land and water resources. This was achieved through a systems approach, combining field activities and crop modeling using ORYZA2000 (Bouman and van Laar, 2006), to quantify probabilistic yields and water requirements of boro rice crop for different times of establishment and varieties, and to balance the water requirement with storage capacity of the internal canal networks of a typical polder in the coastal zone.

Methods

The study site (Polder 30, between 22° 37' and 22°46' North and 89°27' and 89°33' East) is located in Batiaghata Upazila in Khulna district, southwestern Bangladesh. The gross area of the polder is about 7725 ha with a net cultivable area of about 4867 ha (IPSWAM, 2007). The polder is protected from high tides by an embankment 40 km long and 4.3 m wide at the crest. The hydraulic system of the polder is controlled by a system of sluices. The water level of the surrounding rivers fluctuates daily due to tidal effects. During high tide, the water level can rise from 1 to 2.8 m above land level, creating opportunities for gravity irrigation when the water river is not too saline.

The research was organized in three activities as schematically shown in Figure 1.

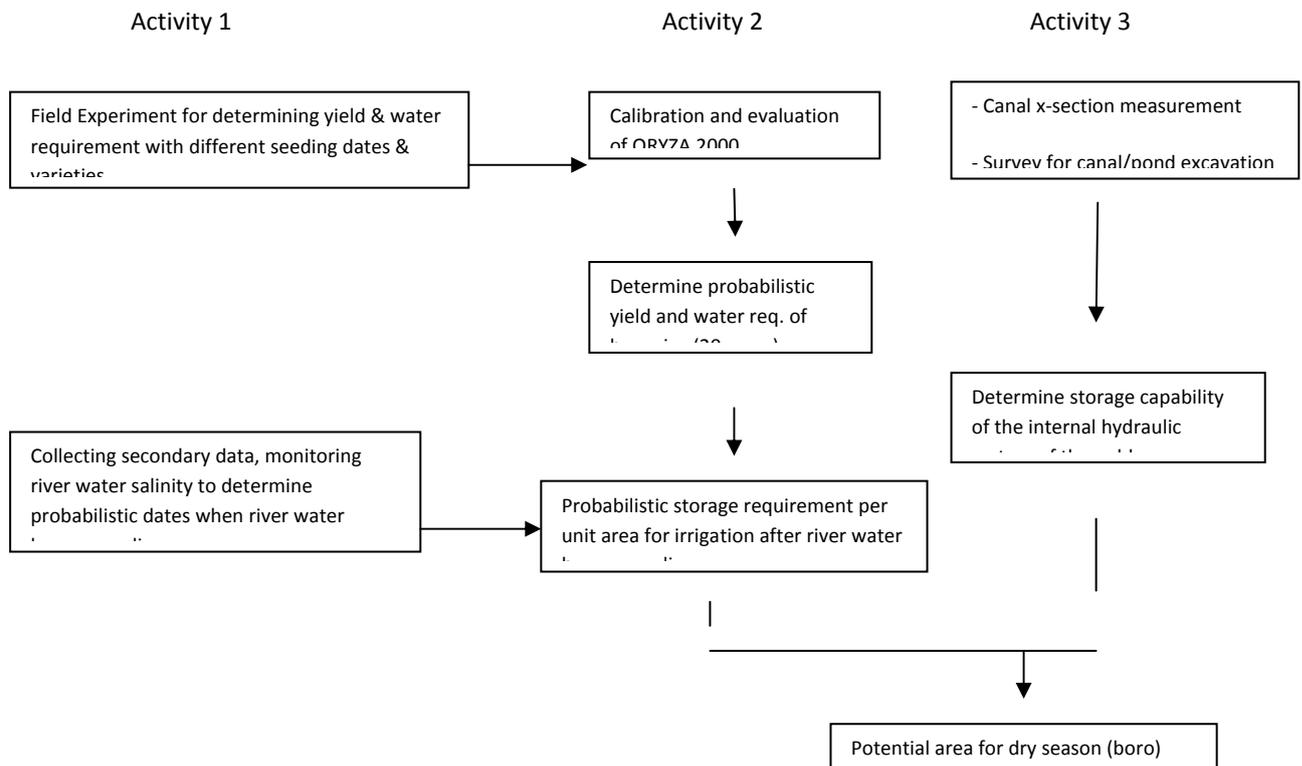


Figure 1. Key research activities in the coastal zone of Bangladesh.

Field experiment

An experiment was carried out in the 2005–06 and 2006–07 dry seasons (DS) with a split plot design. The main plots were four dates of seeding (D1 = 22nd Oct, D2 = 1st Nov, D3 = 7th Nov, and D4 = 15th Nov). The subplots were two cultivars (BRRIdhan 28, a popular variety also known as BR-28 and PVS B8).

Seedlings were transplanted when they acquired four leaves, at three to four seedlings per hill and spacing of 20 cm x 20 cm. All plots were irrigated until 2 weeks before harvest. The amount of irrigation water applied to each plot was measured using a V-notch. This amount was checked against daily subsidence of the water level in the fields, measured by a staff gauge. The subsidence was equivalent to total field water requirement (evapotranspiration (ET) + percolation (P) + seepage (S)). Two 1 m x 1 m GI tanks (0.4 m height, installed to depth of 0.25 m) one with a bottom and one bottomless, were installed in the four main plots. Subsidence of water level in the boxes was monitored daily for the measurement of ET and P. A rain gauge and a class A evaporation pan were installed in the field.

Urea was applied at 120 kg N/ha in four equal splits (basal, 25 days after transplanting (DAT); 5 to 7 days before panicle initiation (PI), and heading). Basal incorporation at last harrowing also included 60 kg P₂O₅/ha, 40 kg K₂O/ha, 10 kg ZnSO₄/ha, and 60 kg CaSO₄/ha.

Crop phenology, biomass, its partitioning and leaf area index (LAI) at critical growth stages, grain yield, and yield components were monitored following standard procedures. Water and crop data were analyzed with standard split-plot analysis of variance (ANOVA) techniques.

River water salinity measurement and data collection

The (EC) of river water was monitored daily to check its suitability for irrigation. When river water EC approached 4 dS/m, sluice gates were opened at high tide to intake river water into the canals to their maximum capacity. Storage water was used for irrigation until the end of the season. The daily recorded EC at the study sites did not differ significantly from those recorded at Khulna, a national permanent water quality monitoring station. Daily Khulna EC data were subjected to frequency analysis to determine the 50% probability of exceedence (P_{excd}) of the date when EC = 4 dS/m, beyond which (cut-off date) the river water cannot be used for irrigation.

Crop growth modeling

Crop data from the third seeding of the 2006–07 DS crop were used to generate variety- and site-specific parameters required by ORYZA2000. They were the crop development rate, percentage partitioning of biomass into its components, indigenous nitrogen uptake, and S&P. The model was then evaluated using data from 2005–06 and other seeding dates of the 2006-07 crops, according to the procedure described by Bouman and van Laar (2006). The third step involved scenario analysis over a period of 20 years (using climatic data from Khulna) of the effects of eight different seeding dates (every 5 days from 15 October) on crop yield and water requirement of the two varieties.

Storage capacity

Total hydraulic storage within the polder was determined from the length and cross-sections of the canal networks and other small water bodies (ponds/ditches) within the polder. Since most of the canals in the study polder were silted, the Bangladesh Water Development Board (BWDB) developed a plan to dredge and widen the canals (IPSWAM 2007). This plan was consulted to determine the future storage capacity of the water bodies of the polder.

Results and discussion

In both years, grain yields varied with seeding date and variety. Grain yields of the first two seeding dates were significantly lower than those of the later seeding dates (Table 1). The lower yields of the earlier seeding dates were mainly attributed to their lower number of spikelets/m² and lower percentage of filled spikelets (data not shown), resulting in significantly lower harvest index (HI) than those of the last two seeding dates (Table 1). Earlier seeding dates exposed the reproductive stage of the crop to low temperature, affecting the spikelet formation processes. This is supported by the linear correlation between HI and the average daily minimum temperature from panicle initiation (PI) to the flowering stage of the crop (Figure 2, for BR 28 – similar results were obtained for PSV-B8).

The average ET increased from 1.7 mm/d in November to 3.5 mm/d in March; and the average S&P rates from 2.1 mm/d to 3.6 mm/d over the same period. The total irrigation amount of D1 was significantly lower than those of other treatments in 2006-07 (Table 1). There was no significant difference in total irrigation water among the last three seeding dates. The effects of higher daily ET and S&P of the later seeding dates on water requirement were balanced by their shorter duration (due to higher temperature during their crop period), resulting in equivalent water requirements. The amount of irrigation taken from canal storage increased as the seeding dates were delayed. The difference of maturity period for the first and last seeding dates was about 15 days; however, almost twice the amount of irrigation water was taken from the canal storage for the last seeding than for the first seeding (Table 1, for the 2006–07 DS season). In the experiment, river water remained suitable for irrigation until the end of January, and most of the irrigation for the D1 crop came directly from the river because the crop matured at the beginning of March, while the D3 and D4 plots had a higher dependency on canal storage water to meet the irrigation water demand after January until they matured in April.

The long-term salinity data analysis indicated that the cut-off date corresponding to $P_{excd} = 50\%$ for using river water was the second week of February.

Table 1. Yield, harvest index (HI), total irrigation water, and irrigation from canal storage for two rice varieties seeded in different dates in 2006-07 DS crop. 2005-06 DS crop had similar results.

Seeding dates	Yield (kg/ha)			HI		Irrigation water (mm)	
	BR-28	PVS-B8	Diff.	BR-28	PVS-B8	Total	Canal storage
D1 = 22 Oct	703 d ^a	940 d	ns	0.07 c	0.08 c	621.2 b	142.7 c
D2 = 1 st Nov	2394 c	2878 b	*	0.24 b	0.34 b	721.8 a	223.1 b
D3 = 7 Nov	5036 a	5218 a	ns	0.47 a	0.49 a	758.8 a	267.8 a
D4 = 15 Nov	4501 b	5111 a	*	0.43 a	0.47 a	761.3 a	278.3 a

^aIn each column means followed by the same letter are not significantly different at 5% level by LSD. Mean values are averaged over four replications.

* = significant at 5% level by LSD and ns = not significant.

The storage capacity of the canal system was about 2,592,164 m³. After subtracting the "dead volume" and the volume needed for fisheries, the extractable volume was 2,137,445 m³. If the canals are dredged and widened according to the plan of BWDB, the extractable volume for irrigation will increase to 5,575,118 m³.

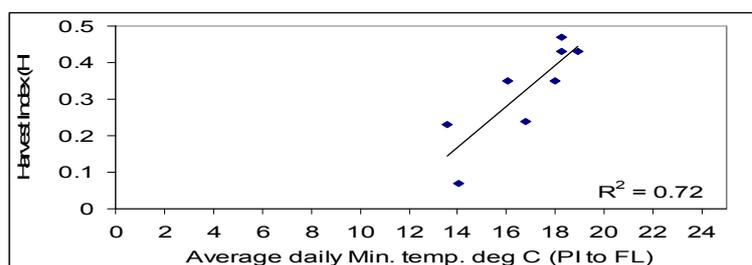
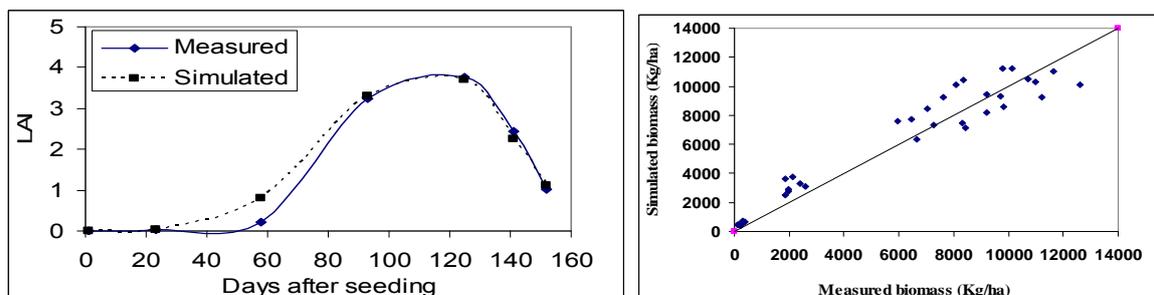


Figure 2. Relationship between HI and the average daily minimum temperature from panicle initiation (PI) and flowering (FL) for cultivar BR-28.

The simulated LAI, total biomass, and ET (Figure 3a, b, and d) satisfactorily agreed with the measured values. In Figure 3c, the simulated yields that exceeded the measured values corresponded to the early seeding dates (15-31 October). This is because ORYZA2000 has not adequately taken into account the effects of low temperature on spikelet formation and pollination. Rice yields obtained by multiplying the simulated biomass by HI (which was obtained from Figure 2) agreed well with the measured values. This method of yield simulation was used in the scenario analysis.



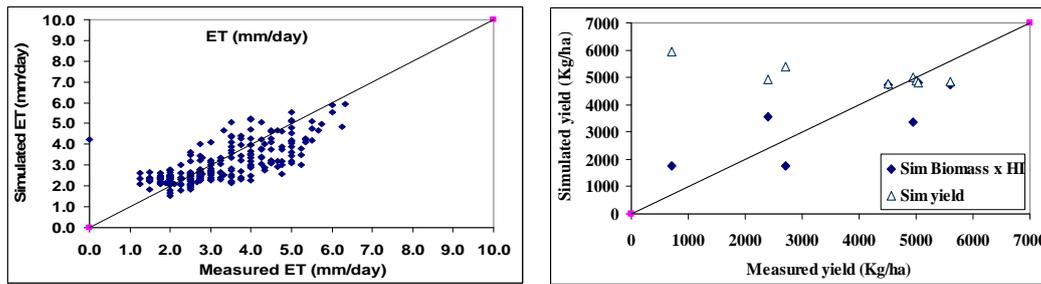


Figure 3. Oryza2000 simulated vs. measured (a) LAI, (b) total above-ground biomass, (c) grain yield, and (d) ET (mm/d) for cultivar BR28, in four seeding dates of 2005-06 and 2006-07 dry season crops. The simulated grain yields (Sim yield) were from simulation Oryza2000 and from simulated biomass multiplied by HI in Figure 1. Similar results were obtained for PSV-B8. The solid line is the 1:1 relationship.

Simulation using 20 years of climate data showed that rice yield increased steadily from about 2,000 to 5,000 kg/ha as the seeding date was delayed from 15 October to 10 November at all probabilities of exceedence. Seeding later than 10 November did not increase yield but increased considerably the amount of irrigation water taken from the canal storage (Figure 4). As a result, the maximum water productivity with respect to irrigation from canal storage was obtained when seeding was carried out on 5 November. At $P_{exd} = 50\%$ the maximum water productivity was 2.2 g/kg.

The area that can be brought into boro rice cultivation declined steadily as the seeding date was delayed (Figure 4, showing the future scenario when canals are dredged according to the BWDB's plan). The total boro rice production, however, maximizes at a seeding date of 5 November (Figure 4), corresponding to the seeding date with maximum water productivity (with respect to irrigation water from canal storage). With this seeding date and at $P_{exd} = 50\%$, the boro rice area that can be irrigated from the storage of the present canals (i.e. silted) is 740 ha (15% of the rice area). This can be increased to 1,924 ha (40% of the rice area) if the canals are dredged. These will bring an additional 3,700 t (present canal conditions) and 9,600 t (dredged canals) of rice to Polder 30, compared with 13,000 t presently produced by the aman rice crop.

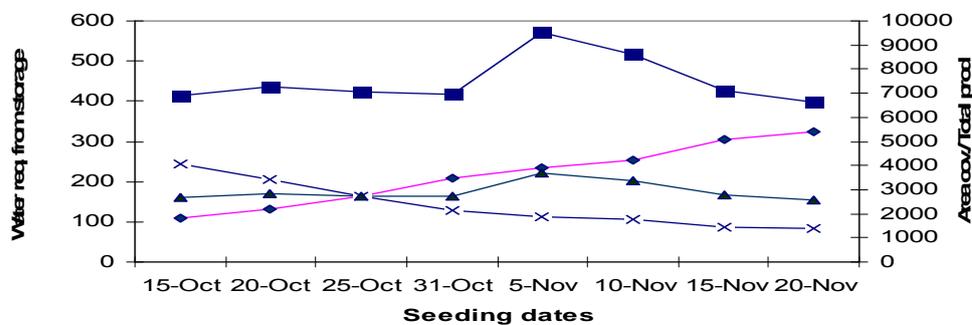


Figure 4. Irrigation water from canal storage (diamond, in mm); the expected area of boro rice (x, in ha) that can be irrigated when canals are dredged according to the plan of BWDB; total boro rice production (rectangle, in tons) when canals are dredged; and boro rice production (triangle, in tons) in the present (i.e. silted) canal condition. All values correspond to the probability of exceedence of 50%, using 20-year simulation.

Conclusions and recommendations

The time of seeding had contrasting effects on the two components of water productivity of boro rice grown in the South Western coast of Bangladesh. Seeding before November resulted in very low yields due to cold stress at the critical reproductive stages of boro rice. Late-seeding required more water to be taken from the limited storage capacity of the canal network, and therefore will reduce the area that can be irrigated. A systems approach, using crop modeling, allowed us to analyze the trade-offs between the two components over a 20-year period. With the optimum dates of seeding around 1–10 November, and with proper water management, 15% of the rice land can be planted with boro rice after the aman season. The percentage can be increased to 40% with some investments to improving

the conditions of the canals. Developing cold-tolerant varieties that can be planted early, hence reducing water required from the canal storage, can also increase the area of boro rice.

Acknowledgments

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Quality and groundwater level dynamics at two coastal sites of Bangladesh: implications for irrigation development

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Abstract

Most ricelands in the coastal region of Bangladesh remain fallow in the dry season because surface water resources are saline and unsuitable for rice irrigation, while groundwater (GW) is not intensively utilized because of the fear of salt-water intrusion into coastal aquifers. A study was undertaken at Batiaghata and Tala upazilas (sub-district) of the southwest region of Bangladesh to test the hypothesis that GW is suitable for irrigation and that its withdrawal for dry season rice cultivation would not result in salt-water intrusion into the aquifers. The depth of the phreatic water surface and electrical conductivity (EC) of groundwater were monitored weekly for 2-3 years along transects perpendicular to the adjacent river on two polders. The GW EC was < 2 dS/m at Tala and 4 dS/m at Batiaghata. At both sites, there was no increase in EC during the monitoring period. The phreatic depth at Tala declined to about 300 cm during each dry season, and to 80 cm at Batiaghata. Deeper drawdown of GW in Tala might have been caused by the intensive pumping for dry season rice irrigation, which farmers have practiced for about 5 years. The phreatic depth is close to the soil surface at both sites during the rainy season. The complete recovery of the phreatic levels suggests that there was adequate recharge to replenish the aquifers. Full replenishment and no increase in EC imply that the use of GW for dry season irrigation can be sustainable in Tala. Irrigation with marginal quality GW in Batiaghata, however, may cause salinity buildup in the soil profile. The findings suggest that the suitability of GW for dry season irrigation is rather site specific, and the use of GW warrants careful studies.

Media grab

The suitability of groundwater in the coastal region of Bangladesh for irrigation is site specific. Proper investigation is needed before development of dry season irrigation.

Introduction

Traditionally farmers of the coastal region of Bangladesh cultivate low-yielding (2.0-2.5 t/ha) local rice varieties under rainfed conditions in the wet season (Karim, 2006). Some farmers grow rice or raise shrimp (Mondal et al., 2006; Karim, 2006; Islam, 2006) in the dry season, but most lands remain fallow due to high soil salinity and lack of good quality irrigation water. While groundwater is intensively used for dry season irrigation in many parts of Bangladesh (BRRRI, 2004; Rashid, 2006), this is not the case for the coastal zone for fear of GW depletion and salt water intrusion in the coastal aquifers (ICZMP, 2004). Locally, farmers have been using GW to irrigate dry season rice for about 5-10 years on a limited scale in the southwest region of Bangladesh, but there are concerns about whether this practice is sustainable. Very limited information on the characteristics of coastal aquifers is available to address this concern. The present study was undertaken to test the hypothesis that GW is suitable for irrigation and that its withdrawal for irrigation in the dry season does not deplete the GW, nor result in salt-water intrusion into the aquifers.

The general objective was to determine the suitability and sustainability of GW for irrigation development in the dry season in the coastal regions of Bangladesh. This was achieved by quantifying temporal (over 2-3 years) and spatial variability of the GW phreatic depth and salinity dynamics at two sites in the southwest coastal region of Bangladesh.

Methods

Study sites

The study was carried out at Polder 30, Batiaghata sub-district and Polder Jetua-Kanaidia, Tala sub-district (Figure 1) in the southwest coastal region where saline intrusion is the most severe in Bangladesh (Karim et al., 1990; SRDI, 2004). In Batiaghata, the farmers mostly cultivate a single rice crop in the wet season under rainfed conditions. Most farmers in Tala have cultivated dry season rice for the last 5 years by utilizing groundwater, in addition to rainfed rice in the wet season.

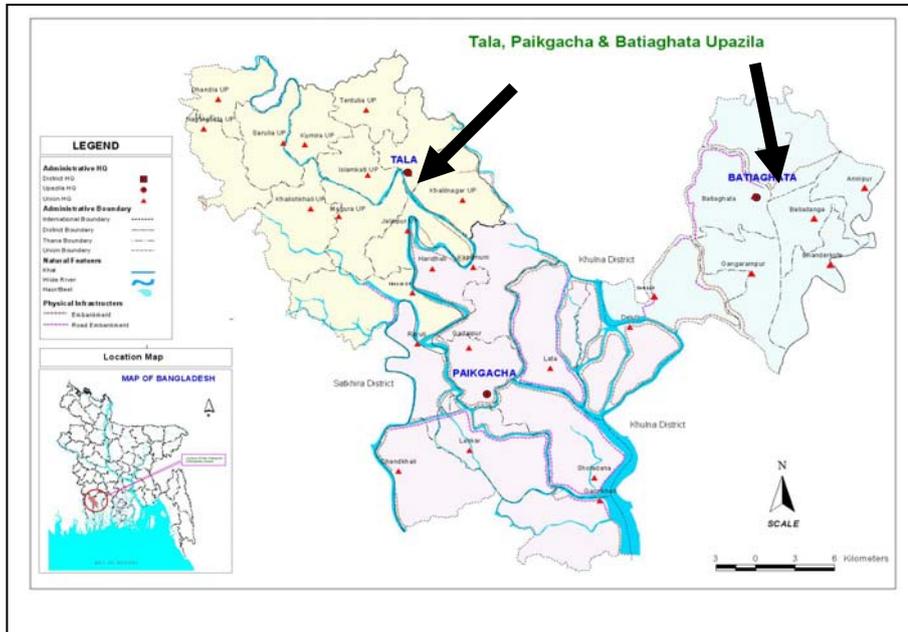


Figure 1. Location of the two study sites, Batiaghata and Tala sub-districts.

Measurement of groundwater depth and salinity

The depth of the phreatic surface and electrical conductivity (EC) of GW were measured in a network of observation wells at both study sites. Elevation (in cm above mean sea level, MSL) of the phreatic level of each well could be computed from the phreatic depth and elevation of the ground surface elevation of the well. In Batiaghata, monitoring was carried out from February 2005 to December 2007. The network consisted of six wells about 50-60 m deep (with a 3 m strainer at the bottom of each well) installed in a transect perpendicular to the bank of the Kazibachha River at distances of 50, 150, 300, 550, 750, and 1000 m from the river. At Tala, monitoring was carried out from January 2006 to December 2007 on 28 shallow tubewells (STWs) 50-70 m deep, installed by the farmers inside the Jetua-Kaniadia sub-polder (constructed by the Local Government Engineering Department). The polder was bounded on two sides by Kobadak River. The STWs were selected in 6 transects, 3-7 STWs per transect, extending to both arms of the surrounding river. All measurements were obtained weekly, on a fixed day for each row. Monthly data reported in this paper are the averages of the measured values for the particular month.

Results and discussion

Water level fluctuation

The phreatic levels at Batiaghata and Tala fluctuated seasonally as shown in Figure 2. The two sites had the same pattern. The lowest phreatic level was within 1 m below the soil surface at Batiaghata and about 3 m below the soil surface at the Tala site, and in both cases it occurred in April. The greater drawdown at Tala may be attributed to the greater withdrawal of groundwater for rice irrigation in the dry season. Despite the deep drawdown in the previous dry season, the aquifers were fully recharged in July-August at both sites. The groundwater level at Batiaghata remained at or above the ground surface until November, whereas it remained near the soil surface until September at Tala. The full recharge at both sites, and no change in water level between years, suggests that there was

no 'mining' of the groundwater. BWDB (1999) reported a similar recharge pattern in almost all locations studied in the coastal region of Bangladesh.

The elevation of the phreatic level of different STWs at Tala during the drawdown (in the first half of April) and recharge (third week of August) periods is shown in Figure 3. In general there was no definite change in the mean elevation of the phreatic water level with distance from the river. This implies that there were no flows from the river to the inland or vice versa in either period, suggesting there was no direct connection between the aquifer and the surrounding river.

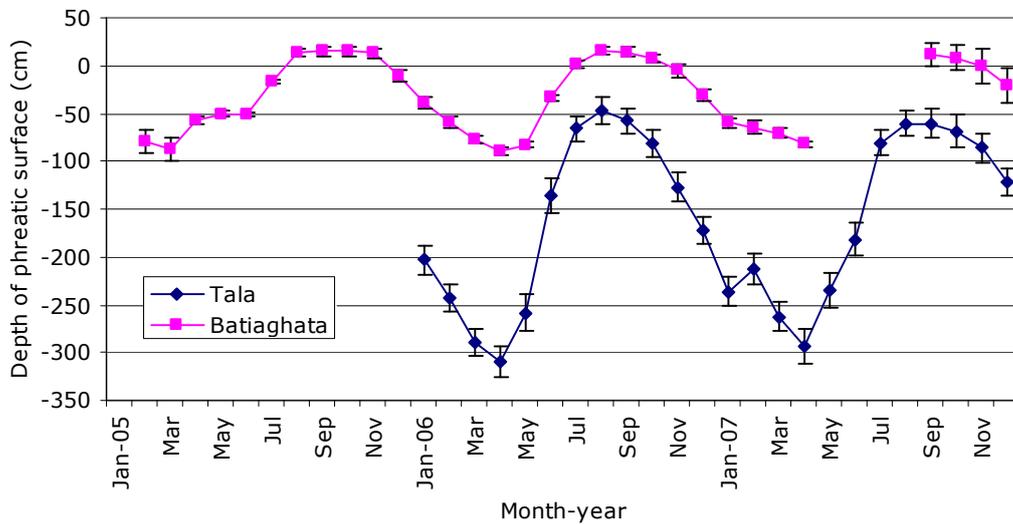


Figure 2. Mean monthly depth of phreatic surface from the ground level in Batiaghata and Tala upazilas of Khulna and Satkhira district, Bangladesh (vertical and capped bars indicate standard errors of the means of 11-56 values per month).

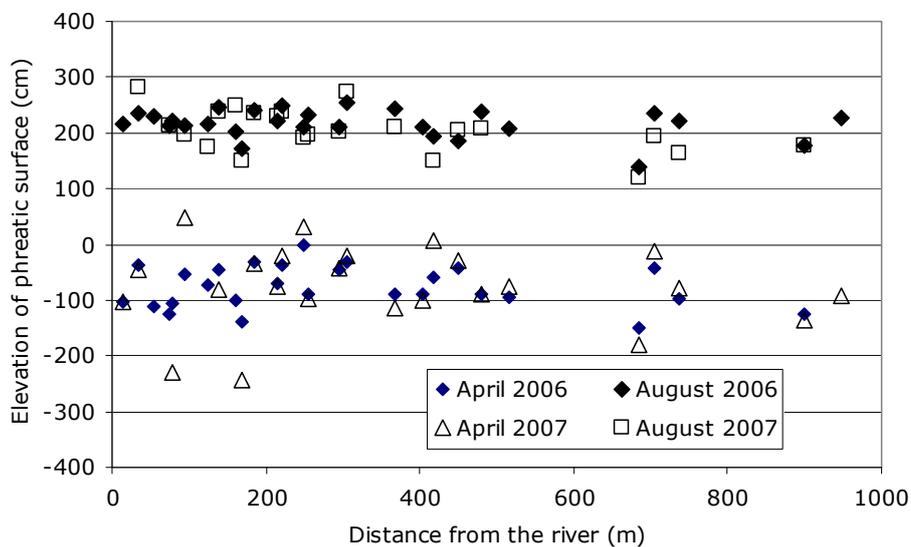


Figure 3. Elevation (in cm above MSL) of the phreatic surface at drawdown (April) and recharge (August) periods as a function of the distance from the Kobadak River at Jetua-Kanaidia polder in Tala upazila of Satkhira district, Bangladesh.

Dynamics of groundwater salinity

Mean monthly EC of the groundwater at Batiaghata and Tala is shown in Figure 4. They varied between 3 and 4 dS/m at Batiaghata and 1-2 dS/m at Tala. In general, there was some seasonal fluctuation of EC, but there was no clear annual increase in EC in the study period. The relatively low

EC at Batiaghata during the 2005–2006 dry season (November 2005 and May 2006) was unusual, since it is expected EC would be higher in the DS than in the rainy season.

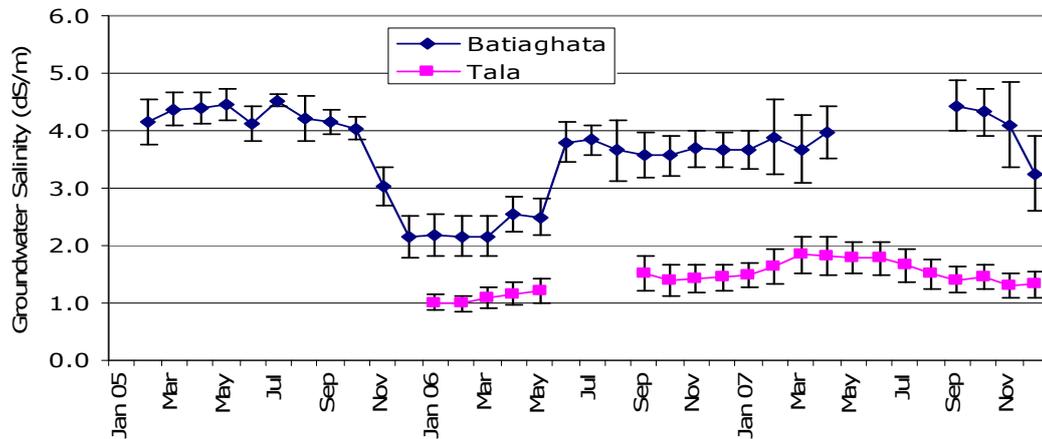


Figure 4. Mean monthly electrical conductivity (EC) of groundwater at Batiaghata and Tala sub-districts, Bangladesh (vertical and capped bars indicate standard error of the means of 8-24 values per month).

The change of EC of the STWs with respect to the distance from the nearest river bank at Tala during the drawdown period (April) is shown in Figure 5. Sixteen STWs (57% of STWs) had EC <1.0 dS/m, irrespective of their distances from the river. Four STWs had EC between 3 and 5 dS/m. The mean monthly EC of these STWs was around 3 dS/m. Their EC gradually went up to 3-5 dS/m as the dry season proceeded. Though the distances from the river to the salt-affected wells (< 200 m) were less than those of other wells, it was not possible to conclude that the salt contamination was caused by their proximity to the river. There were other STWs that were nearer to the river for which EC remained < 1 dS/m. It was observed that the four contaminated STWs were in places with relatively lower elevation than the surroundings. The contamination might have been due to faulty construction of the wells, which might have allowed vertical leakage, allowing salt water intrusion from the soil surface. The contamination would increase with the drawdown created by pumping groundwater. Faulty construction of the STWs is not uncommon because the wells were constructed by local untrained personnel (BWDB, 1999).

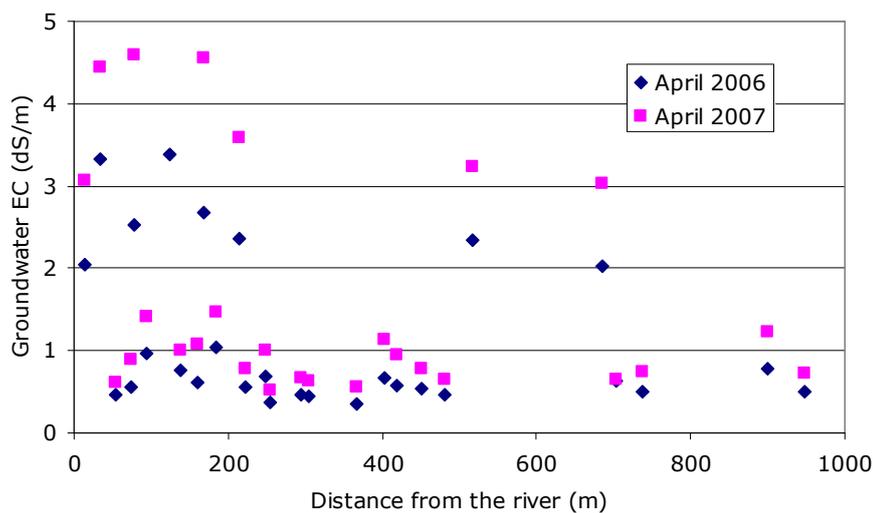


Figure 5. Electrical conductivity (EC) of groundwater as a function of the distance from the adjacent river at Jetua-Kanaidia polder in Tala sub-district, Bangladesh.

Conclusions and recommendations

The groundwater table at Batiaghata and Tala recovered during the rainy season. The complete recovery of the phreatic levels indicates that there is adequate recharge to replenish the aquifers. There was no indication of 'mining' due to irrigation of dry season rice in Tala. Groundwater salinity in Tala sub-district mostly remained < 3 dS/m and can be used for irrigation of dry season rice. Since the aquifer was fully recharged by August and there was no sign of salinity intrusion during the dry season from the river, the use of groundwater for dry season irrigation can be sustainable in Tala. Though there was no sign of salinity intrusion in Batiaghata, its GW has marginal quality. It can be used for short term, supplementary irrigations during the rainy season (at the beginning of the season or during dry spells) as suggested by Mondal et al. (2006). Long term irrigation with groundwater at Batiaghata may cause salinity buildup in the soil profile. The findings suggest that the suitability of groundwater for dry season irrigation is rather site specific, and its use for irrigation warrants careful studies.

Acknowledgments

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Field evapotranspiration and water use efficiency of aerobic rice under different water treatments in the North China Plain

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Abstract

Decreasing water availability threatens agricultural productivity in the North China Plain. Improved understanding of crop evapotranspiration (ET) at different growing stages, and of the effects of deficit irrigation on crop ET and yield, are needed to help design more efficient irrigation practices to increase crop water productivity. Four experiments were conducted in Beijing from 2001 to 2004 with four irrigation treatments each year: adequate irrigation throughout the growing season (W1), limited irrigation before panicle initiation (PI) (W2), limited irrigation after PI (W3), and limited irrigation throughout the growing season (W4). Crop ET was calculated from the soil water balance equation, and soil evaporation was measured using micro-lysimeters installed between the plant rows. Total ET over the whole growing season varied from 574 to 630 mm over years and treatments. The highest daily ET occurred at the booting to heading stage and averaged 9.8 mm. Therefore, booting to heading is the key stage of water requirement for aerobic rice. More than 40% of total ET occurred during the period from emergence to PI, however, most of this was due to soil evaporation. Therefore, to further improve water use efficiency (WUE), measures are needed to reduce soil evaporation at this stage. WUE was highest in the treatment with limited irrigation before PI but sufficient irrigation thereafter.

Media grab

Water use efficiency of aerobic rice could be improved by reducing soil evaporation during the vegetative stage.

Introduction

The system of aerobic rice is a new way of growing specially developed cultivars of rice in aerobic soil conditions, as is done for wheat and maize. The system was developed because of the threat to rice production of increasing water scarcity. From the 1980s to 2002, the area of aerobic rice expanded rapidly to about 80,000 ha in the North China Plain (NCP) (Wang et al., 2002). Though the growing season of aerobic rice is during the rainiest time of year, the distribution and/or amount of rainfall is usually inadequate to fully meet the water requirements of aerobic rice. Supplementary irrigation is essential for aerobic rice in the NCP (Yang et al., 2005; Bouman et al., 2006).

Evapotranspiration is an important part of the field water cycle and has significant influences on crop growth, development, and yield. Improved understanding of ET at different growing stages, and of the effects of deficit irrigation on crop ET and yield, is needed to help design more efficient irrigation practices to increase crop water productivity. Information about the contribution of soil evaporation (E, a non-beneficial loss of water) to ET can also help design measures to increase WUE. Although much is known about E and ET characteristics and the relationship between ET and crop yield (e.g. Sun et al., 2004; Zhang et al., 2006), there have been few studies of aerobic rice systems. We report here the results of field experiments at Beijing to determine ET and E, and the effects of irrigation management on ET, yield, and WUE of aerobic rice.

Methods

Field experiments were carried out at Changping Experiment Station (40°02'N, 116°10'E; 43 m ASL) of the China Agricultural University in Beijing from 2001 to 2004. The soils were sandy loams (*fluvisol*) derived from river sediments. In all years, the groundwater table was deeper than 20 m. Aerobic rice variety HD297 was grown in all four years. Four irrigation treatments (W1, W2, W3, and W4) were applied with four replicates in all years: adequate irrigation throughout the growing season (W1), limited irrigation before PI (W2), limited irrigation after PI (W3), and limited irrigation throughout the growing season (W4). The nitrogen (N) application was 225 kg/ha applied in three splits at sowing (30%), tillering (40%), and booting (30%), respectively. In all years, the seeds were hand dibbled at 3 cm deep in rows 30 cm apart, at a seeding rate of 120 kg/ha. The sowing date was from May 14 to 16 and maturity date was from October 5 to 11. In all experiments, plots were banded and separated by 1 m-wide strips of bare soil. The plots were kept weed-free by an application of pre-emergence herbicide and hand weeding after crop establishment. Fertilizers (P, K, Fe, Zn) and pesticides were applied as appropriate for optimum crop protection (Yang et al., 2005). The method of irrigation was surface flooding, and irrigation water was applied through flexible hoses connected to a subsurface

pressurized pipe system lifting water from a deep groundwater well. The depth to the water table is more than 20 m.

Daily rainfall was measured with a rainfall meter next to our fields. The amount of irrigation water applied was measured with flow meters installed in the flexible hoses. We used a neutron probe to measure soil moisture content in each water treatment in two replicates at selected times in the growing season at 20-cm depth intervals between 0 and 160 cm. The probe was regularly calibrated for different soil layers using readings for a range of soil water content and soil bulk density data. The data were collected several times during the growing season to get an adequate range of water content for the calibration. In 2003, soil evaporation was measured by micro-lysimeter (Boast and Robertson, 1982). Three micro-lysimeters were installed between rows in each plot. To ensure that soil moisture content was the same in the micro-lysimeters as in a field, soil in micro-lysimeters was changed every three days. Each micro-lysimeter was weighed at 8:00 am every day. Soil evaporation was calculated from the weight loss over two days. At harvest, total aboveground biomass was measured from two 1-m row sections. Grain yield was measured from the whole plot in 2001 and 2002, from a 3.3 m² area in 2003, and from 10 m² in 2004, and was expressed at 14% moisture content.

According to Zhang et al. (1999), the contribution of capillary rise to the crop root zone is almost zero in the NCP when the water table is below 4 m. Hence, soil water balance in our experiments can be described by the following equation

$$\Delta W = P + I - ET - D - R \quad (1)$$

where P is the amount of precipitation, I is irrigation, ET is crop evapotranspiration, D is deep percolation beyond root zone, R is the amount of runoff, and ΔW is the change of soil water storage. The 30-cm high soil bunds around each plot prevented runoff. Deep drainage was also considered to be negligible, as the amount of rainfall and irrigation never exceeded the available water-holding capacity to the maximum soil-sampling depth (160 cm) for determination of ΔW . Therefore, the soil water balance equation was simplified as:

$$\Delta W = P + I - ET \quad (2)$$

Consequently, ET could be calculated using formula (2). ET consists of crop transpiration (T) and soil evaporation (E). In our study, E was measured by micro-lysimeter, and T was calculated as $ET - E$. Water productivity was calculated as grain yield (14%) divided by the seasonal combined water inputs by irrigation and rainfall (WP_{IR}), and as grain yield divided by the seasonal ET (WP_{ET}).

Results

Water input

Total rainfall was 253, 386, 404, and 495 mm during the whole growing period of aerobic rice in 2001, 2002, 2003, and 2004, respectively, with 34, 54, 49 and 62% falling before PI each year (Table 1). Irrigation water decreased from 2001 to 2004 because of increased rainfall. Total irrigation water was similar in W2 and W3, while the percentage of irrigation applied before PI was lower in W2 than in W3. In W2, water applied before PI accounted for 31, 0, 33 and 29% of total irrigation in 2001, 2002, 2003 and 2004, respectively. However, the percentage was 57, 100, 67 and 43% in W3 in four years.

Table 1 Total irrigation (I , mm) and rainfall (R , mm), and evapotranspiration (ET , mm) during each growth stage of aerobic rice and its percentages (P , %).

Year	Treatment	Emergence-PI		PI-booting		Booting-flowering		Flowering-maturity		Total ET	Total I	Total R
		ET	P	ET	P	ET	P	ET	P			
2001	W1	283	49.4	80	14.0	83	14.4	128	22.3	574	283	253
	W2	217	44.3	72	14.7	83	17.0	118	24.0	490	217	
	W3	286	54.5	86	16.4	69	13.1	84	16.0	525	233	
	W4	228	50.0	72	15.8	67	14.6	90	19.7	456	167	
2002	W1	301	47.9	55	8.8	111	17.6	162	25.8	630	222	386
	W2	196	39.0	38	7.5	114	22.6	155	30.8	502	74	
	W3	300	54.3	65	11.8	75	13.5	113	20.4	553	148	
	W4	198	46.3	40	9.3	80	18.7	110	25.7	427	0	
2003	W1	274	46.7	64	10.8	82	14.0	168	28.6	587	220	404
	W2	234	46.3	35	6.9	72	14.3	165	32.5	506	150	
	W3	279	51.6	59	11.0	55	10.1	147	27.3	540	180	
	W4	235	49.1	38	8.0	58	12.2	147	30.7	479	110	
2004	W1	286	48.2	59	9.9	88	14.8	162	27.2	594	130	495
	W2	274	48.5	54	9.5	82	14.5	156	27.5	565	90	
	W3	267	48.5	58	10.5	76	13.9	149	27.1	549	85	
	W4	258	51.5	50	10.1	72	14.4	120	24.0	501	30	
Avg	W1	286	48.1	65	10.9	91	15.2	155	26.0	597	214	385
	W2	230	44.5	50	9.7	88	17.1	149	28.7	517	133	
	W3	283	52.2	67	12.4	69	12.7	123	22.7	542	162	
	W4	230	49.2	50	10.8	69	15.0	117	25.0	466	77	

Crop evapotranspiration

In all years, total *ET* during the entire growth period increased with water input, and it was highest in W1, followed by W3, W2 and W4 (Table 1). Compared with the highest value in W1, *ET* was reduced by 13.3, 9.2 and 21.8% in W2, W3 and W4, respectively. During the periods from emergence to PI and PI to booting, *ET* in W1 and W3 was higher than that in W2 and W4, however, from booting to flowering and flowering to maturity, *ET* of W1 and W2 was higher than of W3 and W4. Among the four stages, *ET* was highest at the stage of emergence to PI, then the stage of flowering to maturity. *ET* at the stage of emergence to PI in W2 was 19.6 and 18.7% higher than that in W1 and W3.

Over the entire season, average daily *ET* decreased in the order W1, W3, W2 and W4 (Fig.1). From emergence to PI and PI to booting, daily *ET* of W1 and W3 was higher than of W2 and W4, however, from booting to flowering and flowering to maturity, daily *ET* of W1 and W2 was higher than W3 and W4. Daily *ET* was highest at the stage of booting to flowering and lowest at the stage of flowering to maturity.

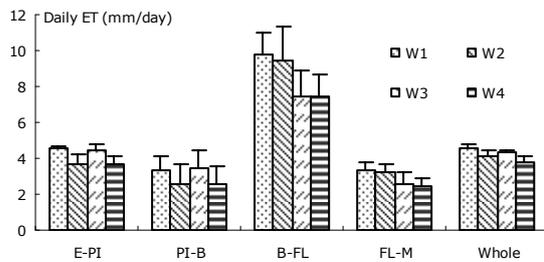


Figure 1. Averaged daily *ET* during each growth stage of aerobic rice over four years.

Soil evaporation and crop transpiration

Data on soil evaporation, crop transpiration, and their percentages of total *ET* in 2003 are given in Table 2. There was very little difference in soil evaporation among water treatments at any stage. In all treatments, the percentage of total *ET* as soil evaporation was highest from emergence to PI, and it was highest in W1 (49.3%) and lowest in W3 (41.8%). Over the entire season, the proportion of *ET* as soil evaporation ranged between 2.5 and 33.6%. Crop transpiration for the entire season increased with water input, and was highest in W1 (438 mm) and lowest in W4 (325 mm). From emergence to PI and PI to booting, transpiration in W1 and W3 was higher than that in W2 and W4. It was higher, however, in W1 and W2 than in W3 and W4 from booting to flowering. Partly due to the long periods from emergence to PI and flowering to maturity, crop transpiration was higher than in the two stages; it averaged 146 mm and 175 mm across water treatments, respectively.

Table 2. Soil evaporation and crop transpiration at each growth stage of aerobic rice, and percentages.

	Treatment	Emergence - PI	PI - booting	Booting - flowering	Flowering - maturity	Entire season
E (mm)	W1	122	7	5	16	150
	W2	110	14	10	19	152
	W3	116	7	6	19	148
	W4	117	11	7	19	153
T (mm)	W1	172	37	46	182	436
	W2	124	21	42	166	353
	W3	173	32	9	178	392
	W4	116	26	9	175	326
E/ET (%)	W1	44.5	10.9	6.1	3.9	25.5
	W2	47.0	40.0	13.9	11.5	30.2
	W3	41.8	11.9	10.9	12.9	33.6
	W4	49.3	28.9	12.1	12.9	32.0
T/ET (%)	W1	55.5	89.1	93.9	96.1	74.5
	W2	43.0	60.0	86.1	88.5	69.8
	W3	58.2	88.1	89.1	87.1	66.4
	W4	50.7	71.1	87.9	87.1	68.0

Water productivity

Yields of respective water treatments were much lower in 2003 than in the other three years, due to much lower grain filling (Fig. 2a). Yield was affected by water treatment in all four years. Compared with the sufficient water treatment W1, yield of W2, W3, and W4 was decreased by 17.9, 11.5, and 28.2% in 2001, and by 17.9, 2.0, and 37.4% in 2002. In 2003, yield was highest in W2, and was 8.6, 46.8, and 90.6% higher than in W1, W3, and W4, respectively. The differences in yield between water treatments in 2004 were smaller than in the other three years, and yield was the same in W1 and W2, but was decreased by 8.4 and 16.6% in W3 and W4, respectively compared with W1 and W2.

Due to the low yield in 2003, WP_{ET} was significantly lower in 2003 than in the other three years when WP_{ET} ranged from 0.71 to 1.0 kg/m^3 . In 2001, 2003, and 2004, WP_{ET} was highest in W2 and lowest in W4. In W2, WP_{ET} was increased 7.9 and 11.5% in 2001, 27.2 and 100.3% in 2003, and 5.9 and 6.9% in 2004, compared with W1 and W3, respectively. In 2002, WP_{ET} was highest in W3 followed by W2. It was 2.9% higher in W2 than in W1. The trends in WP_{IR} were similar to the trends in WP_{ET} . The average values of WP_{IR} over the four years were 0.62, 0.75, 0.29, and 0.83 kg/m^3 in W1, W2, W3, and W4, respectively.

Discussion

Crop ET was highest from emergence to PI and accounted for about 44.5-52.2% of total ET during the entire season, mainly due to the long duration of this stage, and high radiation, high temperature, and low rainfall at this stage. Crop ET was decreased by 19.6 and 18.7% in W2 compared with that in W1 and W3 at this stage. The highest daily ET occurred from booting to flowering. At this stage, aerobic rice experiences the transition from vegetative growth to reproductive growth and water requirement is highest. Crop transpiration is also strong at this stage because of fully expanded leaves and large canopy. This stage, therefore, is the most important for avoiding water deficit stress in aerobic rice. Soil evaporation accounted for about 25.5-33.6% of crop ET for the growing season. This result is comparable to data for winter wheat (31.4%) and summer maize (45%) in the North China Plain (Sun et al., 2004; Zhang et al., 1999). From emergence to PI, 40-50% of the ET was from soil evaporation, because at this stage the plants are still small and LAI is low, and the soil surface is exposed. With limited irrigation during this stage, followed by adequate irrigation after PI (W2), yield was decreased slightly but water productivity was significantly increased compared with W1 and W3. After PI, sufficient water supply in W2 enabled flowering and grain filling reasonable yield. This irrigation regime was therefore most beneficial for high yield of aerobic rice.

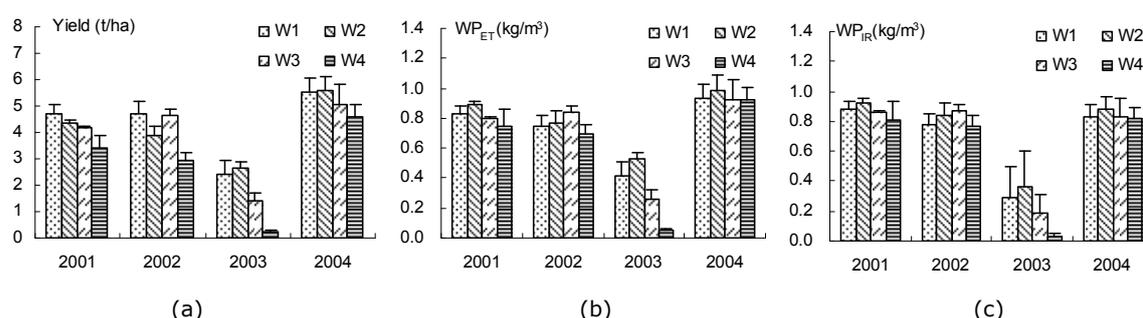


Figure 2 Yield (a) and water productivity (b, WP_{ET} and c, WP_{IR}) of different water treatments in 2001-2004.

Conclusions and recommendations

Under well irrigated conditions, average seasonal ET of aerobic rice was 596 mm. It was decreased to 516 mm with slight water stress between emergence and PI. Crop ET from emergence to PI is about 48.5% of ET during the entire season, however, 40-50% of this is from soil evaporation. This suggests that water productivity could be increased by measures to decrease soil evaporation at the early stage. The stage from booting to flowering has the highest demand for water to meet ET (9.8 mm/day), and this stage is also sensitive to water stress. Consequently, water supply should be assured at this stage for high yield. To save irrigation water and increase its water productivity, irrigation can be limited before PI with a slight yield decrease.

Acknowledgments

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Optimizing yield, water requirements, and water productivity of aerobic rice for the North China Plain

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Abstract

Water resources for agriculture are rapidly declining in the North China Plain. Water-efficient agricultural technologies need to be developed. Aerobic rice is a new crop production system in which rice is grown in nonflooded and nonsaturated aerobic soil. To date, knowledge is scarce on obtainable yields and water requirements to assist farmers in improving their management. We present results from field experiments with aerobic rice variety HD297 near Beijing, from 2002 to 2004. The crop growth simulation model ORYZA2000 was used to extrapolate the experimental results to different weather conditions, irrigation management, and soil types. We quantified yields, water inputs, water use, and water productivities. On typical freely-draining soils of the North China Plain, aerobic rice yields can reach 6-6.8 t/ha, with a total water input between 589 and 797 mm (rainfall 477 mm and irrigation 112-320 mm). For efficient water use, the irrigation water can be supplied in 2-4 applications, and should aim at keeping the soil water tension in the root zone below 100-200 kPa. Under those conditions, the amount of water use by evapotranspiration was 458-483 mm. The water productivity with respect to total water input (irrigation plus rainfall) was 0.89-1.05 g grain/kg, and with respect to evapotranspiration, 1.28-1.42 g grain/kg. Drought around flowering should be avoided to minimize the risk of spikelet sterility and low grain yields.

Media grab

Rice yields of 6-7 t/ha can be achieved with only 2-4 irrigations with the system of aerobic rice production in the North China Plain.

Introduction

Fresh water availability for irrigation is decreasing because of increasing competition from urban and industrial development, degrading irrigation infrastructure, and degrading water quality in the North China Plain (NCP), an important agricultural area in China. Aerobic rice is a new crop production system in which rice is grown in nonflooded and nonsaturated aerobic soil, similar to wheat and maize (Bouman et al., 2006). It may be an attractive option to farmers where water is too scarce to grow lowland rice. Since its introduction in the NCP in the mid-1980s, the area of aerobic rice has expanded rapidly, and was estimated to be 80,000 ha in 2002 (Wang et al., 2002). Yang et al. (2005) and Bouman et al. (2006) reported on yield, water use, and water productivity of aerobic rice cultivars grown under different irrigation regimes in a field experiment near Beijing in 2001-2002. Using variety HD297, they obtained yields of 3-3.5 t/ha with 450-500 mm total water input (rainfall plus irrigation), and 4.7-5.3 t/ha with 650 mm water input and more. More data are needed on other environmental conditions to understand better yield potentials and irrigation water needs of aerobic rice in the NCP. Crop growth simulation models are an ideal tool to explore yield potentials and water needs under a variety of environmental and management conditions. We used ORYZA2000 to extrapolate these experimental results obtained in Beijing to different weather conditions, irrigation management, and soil types that are typical of the NCP. The ultimate objective is to quantify yield potential, water productivity, and water needs of aerobic rice, and to provide suggestions for irrigation water management.

Methods

The three years of experimental data collected near Beijing from 2002 to 2004 were used to determine parameters (using one year of data) and to evaluate the ORYZA2000 model (using the two remaining years of data). The evaluated variables included total above-ground biomass, biomass of crop organs, leaf area index, grain yield, and soil water tension. ORYZA2000 was then used to explore the effects of different irrigation regimes on yield, water requirements, and water productivity of aerobic rice with different soils using historical weather data from Beijing. Water requirements were expressed by evapotranspiration (ET) and by water inputs by rainfall and irrigation. ET flows are real water losses that deplete water from the system (Molden et al., 2003), whereas total water inputs satisfy the ET needs plus any deep percolation losses and additions to the soil water storage.

Results and discussion

Our experimental yields ranged from 0.5 to 4.5 t/ha with 578-688 mm total water input in 2003, and from 4.6 to 6.0 t/ha with 605-705 mm total water input in 2004. For comparison, the 2001-2002

experiments in Beijing yielded 2.5-5.3 t/ha with 500-900 mm total water input (Bouman et al., 2006; Yang et al., 2005). At another site close to Beijing, Tao et al. (2006) reported yields of 5.7-6.1 t/ha with irrigation applied when the soil water tension at 15 cm depth exceeded 15 kPa, resulting in around 1400 mm total water input. At Kaifeng, Feng et al. (2007) reported experimental yields of 2.4-3.6 t/ha, using 750-1100 mm total water input. The lower yields at Kaifeng might be a consequence of shorter crop growth duration at Kaifeng (90 days) than at Beijing (135 days).

ORYZA2000 reproduced total biomass accumulation, grain yield, and leaf area development of aerobic rice reasonably well (Fig. 1), and with about the same level of accuracy as reported for lowland rice and for aerobic rice at Kaifeng. In our validation set, the $RMSE_n$ of simulated yield was 19% (Xue, 2008), which was two times the CV of measured yield, and 3-8 percentage points higher than reported for lowland rice. The SAHEL water balance module for freely-draining soils adequately simulated the dynamics of soil water tension in the root zone between 0 and 100 kPa. Our $RMSE_n$ values of 64-72% for soil water tension were somewhat lower than values of 77-104% (Belder et al., 2007), 123% (Boling et al., 2007), and 69-107% (Feng et al., 2007) reported for lowland rice using the more detailed PADDY or SAWAH modules.

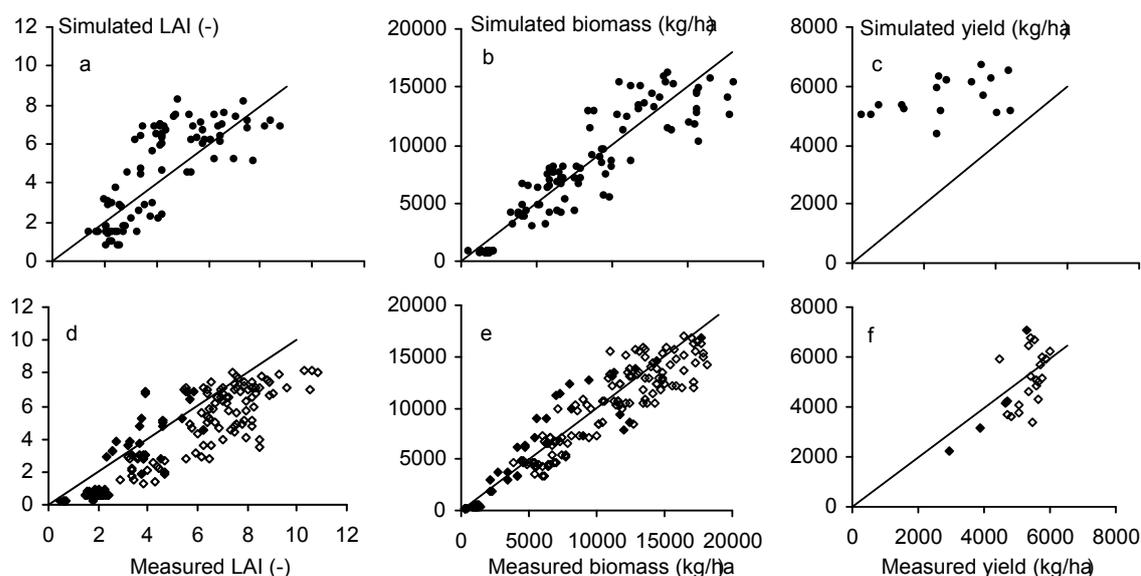


Figure 1. Simulated versus measured values in calibration set (a, b, c) and validation set (d, e, f) of LAI, biomass of whole crop, and yield. Solid lines are the 1:1 relationship.

Average maximum simulated yields were 6.8-7.5 t/ha with soil water potentials in the root zone staying between 0 and 100 kPa. These yields were 0.8-1.5 t/ha higher than the maximum of 6 t/ha obtained in our field experiments. There may be at least three reasons for this difference. First, in nearly all of our treatments, there were periods when the tensiometers failed to record because the threshold of 100 kPa was exceeded, so that higher soil water tensions occurred that could have reduced yields. When simulated soil water tensions were allowed to reach 200 kPa, yields dropped to 6-6.1 t/ha (Fig. 2a). Second, aerobic rice is a relatively new crop and best management practices still need to be developed. Therefore, the management applied in our field experiments may not have resulted in the highest possible yields. Third, the variety HD297 might have been sink limited under high-yielding conditions. Analyzing yield formation in HD297, Bouman et al. (2006) reported that the source strength (quantified by light use efficiency) of this variety was comparable to that of lowland varieties with yield potentials of more than 8 t/ha. The panicle size of HD297, however, may be too small to attain such yields (visual observation by authors). Simulated yields sharply decreased with irrigation water application withheld until soil tension exceeded 100 kPa. Even under completely rainfed conditions, however, yields were still 2.7-4 t/ha, depending on soil type. ORYZA2000 may not, however, adequately simulate yield with severe drought around flowering (as indicated by the poor simulation results for the 2003 experiment).

Total water input declined sharply as irrigation threshold increased from 10 to 50 kPa, and then declined slowly as the threshold increased beyond 50 kPa (Fig. 2b). Since yield followed the opposite trend to irrigation threshold, water productivity WP_{IR} was maximum at intermediate thresholds (Fig. 2c). When water resources are more limiting than land, the best irrigation management for farmers would optimize water productivity rather than grain yield (Bouman and Tuong, 2001). In our simulations, the highest WP_{IR} was obtained at irrigation thresholds of 100-200 kPa, with yields of 6-6.8 t/ha, and only 112-320 mm irrigation water applied (and 477 mm rainfall). In farmers' practice such irrigation amounts would be applied in 2-4 splits of 50-75 mm each, which is about the irrigation frequency used by early aerobic rice farmers in the Kaifeng area (Bouman et al., 2007). This irrigation

water requirement is even lower than that for winter wheat in the NCP (Sun et al., 2006), but higher than that for summer maize (Wang et al., 2001).

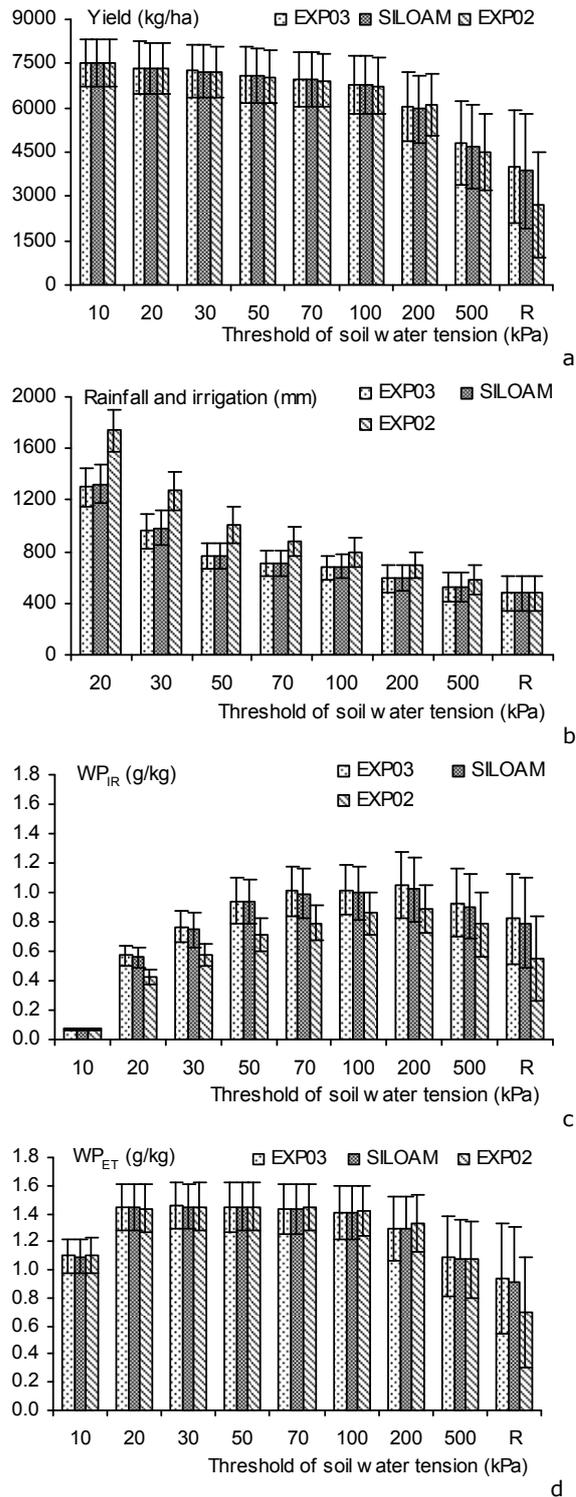


Figure 2. Average simulation results over 34 years as a function of threshold level of soil water tension for irrigation on five soils: yield (a), rainfall plus irrigation (b), water productivity based on total water input WP_{IR} (c), water productivity based on evapotranspiration WP_{ET} (d). The error bars indicate the standard deviation.

Evapotranspiration (ET) was quite stable over a wide range of irrigation thresholds, and only declined slightly from about 690 mm at 20 kPa to 370-416 mm under purely rainfed conditions. At 20 kPa, the total water inputs were 1300-1739 mm (depending on soil type), and hence some 610-1049 mm of water left the root zone by deep percolation. The amount of deep percolation gradually decreased to 61-107 mm under purely rainfed conditions. Although deep percolation is a loss to farmers, it reenters

the hydrological cycle and is potentially available for reuse, for example by groundwater pumping (Hafeez et al., 2007). Therefore, for irrigation system managers where deep drainage losses can be reused, the optimum irrigation scenario could be when the highest water productivity with respect to evapotranspiration is obtained (Loeve et al., 2004). In our simulations, highest levels of WP_{ET} were obtained with irrigation thresholds between 10 and 100 kPa (Fig. 2d). Irrigation thresholds of 100-200 kPa therefore seem a suitable balance between the interests of farmers (striving for high WP_{IR}) and irrigation system managers (striving for high WP_{ET}).

Soil type had relatively little effect on yield except under purely rainfed conditions, with the lighter-textured soil with lowest soil water holding capacity having lowest yields. Soil type had the strongest effect on irrigation water inputs with irrigation application thresholds below 70 kPa. The effect of soil type was most pronounced on input water productivity: WP_{IR} decreased on soils with decreasing water-holding capacity.

Conclusions and recommendations

Field experiments and simulations show that, on typical freely-draining soils of the NCP, aerobic rice yields with HD297 can reach 6-6.8 t/ha, with a total water input between 589 and 797 (rainfall = 477mm and irrigation water = 112-320mm). For efficient water use, the irrigation water can be supplied in 2-4 applications and should aim at keeping the soil water tension in the root zone below 100-200 kPa. Drought around flowering should be avoided by targeted irrigation applications to avoid the risk of spikelet sterility that would result in low grain yields.

To further increase yield and productivity of aerobic rice in the NCP, future research priorities should include:

1. *Management.* Optimizing the productivity of aerobic rice in a cropping system context. Studies should address the potential to increase yields through improved crop management practices such as establishment and nutrient management. Moreover, such studies should look at the potential role of aerobic rice in multiple cropping systems and crop rotations, and should address whole cropping system productivity.
2. *Germplasm improvement.* The development of new varieties should focus on the potential for yield increase through increasing the sink size and harvest index of the current variety HD297.
3. *Model improvement.* The current version of ORYZA2000 captures the effect of water stress at flowering through the effect of increased canopy temperature on spikelet sterility only (Bouman et al., 2001). More insight in the mechanisms of spikelet sterility should be obtained and built into ORYZA2000, especially at soil water tensions above 100 kPa.

1.1 Acknowledgments

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Water regimes and nutrient requirements for aerobic rice production system

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Abstract

With the decline of the already limited water available for rice production, there is a need to adopt water-saving measures such as aerobic rice to meet the challenge of feeding billions of people living and relying on rice. This study was conducted to help develop nitrogen (N), phosphorus (P), and irrigation recommendations for the aerobic rice production system, using PSB Rc-9 rice variety in the Province of Bulacan, Philippines. A water regime by N rate experiment was established to evaluate the effect of water regimes and N rates on agronomic and yield response of PSB Rc-9. The effect of P rate was also studied in the superimposed microplots within the maximum N rate (165 kg N/ha) treatment. Increasing N rate from 0 to 60 kg N/ha significantly increased yield from 2.6 to 3.4 t/ha, and there was no further increase in yield at higher N rates. Increasing the P rate above the basal amount of 60 kg P/ha did not affect crop growth and yield. Thus the optimum fertilizer regime for aerobic rice was 60 kg N/ha and 60 kg P/ha. Mean yields of all irrigation treatments were similar (3.2 t/ha), and water productivity was highest (0.48 kg/m³) with an irrigation regime at every 14 days irrigation interval (2 cm) until tillering, then weekly (4 cm) until flowering, twice a week from one week before to one week after flowering (4 cm), and once every 10 days after flowering until maturity (4 cm). The results should be validated through further experiments and field demonstrations in farming communities where aerobic rice cultivation is highly applicable to further develop recommended management practices.

Media grab

Optimum rate of nitrogen and phosphorus fertilizers and appropriate water management for aerobic rice systems are relevant factors to improve resource use efficiencies and productivity.

Introduction

Increased competition for water and climate change are reducing the amount of water available for agriculture in the Philippines. Rice is the major staple for the large and growing population of the Philippines, and the major user of water. Therefore, new ways must be sought to produce more rice with less water (Guerra et al., 1998). The Aerobic Rice System involves growing input-responsive, drought-tolerant rice varieties in nonflooded and non-puddled soil using supplementary irrigation and fertilizers to achieve high yields (Bouman, 2001).

Nitrogen (N) is the most limiting nutrient to rice growth and yield in almost all environments (Yoshida, 1981). One major consequence of inadequate N is reduced leaf area, thereby limiting light interception, photosynthesis, and finally biomass growth, grain yield, and water productivity (Sinclair, 1990). Since the concept of aerobic rice is new, relatively few insights exist into water, N, and P dynamics and their interactions, and the management of irrigation and fertilizers to optimize yield and resource use efficiency.

Where water is more limiting than land, it has been argued that water productivity becomes more important than yield or 'land productivity' (Guerra et al., 1998; Tuong and Bouman, 2003). Substantial yield and water productivity gains are possible with the application of appropriate nutrients in combination with optimum water management adapted to the target environments. Thus, the objective of this research was to: (1) evaluate the agronomic and yield performance of PSB Rc-9 under different water regimes and N rates; (2) determine water productivity and N use efficiencies under aerobic rice production systems; and (3) evaluate the effect of P addition on the growth and yield of PSB Rc-9.

Methodology

The field site was located at San Ildefonso, Bulacan Province, Philippines (15°44' N, 120°31' E). The field was prepared under dry soil conditions, with two plowings, harrowing, and land leveling. Seeding was done manually in rows 25 cm apart. Seeds (60 kg/ha) were hand-dibbled 2 cm deep and covered with soil. After seeding, a flush irrigation of about 3 cm depth was done to enhance germination. A preemergence herbicide was applied 2 days after the first irrigation, and postemergence herbicide was sprayed 10 days after emergence (DAE). Phosphorus (0-18-0) and potassium (0-0-60) fertilizers at 60 kg/ha were applied in two splits: 30 kg/ha basal by incorporating with the soil in the rows about 2 cm deep before seeding, and 30 kg/ha was applied on the rows at maximum tillering.

Two studies were conducted in the same experimental area during the 2007 dry season (January-May): (1) a water management (W) by N rate study (WxN), and (2) a P addition study in microplots in selected treatments of the WxN experiment (WxP). The WxN study was a split-plot randomized

complete block design with four replications. Water regime treatments (mainplot) were; W_1 , twice a week irrigation, W_2 , once a week (weekly) from germination to one week before flowering, twice a week from one week before to one week after flowering, weekly after flowering until maturity, and W_3 , every 14 days until tillering, weekly until flowering, twice a week from one week before to one week after flowering, once every 10 days after flowering until maturity. N treatments (subplot) were: no N (N_0), 60 kg/ha (N_{60}), 120 kg/ha (N_{120}), and 165 kg/ha (N_{165}). For all water treatments, the irrigation depth at sowing was 3 cm, 2 cm from emergence until tillering, and 4 cm from tillering onwards. N was applied as ammonium sulfate (21-0-0-12S) at 11, 35 and 50 DAE in three equal splits. Aboveground plant samples were taken from a 50 cm row in two locations in all plots for the determination of tiller count, plant height, biomass and N uptake at the following growth stages: mid-tillering (MT), panicle initiation (PI), flowering (FI), and physiological maturity (PM). Crop growth rate was computed using weekly plant height from 11 to 95 DAE. The efficiency of applied N fertilizer to the rice crop was assessed using five different indices (Dobermann and Fairhurst, 1999); (1) partial factor productivity (PFP), (2) agronomic efficiency (AE), (3) recovery efficiency (RE), (4) physiological efficiency (PE), and (5) internal efficiency (IE). Grain yield was determined from the designated harvest area of 6 m² from the center of the plots. Water productivity was calculated as grain yield at 14% moisture content divided by total water input from rainfall plus irrigation.

In the WxP study, additional P fertilizer was applied to microplots (1m x 1m) in the N_{165} treatment under W_1 and W_3 . The microplots were surrounded by a metal plate 45 cm high and inserted 15 cm into the soil. In this study, W_1 and W_3 were the mainplots and 'additional P rate' were the subplots with three treatments: 0 kg/ha (P_{60}), 60 kg/ha (P_{120}), and 120 kg/ha (P_{180}). Average weekly growth rate of the crop was based on weekly plant height taken from 11 DAE up to 95 DAE. Tiller count in the microplots was monitored at 11, 32, 60, and 95 DAE. Grain yield adjusted to 14% moisture content was obtained from the whole area of the microplot.

Depth or volume of irrigation water was measured using the discharge of the delivery hose connected in the pump, time of irrigation, and surface area of the plot. Calibration of water discharge from the delivery hose was done by measuring the discharged water using graduated cylinder at a certain time and fixed engine rpm. It was done in a series of trials at different sections or length of delivery hose. With the given depth of irrigation, size of plot, and average discharge of the delivery hose, the time of irrigation for every plot was computed.

Results and discussion

Crop performance

There was no significant interaction between W and N treatments with the different agronomic parameters. Plant height at physiological maturity (PM), growth rate and tiller production and grain yield increased with increasing N rate (Table 1). Maximum grain yield was achieved with only 60 kg N/ha. There was no effect of water regime on any parameter measured, including grain yield, except for growth rate (increase in plant height), with faster growth in W_1 than W_2 , but plant height was similar in all water regimes at maturity. There was no significant effect of either water regime or N rate on total biomass at PM. There was additional grain yield of 28, 25 and 30% for applied 60, 120, and 165 kg N/ha, respectively, compared with yield of the plot without N fertilizer.

Table 1. Agronomic response as affected by water regime and N rate.

Agronomic data	Water regime			N regime			
	W_1	W_2	W_3	N_0	N_{60}	N_{120}	N_{165}
Plant height (cm)	93.2	87.4	91.6	79.0x	90.5y	94.5yz	98.9z
Growth rate (cm/week) ¹	6.09a ²	5.61b	5.97ab	4.98z	5.88y	6.18y	6.51x
Productive tillers (no./m ²)	495	536	539	476y	508 x	564 x	547x
Biomass (t/ha)	10.7	11.2	11.9	12.3	10.9	10.6	11.3
Grain yield (t/ha)	3.18	3.14	3.22	2.64y	3.37x	3.29x	3.43x

¹From 11-95 DAE.

²Means followed by a common letter in a row are not significantly different at 5% level of significance using LSD.

Added P fertilizer did not affect any of the crop parameters monitored, and plants under the wetter regime (W_1) grew faster but produced fewer tillers (Table 2). Likewise, no significant effect was found of added P on the grain yield of PSB Rc-9 at PM. Data showed that rate of P fertilizer should be limited to 60 kg/ha.

Nitrogen uptake

There was no significant interaction between W and N on nitrogen uptake. Nitrogen uptake was significantly affected by water regime at panicle initiation and flowering but not at maximum tillering

Table 2. Agronomic data as affected by water regime and additional P in the microplots.

Agronomic data	Water regime		N Regime		
	W ₁	W ₃	P ₆₀	P ₁₂₀	P ₁₈₀
Plant height (cm)	107a ¹	100b	105	101	105
Growth rate (cm/week)	6.94a	6.46b	6.77	6.56	6.78
Tiller count (no./m ²)	546a	603b	588	576	559
Grain yield (t/ha)	3.16 a	2.49 b	2.71	3.07	2.69

Means followed by a common letter in a row are not significantly different at 5% level of significance using LSD.

and PM (Figure 1). Generally, N uptake was lower in the wettest regime (W₁), perhaps due to greater leaching. There was a significant effect of N rate on N uptake at all stages, with N uptake increasing with N rate up to the maximum rate (except at maximum tillering) (Figure 2).

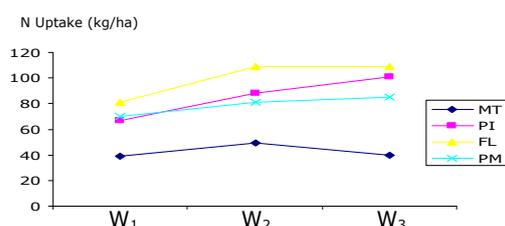


Figure 1. Average N uptake (kg/ha) at different growth stages as affected by

water regimes

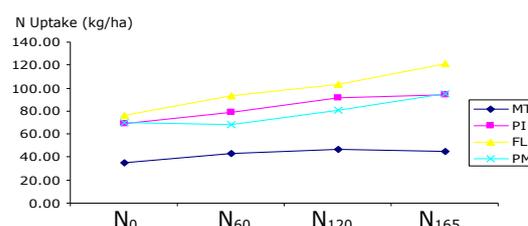


Figure 2. Average N uptake (kg/ha) at different growth stages as affected by

nitrogen rates

Nitrogen use efficiency

Partial factor productivity (PFP), physiological efficiency (PE), and agronomic efficiency (AE) of N fertilizer were highest with 60 kg N/ha, and declined as N rate increased beyond this. Results showed that additional yield of 12.2 kg grain/kg N applied was produced at 60 kg N/ha. Maximum recovery efficiency (53%) occurred with application of 120 kg N/ha. De Datta (1981) reported an N recovery efficiency of 41% under continuously flooded conditions, and 20% under submerged-nonsubmerged regime (SNS) conditions. Theoretically, PE should be close to 50 kg/kg N taken up from fertilizer. N₆₀ produced an additional 39.6 kg of grain for each additional kg of N uptake. The zero N treatment had the highest internal efficiency of 275 kg grain/kg N taken up from indigenous soil N.

Table 3. N use efficiencies as affected by N rate.

N rate	Grain yield (kg/ha)	N uptake (kg/ha)*	PFP (kg grain/kg N applied)	AE (kg grain increased/kg N applied)	RE (kg N uptake/kg N applied)	PE (kg grain/kg N uptake)	IE (kg grain/kg N uptake)
N ₀	2,640	9.60	-	-	-	-	275
N ₆₀	3,370	28.0	56.2	12.2	0.31	39.6	120
N ₁₂₀	3,290	73.2	27.4	5.42	0.53	10.2	44.9
N ₁₆₅	3,430	95.0	20.8	4.79	0.52	9.21	36.1

*N uptake at PM.

Water inputs and productivity

Grain yield and water productivity with respect to irrigation plus rainfall are presented in Table 4. Irrigation and rainfall amounts varied because of different irrigation treatments and crop duration, which was affected by water regime. Total rainfall depth during the growing season (January-June 2007) was 425 mm. Water productivity decreased as total water input increased. Highest water productivity occurred in W₃ (0.48 kg grain/m³ water input), and the lowest was found in W₁ with a water productivity of 0.29 kg grain/m³ water.

Water productivity in this experiment is comparable to values reported by Tuong (1999) for the best performing aerobic rice treatments, with a water productivity of around 0.5 kg grain/m³ water. In this experiment, average grain yield under W₃ was lower by 36% but lower water inputs by 54% with a corresponding higher water productivity of 31% as compared with the average grain yield in irrigated rice of 5 t/ha with water input of 15,000 m³/ha (IRRI, 1997).

Table 4. Water productivity as affected by average grain yield and water inputs.

Water regime	Average grain yield (kg/ha)	Water input (m ³ /ha)			Water productivity (kg grain/m ³ water)
		Irrigation	Rainfall	Total	
W ₁	3,180	9,700	1,360	11,060	0.29
W ₂	3,140	6,100	1,370	7,470	0.42
W ₃	3,220	5,100	1,600	6,700	0.48

Conclusions

Nitrogen rate significantly affected growth and yield of PSB Rc-9 under aerobic rice production systems. There was no significant effect of water regime on the yield of PSB Rc-9. Water inputs and productivity with the tested water regimes showed comparable results to those of irrigated rice. Average N recovery under the aerobic rice production systems was lower by 16% compared with the target N recovery in well-managed irrigated rice. Added P fertilizer did not affect the growth and grain yield of PSB Rc-9 under the aerobic rice production system.

Irrigation once every 14 days until tillering with 2 cm irrigation depth, once a week until flowering with 4 cm irrigation depth, twice a week from one week before to one week after flowering with 4 cm irrigation depth, and once every 10 days after flowering until maturity with 4 cm irrigation depth was the most efficient water regime tested for aerobic rice production systems, without compromising yield. The optimum N fertilizer rate was 60 kg N/ha which was applied in three equal splits. The results from this experiment should be tested through applied experiments and field demonstrations in a range of locations, and to inform the design of the best bet management practices for a range of sites and locations.

Acknowledgments

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Increasing on-farm water productivity through affordable microirrigation vegetable-based technology in Cambodia

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Abstract

Using affordable drip irrigation systems to grow high-value crops, including vegetables, can increase water use efficiency and improve labor productivity in water-limited regions. Research was conducted in Cambodia during two consecutive dry seasons (2006-2007) to evaluate and compare efficiencies in water use, labor, and production inputs in vegetable cultivation under drip, furrow, and traditional hand-watering methods. On-farm trials involving 40-50 farmers were established in Svay Rieng and Prey Ving districts of Cambodia to determine the efficiency and productivity of six vegetables under three irrigation methods. An affordable (low-cost) drip irrigation drum kit developed by International Development Enterprises (IDE) was used in all trials. In 2006, drip irrigation resulted in 95% and 85% increases in water and labor productivity, respectively, compared to the traditional practices of hand watering and furrow irrigation. Economic returns to labor increased by 67%. Drip irrigation increased yield and decreased labor use by almost 50%. In 2007, integration of improved crop management methods, such as combining fertilizer with drip irrigation, increased yield by 30%, water use efficiency by 20%, and net returns from cucumber production by 15%. Overall, average labor use decreased 83% with drip irrigation and increased net returns by 153%. This project demonstrates the benefits of affordable microirrigation, coupled with high-value vegetable production, in increasing on-farm water productivity in regions where irrigation water is a limited resource during the dry season.

Media grab

Affordable drip irrigation benefits small-scale, resource-poor vegetable farmers in Cambodia by reducing the amount of water and labor applied to vegetable crops.

Introduction

Food crop production in most rural regions of Cambodia is based predominantly on subsistence agriculture. Most farmers grow one crop of rice and most of the land is left fallow during the dry season. Poor water delivery techniques limit the expansion of vegetable production in this region during the dry season. The traditional practice of hand watering is labor intensive, thus, vegetable production contributes less than 10% of farmers' incomes. Furthermore, farmers growing vegetables as a source of income are not responding to market demands; they grow traditional crops using traditional watering and cultural practices, and do not produce vegetable varieties sought by consumers.

Recently, a number of innovations have been made for small-scale farmers to manage water effectively during the dry season, and increase on-farm water efficiency using simple, affordable microirrigation systems (Postelet al., 2001; Polak and Yoder, 2006). Microirrigation schemes have been promoted mostly by NGOs rather than by mainstream government agencies. Realizing that better access to water is critical for growing vegetables and other off-season crops to increase farm incomes and alleviate poverty, many NGOs have been promoting small, divisible forms of microirrigation technology. These are affordable to many smallholder farmers in Asia and Africa, even to farmers with small plots who earn less than US\$1 a day (Polak and Yoder, 2006). Affordable microirrigation vegetable-based (AMIV) technology integrates simple, low-cost microirrigation techniques into vegetable farming systems for resource-poor farmers.

The major aim of this project was to demonstrate market-based strategies that could enable resource-poor farmers to earn an income similar to or better than farmers who are competitive and commercially oriented producers. Specifically, the objective of the project was to introduce an affordable and low-cost drip irrigation system to smallholder farmers, and to assess the technical performance and suitability of the technology from social and economic perspectives as well as marketability.

Methods

The project was located in the Mekong Delta Basin, in Svay Teap and Svay Chrum Districts in Svay Reing Province, Cambodia. In 2006, 49 trial plots were established by farmers. Each farmer planted one or two vegetable crops of their choice. Vegetables grown included cucumber, bitter melon, long bean, eggplant, and tomato. A basic study to compare hand watering and furrow irrigation ('farmer's practice') and drip irrigation using the IDE drum kit was conducted by each farmer in varying plot

sizes, ranging from 42 to 140 m² (farmer's practice) and 80 to 500 m² (drip irrigation). The drum kit consists of 130 tiny 1 mm-diameter pipes called "microtubes," fitted to 5 rows of 12-mm diameter pipes called "laterals." These laterals are connected to a drum of water by a 16-mm diameter pipe called 'sub-main' (Postelet al., 2001). Both methods were evaluated in terms of: 1) technical performance (water savings, labor savings, and yield increase); 2) suitability (problems or constraints, effect on men and women, ideas for improvement); and 3) marketability (perceived benefits, price to pay, technology design, information received). Water use was measured in liters by the number of sprinkler cans, buckets, or drums of known volume each time water was applied. In 2007, similar trials were conducted by farmers, but fertilizer treatments were superimposed on selected vegetables including cucumber and yard-long bean. The fertilizer treatments consisted of conventional NPK commercial fertilizer and the NPK briquettes developed by the International Center for Soil Fertility (IFDC—previously known as the International Fertilizer Development Center) containing 30% N, 12% P₂O₅, and 198% K₂O. The NPK briquettes were applied 8-10 cm deep in the soil (deep placement). Data were collected on water use, marketable yield, labor expended in watering and weeding, and other socioeconomic parameters. Statistical analyses were performed in SYSTAT ver. 12 and Excel. Multifactor analysis of variance (ANOVA) was used to compare the effect of irrigation methods and fertilizer source. Unplanned pair wise comparisons were performed using LSD test to interpret interactions between factors.

Results

In 2006, drip irrigation reduced water use by an average of 43% across all crops, and increased total yield of vegetable crops by 15% (Table 1). Total labor use was also reduced by 38% in drip-irrigated plots compared to farmer's practice of hand watering. Overall net income in drip-irrigated plots was 3% higher than plots under farmer's practice (Table 1). The increase in yield coupled with the decrease in water and labor usage led to a significant improvement in water and labor productivity. The return on labor amounts to about US\$3.75 per eight-hour workday, three times the average farm labor wage of about US\$1.25 per day.

Table 1. Effect of drip irrigation on water usage, yield, income and labor use in vegetable production. Cambodia, Dry season, 2006.

Parameter	CIDA-CPWF		CARE		Total		VAR (%)
	FP	DP	FP	DP	FP	DP	
Total water usage (mm)	n/a*	n/a*	189	108	189	108	-43
Total yield (kg/m ²)	0.96	1.13	0.47	0.54	0.52	0.60	+15
Income and expenditures (riel/m ²)							
Gross income	868	970	270	287	336	350	+4
Total expenditures**	139	180	25	28	36	41	+13
Seed***	39	24	0	0	4	2	+47
Fertilizer	65	61	14	16	19	20	+2
Pesticides	35	26	1	1	4	3	-24
Fuel	0	69	10	11	9	16	+81
Net income	729	790	246	259	299	309	+3
Labor usage (hr/m ²)							
Bed preparation	0.10	0.12	0.07	0.06	0.07	0.07	-5
System installation	0.00	0.09	0.00	0.03	0.00	0.03	n/a
Planting	0.02	0.03	0.01	0.01	0.01	0.01	-11
Irrigation	0.49	0.09	0.11	0.03	0.15	0.04	-76
Weeding	0.04	0.03	0.03	0.01	0.03	0.02	-41
Total labor use	0.79	0.36	0.22	0.15	0.27	0.17	-38

FP =Farmer's Practice; DP = Drip; *Excluded due to unmeasured rainfall; **Cost of drip system not included; ***Seed costs for CARE farmers subsidized. 1 USD(\$) = 4000 riel. CIDA = Canadian International Development Agency; CPWF = Challenge Program on Water and Food; CARE = Christian Action Research and Education.

The low net income (3%) in drip-irrigated plots was partly due to slightly higher expenses and produce being used for home consumption. Despite the low net return from drip irrigation, follow-up surveys indicated strong support by farmers for drip irrigation. All farmers indicated they intended to use the drip system again in the next season. Farmers responses support the quantitative results that showed increases in labor and water productivity (Table 2). According to trial farmers, the three biggest advantages of the drip system were time, labor, and water savings. More than 70% of farmers nominated these advantages. Other benefits mentioned included better soil moisture, aeration, fewer weeds, easier to irrigate, and healthier crop.

In 2007, differences in marketable yield, water use, and efficiency were observed between drip irrigated plots and farmer's practice. There was a consistent trend for higher yields of all vegetables under drip irrigation, with significant differences in the cases of cucumber, sponge gourd, and eggplant (Table 3). Differences in yield were significant for cucumber, sponge gourd and eggplant. Water use was significantly lower in drip-irrigated plots than plots under hand watering for cucumber

and yard-long bean. The low water use and higher yields resulted in a consistent trend for high water-use efficiency in drip-irrigated plots with significant differences for cucumber, sponge gourd, and eggplant (Table 3). Overall, labor for weeding and irrigating was reduced under drip irrigation (data not included). Average net return was 153% higher with drip irrigation than hand watering (data not shown).

Table 2. Advantages of drip irrigation as identified by farmers in Cambodia, dry season, 2006.

Advantage/Feature	CIDA-CPWF (%)	Care (%)	Total (%)
Time saving	91	81	84
Labor saving	82	71	75
Water saving	64	76	72
Soil has good moisture	36	62	53
Fewer weeds	18	62	47
Easy to irrigate/use	36	48	44
Healthy crops	18	38	31

Table 3. Marketable yield, water use and efficiency of vegetables under drip and hand watering system. Cambodia, Dry season, 2007.

Crop ¹	Yield (t/ha)			Water Use (ML/ha)			WUE (t/ML)		
	Drip	HW	t-val	Drip	HW	t-val	Drip	HW	t-val
Cucumber (18)	6.7	5.9	2.01*	1.94	3.28	2.28**	3.73	2.65	1.88*
Yard-long bean (14)	6.5	6.1	NS	3.28	5.06	2.22**	2.23	1.75	NS
Sponge gourd (3)	5.9	3.2	2.04*	1.46	1.55	NS	5.94	2.60	2.32*
Eggplant (2)	4.1	3.0	2.17*	2.20	2.09	NS	3.57	1.68	2.19*
Bitter gourd (1)	3.1	1.4	NA	4.65	2.83	NA	0.66	0.49	NA

¹Figures in parentheses are numbers of farmer trials. NS=not significant; NA=not applicable; *=significant; **=highly significant; HW = hand watering; WUE = water use efficiency.

The response of cucumber to irrigation was significant, and to fertilizer application at the $p < 0.10$. Marketable yield was significantly higher in drip-irrigated plots than hand-watered plots, whereas yield from deep placement fertilizer (NPK briquette) was higher than conventional fertilizer (Table 4). Drip irrigation used significantly less water (less than half of hand watering), with about three times higher efficiency in water use in drip-irrigated plots and fertilizer deep placement plots. A similar result was obtained for yard-long bean, but the difference in marketable yield between drip- and hand-watered plots was not significant (data not included).

Table 4. Marketable yield and water use efficiency of cucumber as influenced by irrigation method and fertilizer application. Cambodia, dry season, 2007.

Fertilizer treatment	Yield (t/ha)		Water applied (ML/ha)		WUE (t/ML)	
	DRIP	HW	DRIP	HW	DRIP	HW
NPK briquette	7.30	5.65	0.69	1.55	10.68	3.51
Conventional fertilizer	6.25	4.10	0.66	1.55	9.20	2.45
P value						
Irrigation (I)	0.040*		0.022**		0.005**	
Fertilizer (F)	0.097 NS		1.000 NS		0.067 NS	
I X F	0.854 NS		1.000 NS		0.873 NS	

Discussion

The trial in 2006 demonstrated the benefits of drip irrigation in terms of increased yield, decreased water usage, decreased labor usage, and improved water and labor productivity. Previous studies and development projects support these results (Keller, et al., 2005; Westrap and Schreier, 2004; Karlberg et al., 2007). Although these benefits were realized, the net income from drip-irrigated crops was only 3% higher than the hand-watered plots (farmers' practice), while yields were 15% higher. This is in part due to slightly higher expenses for the drip-irrigated crop, but does not explain the entire difference. It may also be due to more home consumption of the vegetables, or lower quality product due to excessive rain as experienced by some farmers. Low yields also can result from farmers' lack of experience with drip systems. Farmers new to the technology may require more training. One group of farmers (CARE) did not experience any problems with the drip irrigation system, but farmers in the other group (CIDA-CPWF) encountered the following problems: 1) water jar was too high; 2) micro-tubes were clogged; 3) water jar was small (500 L) and not enough for crop irrigation; 4) sub-main was small and water could not reach all the plants; and 5) drip maintenance. Solutions and suggestions for improvement were provided by farmers to address these problems. Follow-up surveys indicated strong support by trial farmers for the drip irrigation system. All farmers indicated they intended to use the drip system again in the next season.

Farmers participating in the 2007 trial increased their yield by an average of 8% using drip irrigation over traditional watering practice. The results were mixed, however: 22% of farmers experienced decreased yields using the drip system, while 22% of farmers increased their yields by more than 50%. The yield response to fertilizer application was greater with the drip system than in hand watering. The combination deep-placement fertilizer briquettes and drip irrigation improved yields by 73% over traditional farming practice. This resulted in a 33% increase in net income. This suggests that farmers can make a profit by investing in fertilizer briquettes first, or in conjunction with drip irrigation, rather than investing solely in drip irrigation.

Conclusions and recommendations

Based on the results from trial plots, drip irrigation of vegetable crops can significantly increase water and labor productivity, and can marginally increase land productivity. Farmers reported high levels of satisfaction with the drip system, and were willing to pay for the equipment. With a relative abundance of water in some areas, however, it was a challenge to motivate farmers to use the drip system. It is better to promote drip irrigation among farmers for whom water is a key constraint: scarce, costly to pump, etc. When integrated with improved crop management practices, drip irrigation can be cost effective compared with drip irrigation using traditional cultural practices. Farmers had little training in how to use drip irrigation efficiently because the technology was also new to the project staff. Crop failures due to pest attack, flooding, and rain damage can negate the benefits of drip irrigation, thus there is a need to address these technical problems. On-farm water management can be improved further with more research into appropriate watering regimes. Future research should include soil moisture measurements to assist farmers in regulating their water usage. Training and knowledge dissemination is vital for effective commercial farming. Training should include use of new technologies, crop protection, packaging, and processing to decrease postharvest loss and improve farmer options. Finally, improved local supply chains within countries and regions should be established for new cost-effective technologies to increase availability and affordability of these products to farmers.

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Crop water productivity in India: some potential improvements

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Abstract

Grains, the staple food in India, provide 65% of daily nutritional supply in India. With increasing population and diversifying consumption patterns, production will have to increase significantly to meet additional food and feed grain demand. At present grain production (205 million t) uses 65% of the cropped area, 62% of the total consumptive water use, and 69% of the total irrigation deliveries. But with increasing water demand for other high-value crops, and from other sectors, grain production will face stiff competition for scarce water resources. Improving water productivity (WP) is one option for coping with water scarcity. This paper discusses some potential improvements of WP of grains in India. WP of grains in India is very low compared to other major grain-producing countries. WP across districts varies significantly at similar levels of yield or at similar levels of consumptive water use (crop evapotranspiration). Small amounts of supplemental irrigation in districts with low irrigation water use or rainfed crops can significantly increase both yield and WP. Significant scope also exists for reducing the gap between actual and maximum yield, which enhances both yield and WP. Deficit irrigation can increase WP and production in districts with high consumptive water use. Expanding the yield frontier and reducing the yield gap with existing water use can help India meet most of its grain and water needs.

Media grab

Improving water productivity by just 1% annually through supplemental irrigation in rainfed districts and deficit irrigation in intensively irrigated areas provides the greatest opportunity for meeting the future food and feed demand without further overstressing river basins of India.

Introduction

National food security and livelihood security of the increasing rural population dependent on limited land resources were key drivers of the green revolution in the 1970s. This was achieved in favorable agroecologies through the introduction of improved varieties, increased use of inputs, and expansion of irrigation. A significant gain in food production through increased land productivity was the main outcome. India is the second most populated country with 1 out of 6 billion of the world's population in 2000. It is the largest grain producer in the world with 124 out of 730 million ha of the world's grain area. India also has 205 out of 1915 million of the world's grain production. It still has one of the lowest land productivities among the major food-producing countries (1.7 t/ha versus 4.0 t/ha in China, and 5.8 t/ha in USA). Doubling land productivity in five decades from now could help India to meet most of its increasing food demand, from about 202 million t in 2000 to about 380-400 million t by 2050). But unlike four decades ago, water, a critical factor for crop production and other uses by humans and ecosystems, is also becoming a scarce resource.

With increasing water scarcity, the need to increase water productivity (WP) is receiving significant attention. Many regions in India are reaching the threshold of physical water scarcity (Amarasinghe et al., 2007a). This is primarily due to inadequate water resources to meet increasing water demand in different sectors. One option proposed for meeting increasing water demand is large inter-basin water transfers. Among alternative options, improving productivity of water use has significant potential. Thus, like the campaign for more crop per unit of land during the period of the green revolution, improving WP is also gaining prominence now. This paper focuses on ways of improving WP of grains in India. It assesses the extent and determinants of spatial variations of WP of grains and pathways of increasing it.

Methodology and data

Grain crops in this study consisted of rice (milled equivalent), wheat, maize, other coarse cereals, and pulses. WP is defined as total production per unit of consumptive water use (kg/m^3). Consumptive water use (CWU) in irrigated areas is defined as actual evapotranspiration (ET) during the crop growth period. The net irrigation (evapotranspiration) (NET) requirement is the difference between Et and effective rainfall. CWU in rainfed areas is estimated as effective rainfall (Amarasinghe and Sharma, 2008).

A brief account of spatial variation of WP of grains across states and districts in India is presented (for more details refer to Amarasinghe and Sharma, 2008). Pathways of increasing WP at district levels, and their potential, are assessed. We hypothesize that a significant potential exists for increasing WP through small levels of supplementary irrigation in rainfed areas and small deficit irrigation in irrigated areas. To test this, first we estimate the maximum yield and WP functions of grains. Next we assess

the potential increase of yield or WP through supplementary or additional irrigation, no additional irrigation, and deficit irrigation. Data for the study consists of district level land use and crop production in 2000. These data were collected from various government of India and other sources (Amarasinghe and Sharma, 2008). Climate data (monthly potential evapotranspiration and rainfall) were taken from the Climate and Water Atlas (IWMI, 2001).

We considered the 20 major states that contribute about 99% of the total consumptive water use and 98% of the total production of grain in India (Figure 1). In 2000, India had 124 million ha under grains, produced 205 million t of grains, and depleted 425 km³ of water as CWU. Of the total area under grains, 54 million ha was irrigated, and that contributed to 68% of the total production and 54% of the CWU. In 2000, India withdrew 428 km³ of water to meet the irrigation requirement of 154 km³, of which the former is 69% of the total irrigation demand, and the latter is 65% of the total CWU in irrigated areas.

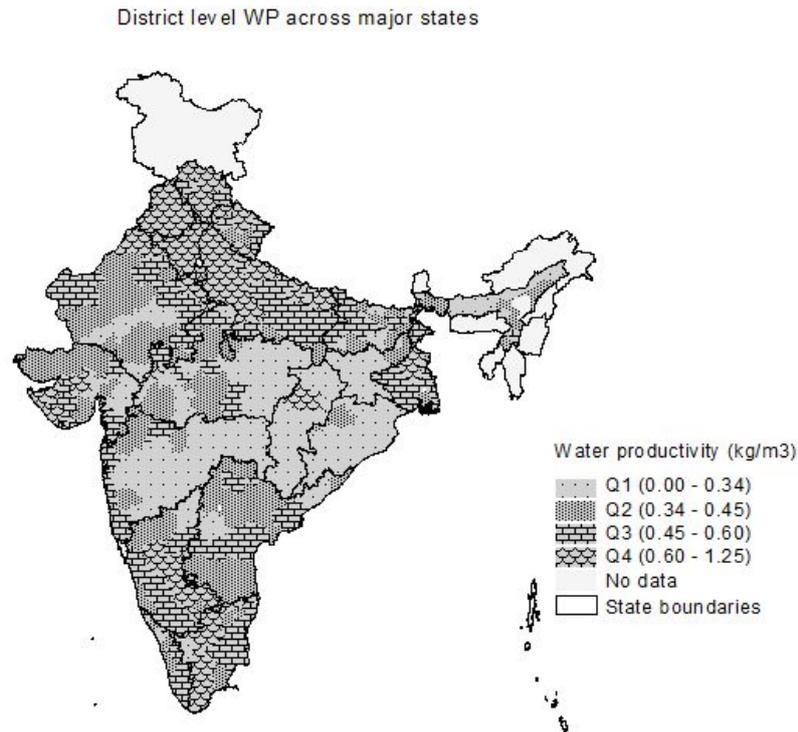


Figure 1. District level WP across major states.

Results and discussion

Spatial variation of water productivity

In 2000, the numerator of WP includes irrigation deliveries, WP of grains is only 0.29 kg/m³ of grains in India was only 0.48 kg/m³ of consumptive water use (CWU). Between states it varied from 0.21 to 1.01 kg/m³. Among the differences we observed:

- Punjab (PU), Haryana (HR), and Uttar Pradesh (UP) in the Indo-Gangetic Basin (IGB) have the highest water productivities of grains. The rice-wheat dominated cropping pattern with irrigation contributing significantly to the higher WP in these states. Bihar, however, also in the IGB with 82% of the area under wheat and rice, has low WP. In Bihar, 60% of the area is irrigated, but irrigation contributes only 33% of the CWU. Effective rainfall meets much of the CWU in Bihar at present.
- West Bengal (WB), a major part of which is in the IGB, and Andhra Pradesh (AP), Tamil Nadu (TN), and Kerala in peninsular basins with rice-dominated cropping patterns, have moderate to high WP. Although irrigation contributes a major part of CWU in AP and TN, its contribution is low in WB and Kerala.
- Maharashtra, Madhya Pradesh (MP), Karnataka and Gujarat, with a mixture of cropping patterns (more than 50% of the area under maize and other coarse cereals and pulses) have lower WP. In Maharashtra and Karnataka, irrigation covers only 15 and 23% of area, respectively, and contributes 17 and 28% of the CWU. Irrigation in MP and Gujarat covers 29% of the grain area, but contributes 52 and 41% of the CWU.
- Orissa, Chattisgarh and Jharkhand, have the lowest water productivities, and share 12.8% of the total CWU but contribute only 6.3% of the grain production. Rainfed rice dominates cropping patterns in these states.

Differences of WP in irrigation and rainfed areas explain a significant part of the variation in total water productivity¹. Additionally, the land use and the cropping patterns of grain significantly influence water productivity differences between states. In 2000, irrigation covered 43% of the total grain crop area in India but contributed 68% of the total production. Thus proper use of irrigation with appropriate cropping patterns can increase both yield and WP in many districts. These are discussed below, by assessing the relationship between yield and CWU at the district level.

The water productivity of all districts varies from 0.11 kg/m³ to 1.25 kg/m³ (Figure 1). WP in the first to fourth quartiles varies from 0.11- 0.34, 0.34-0.45, 0.45-0.60, and 0.60-1.25 kg/m³. Districts in the fourth quartile of water productivities account for only 22% of total grain area and 22% of total CWU, but contribute 38% of total grain production. Irrigation provides water supply to 72% of the total grain area in this group, and contributes 60% of total CWU. In irrigated areas, irrigation accounts for a major part (72%) of total CWU. Districts in the first quartile of water productivities, however, account for 29% of total CWU and 30% of the total grain area. These districts contribute only 15% of total crop production, however. Effective rainfall, the main source of CWU in this group, accounts for 83% of total CWU. From the spatial variations of yield and WP of grains, and also the extent of irrigation of grain crops across districts, we observe that:

- Yield variation explains a major part of the variation in WP across districts ($\ln(WP) = 0.34 + 0.65 \ln(\text{yield})$, adjusted $R^2 = 59\%$).
- Except for a few districts with low CWU, irrigation is a major determinant of higher yield and hence higher water productivity. There is, however, significant variation of yield and WP within different levels of irrigation. Coefficients of variation of yield and WP across different categories of irrigation vary from 20 to 51% and 23 to 50%, respectively.

These observations show that providing small amounts of irrigation could be a major boost for increasing yield and hence WP in mainly rainfed districts. Recent research (Sharma et al., 2006) indicates that providing a small supplemental irrigation of about 100 mm during critical water stress periods of crop growth can significantly increase crop yields in major rainfed districts. A significant scope also exists for increasing yield in many districts with moderate to high irrigation inputs. Improving non-water inputs with improved water management could also be strategies for increasing yield and returns per unit of water consumed (Molden et al., 2003). All these offer opportunities for increasing the numerator of WP calculation. Is there scope for increasing WP by changing the denominator—the consumptive water use? Several studies (Kijne et al., 2003), have discussed potential impacts in different countries for different crops with deficit irrigation. We discuss them in the context of India in the next section.

Pathways of increasing WP

Several strategies exist for increasing WP in Indian districts (Figure 2). WP can be increased significantly by:

- Increasing the numerator (or yield) by bridging the gap between actual and maximum yield at present, or by providing additional irrigation or selecting appropriate crop choices in mainly rainfed districts.
- Decreasing the denominator (or CWU per unit land) without losing any yield or returns to a unit of water consumed.

The relationship between average yield and consumptive water use fits a Cob-Douglas function ($\ln(\text{yield}) = 2.48 - .18 \ln(\text{CWU})$, $R^2 = .29$). We used the 2-3 highest values of yield in each category of CWU (0-50, 50-100, 100-150, 150-200, etc.) for estimating the maximum yield function. We also depict two marginal yield curves ($d(\text{max yield})/d(\text{CWU})$) for increases in CWU of 100 and 200mm.

¹ $TWP = 0.021 + 0.59 IWP + 0.37 RWP + 0.11 PCGRIRAR - 0.09 PCRIAR$, Adjusted $R^2 = 97\%$
 (.029) (0.06) (0.05) (0.05) (0.02)

Values within parentheses are the standard errors of the estimates. TWP, IWP and RWP are total, irrigated, and rainfed water productivity, PCGRIRAR is the irrigated grain area as a % of total grain area, and PCRIAR is the percentage of rice area in grain.

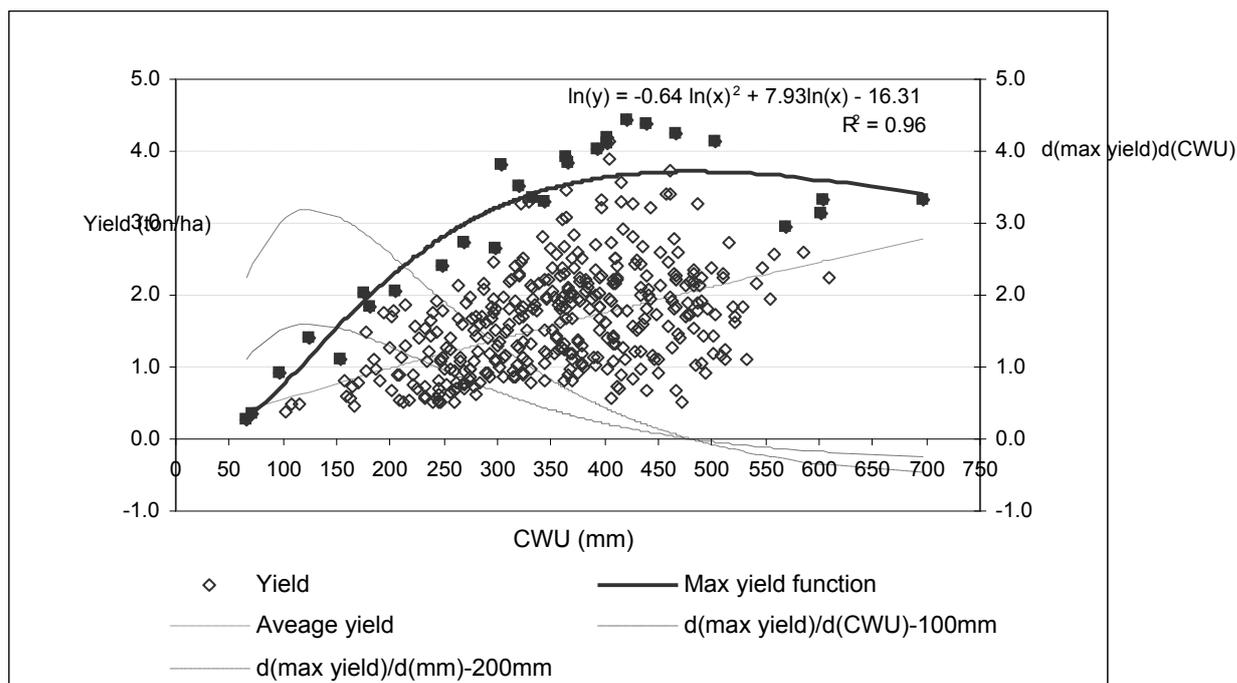


Figure 2. Relationship of yield and consumptive water use (CWU) of grains.

Reducing the yield gap

The first strategy in WP improvement should be to increase yield without additional CWU. At present, a significant gap exists between average and maximum yield in all levels of CWU. And the range of yield, i.e. maximum-minimum, increases in districts with moderate to high CWU.

If the gap between actual and maximum grain yield of each district can be reduced by 25% without additional CWU, total production could be increased from 203 Mt to 252 Mt from the same land and water use, through water and crop management. This increases WP from 0.48 kg/m³ to 0.60 kg/m³. A reduction of the yield gap by 50, 75, and 100% could increase the production to 300, 349, and 397 million Mt, respectively, and WP to 0.72, 0.83, and 0.97 kg/m³, respectively.

Providing additional irrigation

The second strategy for WP improvement is to provide additional irrigation in districts with low CWU and which are predominantly rainfed. The marginal yield curves, $d(\text{yield})/d(\text{CWU})$, show that increasing CWU could significantly increase yield in many districts. With 100 mm of additional CWU, maximum yield can be doubled in districts with less than 150 mm of CWU (Figure 2). With 200 mm of additional CWU yield can be doubled in districts with less than 215 mm of CWU. Many of these districts can increase yield significantly with a small amount of supplemental irrigation.

The gain in yield decreases with supplemental irrigation beyond 215 mm CWU and becomes negative after 475 mm. Growth in WP, however, becomes negative in many districts with CWU well below 475 mm. The marginal WP curves show that additional irrigation can more than double WP in districts with only low CWU (below 150 mm of CWU). WP growth becomes negative with additional irrigation after 225 mm of CWU.

This shows that with the present level of yield and WP frontiers, additional irrigation would increase both yield and WP in districts with only low CWU (below 225 mm at present). Between 225 and 475 mm of CWU, yield increases but WP decreases. Additional irrigation beyond 475 mm CWU would have negative incremental benefits on both yield and WP.

Deficit irrigation

The third strategy for increasing WP is decreasing consumptive water use through deficit irrigation. Reducing CWU through deficit irrigation where CWU is greater than 475 mm, would increase both yield and WP (Figure 2). And deficit irrigation between 225 and 475 mm of CWU would only increase WP. Even with some loss of yield, however, this strategy can use the saved water for increasing production.

In India, 251 districts with more than 25% irrigated grain area, will have 10% less grain yield with 25 mm of deficit irrigation. This group of districts has 63% of the total grain area of India, and contributes to 79% of total grain production. Deficit irrigation of 25 mm on existing areas can save 14% of the NET requirement. If all that saved NET is used for producing grain, this can provide 8% additional production. Deficit irrigation of 50 mm can save 27% of NET and increase production by 17%. Deficit irrigation can increase grain production in all districts with a significant irrigated area. Deficit irrigation can help most in districts where there is scarcity of water but not land.

Conclusion

Although WP of India is generally higher where there is more irrigation, it varies significantly across districts with similar CWU or with similar yield levels. There is significant scope for increasing WP by increasing yield through both better water and other input management. Water management includes supplemental irrigation in districts with low CWU, no additional irrigation in districts with moderate CWU, and deficit irrigation in districts with high CWU.

Reducing the existing yield gap in many districts with moderate to high CWU can increase both yield and WP. In fact, a substantial part of the future grain demand alone can be met by reducing the gap between actual and maximum yield. A combination of better water and other input management would contribute to this yield increase. Districts with high CWU can benefit from deficit irrigation, which can save water with only a marginal loss of yield. Saved water can then be used for additional crop production or other human or ecosystem use. Our analysis shows a significant net increase in crop production with deficit irrigation in many districts.

Acknowledgments

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Variations in groundwater use, water productivity and profitability across a canal command in the Indo-Gangetic Basin

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Abstract

The northwest Indo-Gangetic plain, where rice-wheat is the main cropping system, is one of the most important agricultural regions in India. It contributes nearly 52% of the national food production. Increasing pressure on agriculture due to increasing food requirements, climate change, fluctuating markets, and fragmentation of land calls for efficient resource management. We investigated the effect of unequal distribution of canal water in land and water productivity of the rice-wheat cropping system in terms of head-tail relationships in Bhakra Canal command. This paper presents an analysis of water productivity, land productivity, and profitability at the farmer field level in the command area of Pabnawa minor (tertiary canal) of Bhakra irrigation system. The groundwater contribution in the canal command is very high. Water productivity increases from head to tail due to wastage of canal water upstream and judicious use of groundwater at the tail end. Farmers practicing conjunctive use have higher profitability than tubewell irrigators and canal irrigators. The cost of water increases from head to tail, but because of the flat rate charge for electricity there is only a small difference in the costs of water for paddy and wheat. This system of intensive irrigated agriculture is unsustainable in the long run because of declining water tables and high use of energy. Higher profitability in rice and flat rate of electricity are causing water table decline at a very rapid speed. Therefore under a business-as-usual scenario, continuation of the rice-wheat cropping pattern is likely.

Media grab

Groundwater is important in canal command areas of the Indo-Gangetic Basin. Farmers with access to canal and groundwater resources are in a win-win situation with highest profitability and moderate water productivity.

Introduction

The northwest Indo-Gangetic plain, where rice-wheat is the main cropping system, is one of the most important agricultural regions in India, because it contributes 52% of the national food production. (Abrol, 1999). In this region fresh water from canals is supplied through a rotational *Warabandi* system (Malhotra, 1982), which has been designed to provide equitable water supplies. Canal water allowance, however, is generally not sufficient to irrigate the total landholding of the farmer. Substantial seepage from earthen distribution channels and illegal use of canal water by head-end farmers create large variations in supply, spatially as well as temporally. Because of this variation in supply and the low reliability of canal water supplies, groundwater has become important, including in the irrigated canal command of Bhakra system.

Such an overdependence on groundwater and weak regulatory mechanisms for water use have resulted in growing water scarcity and an increasing threat to the sustainability of water-intensive cropping systems. The challenge for irrigated agriculture will be to grow more food with less water (Guerra et al., 1998). The old notion of increased input applications will have to be changed, and new paradigms of optimized resource use in sustainable ways need to be evolved. The focus of improving land productivity has to be shifted toward improving water productivity. Therefore it is extremely important to address some of the issues at the field level. This investigation studied water productivity in a rice-wheat cropping system at the field level in Pabnawa minor of Bhakra canal command of Haryana in India. This study also tried to assess profitability of farmers across the canal command, and the contribution of groundwater in total irrigation across the canal command.

Methods

The study area is the command area of Pabnawa minor (tertiary canal) of Bhakra irrigation system, located in the semiarid tropics in Haryana, India at 29°31' - 30°12' N and 76°10' - 76°43' E. Average annual rainfall is 625 mm, about 80% of which is received during the monsoon period (July to September). Average evapotranspiration is about 1550 mm. For this study, villages (Jyotisar and Raogarh) at the head of the Pabnawa minor, Barna in the middle, Pabnawa at the far middle, and Faral in the tail stretch of the Pabnawa minor were selected. Details of four watercourses supplying canal water to them are summarized in Table 1.

Fields of 122 farmers (at least 30 farmers in each of the four stretches—with at least 10 located in the head, middle, and tail reaches of each watercourse) were selected for detailed data collection. Information on agricultural practices, irrigation water supply from tubewells and canal water, cropping pattern, cost of cultivation, and yields were collected through specifically designed questionnaires. The primary data for this study were collected for *rabi* 2006-07 and *kharif* 2007. Gauge readings of the canal were collected for the last 3 years from Kurukshetra Irrigation division. Discharges of tubewells were estimated using the coordinate method (Michael, 1978). Historical data regarding the canal irrigated area, water table fluctuations, and various other data related to groundwater were collected from Kurukshetra Irrigation Division, Agriculture Department and Groundwater Cell.

Table 1. Details of selected watercourses.

Watercourse (stretch of canal)	Design discharge (m ³ /sec)	Gross command area (ha)
Pabnawa 2820R (Head)	0.028	231.6
Pabnawa 23400R (Middle)	0.040	213.6
Pabnawa 53705L (Far Middle)	0.041	320.2
Pabnawa 80000L (Tail)	0.052	283.0

Results

Groundwater use

Crop production is directly related to canal water supply. The rigid schedule of water distribution and the inadequacy of the canal water supply do not provide much scope to the farmers for decision-making in respect of canal water utilization. Their decisions are mostly limited to managing the readily available groundwater. The canal irrigated area in Pabnawa minor is shrinking due to management inadequacies. From 1995 to 2005, the canal irrigated area decreased in the middle reach by 11% to 65% during the *kharif* season and by 11% to 44% during the *rabi* season. Tubewell water use is very high in the tail and far middle reaches in both seasons.

Table 2. Use (cm) of canal water and groundwater for irrigation during *rabi* and *kharif* season in 2006-7.

Season	Sources of irrigation	PH (Head)	PM (Middle)	PN (Far Middle)	PT (Tail)
Rabi (wheat)	Canal)	6.8	10.0	3.1	0.84
	Groundwater	18.3	12.8	19.5	19.8
Kharif (Paddy)	Canal	61.7	97.3	40.3	3.2
	Groundwater	94.3	55.9	101	116

Water productivity at field level

Water productivity (WP) refers to the benefits derived from use of water. It is expressed in terms of kg/ m³ of water or Rs/m³ (Indian Rupees) of water. Productivity of total irrigation water (canal + groundwater) increases from head to tail stretches for coarse paddy (2007), Basmati (2007), and decreases from head to tail for wheat (2006-07) (Table 3). The irrigation water productivity for coarse paddy and basmati paddy is higher by 35% and 21% for the tail stretch as compared to the head stretch. This is probably because of wastage of low-cost canal water in the upper reaches, and careful use of groundwater in the tail stretch. Electricity is supplied every alternate day for 6-7 hours, and hence the tailend farmers have to use these electricity supply hours judiciously. The same phenomenon is found for irrigation water productivity within the stretch. For wheat, irrigation water productivity is lower by 12% in the tail stretch and by 2.5% in the far middle stretch than in the head stretch. This was unexpected as the wheat crop in the tail stretch was badly affected due to heavy rain in February 2007 (216 mm). The soil in the tail stretch is clay loam, which encourages water stagnation and yield loss.

Water productivity of paddy and wheat for different sources of irrigation is given in Table 4. The highest irrigation water productivity for paddy is for tubewell irrigated farmers, followed by conjunctive users and then by canal-irrigated farms. Irrigation water productivity is Rs3.63/m³ for coarse rice, Rs5.62/m³ for basmati rice, and Rs14.87/m³ for wheat. The information gives an impression that farmers are cheaply using water for paddy as compared to wheat. But it is worth noting that farmers tend to maximize their crop income, and basmati rice gives the highest gross margin per hectare, followed by coarse rice, and then wheat. This emphasizes the challenge of enhancing water productivity while increasing or sustaining the economic benefits to the farmer.

Table 3. Water productivity for wheat (2006-07), coarse paddy, and basmati paddy (2007).

Crop	Location of watercourse	Irrigation water productivity (Rs/m ³)	Total water productivity (Rs/m ³)
Coarse paddy	Head (PH)	3.30	2.56
	Middle (PM)	3.31	2.57
	Far Middle (PN)	3.44	2.60
	Tail (PT)	4.48	3.18
Basmati paddy	Head (PH)	5.54	4.32
	Middle (PM)	4.49	3.95
	Far Middle (PN)	5.57	4.34
	Tail (PT)	6.88	5.03
Wheat	Head (PH)	15.08	7.17
	Middle (PM)	16.42	7.39
	Far Middle (PN)	14.73	6.84
	Tail (PT)	13.25	5.79

Conversion rate US\$1= 41Indian RS.

Table 4. Water productivity of paddy and wheat for different sources of irrigation.

Crop	Sources of irrigation	Irrigation water productivity (rs/m ³)	Total water productivity(rs/m ³)
Coarse paddy	Canal irrigation	2.19	1.77
	Conjunctive Irrigation	3.07	2.43
	Tubewell Irrigation	4.21	3.06
Basmati	Canal irrigation	4.13	3.39
	Conjunctive Irrigation	4.44	3.80
	Tubewell Irrigation	6.63	4.93
Wheat	Canal Irrigation	18.40	7.96
	Conjunctive Irrigation	15.10	7.15
	Tubewell Irrigation	14.30	6.46

Profitability

The profitability of crop production depends on the crop yield, output price, and cost of production. The cost of production is highest for basmati rice and lowest for wheat (Table 5). The average cost of production is Rs15065/ha for basmati paddy, Rs13301/ha for coarse paddy, and Rs12495/ha for wheat. The gross value of product is calculated using the minimum support prices for coarse paddy and wheat. For basmati paddy the average prices received by the farmers were used. The gross margin is highest for basmati rice, followed by coarse rice and then wheat. The gross margins for basmati paddy and coarse paddy are 3.2 and 1.7 times higher than the gross margin of wheat. The G.M. to C.O.P. ratio is 4.55 for Basmati paddy, 2.76 for coarse paddy compared to 1.76 for wheat. The gross margin of basmati rice cultivation in tail watercourse (PT) was 14% less than the gross margin at the head (PH). Gross margin for coarse rice was 11% less at Pabnawa tail (PT) compared to the head end watercourses (PH). But in the case of wheat the gap in gross margin between the tail and head was 59%. The flat tariff for electricity (based upon the HP of the pump and not the actual pumping hours) helps maintain the higher profitability of rice for the farmers. If the cost of water were different for rice and wheat, this would change.

Table 5. Profitability of crop production (rabi, 2006-07, kharif, 2007).

Crop	Location	Cost of production (COP) (Rs/ha)	Gross value of product (Rs/ha)	Gross margin (GM) (Rs/ha)	GM/COP
Basmati paddy	PH	15705	87771	72066	4.59
	PM	14562	84522	69960	4.80
	PN	15718	84233	68515	4.36
	PT	14275	77047	63452	4.45
Coarse paddy	PH	13309	51719	38409	2.89
	PM	12523	51149	38626	3.08
	PN	13571	48536	34965	2.58
	PT	13800	48398	34558	2.50
Wheat	PH	13098	36550	23452	1.79
	PM	11925	36852	24778	2.08
	PN	12452	35022	22834	1.83
	PT	12506	27248	14742	1.18

Price of output: Coarse paddy-Rs 7.5/kg, Basmati paddy-Rs 25/kg, Wheat-Rs 8.5/kg.

The profitability of crop production was also determined for different sources of irrigation (Table 6). The cost of cultivation was highest for conjunctive irrigation compared to tubewell and canal irrigation alone. But the gross value of product was also highest for conjunctive irrigation compared to other

sources of irrigation, resulting in higher gross margin for conjunctive irrigation of basmati paddy and coarse paddy. This analysis suggests that with the flat rate of electricity and higher return of paddy, high water use will continue. There is an urgent need to look into this serious issue.

Table 6. Profitability of crop production under different sources of irrigation.

Crop	Sources of irrigation	Cost of production (COP) (Rs/ha)	Gross value of product (Rs/ha)	Gross margin (GM) (Rs/ha)	GM/COP
Basmati paddy	Canal	11399	40218	28819	2.53
	Conjunctive	13673	51201	37528	2.74
	Tubewell	13334	50062	36728	2.75
Coarse paddy	Canal	14568	82550	67982	4.67
	Conjunctive	15942	84373	68431	4.29
	Tubewell	14297	82544	68247	4.77
Wheat	Canal	12330	36703	24373	1.98
	Conjunctive	12512	36828	24207	1.93
	Tubewell	12521	31424	18903	1.51

Price of output: Coarse paddy-Rs 7.5/kg, Basmati paddy-Rs 25/kg, Wheat-Rs 8.5/kg.

Options for improvement

Artificial recharge of groundwater

Harnessing surplus monsoon flows and canal flows to recharge the aquifer system could, in principle, augment groundwater resources. Artificial groundwater recharge should be done on a priority basis, through rooftop rainwater harvesting and a combination of recharge shafts and injection wells (CGWB, 2004). The impact assessment of artificial groundwater recharge by combination of recharge shafts and injection wells in Haryana has 3.45 M m³ runoff water recharged in one year and the rate of watertable decline reduced from 1.175 m/year to 0.25 m/year. Recharging of confined aquifers by injection tubewells in Kurukshetra district indicates water recharges at the rate of 7.2 m³/day/tubewell (Kaledhonkar et al., 2003). In 2002-03 many farmers of this area changed from centrifugal to submersible pumps. The abandoned wells and pipes are still there and can be modified and used for groundwater recharge.

Conjunctive use of water

Conjunctive use of water from different sources is considered to be a valuable tool to overcome the constraints of the surface and groundwater systems, if operated independently. A typical canal irrigator in this area gets surface water 12-18 times a year. Most of these head-end farmers also have tubewells for supplemental irrigation. The ratio of canal water and tubewell water for head-end farmers is about 70:30. But if this ratio can be reversed to 30:70 and the surplus canal water can be transferred to tail-end farmers it will minimize tubewell water use. The lining of watercourses is also essential for conjunctive use of water. The lining of watercourse no. 23400R of Pabnawa minor has increased the irrigated area from 18 ha to 40 ha. This lined watercourse can also be used while irrigating from tubewell. Conjunctive use planning requires establishment of firm water supplies and their distribution and use of groundwater and allocation of water to different users.

Promotion of resource conservation technologies

The use of resource conservation technologies needs to be encouraged by providing subsidies to farmers to adopt technologies such as zero tillage, bed planting, laser leveling, and SRI technique for growing paddy. It will improve groundwater use efficiency. Chandra et al. (2007) suggest superiority of zero tillage over conventional tillage in wheat in terms of irrigation water productivity, land productivity, and profitability of crops. Similarly, bed planting and laser leveling have great potential. At the same time there should be some incentives for farmers to save water.

Conclusions and recommendations

In the canal water distribution system, a gap between head and tail farmgate supply always exists, and the system investigated is no exception. The inadequate, inequitable, and irregular canal water supply has led to shrinkage of the canal irrigated area over time and groundwater is playing an important role in crop production. Groundwater accounts for more than 50% of the total irrigation water use in the Pabnawa canal command.

Water productivity increases from head to tail watercourses for coarse and basmati rice. This trend is due to wastage of low-cost canal water upstream and judicious use of costly groundwater at the tail end. The gross margin is highest for basmati rice, followed by coarse rice and wheat. The higher profitability of rice and flat rate electricity charges result in high water use for canal and groundwater, causing water table decline. This system of intensive irrigated agriculture is unsustainable in the long run, because of declining water tables and high use of energy. In the short term, food security, poorly designed electricity tariffs, and high minimum support price for rice need to be rationalized.

Conjunctive use farmers have the highest profitability and moderate water productivity compared to tubewell irrigators and canal irrigators. Conjunctive use of water from different sources is considered to be a valuable tool to overcome the constraints of the surface and groundwater systems, if operated independently.

This study produced some important policy recommendations:

- There is an urgent need to enact groundwater legislation to stop indiscriminate exploitation. A state groundwater body should be set up to regulate and control groundwater development and management on a sustainable basis.
- There should be strong incentives to the farmers for establishing artificial groundwater recharge structures in the form of waiving electricity costs.
- The use of a flat rate for electricity, combined with unreliable electric supply, provides little incentive for efficient use of groundwater. The electricity rate in these states has not changed in the past 10-15 years. There is a need to increase the flat rate by 10-15% and to base it on actual usage or to regulate the power supply hours.
- Conjunctive use farmers have the highest profitability. Conjunctive use planning requires the establishment of firm water supplies and their distribution, effects of water development and use of groundwater, and allocation of water to different users.
- Resource conservation technologies need to be encouraged by providing subsidies to farmers to adopt technologies such as zero tillage, bed planting, laser leveling, and SRI technique for growing paddy. This will improve groundwater use efficiency.
- Artificial groundwater recharge should be done on a priority basis, through rooftop rainwater harvesting, and combination of recharge shafts and injection wells (CGWB, 2004).

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Grain filling characteristic and yield formation of water-saving aerobic rice handao297 as affected by N application and soil type

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Abstract

Water-saving aerobic rice Handao 297 (HD297) faces a problem of low harvest index and low percentage of filled grain. Field experiments were carried out at farm and station sites with different physical and chemical soil properties in 2006, to investigate the characteristics of grain-filling and dry matter accumulation/ translocation as affected by N application and soil type. Grain yield ranged from 3.3 to 4.4 ha and was 14% higher on average on the fertile soil site (farm site) than the poor soil site (station site). There was no significant difference in translocation efficiency among treatments, which ranged from 14.4 to 38.4%. SPAD values of flag leaves decreased rapidly about 16 days after flowering. The contribution of pre-anthesis assimilate to grain (CAVG) was 21.8-67.4%. Superior grain reached the maximum grain-filling rate 15 days earlier than inferior grain, which demonstrated that HD297 is asynchronous and has low yield potential. Poor dry matter translocation and production after flowering were also reasons for low grain yield. Grain-filling and thus dry matter transportation/production after flowering were improved by nitrogen application on the low fertility soil at the station site.

Media grab

The asynchronized characteristic of aerobic rice Handao297 might be an important cause of its low yield potential, and new synchronized varieties should be bred and tested.

Introduction

Aerobic rice is a recently developed rice type that will respond to inputs and give reasonable yields when grown under nonpuddled, nonponded soil conditions (Bouman, 2001). The grain yield of aerobic rice is higher than that of traditional upland rice, but lower than flooded rice (Peng et al., 2006). In 2005, a pre-experiment was conducted under high fertility soil conditions. In this experiment, shoot dry matter of HD297 was as much as 15 t/ha, but harvest index and percentages of filled grain were only 0.33 and 60%, respectively, implying a problem of dry matter translocation during the reproductive stage. Low dry matter translocation in turn limited grain-filling, which resulted in low percentage of filled grain and thus yield.

Grain-filling is determined by genetic characteristics, management such as water and nitrogen inputs, and soil properties. Genetically, there are two grain-filling patterns, synchronized and asynchronized. For synchronized genotypes, the superior (top of panicle) and inferior (base of panicle) grain reached rapid grain-filling periods (RGFP) at similar dates, while those of asynchronized genotypes reached RGFP at different dates (Yang et al., 2000a). Rapid synchronized genotypes have high yield potential and a high percentage of filled grain, while asynchronized genotypes show the opposite trend. With asynchronized genotypes, the grain-filling rate of inferior grain can be improved through better management, which provides the possibility of improving the grain yield of aerobic rice. The objectives of this paper are to firstly clarify the characteristic of grain-filling of HD297, then analyze the effect of management (N fertilization) and soil types on its grain-filling and yield formation characteristics.

Materials and methods

Field experiments were conducted at Shangzhuang Experimental Station (39°54'N, 116°24'E 'station site,' SS) of China Agricultural University, a former maize field with a deep groundwater table, and 17 km away at Shangzhuang Experimental Farm ('farm site,' FS), a rice field with shallow groundwater table in Beijing, North China (Zhang, 2008). Soil fertility of FS was higher than SS. The experiment was a completely randomized block design with four replications and the plot size was 6m×10m. The N application rates were zero nitrogen (N0) and 150 kg/ha (N150) as urea-N, of which 30% was applied at sowing, 40% at tiller initiation, and 30% at panicle initiation. Handao297 was direct seeded at 67.5 kg/ha, 30 cm row space. Rice was seeded on May 2006 and harvested in October. At the time of sowing, 56 kg/ha P₂O₅, 56 kg/ha K₂O, 22.5 kg/ha iron sulfate (FeSO₄) and 15 kg/ha zinc sulfate (ZnSO₄) were applied.

During the heading stage, about 100 panicles that headed on the same day were tagged in each plot. Five to ten tagged panicles from each plot were sampled in 3-day intervals from anthesis to 6 days after anthesis (DAA) and at 6-day intervals from 6 DAA to maturity. The sampled panicles were

divided into three parts, superior, middle, and inferior. Grains on the apical position of the top primary branch were taken as superior grain (SG) and those on the lowest secondary branch were sampled as inferior grain (IG) (except sterility) according to Bo and Cai (1989). Grain was oven-dried at 80°C to constant weight. The grain-filling progress was fitted by Richards' (1959) equation and grain growth equation was described by Zhu et al. (1988): $W = A / (1 + Be^{-kt})^{1/N}$, where W is the grain weight (mg); A is the final grain weight (mg); t is the time after flowering (d); B , K , N are coefficients determined by regression. The aboveground biomass was determined at flowering from two rows of 0.5 m and at maturity from two rows of 1.0 m, after drying at 80°C to constant weight. An area of 9 m² was harvested to analyze grain yield (14% water content), the number of panicles per square meter (PM), the number of grains per square meter (GM), percentage of filled grain (PFG), and 1000-grain weight (TGW). SPAD values of flag leaves after flowering were measured. Data were analyzed by the GLM procedure of the Statistical Analysis System (SAS, version 8.0).

Results and discussion

Grain yield and PFG of HD297 at both sites ranged from 3.3 to 4.3 t/ha and 60 to 84%, respectively (Table 1). Grain yield at FS (higher fertility soil) was significantly higher than that at SS without N fertilizer (N0), but the difference between two sites was smaller with 150 kg/N ha (N150). N application significantly improved grain yield at SS, while there was no effect on grain yield at FS. Among yield components, panicle number per square meter (PM) increased after N application, but percentage of filled grain (PFG) and 1000-grain weight (TGW) decreased at both sites, which implied shortcomings on grain-filling at the reproductive stage (Table 1).

Table 1. Grain yield (14% water content), panicles per panicle (PM), grain per panicle (GP), percentage of filled grain (PFG), 1000-grain weight (TGW), straw dry matter accumulation (DM), dry matter translocation efficiency (DMTE), contribution of pre-anthesis assimilate to grain yield (CAVG) of aerobic rice Handao297 under different nitrogen treatments.

Source of Variation	Yield (t/ha)	PM (/m ²)	GP	PFG (%)	TGW (g)	DM (t/ha)		DMT (t/ha)	DMTE (%)	CAVG (%)
						Flowering	Maturity			
Farm site										
N0	4.3 a A	244 b A	72 a A	81.2 a A	29.2 a A	5.0 b A	4.2 a A	0.8 a A	15.3 a A	21.8 a A
N150	4.4 a A	306 a A	80 a A	59.5 b B	27.6 b A	7.7 a A	4.9 a A	2.8 a A	33.2 a A	67.4 a A
Station site										
N0	3.3 b B	201 b B	63 a A	84.0 a A	27.5 a B	4.5 b A	4.5 b A	0.7 b A	14.4 a A	23.4 a A
N150	3.9 a A	233 a B	74 a A	78.0 b A	26.1 b B	5.8 a B	5.8 a B	2.4 a A	38.4 a A	59.4 a A

a. Figures within each column and experimental site followed by the same small letters are not significantly different; figures within each column and N rate followed by the same capital letters are not significantly different, $\alpha=5\%$.

b. $DMT=DM(\text{Flowering}-\text{Maturity})$; $DMTE=DMT/DM(\text{Flowering})\times 100\%$; $CAVG=DMT/Grain\ yield\times 100\%$.

The time to reach the maximum grain-filling rate (T_{max}) was used to evaluate the grain-filling pattern of rice (Gu 2001). The average T_{max} of SG and IG was 10.3 and 24.9, respectively. The difference of T_{max} between SG and IG was more than 10 days (about 14.6 days) (Fig. 1, Table 2), which indicated a typical asynchronized grain-filling pattern of HD297. The yield potential of asynchronized genotypes is normally low (Yang et al, 2000).

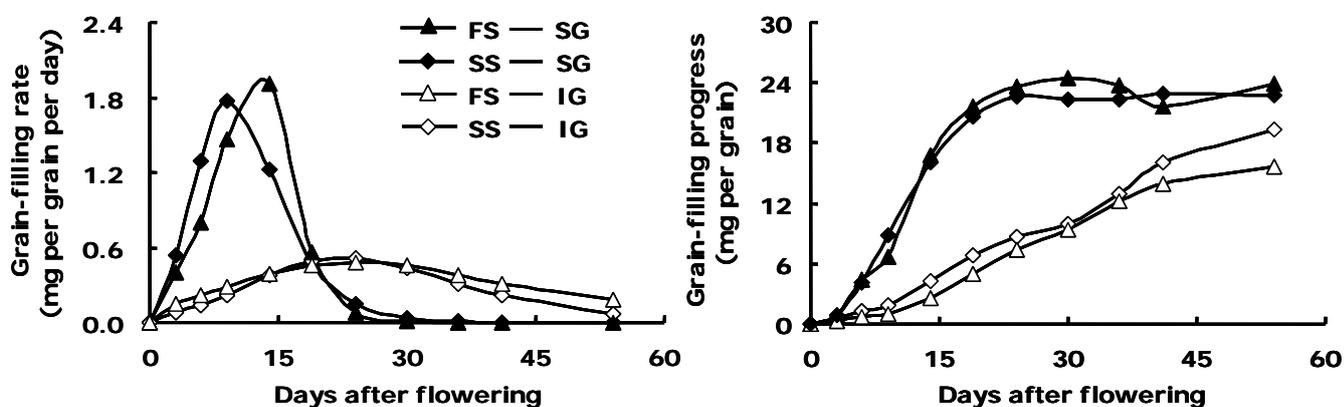


Figure 1. Grain-filling rate and grain-filling progress of superior and inferior grain under farm site (FS) and station site (SS). a SG—superior grain; IG—inferior grain.

Table 2. Parameters and sub-parameters, final grain weight (A), day of reaching the maximum grain-filling rate (Tmax), active grain-filling days (D), the maximum grain-filling rate (Gmax), and the average grain-filling rate (Gav) of Richards equation of aerobic rice HD297 under different nitrogen treatments and experimental sites.

Grain position	Site	N rate (kg/ha)	A (mg)	Tmax (day)	D (days)	Gmax (mg/grain d)	Gav
SG	FS	0	23.2	12.5	16.3	1.97	1.42
		150	24.4	10.1	18.9	1.86	1.29
	SS	0	22.9	9.8	17.9	1.85	1.28
		150	22.6	8.8	20.7	1.61	1.09
	Mean		23.3	10.3	18.5	1.82	1.27
IG	FS	0	22.5	27.4	66.2	0.49	0.34
		150	22.1	25.7	69.0	0.47	0.32
	SS	0	17.9	22.9	50.7	0.52	0.35
		150	15.5	23.7	49.3	0.46	0.31
	Mean		19.5	24.9	58.8	0.49	0.33

Nitrogen application decreased Tmax and increased the active grain-filling days (D) of both superior and inferior grain (Table 2). Therefore, active grain-filling started earlier and lasted longer, which related to increased dry matter translocation (DMT) after N input at both sites (Table 1). Compared to SG, IG had much lower maximum grain-filling rate (Gmax) and average grain-filling rate (Gav), but longer grain-filling days (D). This large gap between SG and IG suggested the possibility of increasing yield through improving the grain-filling of IG. Although Gmax and Gav of inferior grain were not affected by N150, it is possible that grain yield might be increased through optimizing nitrogen application timing or genetic improvement (Zhang, 2008).

SPAD values increased after N application at both sites, especially at the low fertility site (SS). Moreover, SPAD values of the flag leaves decreased rapidly 16 days after flowering, reflecting the reduction of photosynthetic capacity (Figure 2). Dry matter accumulation after flowering was about 32.0% of total shoot dry matter, which directly proved poor photosynthesis of HD297 during this period. Low photosynthesis after flowering would be another cause of low grain-filling that limits grain yield. The contribution of pre-anthesis assimilate to grain increased with N input, so improving photosynthetic efficiency of leaves through changing N application rate or time could increase grain yield (Table 1).

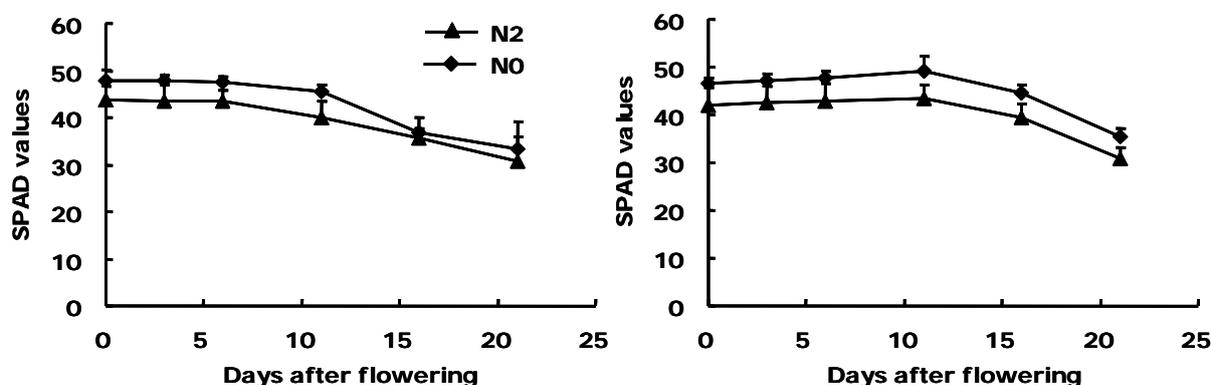


Figure 2. SPAD values of flag leaves after flowering at farm site (left) and station site (right).

Conclusions and Recommendations

Aerobic rice Handao 297 was shown to have an asynchronized grain-filling pattern, which is part of the cause of low grain yield of this genotype. The asynchronized pattern means that the grain-filling rate was improved by nitrogen application at the low fertility site, and was higher on a high fertility soil (farm site). Low dry matter accumulation occurred during grain filling, limiting dry matter translocation from stems/leaves into panicles/grains, and low percentage of filled grains, were observed and may limit yield. We suggest that genetic improvement is needed to overcome these limitations.

Acknowledgments

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Water availability deficit in rainfed farming for semiarid Mzingwane Catchment, Zimbabwe

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Abstract

Rainfed farming in semiarid regions is often affected by water shortage caused by mid season dry spells rather than low annual rainfall. Analyzing the water shortage experienced during a growing season helps in the design of appropriate interventions for mitigating against the negative impacts of the dry spells. Water availability deficit for rainfed farming in Zhulube catchment in the Limpopo River Basin was studied to provide a basis for research in interventions such as rainwater harvesting. The results show considerable potential for rainwater harvesting to improve crop production.

Media grab

Crop water availability deficit, which is key to risk mitigation during dry spells, can be estimated using a simple spreadsheet-based model.

Introduction

Most smallholder farmers in semiarid regions of developing countries rely on rainfed farming for crop production. The crops, however, are negatively affected by temporal rainfall variability that is characterized by mid-season dry spells, leading to food insecurity (Rockström, 2000). A dry spell is defined as a continuous period of no rainfall during a rainfall season lasting for 10 days or more (Stewart, 1988; Sivakumar et al., 1993; Rockström et al., 2003). Crops suffer water stress that results in yield reduction. Occurrence of dry spells varies from year to year in the length of the dry spell period and the number of dry spells within a rainfall season (Chibulu, 2007). Severe dry spells lasting more than 4 weeks result in crops reaching a permanent wilting point and eventually total crop failure. Relieving the negative effects of dry spells is possible where the severity is limited, and rainwater harvesting is one way of doing this. To select and design the most appropriate mitigation technique, it is important to know how much water is required or should be made available by the technique. The water deficit during dry spells should therefore be analyzed.

Studies on soil moisture deficit are reported by Shaw (1990) for various crops on a monthly basis to help irrigation engineers plan for irrigation schemes, rather than to help water managers plan for rainwater harvesting systems. In the latter, the water to reduce the water availability deficit has to come from rainfall events prior to a dry spell. The deficit for shorter durations than one month therefore becomes critical. Rainwater harvesting is increasingly being considered as a viable strategy for improving food production in rainfed agriculture for semiarid areas of developing countries. The southern African region is largely made up of semiarid regions, such as the Limpopo River Basin. Rainfall is low and highly variable. Frequent crop failure occurs in smallholder farms. Various studies have been carried out under the CGIAR Challenge Program on Water and Food (CPWF) to improve food productivity in the Limpopo Basin. Some nongovernmental organizations have introduced water conservation technologies to improve water availability for crop growth. One such innovation is the introduction of a modified form of contour ridges, referred to as dead level contours, whose effectiveness has not been evaluated. As a way of evaluating rainwater harvesting technologies, the improvement in water availability after their adoption should be measured. Estimation of water availability deficit enables evaluation of mitigation measures against effects of dry spells. This study proposes a model for use in estimating water availability deficit in a semiarid region using Zhulube Catchment as a case study.

Zhulube Catchment is the catchment area of Zhulube Dam that is constructed on the Tshazi River, a left bank tributary of Mzingwane River. The Mzingwane River is a tributary of the Limpopo River. The dam supplies water to a 40 ha irrigation scheme. It is, however, under threat of sedimentation because poor land use practices in its 21 km² catchment area (see map in Dondofema, 2007).

Methods

We developed a model for estimating water availability deficit. The model was coded in a computer spreadsheet where input data are entered. Input data were obtained from various studies that have been carried out in the Zhulube Catchment by various researchers (see Acknowledgments).

Theory and modeling

Water availability for crop growth under rainfed agriculture is considered as the soil moisture within the root zone of the crops. To assess the water deficit, the water balance of the soil profile constituting the root zone should be considered (Figure 1). The inflow into this profile is infiltration, lateral soil moisture flow, and capillary rise. The outflow consists of lateral flow, percolation, and evapotranspiration. The water balance equation is represented by:

$$dS/dt = F + C_{ap} + Q_{in} - Q_{out} - P_{erc} - ET \quad \text{Equation 1}$$

In equation 1, dS/dt is change in storage (soil moisture) during the time, F is infiltration, C_{ap} is the capillary rise, P_{erc} is the percolation to groundwater, and ET is evapotranspiration during the time. Q_{in} and Q_{out} are the lateral flow into and out of the soil profile during the time period.

The exchange of water between the root zone and the groundwater zone through percolation and capillary rise occurs when the moisture in the root zone exceeds field capacity or when the water table is close to the root zone. This is usually not the case in most semiarid conditions, as the water stored in the root zone will rarely find its way beyond the root zone. If the width of the soil profile considered is small enough, the lateral flow into the soil profile and out can be considered to be the same. Equation 1 can therefore be reduced to equation 2:

$$dS/dt = F - ET. \quad \text{Equation 2}$$

Water availability deficit occurs when available soil moisture is less than field capacity. Thus, the water availability deficit algorithm can then be represented in equation 3:

$$\begin{aligned} \text{WAD} &= FC - \text{ASM} + F - ET; \text{ if } \text{ASM} < FC \\ &= 0; \text{ if } \text{ASM} \geq FC \end{aligned} \quad \text{Equation 3}$$

WAD is the water availability deficit during the time step t , ASM is the available soil moisture during the time step $t-1$, FC is field capacity.

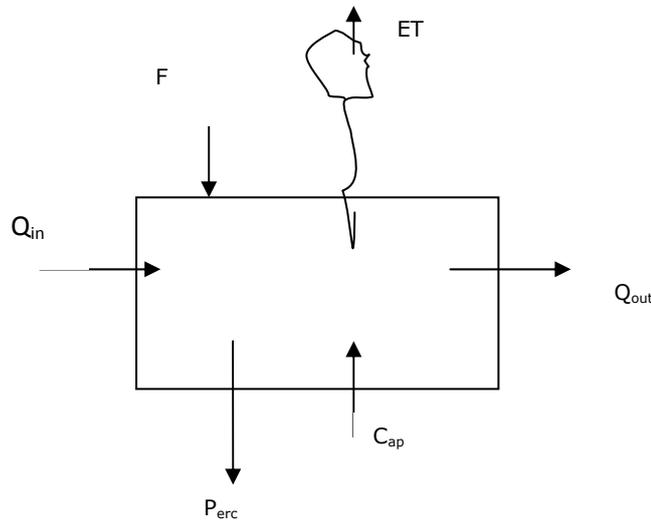


Figure 1: Water movement in the root zone soil profile.

The parameters that need to be determined during a time step are infiltration and evapotranspiration. Infiltration can be estimated in terms of daily precipitation using the Horton infiltration equation, provided the time of a rainfall is known. Storm duration can be related to the amount of rainfall received through an empirical equation as modified from the Department of Meteorological Services

formulas for storm duration, as shown below. In this study a constant daily evaporation figure has been assumed.

$T = [2050 \log(P)]/dt$, T is storm duration, P is daily precipitation, and dt is time of day related to units of storm duration.

The storm duration time can be taken as the infiltration time in Horton's equation. Thus potential cumulative infiltration is then given by:

$$F = f_c t + (f_0 - f_c)/k (1 - e^{-kt})$$

Where

F is cumulative infiltration for the day, f_c is constant infiltration rate reached when steady state conditions are reached, f_0 is initial infiltration rate, k is recession constant, and t is the equivalent storm duration for the daily precipitation.

The water availability model then requires input consisting of time series data and soil characteristic data of infiltration capacity, recession constant, and field capacity. The time series data consists of daily rainfall and open pan evaporation data.

Results

The results (Figure 2) obtained are still preliminary. The empirical formulas for the estimation of storm duration and evapotranspiration still need refinement by using data from the study area.

Discussion

The model is able to predict periods when soil moisture deficit is expected to be high as well as when it is expected to be low. It could not be established, however, whether the model accurately predicts the soil moisture deficit as data on soil moisture were not available. The study is ongoing, and the model will be calibrated when necessary data becomes available. The area below the water availability deficit gives the amount of water that a rainwater harvesting technology should provide. Different amounts are required to mitigate against different dry spells that occur, and after different rainfall amounts.

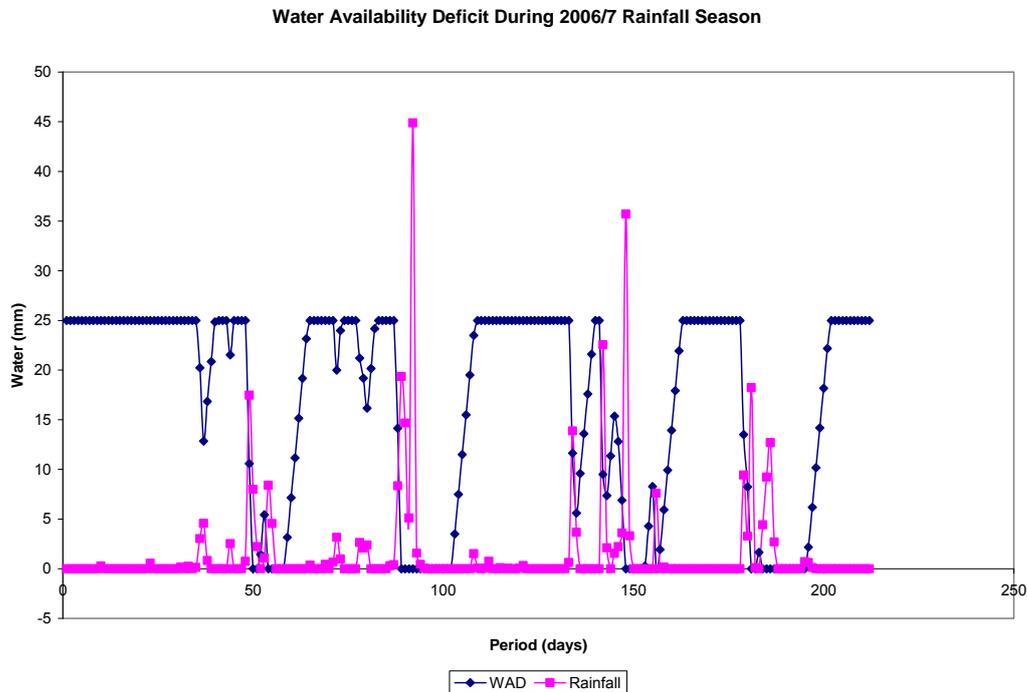


Figure 2: Variation of water availability within the Zhulube Catchment, Zimbabwe. Source: Ngwenya, 2006; Chibulu, 2007.

Conclusions and recommendations

A model for estimating water availability deficit was developed. The model for Zhulube Catchment still requires refinement through the use of additional data, as well as verification when soil moisture data are obtained.

Acknowledgments

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Water productivity in the salt-prone areas of Lower Karkheh River Basin, Iran

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Abstract

Waterlogging and soil salinity are major threats to the productivity and sustainability of agriculture in the Lower Karkheh River Basin (LKRB). More than 78% of agricultural production in Dasht-e Azadegan region of LKRB is dominated by grains, mainly wheat and barely. The problem of soil salinity is exacerbated due to poor farmer practices and inadequate drainage networks. Soil salinity is the major cause of low yields and low water productivity (WP). In general, the main cause of soil salinity is the high water table, varying between 1.2-3.0 m below the soil surface. The objective of this research was to evaluate WP of irrigated wheat under saline conditions and to develop management guidelines to reduce salinity and waterlogging. The research was conducted in 14 farmers' fields, typical of the farms in the region, during cropping seasons in 2006-07 and 2007-08.

Variation in irrigation WP was high, ranging from 0.1 to 2.1 kg/m³. There were four main sources of inefficiencies: (1) sociocultural problems (e.g. low farming skills, low motivation for investing in irrigation management and on-farm improvement activities, and low motivation for participatory works); (2) limitations out of farmers' control and authority (e.g. irrigation intervals and rationing, and shortage of agricultural inputs); (3) technical and infrastructure limitations and problems; and (4) farmer managerial problems and limitations associated with irrigation (e.g. flow control, irrigation and land preparation methods, and improvements in water intake structures). These can be overcome easily and do not need major investment.

Media grab

Water productivity of irrigated wheat under saline-waterlogged conditions is low in the Karkeh River Basin, but it can be improved with simple irrigation management techniques.

Introduction

The Karkheh River Basin (KRB) is one of the large basins in Iran, where dryland and irrigated agricultural production systems are practiced. Water in the KRB is limited and becoming scarcer as population and demand are increasing (Anonymous, 2007). KRB's agricultural strategy identifies water productivity improvement as a top priority.

The KRB encompasses one of the poorest regions of Iran, because it has very poor infrastructure and was severely affected by the war with Iraq. Low production under dry farming and irrigated conditions are issues of crucial importance to increase per capita income of farmers in the basin. Two major agricultural production systems exist in the KRB: the dryland system in the upstream, together with some areas with supplementary irrigation and limited areas that are fully irrigated areas; and fully irrigated areas located predominantly in the lower basin. The dryland areas are well established and cover most of the basin agricultural lands, occupying about 900,000 ha. About 380,000 ha are currently irrigated, but this is expected to expand by 340,000 ha following completion of the irrigation schemes downstream of Karkheh Reservoir Dam (Anonymous, 2007). The main source of irrigation water is direct pumping from the Karkheh River. There are also limited irrigation networks in the region (mainly pumping from the river to the canal).

Waterlogging and soil salinity are the major threats to water productivity and sustainable agricultural production in the southern parts of LKRB (Hajrasuliha, 1970). Heavy soil texture and recharge from upstream areas cause waterlogging and secondary salinization, due to high water tables (1.2-3 m). This situation is a result of large water losses caused by inefficient irrigation and lack of land leveling. The problem is likely to worsen with the current plans for expansion of irrigation networks in the region.

In the southern parts of LKRB, mainly in Dasht-e Azadegan plain (DA), the problem of soil salinity is magnified due to lack of farmers' knowledge and skills, inadequate drainage networks, and absence of new and improved farm practices. Current crops in Dasht-e Azadegan are diversified and include cereals such as wheat, barely, and rice; vegetables such as watermelon, tomato, and cucumber, and fodder crops such as alfalfa, barely, corn, and Sudan grass. More than 78% of agricultural production

in DA region is dominated by grains, mainly wheat and barley. This is due to saline-sodic soil with high toxicity, which makes cultivation of other crops almost impossible. Farmers, however, are more interested in wheat due to subsidies and low production costs.

There are no available data on WP of irrigated crops in LKRB. A preliminary survey suggested that wheat irrigation water productivity is approximately 0.6 kg/m³ (Heydari, 2006). The objectives of this research are to evaluate the water productivity (WP) of irrigated wheat in the Dasht-e Azadegan plain in LKRB, and to find out the managerial problems and limitations to improved productivity, and to recommend simple and adoptable management guidelines to reduce salinity and waterlogging and thus increase crop yield and WP.

Materials and methods

The research was conducted in 14 farmers' fields located in the DA plain in Khuzestan Province, during the 2006-07 and 2007-08 cropping seasons. The fields were typical of the farms in the region, and the farmers grew their own varieties and used their own management. The measured parameters were water inflow and outflow, and a wide range of soil properties including texture, salinity, pH, organic matter, P, K, Fe, Mn, Zn, Cu, depth, and quality (EC) of groundwater during growing season, and crop yield. Some soil and water characteristics of the fields measured before planting the first crop are given in Table 1. Crop yield and yield components were measured through 20 field samples (1.0 m x 1.0 m quadrats) before harvest. The amount of applied irrigation water was measured by WSC (Washington State College) flumes. The irrigation intervals were as practiced by the farmers. The WP was calculated by dividing grain yield (14% moisture) by irrigation amount.

Table 1. Some soil and water characteristics of the study farms at the time of planting.

Field	Area (ha)	Soil texture	EC _e (dS/m)	Depth of water table (cm)	EC of ground water (dS/m)
F1	1.05	SiL	26.4	105	8.8
F2	1.47	SiCL	10	205	39
F3	4.49	CL	52.6	180	71.5
F4	3.44	C	17	195	31
F5	1.73	C	21.5	182	48
F6	0.46	SiC	21.3	173	46
F7	5.24	C	10.5	213	8.7
F8	3.79	SiL	51.4	207	34
F9	4.86	SiCL	17.8	193	48
F10	3.71	SiC	16.2	153	19
F11	6.92	SiC	15.9	205	88
F12	1.17	SiC	21.6	172	15
F13	1.93	CL	16.8	213	98
F14	23.48	C	81.3	186	24

Results and discussion

There was a wide range in irrigation amount (2190-4140 m³/ha), yield (0.5-4.9 t/ha), and irrigation WP (0.1-2.1 kg/m³) (Table 2). Based on the latest agricultural statistics, Iran produced 67 Mt of agricultural products, which consumed 84 BCM of water. Therefore, currently the country's average WP is almost 0.8 kg/m³ which seems quite low compared with the world's average value (around 1.5 kg/m³) (Heydari et al., 2005). Previous results of field studies conducted in three provinces in Iran (Kerman, Golestan, and Khuzestan) indicated that WP of farmer-managed irrigated wheat is in the range of 0.56-1.46 kg/m³ (Heydari et al., 2006). Zwart and Bastiaanssen (2004) based on review of 84 references on WP during the past 25 years determined that the average WP of wheat is 1.09 kg/m³. The range of WP is generally wide and, for wheat, varied between 0.6 and 1.7 kg/m³.

Table 2. Applied water, crop yield, and irrigation water productivity of wheat in different studied fields.

Field	Water applied (m ³ /ha)	Yield (kg/ha)	WP (kg/m ³)
F1	3109	2392	0.77
F2	3460	1022	0.30
F3	2062	1336	0.65
F4	3792	1453	0.38
F5	3527	3032	0.86
F6	2311	4851	2.10
F7	5933	1431	0.24
F8	3705	2573	0.69
F9	2188	1317	0.60
F10	2282	1617	0.71
F11	2518	1699	0.67
F12	3496	2094	0.60
F13	3142	1088	0.35
F14	4636	468	0.10

The amount of irrigation water applied per unit area tended to increase with field size ($R^2=0.35$). This is an indicator of the problems associated with irrigation management in larger field sizes. The lack of equipment, facilities, and farmers skills in proper water management has led to higher application rates.

Evaluation of the relationships between WP and irrigation water, yield, initial soil salinity, initial ground water salinity, groundwater depth, and field size indicated that there is no direct correlation between WP and each of these factors. Based on observations while working with the farmers estimating WP in the region, the sources of inefficiencies and factors limiting WP in the southern part of LKRB can be classified into four main categories:

- Sociocultural problems associated with the farmer communities leading to low motivation among the farmers for individual or joint-investment with the government in irrigation management and on-farm improvement activities.
- Limitations that are out of farmer's management control and authority (e.g., irrigation intervals and rationing, and shortage of agricultural inputs–fertilizers, other agrochemicals, machinery).
- Technical and infrastructure limitations and problems (e.g., inadequate drainage and reclamation, and incomplete irrigation and drainage networks) that need extensive planning and investments and which should be supported by the government.
- Farmer management problems and limitations whose solution is simple and which do not need much investment and can be accomplished easily (e.g., flow control, irrigation and land preparation methods, improvements in water intake structures, growing improved varieties, fertilizer, and weed control management).

The results indicated that these limitations vary depending on the farmer and location of the farm. Some of these limitations are:

- Traditional common irrigation in the area is a mixture of border-basin irrigation methods. The long borders (up to 400 m, 12-15 m wide) are divided into small basins (30-60 m long). Every basin receives its water from the previous (upstream) basin. Water is ponded for a long time in the upper basins in the sequence until the bottom basin has been irrigated, damaging the seed in the upper basins due to prolonged waterlogging. The high inflow rate at the top also results in erosion and exposure of the seeds. As there is not enough control on cutoff time, large amounts of water accumulate in the lower parts and create surface waterlogging. Irrigation via a farm ditch alongside the border, and a proper intake into each basin, are recommended.
- Problems in water intake and conduct of water into the irrigation plots due to lack of properly constructed intake structures. This problem leads to waste of time and effort for the farmers to control irrigation flow (start and terminate the flow to the plot). This directly leads to extra runoff, deep percolation losses, and poor water management in the field. Construction of temporary and low-cost intake structures (gates) to facilitate water intake and improved water management are recommended.
- Improper leveling and slope of the fields causes nonuniform distribution of water in the plots.
- Improper land preparation and agronomic practices (weed control, planting date).

Conclusions and recommendations

Considering the above limitations and problems, the following solutions are recommended to improve WP in the saline area of LKRB:

- Conversion of traditional and locally common irrigation methods to proper basin/border methods.
- Construction of fixed and low-cost water intake structures on farm ditches.
- Proper land leveling and bedding according to farm slope.
- Application of onfarm management improvement instructions provided by rural extension services.
- Farmer training and supervision by irrigation experts for guidance, and enhancement of irrigation management.
- Preparing the required conditions and enabling environment for volumetric allocation of water to the farmers through extension services.

Acknowledgments

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Best irrigation management practices for improving water productivity in salt-prone areas of Lower Karkheh River Basin

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Abstract

The Karkheh River Basin (KRB) is one of the nine Benchmark Basins of the CGIAR Challenge Program on Water and Food (CPWF). Despite generally favorable climate, soil, and water resources for agricultural production, overall agricultural water productivity, especially in the lower and downstream areas of the KRB (mainly Dasht-e Azadegan (DA) plain in the Basin outlet), is very low (about 0.6 kg/m³). This is mainly due to inefficient use of these resources, including lack of sound agronomic, water, and salinity management practices. In the Lower KRB (DA plain) human factors together with the heavy soil texture, recharge of water table by subsurface flows from upstream areas, and low irrigation efficiency cause waterlogging and soil salinity, which are the major threats to water productivity and sustainable agricultural production in this plain. Wheat is the main cultivated crop in this area. Sound irrigation management solutions that can be adapted and adopted by the farmers are needed to help improve agricultural WP and livelihood of the communities.

The main objective of this research was to find cost-effective and short-term solutions for solving these problems, and to improve water productivity (WP) of wheat in the salt-prone areas of the lower KRB. The research was conducted in the DA plain, during two cropping seasons (2006-07 and 2007-08). The treatments were a combination of two irrigation methods (Border and Basin) and three sowing methods (centrifugal broadcaster, seed drill machine (TAKA type), and three-row bed seeder (Barzegar-e-Hamadani type), which were compared with a control (farmer traditional irrigation and sowing methods). Crop yield and other components and the volume of applied irrigation water were measured.

Border irrigation with the centrifugal sowing method or Hamadani sowing methods provided the highest WP in the first and second years, at 1.60 and 1.88 kg/m³, respectively. Border irrigation had the highest WP (1.36, 1.74 kg/m³ in the first and second years), whereas the farmer-managed treatment (traditional border-basin irrigation method under centrifugal sowing with 350 kg/ha seed) had the lowest, 0.61 and 0.81 kg/m³ in the first and second years. There was no significant difference ($\alpha=0.05$) in yield between applied treatments and the control treatment in the first year. In the second year, however, because of severe drought, the improvement in WP of the treatments in comparison to the control was higher. The seed rates used in the TAKA and Hamadani sowing methods were almost 50% less than with the centrifugal broadcaster method, and seed germination and establishment of the crop was higher with the former leading to higher yields. The improved border and basin methods can be recommended, but the basin irrigation method is more adoptable and sustainable in the region because of sociocultural conditions of the area. Considering the 50% reduction in seed consumption, high establishment of the crop, and better conveyance and advance of water in irrigation strips, use of the seed drill machine (TAKA type) or three rows bed seeder (Barzegar-e-Hamadani type) are recommended.

Media Grab

Improvement of traditional surface irrigation methods in the saline and waterlogged areas can help ameliorate the situation and improve crop water productivity.

Introduction

The Karkheh River Basin (KRB) is one of the main agricultural basins in Iran. Despite favorable potentials with respect to climate, soil, and water resources, the overall agricultural water productivity (WP) of the basin, especially in the lower and downstream areas of KRB (about 0.6 kg/m³), is relatively low. This is mainly due to inefficient use of these resources through lack of sound agronomic, water, and salinity management practices.

The Lower KRB (LKRB) is typically hot and almost arid, and agricultural production is essentially dependent on irrigation. This area is designated for further development following the model of the adjacent Dez irrigation district in Iran. It is estimated that about 1 million ha are irrigable in KRB, of

which about 380,000 ha are currently under irrigated agriculture annually. About 340,000 ha of additional available arable lands will be brought under irrigation following completion of irrigation networks below the Karkheh Dam in the LKRB. On the other hand, frequent droughts and recent trends in increased use of water in the upper KRB, due to expansion of irrigated areas and supplemental irrigation, will make it more difficult to supply sufficient irrigation water for the developed areas below Karkheh Dam in the LKRB.

Waterlogging and soil salinity are the major threats to WP and sustainable agricultural production in the DA plain (Hajrasuliha, 1970). The large areas of saline/sodic soils in LKRB are partly natural and partly caused by human activity. The main cause of salinity in the LKRB is excessive deep percolation due to poor irrigation management. The soil texture in the area is mainly heavy with low hydraulic conductivity. The overall natural drainage is very low and there is a natural tendency for waterlogging and secondary salinization. The installation of drainage networks could provide a rapid solution for the salinity-waterlogging problem. Based on past trends, however, expansion of drainage networks will not be in parallel with the development of irrigation networks in the region. Therefore, the mitigation of salinity and waterlogging hazards and agricultural WP improvement in the LKRB should be tackled by soil, water, and crop management and overall it is a complex issue that needs integrated planning and action.

Wheat is the main cultivated crop in the LKRB, with average yield of 1.5 t/ha. Irrigation management practices are traditional and the region suffers from poor water management that is partly due to lack of modern irrigation infrastructure and onfarm improvement activities. Therefore, sound solutions that can be adopted by the farmers are necessary. It is evident that the basic approaches to solving this problem will mainly be the construction and or completion of modern irrigation and drainage networks, and managing the system based on integrated and scientific programs. But such programs are costly and time consuming, and may not become effective in the near future. Research activities related to water-table management, soil salinity control, irrigation water management, selection of suitable crop varieties, and improved agronomic practices will help improve agricultural WP and farmers' livelihoods in this region. It will ameliorate the current situation without requiring heavy investments.

Based on review of 84 references on WP during the past 25 years, Zwart and Bastiaanssen (2004) found that the average WP of wheat is 1.09 kg/m³. The range of WP is wide and varies between 0.6 and 1.7 kg/m³. Fahong et al. (2004) compared basin and furrow irrigation of wheat and concluded that cultivation of wheat in flat basins with flood irrigation causes surface sealing, reduces irrigation efficiency, and increases fertilizer losses. They found that furrow irrigation of wheat led to a 17% reduction in water consumption, increased irrigation efficiency (21-30%), increased fertilizer efficiency, and reduced crop disease.

The main objective of our research was to find cost-effective and short-term solutions to problems of waterlogging and salinity, using the following approaches:

- Recognition of simple management practices for reducing soil salinity hazards and improving agricultural WP.
- Comparison of WP under different irrigation methods and management (i.e., traditional vs. improved border-basin irrigation method).
- Investigation of the effect of different cultivation/sowing methods on wheat WP.

Methods

This research was conducted during the cropping seasons of 2006-07 and 2007-08 in the DA plain, located in the most southern part of the delta of the Karkheh River. The area is located between 47° 55' to 48° 30' E longitude and 31° 15' to 31° 45' N latitude and is 3 - 12 m above mean sea level. Soil texture was silty clay loam to clay-loam, average soil pH was 7.8, and average soil salinity at depths of 0-90 cm was 10.5 dS/m. The source of irrigation water was the Karkheh River. The EC of the groundwater and irrigation water were 11.3 and 1.4 dS/m, respectively. Sowing and harvesting dates were in November and May, respectively. Groundwater depth at the beginning of the growing season, before the start of rainfall and irrigation, was 237 cm, and in winter, following irrigation, the groundwater depth varied from 35 to 98 cm below the soil surface.

The research treatments were as follow:

- T₁= border irrigation + sowing by centrifugal broadcaster + one pass disc.
- T₂= border irrigation + sowing by seed drill (TAKA type).
- T₃= border irrigation + sowing by three rows bed seeder (Barzegar-e-Hamadani type).
- T₄= basin irrigation + sowing by centrifugal broadcaster + one pass disc.
- T₅= basin irrigation + sowing by seed drill machine (TAKA type).
- T₆= basin irrigation + sowing by three-row bed seeder (Barzegar-e-Hamadani type).
- T_c= traditional irrigation and sowing method by farmer (as control).

The dimensions of the border and basin treatments were 160 m x 10 m (for T₁, T₂, T₃) and 40 m x 10 m (for T₄, T₅, T₆), respectively. These dimensions were considered to be optimal based on SCS recommendations. The traditional method of irrigation (control) was similar to a combination of basin and border irrigation. Farmers choose border length according to their farm dimensions (usually 100-400 m), and then divide the borders into several basins 30-70 m long, depending on field topography. They fill the first basin and then transfer water to the second one, and so on. The width of borders was usually between 5 and 14 m.

Chamran wheat variety was sown in all the treatments. The seed rate was 250 kg in treatments sown by centrifugal broadcaster and managed under optimized irrigation (T₁, T₄). The other treatments (T₂, T₃, T₅, T₆) were sown using a seed drill (TAKA) or a three-row bed seeder (Hamadani) at 180 kg seed/ha. In the control treatment (T_c), which was sown by centrifugal broadcaster and managed by the farmer, the seed rate was 350 kg/ha. Other farming practices were the same for all treatments. Soil chemical characteristics measured before planting (Table 1) and water table depth fluctuations during cropping season (Figure 1) are presented.

Table 1. Soil chemical characteristics measured before planting (avg of three samples and 2 years).

Soil depth (cm)	EC (dS/m)	pH	O.C (%)	P (ppm)	K (ppm)	Fe (ppm)	Zn (ppm)	Cu (ppm)	Mg (ppm)
0-30	15.0	7.7	0.4	4.2	166	3.8	1.5	0.6	5.2
30-60	12.9	7.9	0.1	2.0	89	2.3	0.1	0.4	1.2
60-90	15.2	7.9	0.1	1.5	56	3.1	0.1	0.6	1.5

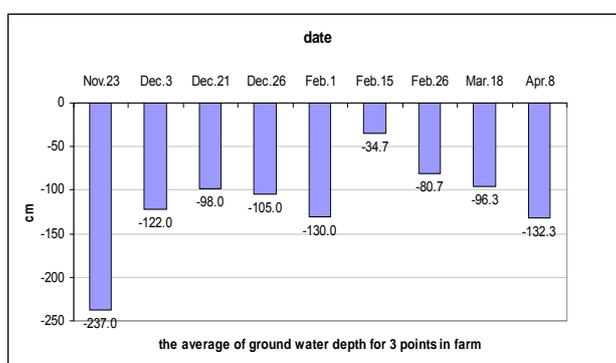


Figure 1. Variation of the groundwater depth (average of three points) during growing season.

Crop yield and yield components were measured through sampling (20 samples, 1 m x 1 m) before harvest. The amount of applied irrigation water was measured by WSC (Washington State College) flumes. There was no difference between the farmer and optimum management treatments in terms of interval and number of irrigations. In fact, the difference was in how to manage water flow on the land and the method of irrigation, both of which directly affected water consumption.

Results

Border irrigation with the centrifugal and Hamadani sowing methods (T₁, T₃) provided the highest water productivities in both years, being 1.60 and 1.88 kg/m³ respectively. Among the irrigation methods, the optimum border irrigation had the maximum WP (1.36, 1.74 kg/m³) each year, whereas the farmer control treatment (traditional border-basin irrigation method under centrifugal sowing with 350 kg seed used) had the lowest WP of 0.61 and 0.81 kg/m³ (Table 2). There was no significant difference ($\alpha=0.05$) in yield between treatments. In the second year of experiments,

however, because of severe drought, the improvement in WP of the treatments in comparison to the control was even higher. Although the consumption of seed used in TAKA and Hamadani sowing method was 50% less, establishment was higher than with the centrifugal method (Table 3).

Table 2. Yield, amount of water applied, and water productivity (WP) of studied treatments.

Irrigation method	Sowing method	Yield (kg/ha)		Applied water (m ³ /ha)		WP (kg/m ³)		WP (avg of irrigation treatment) (kg/m ³)	
		2006-07	2007-08	2006-07	2007-08	2006-07		2006-07	2007-08
		Basin-border (farmer)	Centrifugal	1953	1940	3205	2388	0.61	0.81
Optimum border	Centrifugal	2590	2144	1618	1348	1.60	1.59	1.36	1.74
	Taka	2434	2471	1774	1414	1.37	1.75		
	Hamadani	1901	2400	1729	1277	1.10	1.88		
Optimum basin	Centrifugal	2730	2251	2394	1663	1.14	1.35	1.04	1.53
	Taka	2521	2606	2417	1633	1.04	1.60		
	Hamadani	2198	2564	2344	1576	0.94	1.63		

Table 3. Seed consumption, number of shrub and sprouting percentage of the treatments.

Irrigation method	Sowing method	Seed consumption rate (kg/ha)		Plant density (no./m ²)		Sprouting (%)		Yield (kg/ha)	
		2006-07	2007-08	2006-07	2007-08	2006-07	2007-08	2006-07	2007-08
		Basin-border (farmer)	Centrifugal	350	350	247	270	34	31
Optimum border	Centrifugal	250	250	341	290	56	47	2308	2338
	Taka	180	180	262	302	60	61		
	Hamadani	180	180	286	316	65	64		
Optimum basin	Centrifugal	250	250	387	320	63	52	2483	2474
	Taka	180	180	332	321	75	65		
	Hamadani	180	180	353	352	80	71		

Conclusions and recommendations

Improved basin or border irrigation methods can be recommended for the improvement of water management and WP in the studied area. The basin irrigation method, however, is more adaptive and sustainable because it is better suited to the sociocultural conditions of the area. The reasons for this are:

- It requires low levels of land leveling and uniform slope along the irrigation plot so requires low levels of onfarm improvement activities.
- It is more adoptive to farm micro relief caused by common cultivation practices.
- It requires less labor (considering shortages in agricultural labor in the area).
- It requires less control on flow considering the high rate of flow variation.
- The Basin method provides precultivation leaching opportunities, a common practice for reducing soil salinity prior sowing, which in local language is called 'Makhar' water (considering high levels of salinity and its variation in the wheat farms of the area).

Because of a 50% reduction in seed consumption, high rate of seed germination, and better flow of water, the use of the seed drill (TAKA type) or three-row bed seeder (Barzegar-e-Hamadani type) is recommended.

Overall, soil salinity and waterlogging, in addition to the other sources of inefficiencies in agricultural WP improvement, are the major limiting factors in the LKRB. These problems are somewhat due to physical characteristics of the region, but are mainly problems created by human activity and can be

managed by proper measures, including infrastructure activities (hardware) and to a greater extent by water management (software) measures.

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Increasing livestock water productivity

Opportunities for increasing livestock water productivity in Sudan

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Abstract

Livestock and irrigated and rainfed crop production make up most of Sudan's agricultural GDP. Sudan is highly dependent on Nile waters flowing from upstream countries and on rainfed cropping and grazing within the country. This region has experienced high human and livestock population growth rates, increased cropping and widespread deforestation. This study addresses livestock water productivity (LWP) in the central belt of Sudan. In most of the belt there is a severe drinking water shortage for both animals and people. Livestock also suffer from feed shortages. The research suggests that LWP is low near watering points, because high animal concentration has degraded the nearby pastures. LWP is also low far from watering points because lack of water prevents animals from accessing otherwise available feed. The study concludes that improved natural resources legislation, institutional arrangements, marketing of livestock products, and veterinary care, combined with efforts to optimally expand watering sites while limiting animal densities near them, can help increase LWP in an environmentally sustainable manner.

Media grab

Better balancing of livestock densities with available feed and drinking water resources can help increase livestock water productivity, thereby improving productive assets for the poor in Sudan.

Introduction

Sudan's livestock numbered about 138 million animals in 2006 (MoARF, 2006), playing pivotal roles in the economy, contributing 22% to total GDP, and providing livelihoods for many people. In five out of the 15 states of North Sudan, income from livestock exceeds that from crops, and in four others it forms over 40% of agricultural income (Faki and Nur, 2008). Livestock therefore contribute significantly to poverty reduction. Most domestic animals depend partly on the waters of the Nile for feed production and for drinking, especially during the dry season. Without access to the Nile in dry periods, livestock could not fully benefit from vast grazing lands accessible during more favorable periods. Yet the sector faces tremendous challenges created by fragile and loosely controlled natural resources in predominantly transhumant and nomadic natural pastures. Suboptimal, rather than misuse, of land and water resources, especially in rainfed areas, leads to resource degradation and variable and low livestock productivity. The situation originates from decades-long irrational communal exploitation of land, leading to competition over land and water, and contributing to conflicts for which water scarcity is an important driver (WFP, 2007). Emerging understanding suggests that better integration of livestock and water development can help improve agricultural water productivity in the Nile region (Peden et al., 2007). Our results highlight the need to balance and harmonize the spatial distribution and balance of livestock, land, and water resources in Sudan. The results are based on a synthesis of literature reviews and analyses of secondary data, recognizing that relatively little integrated consideration has been given to the links between river basin water, the region's extensive livestock sector, and its demands for water.

Results and discussion

Major characteristics of the central belt of Sudan

The central part of Sudan extends from its western to eastern borders (roughly between latitudes 10° and 20° N), and is the hub of Sudan's crop and livestock production. Regional livestock movements often involve crossing borders with South Sudan and bordering countries, especially Chad, Central African Republic, and Ethiopia. The belt's link to the Nile Basin is strong in terms of irrigated livestock activities from the Nile and its tributaries, livestock mobility between rainfed and irrigated systems, and livestock trade with other Nile Basin countries such as Ethiopia.

The belt covers 75% of Sudan, accommodates 80% of its people, and hosts 73% of Sudan's total livestock. Rainfall is the major water source, ranging from less than 100 mm/year in the far north to about 800 mm/year in the south. Surface water is available from the Nile system (see Kirby et al.,

2007) and seasonal rivers in the east where most major irrigation schemes exist. The western region depends primarily on rainfall, groundwater, and some seasonal streams. Livestock rearing is a major livelihood strategy dependent on natural pastures and partly on irrigated fodder. Modern peri-urban dairy farms are increasingly important. Historical developments in use patterns resulted in serious degradation of the region's rich natural resources. Consequently, most of the acute poverty in the country lies within the belt, but civil strife is also a factor. Livestock-water related problems differ in severity across the belt.

Development of pressures on natural resources

Four factors place pressure on and underpin the currently inefficient use of natural resources: land tenure, population growth, crop expansion, and increasing livestock numbers.

Land issue

The Land Resettlement and Registration Ordinance that dates back to 1925 is still largely in force (De Wit, 2001). All unregistered land belongs to the Government, but community rights are recognized over its use under customary rules. Individual land registration is limited; while long land lease applies in public irrigation schemes and large semimechanized rainfed private holdings. Despite incentives to increase herds irrationally under communal land use, fairly balanced management and protection of natural resources and harnessing local conflicts had been practiced within the traditional leadership systems. But two legal developments in the 1970s had far-reaching implications on land use. First, the Unregistered Land Act of 1970 transferred all unregistered land to the Government from rural dwellers, especially pastoralists, compromising communal and tribal ownership (De Wit, 2001). Second, the Local Government Act of 1971 dismantled traditional authorities and largely transferred their functions to local governments that have limited experience and resources to handle issues such as local conflicts. Thus, control over natural resources has undergone profound relaxation resulting in misuse through deforestation and overgrazing. Official regulations governing access to pasture and water in rainfed areas remain rudimentary, but 1984 legislation allowed for pasture land allocation to communities. Water use legislation has been confined to water-pumping from the Nile and its tributaries for irrigation purposes. The existing legal setting for land, pastureland, water, and forests has been diverse and contradictory, giving little or no attention to traditional land use systems, especially grazing (De Wit, 2001).

The land issue has strongly emerged within the Comprehensive Peace Agreement (CPA) of 2005 that ended the South-North war. The CPA authorizes national and regional land commissions to consider mechanisms that transfer current land use rights to long-term lease rights. This will convey additional value to lease holders and encourage more rational use of natural resources. (Pellekaan and Faki, 2008).

Human and livestock population growth and crop expansion

Fifty years ago, available land far exceeded demand and natural resources sustained the people's livelihoods even under problematic land use patterns (Tothill, 1948). Yet water supply in pastoral areas was generally more limiting than fodder, resulting in limited livestock grazing around watering sites with consequent fodder scarcity and low-quality drinking water. The prevailing land tenure system has aggravated these constraints. Increases in human and livestock populations and croplands (Table 1), as well as deforestation (UNEP, 2007) have exerted high pressure on land and water resources. In irrigated areas, drinking water is abundant but fodder is scarce, and periodic movement to pastoral areas and fallow land is a normal practice.

Table 1. Growth in human and livestock population and crop areas within the belt, 1973-2007.

Region	Human population (million)		Livestock population (million)		Crop areas (million ha*)	
	1973	2007	1973	2007	Average 1971-1976	Average 2003-2007
Khartoum	1.096	6.203	0.506	1.310	0.01	0.08
Central	3.623	8.079	7.031	31.603	1.64	3.48
Eastern	1.497	4.335	2.472	8.955	1.07	2.87
Kordofan	2.098	4.128	6.819	24.529	2.57	3.91
Darfur	2.077	7.198	11.039	30.374	0.94	3.23
Total	10.391	29.943	27.867	96.771	6.23	13.57
Growth (%)**	3.02		3.56		2.2	

*1 ha=2.38 feddans.

**Average Annual Growth (%)—exponential for human and livestock population.

Source: Authors' computations from various records of the Central Bureau of Statistics, Ministry of Agriculture & Forests, Ministry of Animal Resources and Fisheries, Sudan.

Livestock population growth rates (Table 1) exceed those of people implying that per capita livestock numbers are growing at 0.53%/year, but they vary among regions. They are highest in the Central region (2.0%) and Kordofan (1.72%), but negative in Khartoum and Darfur due to migration influxes. Growth rates in terms of Tropical Livestock Units (TLU) have been lower in all regions (except the

Central), indicating a shift towards small ruminants. During the same period, cropping increased by 2.2%/year implying that unless yields increase, per capita production of food will decrease. Although beyond the scope of this paper, deforestation is significant and amplifies pressure on grazing and water resources. Between 1972 and 2001, 67% of the forests disappeared (UNEP, 2007).

Water and feed balances and sustainable livestock water productivity

Water supply for livestock is critical, especially in the dry season in pastoral areas when use is made of human-made water points. For many years, the government embarked on establishing water sources in the form of wells, dams, small pumps, and 'hafirs' (a water harvesting system in which earth embankments catch and store rainwater according to topographic contours). Between 1989 and 2007 the annual total rural water supply from these sources increased from about 100 million to 349 million m³. Water, however, supplied for household and animal consumption must be weighed against requirements. In most states in the belt, there is a drinking water deficit (Table 2).

Table 2. Average daily rural drinking water availability from available human-made infrastructures, demand, and balance (m³/day) in different states within Sudan's central belt, 2007.

State/Region	Available water	Average drinking demand	Peak drinking demand	Balance at average demand	Balance at peak Demand
Red Sea	126410	20075	31677	106335	94733
Kassala	43972	61441	86709	-17469	-42737
Gedarif	55096	66417	85896	-11321	-30800
Blue Nile	19133	151871	203441	-132738	-184309
Sennar	32839	71622	92136	-38783	-59297
Gezira	61507	140928	170469	-79421	-108963
White Nile	48184	118823	156805	-70639	-108621
Greater Kordofan	244488	335245	464446	-90757	-219959
North Darfur	52448	87478	115947	-35030	-63499
South Darfur	51088	187184	235637	-136096	-184549
West Darfur	29495	172336	229290	-142842	-199795
Khartoum	83210	24979	28083	58231	55127

*Requirements are calculated according to Payne (1990): average demand 25, 30, 4, 4 l/day for cattle, camels, sheep, and goats; at peak summer months, respective values: 35, 65, 4.5, and 4.5 l/day. Human rural requirements are 20 l/day/person according to the Ministry of Irrigation. Source: Available water computed from data of the Ministry of Irrigation; Livestock in 2007 estimated from data of MoARF (2006).

Most of the pressures and water imbalances exist in the states of West and South Darfur, West Kordofan, Blue Nile, Gezira, and White Nile. Within states, many areas still lack drinking water infrastructure. But the latter three states are endowed with rich and fairly permanent surface water sources, leaving most of the pressures in the former three states. Positive balances exist in Khartoum and Red Sea states because of proximity to the Nile River and high priority for water development respectively. The map does not depict the distribution within states, implying that further analyses are needed within them.

Although drinking water is critical, feed availability is jeopardized by low and variable rainfall in pastoral areas, which provide about 74% of animal intake. Feed shortages (pasture and crop residues) amount to 2.3 million t dry matter (17%) in North Kordofan in 2007/08, 1.24 million t in the White Nile (12%), and 30% in South Darfur (Ahmed El-Wakil, personal contacts). Total feed requirements in the country, projected at 200 million t for 2008, are hardly covered by available sources, where an 8% gap is estimated (Ministry of Agriculture, 2004). Nutritive value of pastures has been negatively affected by land degradation and overgrazing.

Livestock water productivity in rainfed areas at a basin level requires managing livestock and water resources in ways that reduce excessive positive feed-water balances, and reduce or eliminate negative balances. Accordingly, livestock productivity is low, and abortion, morbidity, and mortality losses are high. Fertility rates of sheep range from 60 to 83%, and the lambing rate drops to 71 and 49% in medium and poor seasons, respectively (El Rasheed, 2005).

Conclusions

Breakdowns and changes in governance of water and pasture resources and increasing pressure on natural resources have contributed to low livestock productivity and land and water degradation in pastoral areas of the Sudanese Nile. Access to water for feed production and drinking is a critical constraint. On one hand, LWP is low near the watering points because overgrazing causes soil and vegetation loss. Available rainfall produces little feed if vegetation is absent. On the other hand, LWP is also low far from watering points because animals cannot get access to surplus available feed. There is need to limit grazing near watering points and to expand watering points into areas where there is surplus/unused pasture. Improvement in legislative structure and institutional arrangements,

promotion of community-based natural resources management and marketing opportunities, and provision of better veterinary services can help increase LWP in this important part of the Nile Basin.

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Options to improve livestock-water productivity (LWP) in the cattle corridor within the White Nile sub-basin in Uganda

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Abstract

The 'cattle corridor' is generally too dry for crop production and suffers from land degradation caused by overgrazing and indiscriminate harvesting of trees for charcoal burning. Drinking water is seasonally scarce forcing farmers to migrate with their animals to the Nile. Makerere University established a study site in Kiruhura and Nakasongola districts within the cattle corridor, as part of the CPWF Nile Livestock Water Productivity (LWP) project, to identify options for enhancing LWP and increasing animal production. The sustainability of water harvesting systems, options for reseeding highly degraded pastures, and gender and social-science dimensions of livestock keepers were studied. This paper is a synthesis of the work and suggests options for improving LWP, livelihoods, and environmental sustainability. Rehabilitation trials suggested use of cattle manure as the key to reseeding highly degraded areas. Total dry matter (DM) production, ground cover, and species richness were greatly increased by manure application. Water resource utilization and livestock productivity in the pastoral communities were seriously affected by inadequate water, gender, land ownership and utilization, access to and ownership of water sources, and distance to a water source. Sedimentation, evaporation, and degradation of water are critical factors that reduce the availability and quality of water.

Media grab

With control of termites permitting restoration of pasture vegetation, here comes the opportunity to improve the quality and sustainability of water in reservoirs.

Introduction

Livestock water productivity (LWP) is a measure of the amount of water depleted to produce animal products and services. It is computed from the livestock benefits divided by the amount of water depleted for production (Σ Beneficial outputs/ Σ Water depleted). Since agriculture uses up to 80% of the world's developed water resources, the overarching challenge is to produce current and future food supplies in sustainable ways without using more water.

Uganda's rangelands are highly degraded. Nutritious pasture and topsoil have been lost through overgrazing and charcoal production. Without adequate vegetation cover, rain washes soil down slopes filling water bodies such as ponds that provide water for livestock and domestic purposes. During the dry season, the situation is exacerbated by termites, which quickly consume virtually all useful plant material including forages on which livestock depend. Degraded pastures upslope are sources of sediment that quickly fills the tanks, thereby reducing their water-holding capacity. Without drinking water, livestock are forced to travel long distances in the dry season in search of watering sites. Lost pasture, coupled with jeopardized drinking water, is a threat to livestock-based livelihoods. In essence, livestock water productivity is very low and the land is not suitable for alternative livelihood strategies.

The LWP project in Uganda was initiated with the objective of identifying options to improve management of livestock and water resources. The study was aimed at contributing to innovative efforts to ensure that livestock efficiently and effectively use available water resources in the Nile River Basin.

Methods

The study approach was integrated research on livestock and water management in collaboration with the local administration (Nakasongola District), together with local livestock-keeping communities. The research comprised: (a) a community-based initiative for harvesting and managing water resources in the rangelands; and (b) four graduate research projects aimed at: (i) establishing the socioeconomic factors that affect LWP and estimating LWP in rainfed pastoral production systems (Owoyesigire et al., 2008), (ii) rehabilitation of degraded rangelands with extensive bare patches through reseeding, fencing, and use of cattle manure, to restore pasture productivity while controlling soil erosion for improved livestock water productivity (Mugerwa et al., 2008); (iii) determining the effect of upper catchment management and water cover plants on the quality and quantity of water in reservoirs for improved livestock water productivity (Zziwa et al., 2008).

Results and discussion

Socioeconomic study

Over 90% of the pastoral keepers ranked inadequate water supply as the main cause for migrating with their herds of cattle toward rivers and lakeshores. The other reasons for migration ranked in order of importance, included: lack of pasture, conflict and competition among farmers for land, desertification, disease epidemics, economic development, and government policies of relocating people for national economic activities like game and forest reserves. The study also revealed that

water resource utilization and livestock productivity in the pastoral communities were greatly affected by gender, land ownership and utilization, access and ownership of water sources, and distance to a water source.

The same study also compared LWP of settled and nonsettled agro-pastoral communities of Kiruhura and Nakasongola districts, respectively. LWP in the settled agro-pastoral community was higher (US\$0.07/m³) than in the nonsettled community (US\$0.04/m³) (Table 1). Because there was more water available in the settled communities, the amount of water depleted was higher compared to the nonsettled community. The benefits from livestock, however, were also much higher in the settled community and thus the higher LWP. The average area of land per household for pasture was 39.5 ha for nonsettled and 83.4 ha for settled, respectively. Degradation and encroachment by thickets was higher in the nonsettled community (i.e. 14.5 and 18.1 ha compared to 0 and 2.1 ha for the settled community).

Table 1. Estimates of LWP for the pastoral communities.

Parameters	Settled agro-pastoral community	Nonsettled agro-pastoral community
Milk (US\$)	67,776	19,463
Meat (US\$)	321,548	12,904
Manure (US\$)	195,289	126,473
Draught power (US\$)	0	3,809
Estimated value (US\$)	584,613	162,649
Total water used (m ³ /year)	8,280,656	3,965,259
LWP (US\$/m ³)	0.07	0.04

Rehabilitation of degraded rangelands

Application of cattle manure significantly improved the soil physico-chemical nutrient status of degraded areas (Table 2). The improved nutrient status was attributed to the fact that cattle manure acts as a source of nutrients to the soil. This is due to the greatly elevated concentrations of extractable P, K, and total N as reported by Naramabuye et al. (2007). Whalen et al. (2000) also reported a rapid rise in pH as a result of application of cattle manure. Although not measured in this study, cattle manure is also expected to add significant amounts of micronutrients to the soil.

Table 2. Effect of manure application on pH and major soil nutrients in degraded rangelands.

Treatment	pH	%OM	%N	Av. P (mg/kg)	K Cmoles/kg
Initial (before treatment)	3.93	1.31	0.06	1.50	0.38
Control	4.30	1.38	0.04	1.38	0.25
Fencing + reseeding only	4.30	1.34	0.06	1.64	0.38
Fencing + reseeding + manure	5.13 (31%)	2.02 (54%)	0.21 (250%)	4.58 (205%)	1.27 (234%)

Total dry matter (DM) production, ground cover, and the number of pasture species were greatly increased by manure application (Table 3). The highest DM yield (3641 kg/ha) was recorded during the wet season for plots subjected to fencing + reseeding + manure, while the treatments in which no intervention was done consistently recorded 0 kg/ha DM production. The most interesting results were that during the dry season, the DM yield in the manured plots remained high (2964 kg/ha) and there was no evidence of termites affecting the pastures. In a preliminary trial before manure was introduced, the established pastures were completely wiped out by termites during the dry season. The higher DM yield in the manured plots was attributed to the greatly elevated concentrations of available nutrients (Naramabuye et al., 2007). The lower biomass yield in the dry season was mainly due to the limited availability of soil moisture and low rainfall (Crowder and Chheda, 1982; Snyman, 1999).

The low mean DM production in nonmanured plots was attributed to poor soil properties and the severe destruction of pasture plants by termites. The destruction of vegetation by termites was associated with low levels of organic matter (1.3%) in the soil of the nonmanured plots (Table 2). Limited organic matter meant that the termites (one of the major consumers of soil organic matter) were deprived of their major source of food, and thus resorted to the pasture plants as an alternative source of organic matter. These results implied that poor soil properties coupled with termite activities are the major constraints to recovery/rehabilitation of degraded rangelands and need to be addressed by future restoration programs.

Table 3: Effect of manure application on DM productivity and species richness.

Season	Treatment	% ground cover		Dry matter (kg/ha)	Species (No./m ²)
		Bare	Vegetation		
Wet	Control	100	0	0	1
	Fencing + reseeding only	60.6	39.1	1778	7
	Fencing + reseeding + Manure	12.2	89.5	3641	9
Dry	Control	100	0	0	0
	Fencing + reseeding only	79.1	21.2	1426	3
	Fencing + reseeding + manure	35.6	65.2	2964	3
	SE	5.3	3	396.4	0.83

Kraaling cattle at night in temporarily fenced paddocks for about 2 weeks resulted in deposition of significant quantities of manure on the degraded soil (Figure 1). After a 2-week period, the kraals can be shifted to a new place. When reseeded, vegetation cover was restored on the area that was fenced

and manured (Figure 2). The termites appeared to feed on the manure rather than the grasses. In effect, the application of the manure served as a biological control to deter termites from consuming the newly seeded pasture grasses, giving the vegetation time to mature. It is also possible that reestablishment of vegetative cover may have caused a shift in the mix of termite species and possibly reduced the numbers that feed on pasture grasses. The researchers also noted that after manuring and reseeding pastures, termites reduced their attacks on wooden fence posts.

Upper catchment management

Valley tanks receiving water from unvegetated upper catchments and gullies experienced high rates of sedimentation, 501 m³ in 18 months compared to 23 m³ in valley tanks with vegetated catchments (Table 4). Sedimentation, evaporation, and degradation of water are critical factors that reduce the availability and quality of water in pastoral communities.

Table 4. Effect of upper catchment management and water cover plants on the quantity of water and of silt deposition in valley tanks.

	Period	Max. vol. of water (m ³)	Volume of silt deposited (m ³)	Reduction in pond capacity (%)
Unprotected (degraded) catchment	Nov. 06 – Apr. 07	1260	233	16.9
	Apr. 07 – Oct. 07	1135	15	1.3
	Oct. 07 – Apr. 08	1001	253	22.4
	Total		501	
Protected (vegetated) catchment	Nov. 06 – Apr. 07	1861	-	-
	Apr. 07 – Oct. 07	1857	9	0.48
	Oct. 07 – Apr. 08	1846	14	0.76
	Total		23	

Table 5. Effect of pond management on quality of water for livestock and domestic purposes in pastoral communities of the White Nile sub-basin.

Parameters	Uncovered ponds		Ponds with <i>Azolla</i> , <i>Pistia</i> <i>Nymphaea</i>	Ponds with <i>Lemna</i> spp.
	Good mgt	Poor mgt		
pH	6.88	6.60	6.60	6.60
Ammonium (NH ₄ ⁺)	1.24	4.41	1.62	0.69
Nitrates (NO ₃ ⁻)	0.05	1.04	0.10	0.12
Nitrites (NO ₂ ⁻)	0.02	0.28	0.07	0.05
Total nitrogen (tn)	0.93	7.75	2.84	2.10
Total phosphorus (tp)	1.64	1.84	1.87	0.26
Total dissolved solutes (tds)	42.5	36.5	29.3	49.5
Total suspended solids (TSS) (mg/L)	35	107	64	30
Turbidity (FAU)	40.5	189	63.1	21.5
Total coliform (CFU/100ml)	5312	6828	23923	1147
Total fecal coliform (CFU/100ml)	248	656	4490	350

Mineral nutrients, dissolved solutes, suspended solids and turbidity are generally high in unvegetated catchments and open gullies and lowest in vegetated catchments and gullies (Table 5). Aquatic plants are common on the surface of valley tanks in the cattle corridor. Valley tanks covered by *Nymphaea* spp., *Azolla* spp., and *Pistia* spp. had higher NH₄⁺, NO₂⁻, TN, and TP concentrations and coliform counts than uncovered valley tanks. Valley tanks, however, covered by *Lemna* spp. had lower nutrient and coliform counts. These findings could be explained by the fact that some macrophytic plants form a dense mat cover on water surfaces (*Azolla* and *Pistia*) and create anaerobic conditions that favor the proliferation of microorganisms in water. The decay and decomposition of dead macrophytic plants recycles N and P thus increasing their concentrations in the water. The higher the plant biomass, the greater the amount of nutrients recycled (Hoyer and Canfield, 1997). In particular, *Azolla* spp are known to have a symbiotic association with a bacteria *Anaerobaculum azollae* (Rogers, 1996). This increases the decomposition and imparts a foul smell to the water which subsequently reduces livestock water intake or make animals reject such water. This explains the farmers' complaint especially in Kiruhura district, that water in some ponds smells 'bad' especially during the dry season. These results confirmed the farmers' allegations. The dams that were covered with plants had the foul-smelling water.

Conclusions

A multifaceted approach to improving LWP involving communities in management of upper catchment, effective use of manure, and identification of suitable cover plants and understanding the socioeconomic dynamics of pastoralists is key to improving LWP and hence livelihood and sustainability.

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Photo 1. Typical degraded grazing land near Nakasongola, Uganda, with high levels of run-off and near zero water productivity. Termites consume any pasture vegetation that grows. In its present condition, this land cannot support livestock production



Photo 2. Fencing + reseeding + kraaling livestock to deposit manure restores pastures and apparently results as a biological control measure whereby termites shift their diets from pasture vegetation to manure enabling restoration of pasture and

Cattle manure and reseeding effects on pasture productivity

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Abstract

Uganda's rangelands are seriously degraded due to overgrazing, which causes loss of vegetation cover and soil erosion. Consequently, soils have low levels of nitrogen, phosphorus, potassium, and soil organic matter (SOM). Low SOM eventually increases the destructive effects of termites on pasture. Under such conditions, water is used inefficiently regardless of the quantity received, leading to low livestock water productivity. This work was aimed at rehabilitation of degraded pastures through reseeding, fencing, and use of manure for improved livestock water productivity. The effects of these treatments on pasture productivity in wet and dry seasons are presented. In both seasons, dry matter yields varied significantly with treatments. Highest dry matter yields (3820 kg/ha) occurred in the manured reseeded treatment. Vegetative ground cover was significantly affected by the interaction between season and treatment. Control plots had no vegetative cover in either season, whereas only 2% and 29% of the manured reseeded plots had bare ground in the wet and dry seasons, respectively. Generally, manured plots showed high dry matter production, species richness, percentage cover, and drastic changes in botanical composition compared to nonmanured plots. Reseeding and manure application is an effective and practical intervention to rehabilitate degraded rangelands and increase livestock water productivity.

Media grab

Reseeding and manure application are effective and affordable ways of rehabilitating and increasing livestock water productivity in degraded rangelands in the Nile Basin.

Introduction

In Uganda, rangelands cover approximately 84,000 km² or 40% of the total land area. They are of great economic importance because they support about 95% of the cattle population. Furthermore, about 85% of milk and beef are produced from cattle on natural pastures in the rangelands (Mpairwe, 1999). The current problem facing rangelands in Uganda is degradation, which has been attributed to overgrazing and cutting trees for charcoal burning. When degradation caused by intensive herbivory sets in, it initially affects plant population demography, causing diversity and productivity to decline. A reduction in perennial plant cover then facilitates the establishment of ephemeral and weedy species. Ultimately vegetation cover is lost and geohydrological processes are severely altered (Kraaij and Milton, 2006). The condition of the rangelands in Nakasongola district is characterized by poor, sparse, and unstable vegetation cover, heavy soil erosion, and severe encroachment of weedy species. The situation is exacerbated in the dry seasons by termites, which cut the remaining grass cover as they search for moisture and organic matter. This has created very large areas of land with bare ground locally called '*Biharamata*.'

Milton (1994) suggested that an optimistic management approach, which includes reseeding and stock withdrawal (fencing off animals) from overgrazed areas, could optimize the restoration potential of degraded rangelands. This study was therefore undertaken with the objective of restoring the lost vegetation cover through use of different rehabilitation interventions.

Methods

The study was undertaken in Nakasongola district (55° 14'N, 32° 50'E), which forms part of Uganda's cattle corridor. Temperatures range between 25 and 35°C. Annual rainfall varies between 500 and 1000 mm. Soils are generally lightly textured and of alluvial origin. The vegetation type is open deciduous savannah woodland with short grasses. Trees include *Ceasalpinia decapetala* and *Zanthoxylum chalybeum*.

The experiment involved a 2 x 6 (season and rehabilitation treatments) factorial arrangement in a complete randomized design. The trial ran from June 2007 to June 2008 covering two wet and two dry seasons. Six treatments were compared: (MO) manuring only, (FO) fencing only, (RO) reseeding only, (MR) manure left on the soil surface plus reseeding, (MRI) manure incorporated into the soil plus reseeding, and (C) control (no manuring, fencing, or reseeding). Manuring was done by night kraaling a herd of 80 cattle for a period of two weeks in each plot. Two grass and two legume species were used for reseeding using the strip planting method. The legume species comprised of *Centrocema pubescens* and siratro sown at a seed rate of 4 kg/ha. The grasses *Panicum coloratum* var. *makarikariense*, *Panicum maximum*, *Brachiaria ruziziensis*, and *Brachiaria brizantha* were sown using rooted splits. Single superphosphate (SSP) was applied a week before planting at a rate of 125kg/ha. Plots remained ungrazed during the study period.

Soil samples were taken randomly in each plot to a depth of 15cm before treatments were applied and after each season, to determine total nitrogen and organic matter, available phosphorus, available potassium, magnesium, calcium, sodium, and soil pH.

Data collected included: pasture botanical composition, dry matter yield, growth rate, species richness, and ground cover. A 1 m² quadrat was randomly placed over the pasture canopy at four locations in each plot. The above-ground pasture vegetation within each quadrat was hand harvested (cut at ground level) using a sharp knife, put in polythene bags, and weighed. The samples were dried at 60^o C to a constant dry weight for 72 hours in an air-circulating electric oven to determine the mean dry matter yield for each plot, and later the chemical composition. Species richness was determined by recording the average number of individual species per quadrat per plot. Botanical composition, cover, and growth rate were determined using Tothill's methods (1978).

The data were subjected to analysis of variance using SAS General Linear Model procedure.

Results

The dry matter yield, percentage ground cover, growth rate, and species richness for different rehabilitation treatments in the different seasons are given in Table 1. In both seasons, the dry matter yield varied significantly ($p \leq 0.0234$) with treatments. Mean dry matter production (3300 kg/ha) from manured plots was 125% higher than that from non-manured plots (1600 kg/ha). Season significantly affected dry matter production ($p \leq .0001$). Mean dry matter production (2890 kg/ha) in the wet season was 23% higher than in the dry season (2340 kg/ha), with highest and lowest mean dry matter yields recorded for MR and C treatments, respectively.

Table 1. Dry matter yield, percentage ground cover, growth rate, and species richness for different rehabilitation treatments in different seasons.

Season	Treatment	% Cover				DM (kg/ha)	Growth rate (cm)	Species (no./m ²)
		Bare	Forbs	Grass	Weeds			
Wet	Control	100	0	0	0	0	0	1
	MR	2.4	37.5	56	3.2	4500	5.2	9
	MRI	22.8	31.5	43	2.2	2710	8.7	10
	MO	11.5	11.3	74	3.2	3700	10.7	9
	RO	50.4	17.6	31	0.4	1940	2.7	9
	FO	70.8	0	29.2	0	1600	10.1	5
Dry	Control	100	0	0	0	0	0	0
	MR	29.1	15.3	54.5	1	3130	-3.4	4
	MRI	49.1	8.6	42.7	2.3	2500	-5.6	3
	MO	28.7	2.7	68.2	0.7	3250	-4.5	2
	RO	72	7.9	20.1	0.5	1680	7.2	2
	FO	86.1	0	13.6	0	1160	9.8	1
	SE	5.3	3	5	0.9	396	6.5	0.83
Significance (p. values)								
Treatment		0.0001	0.0001	0.0001	0.0003	0.0234	0.0858	0.0001
Season		0.0001	0.0001	0.0227	0.098	0.0001	0.4859	0.0001
Season*Treat		0.0498	0.0001	0.4114	0.33	0.4229	0.4229	0.0003

Regardless of the season, the control plots remained bare (100% bare ground) throughout the two years. Manuring significantly ($p < 0.0001$) increased the percentage vegetation cover in the study area. Generally, the percentage of bare ground for nonmanured plots was 5 and 2 times more than that for manured plots in the wet and dry seasons, respectively. Furthermore, the percentage bare ground for all treatments shows an average increase of 21% in the dry season. A similar trend was observed for fodder and grass cover.

Pasture growth rates were not affected ($p > 0.05$) by either season or the rehabilitation intervention treatments (Table 1). There were, however, significant season and treatment interactions for species richness (Table 1). The highest species richness (10 species per m^2) was shown by MRI treatment in the wet season, and the lowest, (1 and 0 species per m^2) by FO and control treatments, respectively, in the dry season.

The botanical composition for different rehabilitation treatments under different seasons (species listed when cover is at least 1%) is presented in Table 2. In both seasons, treatments caused drastic increases in percentage species cover. *Cynodon dactylon* was the dominant species in all manured plots, whereas *Sporobolus marginatus* and *Hyparrhenia hirta* were the dominant species in nonmanured (non-reseeded) plots. Overall, the percentage species cover for all species showed an average decrease of 3.5% in the dry season.

Table 2. Botanical composition (% species cover) for different rehabilitation treatments under different seasons (species listed if % cover is at least 1%).

Treat	Wet season						Dry season					
	C	MR	MRI	MO	RO	FO	C	MR	MRI	MO	RO	FO
Bs	0	14.3	17.1	14.9	22.9	8.6	0	10	12.5	19.3	11.3	-
CP	0	7.2	8.9	-	10.7	-	0	5	3.1	-	3	-
Cs	0	6.5	1.7	6.1	-	-	0	5	-	2.7	-	-
Cd	0	26.7	14.5	37.1	-	-	0	30	17.8	23.6	-	-
Da	0	13.2	7.3	27	-	-	0	11.8	7.6	24.4	-	-
Hh	0	-	-	-	-	7.2	0	-	-	-	-	-
												5.2
Ma	0	23.3	8.9	-	12.2	-	0	6	5.4	-	3.1	-
Mv	0	-	-	-	4.3	-	0	-	-	-	1.1	-
Ps	0	3	2.1	-	4.3	-	0	3.8	2.1	-	-	-
Ss	0	-	-	-	-	-	0	-	2.3	-	-	-
Se	0	-	-	-	1	2.3	0	-	-	-	-	-
So	0	3.3	1.8	2.4	-	-	0	-	-	-	-	-
Sr	0	-	-	-	-	-	0	-	-	-	3.8	-
Sm	0	-	-	-	-	-	0	-	-	-	-	-
												5.6

Bs (*Brachiaria* spp), Cp (*Centrosema pubescens*), Cs (*Commelina* spp), Cd (*Cynodon dactylon*), Da (*Dactyloctenium aegyptium*), Hh (*Hyparrhenia hirta*), Ma (*Macroptilium atropurpureum*), Mv (*Mitracarpus villosus*), Ps (*Panicum* species), Ss (*Saccharum spontaneum*), Se (*Setaria sphacelata*), So (*Solanum* spp), Sr (*Sida rumbifolia*). Sm (*Sporobolus marginatus*)

Discussion

Mean dry matter production from manured plots was significantly higher than that on nonmanured plots. A possible explanation is that cattle manure improved soil pH, soil organic matter, and the nutrient status of degraded soils (Table 3). The low mean dry matter production (1380 kg/ha) for RO treatment, despite addition of SSP fertilizer, was partly attributed to severe destruction of pasture plants by termites 3 weeks post emergence. The possible cause of this destructive behavior by termites may be due to the extremely low levels of organic matter in plots with no manure. It was hypothesized that due to lack of alternative sources of food (organic matter), the termites resorted to the established pasture plants. This implies that termites present an additional barrier to recovery/rehabilitation of degraded rangelands and therefore need to be controlled. There is, however, a need to do more confirmatory studies about termite activity in the area.

Table 3. Soil (0-15 cm) parameters for the different rehabilitation treatments.

Parameter	Before treatments						After two seasons					
	MO	MR	MRI	RO	FO	C	MO	MR	MRI	RO	FO	C
pH	3.5	3.4	3.6	3.7	4.3	4.3	5.2	4.9	5.3	4.3	4.3	4.3
SOM(%)	1.04	1.33	1.34	1.22	1.38	1.38	2.03	1.9	2.13	1.3	1.38	1.38
% N	0.08	0.07	0.09	0.09	0.04	0.04	0.2	0.2	0.22	0.09	0.04	0.04
Av.P(mg/kg)	1.5	1.64	1.33	1.9	1.38	1.38	5.42	4.0	4.34	1.9	1.38	1.38
K(Cmoles/kg)	0.39	0.87	0.3	0.5	0.25	0.25	1.2	1.42	1.2	0.5	0.25	0.25

The significant differences between dry matter production across seasons were attributed to low availability of water (Snyman, 1999). Rainfall is the greatest single factor affecting plant growth and herbage dry matter production in tropical countries. Similarly, the general reduction in species richness in the dry season was attributed to the low water availability, since many pasture species (especially annual species) rarely withstand drought conditions. The implication of our findings is that the suitability of any restoration/rehabilitation treatment in improving dry matter production will always depend on water availability. In addition, failure of vegetation cover in the control treatment was attributed to continued soil erosion. Khresat et al. (1998) noted that the development of large bare patches, which is a result of overgrazing, eventually facilitates high rates of erosion. Consequently, the soils in these rangelands have relatively low levels of nitrogen, phosphorus, potassium, and organic matter. This tends to inhibit grass growth, especially for the less competitive species such as *B. brizantha*, *Panicum*, and *Setaria* spp.

The highest percentage of vegetation cover exhibited by the manured plots was attributed to the improved soil nutrient status (Table 3), and the growth characteristics of the dominant species, especially *Cynodon dactylon* (Table 2). *Cynodon dactylon* is perennial and spreads quickly by stolons and rhizomes to cover a large area in a short time (Skerman and Riveros, 1990). The grass responds strongly to farmyard manure application and quickly invades areas with animal manure. The grass highly favors sites with animal manure since cattle kraals and/or cattle paddocks are some of its natural habitats. On the other hand, *Hyparrhenia hirta* was the dominant species on nonmanured plots due to its wide soil tolerance, including dry, hard, rocky soils, and deep dry sand with very low nutrient levels (Skerman and Riveros, 1990). From these results, it was therefore recommended that, in any programs aimed at restoration of vegetation in degraded rangelands of Uganda, the technology of manure application and reseeding with manure, favoured grass species such as *Cynodon* spp., and drought-resistant forage species such as *Hyparrhenia* spp. should be included.

Manured plots had higher species richness than nonmanured plots, and this was also attributed to the improved nutrient status by the cattle manure particularly N, P, and K, and OM (Table 3). Harrington (1968) noted that these nutrients are usually limiting and always inhibit the establishment of particular pasture species such as *B. brizantha* and *Panicum* spp. among others. The fact that cattle dung is a source of a variety of endozoochorous seeds, which germinate into a variety of pasture species (Malo and Suarez, 1995), could also have contributed to the increased vegetation cover in the manured plots. Our results agree with the findings of Girma et al. (2003), who determined that species richness was higher on manured plots than on nonmanured plots regardless of the grazing pressure.

Restoring the ground cover and pasture production is vital to increasing livestock water productivity, because this results in more feed for production, reduced surface runoff, evaporation, silting of water reservoirs, and increased water infiltration and transpiration.

Conclusion

The destruction of pasture seedlings by termites in nonmanured plots gave the answer to why most interventions aimed at rehabilitating degraded rangelands have failed in the past. The improved vegetation cover and species richness in the manured plots, irrespective of the season, showed that poor soil properties (particularly low N, P, K, and OM) are the major constraints to rehabilitation of degraded rangelands. Reseeding and application of cattle manure on degraded bare patches is an

effective, practical, and affordable way of recovering the lost vegetation cover in degraded rangelands. The practice of kraaling cattle in fenced paddocks, together with reseeding, provides the answer to rehabilitating degraded rangelands, and therefore there is need to up-scale the technology.

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Upper catchment management and water cover plants effects on the quality and quantity of water in surface reservoirs

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Abstract

The effects of upper catchment management and water plants on water quantity and quality in two Ugandan pastoral communities were investigated. The objective was to assess effects of land and livestock management on water resources and livestock water productivity. Water quality and quantity in valley tanks were monitored. Results indicate that upper catchment management significantly affected total coliform (TC), fecal coliform (FC), NH_4^+ , NO_2^- , total nitrogen, total phosphorus, TSS, and turbidity. Valley tanks in catchments with unvegetated catchments and gullies were more contaminated than in vegetated catchments and gullies. Reseeding of an unvegetated upper catchment greatly decreased the concentration of NH_4^+ , NO_2^- , NO_3^- , TP, and turbidity. Silt from unvegetated catchments and gullies reduced reservoir storage capacity by 248 m³ in a year. Valley tanks covered with *Nymphaea* spp. had significantly higher concentrations of NH_4^+ , NO_2^- , NO_3^- , TN, TDS, TSS, pH, and turbidity, whereas *Azolla* spp. were associated with higher TP, TC, and FC than other cover plants. Unvegetated upper catchments and gullies have detrimental impacts on water quality and reservoir capacity. Evaporation, sedimentation, and degradation of water quality were critical factors that reduced the availability and quality of water in pastoral communities. Only valley tanks with vegetated catchments and gullies and those covered with *Lemna* species had acceptable levels of FC.

Media grab

Vegetated upper catchments and gullies and use of suitable cover plants improve water quality, reduce sedimentation and degradation of surface water resources in pastoral communities.

Introduction

Valley tanks are the major sources of water for livestock and humans in the pastoral rangeland communities of Uganda. These water resources, however, face major problems of siltation and seasonal fluctuation of water quality and quantity that greatly affects livestock productivity (Sabiiti, 2001; MWLE and DWD, 2003). Poor upper catchment and water resource management lead to contamination, sedimentation, eutrophication, and enhanced discharge into water reservoirs. The amounts of water used directly by livestock for drinking are relatively small, with much larger amounts being used to produce feed (Peden et al., 2003). Water contained in feed is highly variable (Sirohi et al., 1997). When the water content of the feed ingested is low, drinking water requirements increase and provision of water to livestock becomes the main concern (Degen, 1997). The quantity of water consumed per unit weight gain increases as the dry season progresses because the forage becomes senescent and moisture content declines (Willms et al., 2002). Factors that increase water loss and degradation of surface water resources, or that increase water intake per unit of livestock product and service produced, negatively affect livestock water productivity (Peden et al., 2007). To improve the livestock water productivity management, it is necessary to understand the impacts of upper catchment management and water cover plants on water quality and quantity.

Methods

Site

The study was conducted in the pastoral communities of Nakasongola and Kiruhura districts within the Nile Basin where livestock production is the most important agricultural activity. The two districts experience a bimodal annual rainfall pattern ranging from 500 to 1000 mm (MAAIF, 2003) with periodic droughts. Temperatures range from 24 to 35°C. The dominant vegetation type in both

districts is open savannah woodland with short grasses highly suitable for pasture. Tree species include *Commobretum*, *Terminalia*, *Acacia ceasalpinia decapetala*, and *Zanthoxylum chalybeum*.

Water quality and quantity monitoring were done on eight valley tanks supplied with water from un-vegetated catchments, vegetated catchments, vegetated gullies and open gullies, and on eight valley tanks covered by *Azolla*, *Lemna*, *Pistia* and *Nymphaea* spp. from November 2006 to October 2007. All dams used in these experiments were under similar livestock watering practices (watering in troughs), because an earlier pilot study had shown that valley tanks where direct watering is practiced had higher nutrient and microbial concentrations than their counterparts.

Measurement of reservoir volume

A concrete block tied on a calibrated rope was used to establish the depth profile of the valley tanks by measuring the depth of water at 2-m intervals following ropes tied at a distance of 10 m across the width of the valley tank, using a small wooden boat. An evaporation pan (A-/class) and a rain gauge were installed and used to measure evaporation (mm) and precipitation (mm). The number of animals drinking from a given valley tank were counted and the volume of water taken by animals was measured by counting the number of 10 L buckets used to fill water troughs during watering.

Water quality analysis

Water samples were collected and delivered to the laboratory in an icebox, where they were frozen until analysis was made within 36 hours. A spectrophotometer (HACH, DR/4000) was used to measure NO_2^- , NO_3^- , NH_4^+ , total nitrogen (TN), total phosphorus (TP), total dissolved solutes (TDS), and turbidity (FAU). Total suspended solids (TSS) (mg/l) were determined by filtering and weighing oven-dried sediments collected on prewashed Whatman GF/F Glass filters. pH was measured using WTH pH meter LF 90. Total and faecal coliform concentration (most probable number-MPN) of colony-forming units (CFU) per 100 ml was measured according to the coliform test, with membrane lauryl sulfate broth and incubated at 44°C for 18-24 hours. Student's t-tests were performed in STATA to determine significant differences in water quality between treatments.

Results

Reservoir hydrology

Annual precipitation was higher than annual evaporation. However, evaporation was higher than precipitation in dry seasons. Valley tanks experienced high annual evaporative water loss (Table 1). Valley tanks receiving water from unvegetated upper catchments and gullies experienced high rates of sedimentation (248 m³ in one year) and water degradation (46.5 m³ in dry season).

Table 1. Monthly rainfall (R, mm), evaporation (Ev, mm) and volume of water in valley tanks (m³) in un-vegetated (UV) and vegetated (V) catchments.

	Nov	Dec	Jan	Feb	Ma	Apr	May	June	Jul	Au	Sept	Oct	AE	VS	
													r	g	v
R	152	52	0	0	36	143	146	39	131	78	240	258			
Ev	47	59	75	70	54	71	72	49	54	51	43	58			
U	138	361	47*	-	73	114	114	979	709	75	113	113	85	24	
V	0				6	0	0			6	0	0	0	8	
V	186	153	117	59	26	529	186	161	106	58	139	185	60	7	
	0	0	0	1	5		0	0	0	9	0	0	7		

AEV-Annual evaporative loss from valley tanks (m³) and VS-Volume of silt deposited (sedimentation) into valley tanks (m³). Italic text indicates full capacity of valley tanks, *Degraded water.

Effect of upper catchment on water quality

NH_4^+ , NO_2^- , NO_3^- , TN, TP, TDS, TSS, and turbidity were generally high in valley tanks with unvegetated catchments and open gullies, and lower in valley tanks with vegetated catchments and gullies (Fig. 1). There were significant differences between treatments and seasons, with high concentrations of NH_4^+ , NO_2^- , NO_3^- , TP, TDS, TSS, and turbidity being observed in the rainy season. Management interventions geared at revegetation of the upper catchment (reseeding, fencing, fencing and reseeding) significantly ($p < 0.0001$) reduced water pollution compared to the control (where no intervention was made on unvegetated catchment) (Table 2).

Table 2. Effect of upper catchment management interventions on valley tank water quality.

Treatment	NH ₄ ⁺	NO ₂ ⁻	NO ₃ ⁻	TN	TP	TDS	TSS	Turbidity	pH
Reseeding (R)	0.66	0.02	0.01	2.52	0.13	30	112	1110	5.95
Fencing (F)	0.94	0.01	0.05	1.86	0.18	22	96	571	5.92
R + F	1.33	0.07	0.13	2.33	2.14	22	115	1060	6.05
Control	4.27	0.38	0.42	4.95	2.19	37	120	3500	5.67
LSD	0.15	0.02	0.03	0.18	0.08	13	9	32	0.05

Effect of water cover crops on water quality

Valley tanks covered with *Nymphaea* spp. had significantly ($p < 0.01$) higher NO₂⁻, NO₃⁻, TN and TDS concentrations. *Azolla* spp. were associated with significantly higher TC and FC concentrations, and *Lemna* spp. were associated with significantly lower TC, FC, TSS, and turbidity (Figure 2). NH₄⁺, TP and pH were not significantly different ($p > 0.01$) between treatments in all seasons.

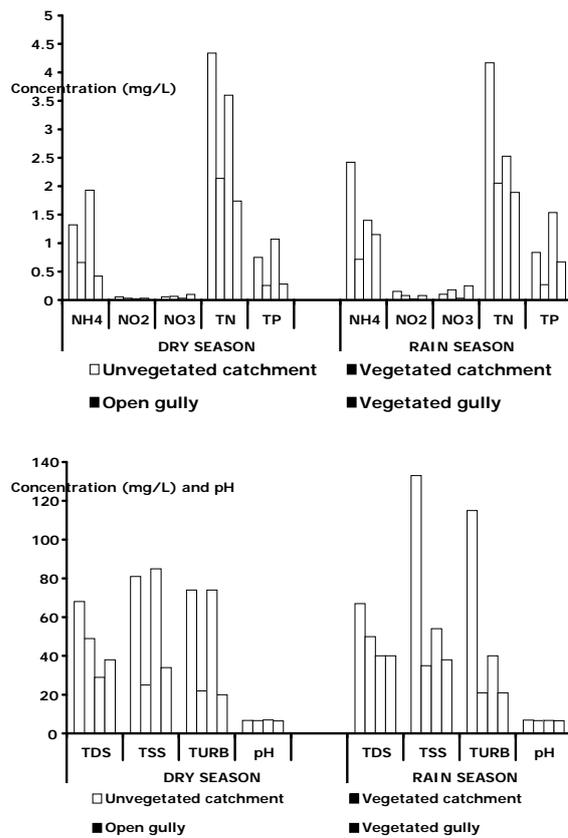


Figure 1. Effect of upper catchment management on water quality.

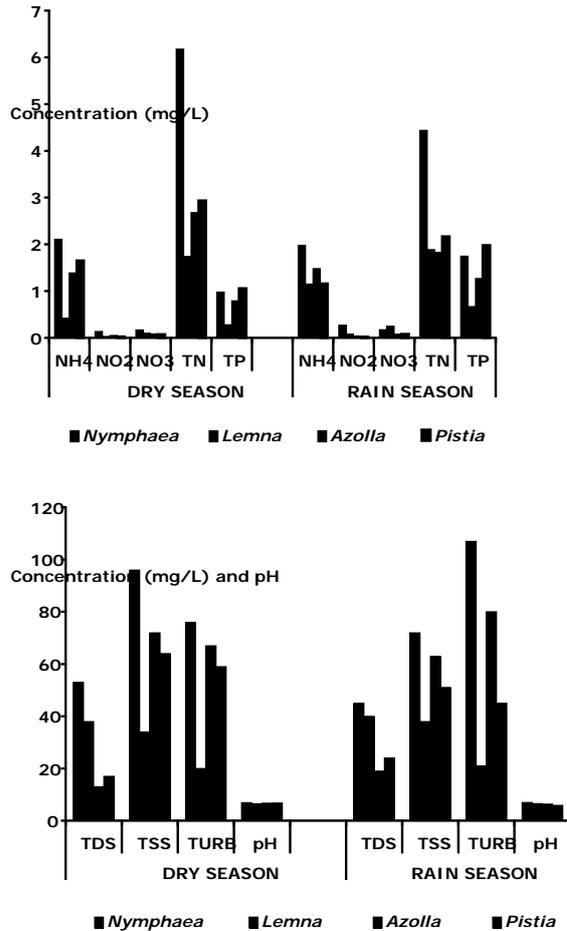


Figure 2. Effect of water cover plants on water quality.

Discussion

Reservoir hydrology

Although evaporation increases with surface area (Ferhat and Ozhan, 2006), high TDS and TSS concentrations in valley tanks with unvegetated catchments and open gullies (Figure 2) also increases evaporation rates due to increased heat conduction. Bare ground in the upper catchment increases runoff speed and erosion resulting in reservoir sedimentation. This explains the reduction in the capacity of reservoirs with unvegetated catchments and gullies. The deposited sediments increase TSS, which reduces the quality of water and imparts a muddy smell which makes animals reject the degraded water. This implies that high water evaporation, sedimentation of reservoirs, and water degradation cause significant water losses from valley tanks.

Upper catchment management

The presence of vegetation in upper catchments and gullies stabilizes the soil, and reduces storm water velocity, thereby reducing soil erosion, manure and nutrient deposition, and reservoir sedimentation. Vegetation also increases water quality through its functioning as sponges, absorbing and filtering out sediments and nutrients from runoff. This is consistent with earlier studies that showed that maintaining good plant cover in upper catchments and gullies is one of the most effective ways to reduce the amount of siltation and to keep nutrients out of reservoirs (Streamlines, 1998; Simmons 2004).

Water cover plants

Numerous biological and physical processes transform nitrogen between various forms. Ammonification, nitrification, and denitrification are the major nitrogen transformation processes. Reservoirs with macrophytes that have a high biomass yield (*Pistia* spp and *Nymphaea* spp) have high levels of NH_4^+ and phosphorus released through decomposition than low biomass plants (*Azolla* spp and *Lemna* spp). *Azolla* spp and *Pistia* spp form a dense mat cover on water surfaces that creates anaerobic conditions. This reduces nitrification and increases denitrification, thus the lower levels of nitrates and nitrites compared to *Nymphaea* spp and *Lemna* spp. The roots of *Pistia* spp, *Nymphaea*

spp, and *Azolla* spp often detach and suspend in the water column. This increases the TSS and turbidity in reservoirs covered by such plants, as opposed to *Lemna* spp that do not have distinct plant parts that can disengage into water. *Lemna* spp also present a high surface area over which sediments are adsorbed, thus significantly reducing turbidity. The decomposition of decayed aquatic plants increases bacterial concentration. Limited water aeration increases bacterial concentrations because of the favorable anaerobic conditions. *Azolla* spp and *Pistia* spp thus have higher coliform counts than *Lemna* spp and *Nymphaea* spp. This is supported by earlier research that indicated that *Azolla* spp have a symbiotic association with a bacteria *Anaebaena azollea*, hence the higher bacterial concentrations in valley tanks covered by *Azolla* spp.

Conclusion

Unvegetated upper catchments and open gullies have detrimental impacts on water quality and reservoir capacity. Without vegetation in the upper catchments and gullies, water quality is greatly impaired and reservoir sedimentation and water degradation greatly increase. Rainfall amount is not the factor limiting the amount of water available in reservoirs to sustain livestock and human needs through dry seasons in the pastoral communities of Uganda. Evaporation, sedimentation, and degradation of water quality are critical factors that reduce the availability of water in pastoral communities. Use of *Lemna* spp, may be of great importance in reducing evaporative water loss and increasing water quality, since the plant is known to reduce evaporation by 20% from open water resources. Water from all valley tanks had nutrient concentrations falling below the maximum recommended intake for livestock drinking water. Only valley tanks receiving water from vegetated catchments and gullies and those covered by *Lemna* spp had fecal coliform counts falling below the recommended concentration (<100) for livestock drinking water (ANZECC, 2000).

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Socioeconomic factors affecting livestock water productivity in rainfed pastoral production systems

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Abstract

A study was conducted in Nakasongola and Kiruhura pastoral communities of Uganda to estimate livestock water productivity (LWP), and establish socioeconomic factors that affect LWP in rainfed pastoral production systems of the Nile Basin watershed. A semistructured questionnaire was administered to 185 households. Crop water requirements and livestock benefits were estimated and data used to compute LWP. The main factors affecting LWP included gender within the household, level of education, land ownership and utilization, access and ownership of water sources, and tree harvesting for use in charcoal burning. Livestock water sources included: boreholes, wells, ponds, valley dams, swamps, rivers, and lakes. Livestock water sources varied with seasons with an average distance of 7 km in the dry season and 3 km in the wet season. Important livestock beneficial outputs included milk, meat, and sales from live animals. Average annual milk production was 3260 l/household in Nakasongola and 15,070 l/household in Kiruhura. In all the surveyed pastoral communities, LWP was < US\$/1m³. It was concluded that to improve LWP, pastoral communities should improve overall allocation and use of water and land resources for all users.

Media grab

Well-managed settlement of pastoralists may foster higher livestock water productivity, and also help reduce poverty in the Nile Basin.

Introduction

Livestock production makes up about 25% of the world's agricultural GDP (Mengesha et al., 1998), occupies two-thirds of the world's surface under agriculture, and sustains 20 million pastoral families. In Uganda, livestock production accounts for 17% of the agricultural gross domestic product (GDP) and 7.5% of the total GDP (MAAIF, 2003). Agricultural productivity is normally and universally measured with respect to land and rarely with respect to water. Nevertheless, water is becoming increasingly scarce, especially in the drought-prone semi-arid and arid areas. Water is essential for human consumption and for other domestic purposes. It is also vital for watering livestock, producing feeds, crop production, and for processing agricultural products. As the human population increases, per capita water use will also increase due to increased demand for food, including livestock products such as milk, meat, and eggs. Managing this demand for additional water dictates a thorough understanding of livestock water productivity (LWP). LWP is measured as the ratio of beneficial outputs to amount of water depleted in producing them (Peden et al., 2007). Although studies of LWP on other communities have been carried out, no such studies have been conducted in the pastoral communities of Uganda. This study was therefore initiated to establish socioeconomic factors affecting LWP, and estimate LWP using the pastoral communities of Nakasongola and Kiruhura districts as a case study.

Methods

The study was conducted in the districts of Nakasongola and Kiruhura within the Nile Basin, where pastoral livestock production is the most important agricultural activity. A household survey was conducted using a pretested semistructured questionnaire. The questions were designed to obtain information from respondents on general household characteristics, herd size and ownership, benefits from livestock, crops grown, amount of water consumed, issues of overgrazing, water sources, and challenges faced in managing them. Field measurements of acreage under various crops and area under pastures were also conducted at household/plot level. A total of 185 households participated in the study. The household survey was designed to cover settled agropastoral and nonsettled agropastoralist communities.

The amount of water depleted by crops and pastures was estimated using the pan evaporation method. Pan evaporation is related to the reference evapotranspiration E_{To} (eq.1), by an empirically derived pan coefficient (Richard et al. 1998).

$$E_{To} = K_p E_{pan} \dots \dots \dots \text{Eq.1}$$

Where: E_{To} = reference crop evapotranspiration (mm/day); K_p = pan coefficient and E_{pan} = pan evaporation (mm/day). Crop evapotranspiration/crop water requirements (CWR), which is the amount of beneficial water depleted, was derived by the formula $CWR = E_{Tm} \times \text{growing period} \times \text{area planted}$. The maximum E_{Tm} relates to E_{To} by multiplying it with their respective crop coefficients K_c .

Modified model by Girma Tadesse et al (2006) was used to compute the beneficial outputs from livestock

$$L_o = \sum (D_p + M_p + P_m + HS) * P + \sum \{(M_c * M_y) - M_s\} * M_{pr} \dots \dots \dots \text{Eq.2}$$

L_o = livestock output (US\$), D_p = Total acres plowed * Price of plowing an acre; M_c = number of milking cows, M_y = milk yield/cow (kg or liter); M_s = milk self consumption (kg or liter), M_{pr} = milk price per kg or liter of milk; M_p = manure production = Animal number * average daily manure production (kg)* price per kg; P_m = produced meat = livestock slaughtered-meat self consumption (kg)* price per kg; HS = hides and skins = slaughtered animal * Price per kg of hides skins

Livestock water productivity was derived using the formula

$$LWP = \frac{\sum (\text{Beneficial outputs})}{\sum (\text{depleted} + \text{degraded water})} \dots \dots \dots \text{Eq.3}$$

Data were compiled and analyzed using an SPSS package. Comparisons were based on differences by resource ownership, gender, and livestock type within pastoral communities, using frequency distributions and percentages. Livestock water productivity indices were derived by use of MS Excel spread sheet modified by Amare (2006).

Results and discussion

General household information

The largest percentage of respondents were male: 78 in the settled and 85 in the nonsettled communities. Education level varied from primary, secondary, post-secondary, and those that had never gone to school. The proportion of the respondents that had not gone to school in all the communities was high: 41% in the non-settled and 37% in the settled agropastoral communities. The overall family size was 11.6, although families in the settled pastoral system had relatively larger families (12) compared to the non-settled pastoral system (10.8).

The average livestock herd size for the nonsettled pastoral systems were 64, 5, 0.9, 4.4, and 0.5 for cattle, goats, sheep, poultry, and pigs, respectively. The corresponding numbers for the settled agropastoral system were much higher (cattle 98, goats 20, sheep 2.4, and pigs 0.6, except poultry 3.7).

More men than women and children owned livestock. Ownership by women and children increased in small stock especially in poultry, where men had the lowest ownership.

Access, ownership and utilization of production resources

Although all the households had access to land, 33.3% did not own land in the nonsettled and 8% in the settled agropastoral communities. Levels of land ownership included government, private (men, women), and communal. In the nonsettled pastoral community of Nakasongola, more land is owned by government (27%) compared to the settled community (8%). The results indicate that land acquisition by individuals affects the mobility of the pastoralists. As individualization of land ownership increases, mobility decreases. The results further revealed that land ownership still remains a male domain, as they own a significantly higher percentage (57% for the nonsettled and 86% for the settled communities).

Land use patterns were similar in all the communities (Table 1). The proportion of degraded land and land encroached by thickets was high in nonsettled pastoral system. Land degradation was attributed to increased overstocking and harvesting of trees for charcoal burning. Increased land degradation and encroachment by thickets reduces the quality and quantity of pasture biomass available, thus lowering animal productivity.

Table 1. Land utilisation per household in hectares.

Category	Nonsettled	Settled
Pasture	39.5±55	83.4±146.5
Cultivated	2.42±2.9	1.7±2.3
Degraded	14.5±44	0
Thickets encroached	18.1±40.4	2.1±5.5

Available water resources and utilization

The available water resources in the study area included: valley tanks, wells, boreholes, lakes/swamps, and ponds. Valley tanks (ponds) were the most abundant water resource (Table 2), although cases of drying up during the dry season were common. Utilization of natural lakes as a source of water significantly increased during the dry season.

Table 2. Percentage households using various water sources in different seasons.

Water sources	Non-settled		Settled	
	Wet season	Dry season	Wet season	Dry season
Valley tanks	63	28	44	83
Well	47	0	47	0
Borehole	15	11	7	0
Lake	10	58	2	17
Pond	9	3	0	0

Access to water especially in the dry season was the the major factor affecting LWP. As a strategy to offset water problems in the dry season, families have to shift and or trek/travel long distances to permanent water sources such as lakes and rivers. Most of the farmers revealed that they shift and concentrate along the River Nile and the shores of Lake Kyoga. Farmers also reported that when they shift, there is an incresed loss of animals due to death, mainly as a result of diseases and shortage of pastures around the new settlements. This has a direct effect on productivity in terms of growth rates and milk yield, and hence the LWP.

The average distance to a water source in the dry season was 7 km for nonsettled and 6 km for settled systems. In the wet season, the distance covered to water source was shorter (3.0 and 1 km). Access to water directly affects LWP as livestock travel long distances, and this results in loss of body condition and a reduction in benefits such as milk. This increased movement of livestock and people to access water usually results in increased conflicts due to competition for water, consequently reducing animal productivity.

Ownership of water sources was mainly communal, and the mean percentage was 73 in the nonsettled and 82 in the settled pastoral communities (Table 3). As the water resource ownership becomes more public/communally owned, the responsibility for its maintenance is not owned by any individual. Management of water resources, especially valley tanks, directly affects their ability to hold water throughout the year since most of them dry up due to increased silting. Silt accumulation in the valley tanks reduces the amount of water available for livestock, thereby lowering animal productivity.

Table 3. Ownership and management of available water resources in percentages.

Ownership	Nonsettled agropastoral			Settled agropastoral		
	Valley tanks	Well	Borehole	Valley tanks	Well	Borehole
Man	9	57	0	0	86	2
Woman	5	0	0	0	0	0
Family	11	0	17	18	14	0
Community	36	43	67	46	0	90
Government	34	0	17	36	0	8
Landlord	5	0		0	0	0
Management						
None	40	0	41	0	0	0
Man	9	57	0	16	85	0
Woman	6	0	0		0	0
Family	9	0	0	33	10	15
Community	27	43	59	50	5	85
Government	9	0	0	0	0	0

Landlord	0	0	0	0	0	0
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Livestock water productivity

The two communities cultivate similar crops, except cotton, which was rarely cultivated in the settled agropastoral system of Kiruhura. The estimated crop water requirements using pan evaporation methods is given in Table 4. Livestock water productivity in the settled agropastoral community was higher (0.07 US\$/m³) than in the nonsettled community 0.04 US\$/m³ (Table 5). There was more water available in the settled communities, and therefore the amount of water depleted was higher compared to the nonsettled community (Table 4). In settled communities, there have been attempts to improve the genotypes by crossing the local livestock with Friesian cattle and Boer goats. Therefore higher livestock benefits have been realized from increased sales of live animals and high milk yields. In addition, the settled community had more land available for pastures per household (83.4 ha) and less land degraded and encroached by thickets compared to the nonsettled one (Table 1). This provides more pastures for the animals.

Table 4. Water requirements for different crops in the study area.

Crop	Nonsettled agropastoral system				Settled agropastoral system			
	Area (m ²)	ETm	LGP	CWR m ³ /year	Area (m ²)	ETm	LGP	CWR m ³ /year
Banana	7700	0.00176	547	7413	166000	0.00176	547	159812
Cotton	113000	0.001248	190	26795	0	0	0	0
Cassava	255000	0.00088	270	60588	17400	0.00088	270	66528
Maize	107000	0.00168	110	19774	21900	0.00168	110	29933
Sorghum	17600	0.00192	130	4393	44000	0.00192	130	10983
Beans	30100	0.00168	95	4804	40000	0.00168	95	6384
S. potato	168000	0.00104	128	22365	26900	0.00104	128	22364
Groundnut	135000	0.001408	130	24710	40500	0.001408	130	40635
Millet	46500	0.00112	105	5468	20000	0.00112	105	6586
Grassland	23740000	0.0012	133	3788904	51316000	0.0012	133	8190035
Total				3,965,259				8,280,656

Table 5. Estimates of LIVESTOCK water productivity for the pastoral communities.

Parameters	Settled agropastoral community	Nonsettled agropastoral community
Milk (US\$)	67,776	19,463
Meat (US\$)	321,548	12,904
Manure (US\$)	195,289	126,473
Draught power (US\$)	0	3,809
Estimated value (US\$)	584,613	162,649
Total water used (m ³ /year)	8,280,656	3,965,259
LWP (US\$/m ³)	0.07	0.04

Conclusions

Livestock water productivity in the pastoral communities is affected by access and ownership of production resources of land, water, and livestock. Increased land degradation coupled with an increase in encroachment of thickets affected pasture availability for livestock, thereby reducing LWP. Distances covered to access water by livestock especially in the dry season in the pastoral communities was high, thereby negatively influencing LWP. To improve LWP, pastoral communities should improve allocation and use of water and land resources for all users.

Acknowledgments

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Livestock water productivity in relation to natural resource management in mixed crop-livestock production systems of the Blue Nile River Basin, Ethiopia

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Abstract

Mixed crop-livestock farming is the most important production system in the Ethiopian highlands. Traditional livestock management practices often jeopardize water quality, human and animal health, and aggravate water mediated land degradation. The objectives of this study focused on determining livestock water productivity and investigating the effect of traditional livestock management patterns on sustainability of natural resource use in the Blue Nile Subbasin. Overall, livestock water productivity (LWP) was about 0.65 Birr/m³ of water under the traditional farming practices. LWP tended to increase proportionally with the volume share of crop residue in livestock feed. Communally owned and open unrestricted grazing land suffered most from erosive runoff events, with the concomitant sedimentation amounting to more than 40 t/ha at a slope of 15-25% by washing away pasture top soil. Traditional farming practices have evolved toward maximizing water use efficiency by exercising a double cropping pattern which takes advantage of residual moisture left after first cropping. This practice favors availability of more feed resources in the dry season, and thus contributes to increased livestock productivity. There is great opportunity to further increase LWP by implementing practical and relevant interventions that improve existing low levels of animal productivity.

Media grab

Livestock water productivity likely increases with an increase in the proportion of the volume share of crop residues in livestock feed to meet the annual requirement.

Introduction

In Ethiopia, the present level of livestock productivity is low. For instance, beef productivity (110 carcass kg/head) is about 25-30% lower than the average for East Africa (143 kg/head) (FAO, 1997). Milk production from indigenous cows ranges from 200 to 250 kg in a lactation period of 150-200 days. Mean carcass weight of small ruminants is 10 kg/animal. There is a vicious cycle of increasing human population leading to more intense pressure to convert pastures to cropland, and to raise livestock stocking rates by keeping larger numbers of animals on a unit area of land, to maintain rural incomes. This leads to natural resource degradation, which in turn reduces the capacity of the feed resources to support livestock and the people that rely on them. A great challenge for the country is therefore to change present agricultural production toward sustainable farming systems based on better natural resource management.

Ethiopia is prone to water-mediated threats causing a high degree of soil erosion and land degradation (Degefu, 2003). Water supply services in Ethiopia are among the lowest in Africa. Only 19% of the country's population and 11.5% of the rural population have access to safe water (Rahmato, 1999). There is an urgent need for better water resource management and sustainable development. Livestock production in mixed crop-livestock production systems of Ethiopia has hardly been considered as an integral part of water resource development. Water development projects targeted at rural water supply and irrigation are inevitably impacted by livestock causing pollution of water and degradation of the natural resource around the water points. This paper investigates livestock water productivity under rain-fed agriculture, in which the bulk of animal feed comes from grazing of nonirrigated pasture and crop residues and by-products.

Methods

The study was carried out on-farm in Gumara watershed areas of the Blue Nile Basin to assess livestock water productivity and natural resource management in mixed crop/livestock production systems at community and household levels.

Livestock water productivity was assessed under three different cropping scenarios in mixed crop/livestock farming practices. The scenarios of mixed crop/livestock farming in the Gumara watershed for this particular study were:

- Rice and niger seed-based (locally named 'noug,' (*Guizotia abyssinica*) cropping complex that dominates in the plain area at an altitude of 1700-1800/m;
- Teff, finger millet, wheat, and maize-based cropping complex occupying the areas with elevations between 1900 and 2300 m; and
- Barley, wheat/triticale, and potato-based cropping complex that dominates ecologies with elevations greater than 2400 m.

Fifteen smallholder farmers were selected from each of the three strata to monitor livestock performance and services at household and community levels on a year-round basis. Crop and livestock production were monitored over a one-year period at household and community levels. Livestock water productivity was determined at household level by summing of benefits obtained from livestock per unit of water input used for all aspects of livestock production.

The effect of different strategies of pasture management on natural resource use management was assessed under three distinct ownership regimes: 1) communally owned and open unrestricted grazing; 2) community owned pasture supported with local by-laws; and 3) privately owned enclosed pasture. Two distinct slope levels (<10%, 15-25%) were identified for each pasture land type. A 4 x 2 m² plot was demarcated with iron sheet and a metal gutter at the lower end of the plot. This device was put at each slope level in three replications to measure runoff and sedimentation. All the plots were accessible for grazing, as was the surrounding grazing land being managed by the community itself. The collected data was subjected to statistical analysis in SAS.

Results and discussion

The barley-potato based cropping complex appeared to integrate sheep production more than other livestock as this is agroecologically favorable with increasing rural human population density (Table 1). Horses serve as the main source of draught power in this area. Cattle are kept in a larger number per household toward the plain area where rice-noug based cropping complex predominates. Farmers tend to keep all kinds of livestock in mixture in varying proportions. Hence, livestock production is an integral part of the mixed crop-livestock farming practice. Farmers tend to make a choice of livestock species deemed to be best adapted to the local context. Livestock productivity in Gumara watershed area was noticed to be suboptimal with milk yield ranging from 0.6 to 1.8 l/day and the average live-weight of mature cattle reaching about 210 kg/head. It is now essential to improve livestock productivity through introduction of multipurpose forage crops that help to increase quality feed production and minimize soil erosion. Moreover, the traditional livestock production must target at keeping few but more productive animals in accord with carrying capacity of the existing pasture.

Table 1. Livestock holding of a household in different cropping systems of the mixed crop-livestock farming practices in Gumara watershed areas.

Cropping system	Livestock holding at a household level			
	TLU*	Cattle heads	Shoats	Equine
Barley-potato based complex	3.6±0.3	4.2±1.6	14.4±4.5	2.37±2.1
Teff-finger millet-wheat based complex	3.7±0.2	7.7±1.8	5.5±2.4	1.9±1.7
Rice-noug based complex	3.0±0.3	9.1±1.6	4.0±2.2	1.2±2.1

SE = standard error.

Livestock water productivity (LWP)

In computing LWP benefits from livestock, milk production, carcass weight, draught use, and manure values per unit of water used for raising the mix of livestock species owned by a household. Virtual water in the crop residue was accounted for, with reference to its relative value to that of grain, based on local market prices. LWP tends to increase with an increase in the proportion of crop residues used to meet annual livestock feed requirements (Table 2). Overall LWP appeared to be 0.65 Birr/m³ of water input under traditional mixed crop/livestock farming in Gumara watershed area. The higher LWP under rice-noug based cropping complex (Table 2) can probably be explained by the double cropping practice that exploits the residual moisture after the end of the main rainy season. This practice favors the availability of more crop-residues as supplemental feed resources during dry season at times when feed supply becomes critical. The present estimate of LWP is derived empirically and appears a

little bit lower than that estimated by Peden et al. (2007). This lower estimate might be associated with subsistence-based livestock production in this area, unlike the situation described by Peden et al. (2007) in Awash Valley where marketing opportunities, through encouraging farmers to fatten beef and small ruminants around areas of sugar industries, might be related to better livestock productivity.

Table 2. Livestock water productivity in different cropping systems of the mixed crop-livestock farming in the Blue Nile Basin.

Cropping system	Proportion of crop-residues produced/annual feed requirement (%)	LWP (Birr*/m ³)
Barley-potato based	28.7	0.60
Teff-finger millet-wheat based	31.6	0.54
Rice-noug based	56.8	0.82
Mean	39.0	0.65

*1USD = 9.76 Birr.

Influence of livestock management on natural resources

The impact of traditional livestock raising practices on aggravating runoff and soil erosion takes different scales and patterns, and depends on the ownership type and management of pasturelands. Communally owned and open unrestricted grazing management was found most susceptible to erosive runoff with the resulting sedimentation amounting to more than 40 t/ha at slopes of 15-25% (Table 3) during the main rainy season alone. There is considerable opportunity for improving this situation through altering the way communal grazing lands are managed and utilized. This particular case study shows that the level of soil erosion, measured as sediment load, was reduced by more than 60% on the same slope as a result of the changes in using community-based pastureland. These changes were communally agreed upon and supported with local by-laws. The present finding on soil loss from grazing pastures on flat lands is in agreement with the reports of Girma *et al.* (2002). The figures from grazing lands of 15-25% slopes are higher than those reported by Girma *et al.* (2002), particularly in open and unrestricted grazing lands, because of differences in terrain, stocking density, and rainfall intensity.

Table 3. Runoff volume and sediment load of the main rainy season from pastures having different ownership patterns and slopes.

Pastureland ownership pattern	Slope of the pastureland (%)	Runoff (m ³ /ha)	Sediment load (t/ha)
Communally-owned and open unrestricted grazing	<10	10,125.0	26.3
	15-25	12,825.0	45.27
Community-owned pasture supported with local by-laws	<10	3,307.5	7.84
	15-25	4,927.5	14.24
Privately owned enclosed pasture	<10	1,147.5	1.65
	15-25	1,687.5	3.39
SE±		607.5	1.47

Conclusions

Livestock water productivity is likely to increase with an increase in the proportion of crop residues in meeting the total livestock feed requirements. Integrated mixed crop/livestock farming systems offer ample opportunity to improve upon the existing very low level of productivity per head of animal. Integrating suitable multipurpose forage crops with existing farming systems will help increase supply of nutritious livestock feed, improve fertility of crop lands and minimize erosion of top soil. Promotion of community-based initiatives for improving utilization of communal grazing lands will further increase LWP. These initiatives will focus on practical ways of increasing communal pasture productivity through renovation of degraded grazing land and alleviation of the overstocking problem. This would ultimately bring about increased livestock productivity in a sustainable manner.

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Impacts of access to resources on water productivity: the case of the Blue Nile

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Abstract

Producing more product per unit of agricultural water used is a key for future food and environmental security. We report how access to productive resources (here referred as level of wealth and poverty), such as land and livestock, affects farmers' management decisions and resultant water productivity (WP); and how in mixed crop-livestock systems, WP of crops and livestock complement each other. The mixed farming systems in the highlands of Blue Nile Basin (Gumera, Ethiopia) were selected. Farm data were collected from 180 randomly selected households, using a structured questionnaire. The sample farm households were stratified into three wealth categories (rich, medium, and poor) using a participatory wealth ranking method. New LocClim (version 1.06) was used to estimate evapotranspired water in producing animal feed and food-crops, and beneficial outputs of livestock and crop yields were calculated from primary data and empirical knowledge. Finally WP was estimated as ratio of beneficial outputs to water depleted. Our results indicated significantly lower WP values for the poor farm households. In view of the results, we concluded that poverty alleviation and fostering pro-poor intervention technologies must be part of strategies to ensure sustainable water use.

Media grab

CPWF research in Ethiopian Blue Nile River Basin suggests that poverty reduction and pro-poor water management technologies are fundamental to increase water productivity.

Introduction

In a recent global comprehensive assessment of water management in agriculture, Molden et al. (2007) emphasized the necessity and opportunity for increasing agricultural water productivity in sub-Saharan Africa as one means to reduce poverty and increase food security. In this context, increasing agricultural WP includes crops and livestock and is an effective means of intensifying agricultural production and reducing environmental degradation.

The inclusion of livestock in WP concepts is relatively new, but like its counterpart, crop-water productivity (CWP), it is based on principles of water accounting (Molden et al., 2003). The CPWF project, Nile Livestock-Water Productivity (LWP), set out to integrate livestock use of and impact on Nile River water resources into the WP framework. Peden et al. (2007) developed an LWP assessment framework with the intent of understanding how livestock affect basin water resources in different production systems. This paper describes the application of this LWP framework in the mixed crop-livestock systems in the Gumera watershed (Blue Nile River Basin in Ethiopia). The discussion draws conclusions about the relationship between CWP and LWP, and tests the hypothesis that reducing poverty may lead to increased WP.

Materials and methods

Study area and farm survey

Gumera watershed is situated on the northeastern escarpment of the Blue Nile Basin in the western Ethiopian Highlands. It covers an area of 1644 km² with a considerable variation in soils and climate. Mixed crop-livestock farming systems are typical in Gumera. Depending on local agroclimatic conditions a variety of crops are grown. In the lower altitude ranges (1700-1806 m where flooding frequently occurs, rice (*Oryza sativa*) is the most important crop. Farmers usually practice relay cropping to make use of the residual moisture after the flood, and plant chickpea (*Cicer arietinum*) or rough pea (*Lathyrus hirsutus*). In the mid altitude range (~1800-2300 m) maize (*Zea mays*) and finger millet (*Eleusine coracana*) dominate the cropping pattern. There are also areas where teff (*Eragrostis tef*) and wheat (*Triticum durum* and *Triticum aestivum*) have significant coverage. On the high mountains (~2300-3700 m) cereals such as barley (*Hordeum vulgare*), pulses (e.g. faba bean, *Vicia faba*), and tuber crops such as potato (*Solanum tuberosum*) are important. Livestock are also important household ventures. Farmers manage different livestock groups in the Gumera watershed: cattle (e.g. *Bos indicus*), sheep (*Ovis aries*), goat (*Capra hircus*), horse (*Equus caballus*), and donkey

(*Equus asinus*). Livestock provide meat, milk, and energy. Manure fulfils an important role through nutrient cycling between and within farms, which enables the continued use of smallholder farms. Crop and livestock enterprises are complementary and competitive: complementary in the sense that livestock are a source of traction power, sources of organic fertilizer, and cash for inorganic fertilizer, whilst crop residues provide up to 30% of livestock feed sources. At the same time they are competitive for land and water.

WP studies for crop-livestock systems in Ethiopia revealed strong variability across different spatial scales. To get more insight on how this variability is related to farm households' access to resources and to capture interaction between the different farm enterprises (i.e. livestock and crops), nine Peasant Associations (PAs) covering the major systems of the Gumera watershed, were selected. Then, in each of the PAs, 20 farm households were randomly selected for interview (systematic-random sampling). Participatory wealth ranking methods were used to group those sample farms into three wealth categories (*rich*, *medium*, and *poor*—Hailelassie et al., 2007). Major criteria used in the wealth ranking exercises focused on productive resources such as arable landholding, oxen number, and other livestock group ownership. We used structured and pretested questionnaires to collect data on landholding, areas under different crops, type of crops cultivated, crop productivity, grazing land management, crop residue use, livestock holding, breed, livestock productivity, prices of livestock products, and services.

Conceptualization and quantification of water productivity

The concept of livestock and crop water productivity

Generally, WP can be defined as the ratio of products and services to the amount of water depleted and degraded in producing these goods and services (in kg/m³, USD/m³, kJ/m³ (Kijne et al., 2003)). For CWP, total dry or fresh biomass of harvested products and byproducts can be used as numerator. Frequently, the quantity of water depleted by evapotranspiration is used as the denominator. LWP concept is a relatively new idea, but like its counterpart CWP, it is based on principles of water accounting (Molden et al., 2003): it takes the values of livestock products and services as a numerator and water depleted and degraded in producing livestock feed as denominator. In this study only depleted water is considered.

Quantification of depleted water and beneficial outputs of crops and livestock

Penman-Monteith methods have been used successfully to estimate reference crop evapotranspiration as presented in New LocClim (version 1.06 (FAO, 2005)). In this study, the same procedures were applied. We used either quantities of grain and tubers or their financial values (as a denominator) to estimate the CWP. In the denominator we used the evapotranspired water during crop growth period. To relate crop evapotranspiration (ET_c, mm/day) to ET_o and to calculate evapotranspired water from the different crops, private and communal grazing lands, literature values of the crop coefficients (K_c) were used. Then, the amount of water that goes to the grain and (as a residue) to livestock compartment was separated using harvest index of the different crops. Part of the evapotranspired water that goes to the residues was used as denominator for LWP estimation.

We focused on products and services of livestock reported by the sample farm households. To quantify those products and services, total livestock populations of each household were converted to Tropical Livestock Unit (TLU) using a conversion factor of 0.79 for cattle, 0.1 for sheep and goats, and 0.66 for equines (Hailelassie et al., 2007). Dung production was calculated using dry weight daily dung production of 3.3 kg/day/TLU for ruminants and 2.4 kg/day for equines (Hailelassie et al., 2007). The nutrient value of manure was calculated based on literature sources and converted to fertilizer equivalent monetary values (e.g. Lupwayi et al., 2000; Hailelassie et al., 2007). Annual milk production was estimated as a function of: number of lactating cows, lactation period and milk production in liters/day/ cow and this was converted to monetary values. We estimated meat production using parameters such as: off-take rate, carcass weight, and average slaughter age for different livestock species and applied a similar procedure to estimate the values of hides and skins. Traction power is the key livestock's beneficial output as reported by farm households in the Gumera watershed. We collected data on the daily hiring cost of draft animals (e.g. oxen) and number of working days/year spent for plowing, threshing, and transport in every sample farm household. All statistical analyses such as one-way analysis of variance (ANOVA) and correlations were performed with SPSS 12 for windows.

Results and discussion

Water productivity of crop and livestock: effects of smallholder farmers' wealth status

Our results revealed stronger mean value of LWP than CWP for every wealth group (Figure 1a). This is in good agreement with Peden et al. (2007) who suggested that LWP is higher than cereal crop water productivity and fairly comparable to irrigated tomato. Variability of LWP across sample farmers' wealth groups was apparent: the rich farm households showed significantly higher values of LWP than the poor (Figure 1a). This can be explained by different factors: First, the rich groups maximize benefits from communal grazing lands through keeping more livestock. This is demonstrated by significantly higher values of livestock income per unit of area for the rich farm households compared to the medium and poor (data not shown). Second, rich farmers own more oxen, so that they can benefit more from livestock services like traction power (significantly higher USD/TLU for traction power and lastly, wealthier farmers seem to produce ~ 30% of their animals' feed (i.e. crop residues) with higher water productivity (Figure 1a).

The estimated CWP ranges between 0.05 and 1.5 kg/m³ of water. The overall mean was lower compared to the global average (Hoekstra et al., 2002; Figure 1a,b). Apparent differences were observed, in values of CWP, between the wealth groups (Figure 1a,b): the rich farmers' mean CWP were significantly higher than the poor and the medium wealth groups (Figure 1a). The poor farm households had the lowest grain yields and associated CWP (Figure 1b). This can be accounted for by the number of agronomic practices and farm household land-use decisions: fertilizer application, cropping pattern, and negotiation power for product farmgate prices. Haileslassie et al. (2007) reported a strong association of those decisions with farm household wealth status. According to Molden et al. (2007) the highest potential for WP gain can be found in those low-yielding areas. Our results (Figure 1b) agree with this, and at the same time reveal that smallholder wealth status as one of the drivers for low crop yield and related WP. The observed trends of bifurcation (Figure 1b) can be accounted for by the location of sample farm households in subsystems with different crop type and productivity per unit area. In general, in view of those arguments, reducing poverty can be one of the solutions to the overriding problems of water scarcity in sub-Saharan Africa.

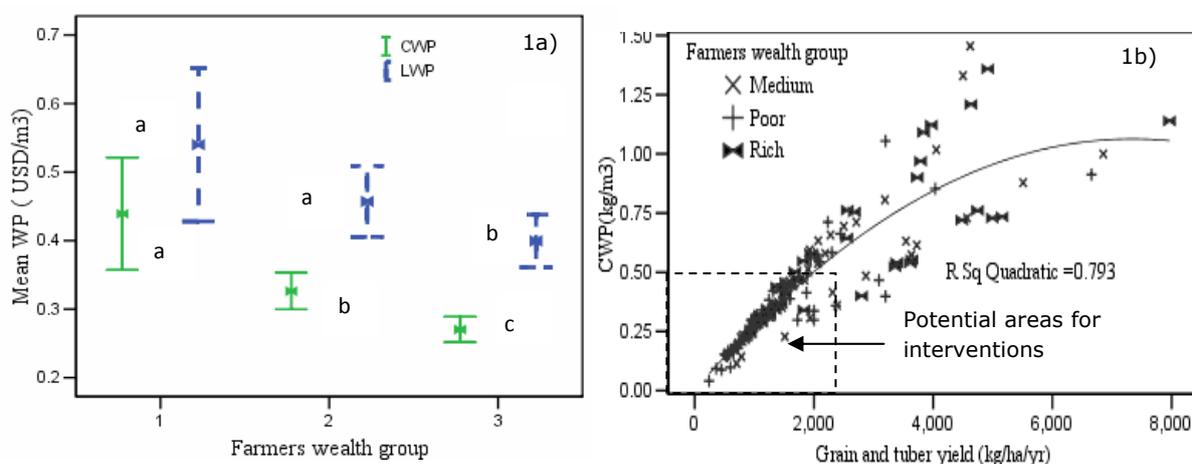


Figure 1. LWP and farmers wealth groups (a) and relation between CWP and grain and tuber yield (b) (1 stands for rich, 2 for middle, and 3 for poor; Tukey's HSD test at 0.95 confidence intervals; a, b, and c indicates significantly different means).

The above point of reducing water scarcity in sub-Saharan Africa can be also viewed from perspectives of enhancing rate of technology adoption by the smallholder farmers. A number of studies have already suggested technologies to improve WP: Bossio et al. (2007) indicated that investing in improved soil management can considerably improve water productivity in rainfed and irrigated agricultural systems. Those investments can take the form of increased nutrient inputs, leading to 15-25% gains in water use efficiency. Similarly, Peden et al. (2007) identified a number of strategies to improve LWP, such as selecting and breeding cattle and improved veterinary services. Farmers' capacities to afford those investments and adopt improved livestock, land, and water management technologies, however, are low and the need to foster pro-poor technologies innovation can be a point of concern.

Relation between crop and livestock water productivity: implications for land rehabilitation

The relation between CWP and LWP and LWP and arable landholding size is shown in Figure 2a and 2b. In Figure 2a, LWP decreases with increasing CWP for relatively low CWP. After a certain turning point the two variables relate positively. It can be argued that the low CWP is an indicator of low crop yields associated with land degradation such as nutrient mining. It is also noticeable that some areas of the Gumera watershed are not suitable for crop production due to terrain structure. Theoretically, both circumstances can lead to a shift in land use (marginalized arable land to grazing area) and farmers' livelihood strategies (e.g. livestock focused). This relation can be clearly observed from Figure 2a. In general these processes describe the negative relation between CWP and LWP. More interesting is the case where both LWP and CWP increase. This trend might not be the result of increases in livestock beneficial outputs. It is explained by the fact that a significant amount of crop residues, produced with better water productivity, is transferred to the livestock enterprise. In view of enhancing sustainable crop-livestock systems, intensification of these complementarities can be a good opportunity. The challenge is, however, to bring changes in areas of negative LWP and CWP relations, where important parts of our observations lie (Figure 2b). Peden et al. (2007), suggested a number of scenarios including land rehabilitation.

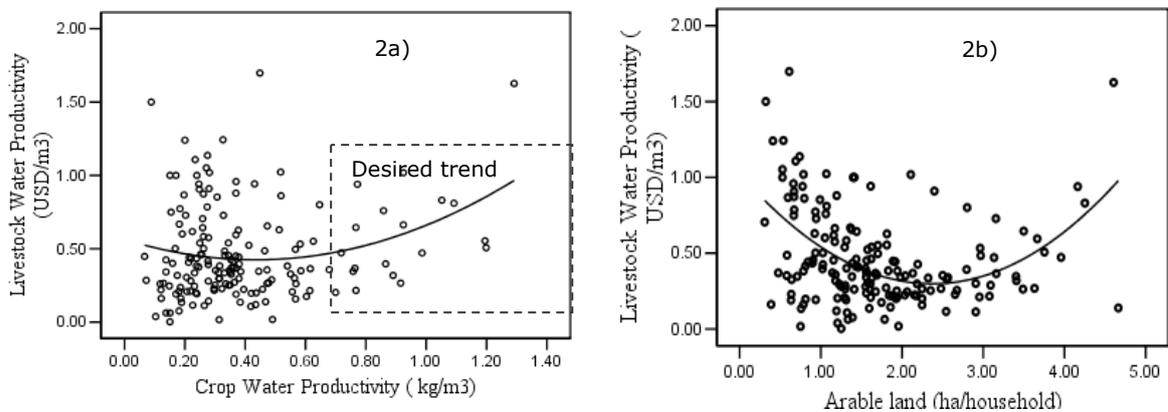


Figure 2. Relations between LWP and CWP (a) and arable land size of farm households and LWP (b).

Conclusions and recommendations

This study explores how farm wealth status affects WP, and to see complementarities and competitiveness between CWP and LWP. In view of the results, it is concluded that level of wealth of smallholder farmers is one of the causes of low WP. This means also that ability of farmers to pay for improved livestock, land, and water management technology is an important determinant of whether farmers will adopt it or not. Therefore, empowering the poor to implement those strategies and use water more effectively, should receive priority in measures to combat unsustainable water management practices. It is also realized that intensification of uses of the available natural resources in these areas increases overall system productivity. This will obviously enhance the complementarities of the crop and livestock compartments of a farm.

Acknowledgments

This paper presents findings from PN 37, 'Nile River basin livestock-water productivity,' a project of the CGIAR Challenge Program on Water and Food (CPWF). The authors are grateful to CPWF and sample farm households for unreserved willingness to provide information.

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Estimation of livestock, domestic use, and crop water productivities of SG-2000 Water Harvesting Pilot Projects in Ethiopia

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Abstract

The quantification of water productivity of each activity in agriculture is important to improve the allocation of scarce water resources and the efficiency of their use. The major objective of this paper is to estimate the water productivity of domestic use, livestock, and crops in Sasakawa Global-2000 (SG-2000) water harvesting pilot projects in Ethiopia. The research work was entirely based upon secondary data obtained from various organizations and publications. Water productivity was calculated using simple arithmetic methods and values of parameters from various sources. Water productivity of livestock, domestic use, and crop production was estimated at US\$4.82, 25.06, and 0.95/m³ of water, respectively (1US\$ = 8.5 Ethiopian Birr (ETB) in 2008). To show the scarcity value of water or the opportunity cost of investment in water development, these productivity values were recalculated taking the value of water in rural areas as the denominator. The resulting productivity magnitudes for livestock, domestic use, and crop water were, respectively, US\$1.60, 8.50, and 0.32/dollar of water. The results show that water used for domestic purposes and livestock generated positive gross returns for rural households in the study areas.

Media grab

In household-level water harvesting systems in Ethiopia, water productivity was greatest for domestic water use, though the investment was initially aimed at agriculture and domestic use is overlooked by planners. Providing sufficient water for rural people helps to eradicate poverty in Ethiopia.

Introduction

The negative impacts of water scarcity on agricultural production and health are pronounced in developing countries because they lack sufficient resources to adopt appropriate technologies to mitigate these problems. Natural occurrences such as drought, desertification, climate change, influences of human activities in agriculture, population growth, deforestation, and land use changes constitute the major causes of increasing scarcity and decreasing quality of fresh water. As the scarcity of water worsens, the production of food may decline while the population continues to increase in developing countries. Under these circumstances the ever-increasing demand for food must be met by increasing the productivity of water and land, which are scarce resources in arid and semiarid areas.

Many development projects intended to alleviate poverty in developing countries concentrate on water mobilization, such as irrigation projects aimed at crop production. In the agricultural sector, however, there are complementary activities that are important for eradicating poverty in developing countries. Thus it is important to quantify the magnitude of benefits and to increase awareness of policymakers to the benefits derived from any water investment. The major objective of this study is to estimate water productivity of livestock, domestic use, and crop production in several pilot water harvesting projects in Oromia and southern regions of Ethiopia.

People in the study areas practiced a mixed crop-livestock farming system in which the major income source is crop production using traditional methods of cultivation. The average family size was eight and most households cultivated 1.8 ha or less. Most beneficial households had their own livestock with an average herd size of 11 cattle. Most households (72%) in the study areas used open grazing as the main source of cattle feed. Each household in the study area had its own water harvesting structure in the homestead. The harvested water was used for livestock, domestic uses, and crop production. Many of the households (77%) irrigated 0.03 to 1.5 ha of their own land.

Methods

The empirical analysis was based on the census data obtained from the baseline survey on water harvesting pilot projects conducted in July 2006 by the nongovernmental organization SG-2000 in Oromia and Southern Regions of Ethiopia. In addition, other sources of information were used, such as the International Livestock Research Institute (ILRI), the International Water Management Institute (IWMI), Ethiopia's Central Statistical Authority (CSA), Ministry of Agriculture, Oromia Irrigation Development Authority, Oromia Health Bureau, and Ministry of Finance and Economic Development. The productivity analysis was done using simple arithmetic methods.

To measure the productivity of any input used in production, usually the value of total output per unit of input is calculated. Water productivity can be calculated with the formula

$$WP = \frac{\text{sum of values of all outputs produced using water as input.}}{\text{quantity of water depleted in the production}}$$

The data of the numerator of the WP equation were collected as gross value of output (GVO) and not in the form of the net value of output (NVO) because of the availability of data.

Livestock water productivity (LWP)

LWP can be defined as the sum of beneficial outputs of livestock per total depleted and degraded water in livestock production. Depleted water is the amount of water that is used for feed production, washing, drinking, and barn management. Degraded water, on the other hand, is contaminated water not suitable for further use due to pollution (Molden et al., 2003). In this study, the amount of depleted water included only water depleted in the production of feed (crop residues and grass) and drinking. Water used for animal washing, barn management, and polluted water were not considered due to lack of data.

LWP was calculated with the following formula, where *i* represents different livestock products and services (Molden et al., 2003).

$$LWP = \frac{\sum_{i=1}^n \text{value of livestock products and services } i}{\text{quantity of depleted water}}$$

The numerator is the sum of the values of the product and services of farm animals such as milk, meat, hides and skin, manure, animal power (plowing and thrashing), and transport. The amount of water depleted to produce those outputs and the amounts of outputs that can be produced from a given population of livestock were calculated using the parameters estimated by Asrat et al. (2006) and Pallas (1986, in Peden et al. 2005). The water requirements for crop residues and grass for 1 tropical livestock unit (TLU) are 136 and 1557 m³/year, respectively (Asrat et al., 2006). According to Pallas (1986, in Peden et al., 2005) the voluntary daily water intake (liter/TLU) in the dry season with an average temperature of 27°C is 27.1 l/TLU/day for cattle, 40 for sheep and goats, 21.9 for camels, and 27.4 for donkeys. To avoid double counting the water requirements for crop residues were excluded from the calculation of LWP, because these were incorporated in the estimation of crop water productivity below.

Domestic water productivity (DWP)

Domestic use included water used for drinking, cooking, bathing, washing clothes and utensils, food processing, house construction, and production of handicrafts. We used the WHO estimate of 20 l/capita/day as a basic requirement of water for moderate health in poor developing countries (Howard and Bartram, 2003). This was divided between drinking (3 l), cooking (2 l) and 15 l for personal hygiene. The value of the numerator of the DWP equation is also based on parameters obtained from other sources (especially CSA, 2005). Thus,

$$DWP = \frac{\text{sum of all domestic outputs produced using water as input}}{\text{quantity of water depleted in domestic production}}$$

The activities and outputs included in domestic use of water were: (1) drinking, bathing, laundry, washing utensils, and food processing, which together give an output of improved health (better hygiene and sanitation); (2) cooked foodstuffs; (3) brewed local drinks; (4) mud plaster or bricks made for construction; and (5) produced handicrafts.

Crop water productivity (CWP)

The total amount of water harvested in a given period of time is equivalent to the sum of water used for livestock, domestic use, crop production, and losses. Since each household used 53.2 m³/year (22%) for livestock and 19.4 m³/year (8%) for domestic uses, and assuming 252 m³ (10%) is lost due to seepage, then from the total harvested water in a year, the water available for crop production would be 1512 m³ (60%). Based on information from SG-2000 we can safely assume that all this water was in fact used for the production of vegetables and other crops.

The CWP is calculated using the usual formula but the denominator is not the magnitude of the crop water requirements, but the amount of water left in the reservoirs for vegetables and crop production after livestock and domestic use and losses. Hence the value of CWP assumed that rainfall was not used for the production of crops. Even if we consider the opportunity cost of rainfall in production it would not change the value of CWP since the price of rain is zero.

$$CWP = \frac{\text{Total sales value of vegetables \& other crops grown on irrigated plots}}{\text{Amount of water available for irrigation}}$$

To see the opportunity cost of water in alternative uses (the value of water sacrificed to produce the given level of output), we used the price of water in the study area which is US\$2.94/m³. Then using the equations but changing the denominators into value, we obtained the gain from each activity (LWP_m, DWP_m and CWP_m) in terms of per unit of money devoted to supply the resource-water.

Results and discussion

The results of the study show average water productivities of US\$4.82/m³ of water for livestock, 25.06 for domestic uses, and 0.95 for crops. In terms of the monetary value of the resource LWP_m, DWP_m and CWP_m, constitute US\$1.60, 8.50, and 0.32/dollar of water, respectively. In terms of both measures, domestic water productivity (DWP) is highest, followed by LWP, while CWP the lowest. Previous estimates of LWP in Ethiopia were calculated to be between US\$ 0.25, and 0.31/m³ (Ayalneh et al., 2004), much lower than the value of US\$4.82/m³ that we found. This difference may be caused by differences in market access, availability and cost of feed, cattle breeds, and level of education of farmers. It is remarkable that while crop production appeared infeasible in terms of CWP_m (US\$0.32/US\$), farmers were still growing crops. A probable reason for this is that water harvesting structures are highly subsidized investments in Ethiopia, while capital investments for livestock are much less accessible to poor farmers.

Conclusions and recommendations

Water productivity from domestic uses and livestock are found satisfactory and attractive. Even if the water productivity of one sector is higher than the other, however, it would be very difficult to recommend that households use water only for activities that have high WP values. In daily rural life the three sectors (livestock, domestic use, and crop production) are complementary and necessary. This is illustrated by the fact that regardless of the lower CWP, farmers in the study areas have widely used the harvested water for horticultural and other crop production.

The high values of domestic water productivity are most relevant to planners and policymakers as the importance of domestic use of water to the contribution of the overall output of households are often overlooked. Providing citizens with the minimum amount of water for drinking and other domestic purposes could have a spillover effect on all other activities in a household. In areas where health problems are serious, sufficient water for hygiene and sanitation can play an important role in getting people out of poverty.

Though the main objective of introducing water harvesting technologies in the study areas was to secure food through irrigation practices, the importance of domestic use of water was clearly shown by its high water productivity values. The implication is that water development investments such as water harvesting and even irrigation projects should be designed in such a way as to ensure multiple use water services that improve the welfare of farmers in rural Ethiopia. Thus, an integrated approach toward the systematic development of multiple use water services (MUS) could be a major strategy to alleviate rural poverty.

Acknowledgments

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Cost-effective Assessments of Livestock-water Productivity Using Previous Animal Feeding Trials

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Abstract

Assessments of Livestock Water Productivity (LWP) require land, water, livestock, and climatic data. Thus it is claimed to be time consuming and expensive. In this paper we report the results of a study on the effects of feed, age and weight on LWP using previous feeding trial data at ILRI Debre Zeit, Ethiopia. In the feeding trials, various feed types were combined with different proportions to make 16 unique rations. These were fed to experimental animals of different age, and weight. We estimated the LWP as the ratio of livestock products and services to the depleted water in producing these feeds. There were apparent differences in values of LWP across feed types, age and weight of experimental animals. The value of LWP tends to increase with increasing age and weight of dairy cows. There were also significant impacts of feed composition on LWP values. The highest LWP values were observed for oats, vetch and wheat bran mixes. This paper, therefore, provides an insight of the conversion effectiveness of some feed types. In conclusion, optimal feed composition and better herd management can be adapted to enhance LWP. We also found that using existing experimental data in identifying system specific strategies, for sustainable water use, is a cost-effective approach.

Media Grab

Changing dietary composition of animals' feeds may help increase the water productivity of animal source food consumed by people.

Introduction

One of the major challenges facing global agriculture is to sustainably increase food production without depleting more agricultural water. Increasing agricultural water productivity is therefore a priority issue. Crop-water productivity (CWP) is the ratio of economic or biological yield of a crop to the total amount of water depleted including evaporation, transpiration and discharge. From an agricultural water productivity perspective, livestock use of and impact on water resources has been largely neglected (Peden et al. 2007). The concept of LWP like its counterpart, CWP, is based on principles of water accounting and its applications to a controlled animal feeding trial is costly and time consuming. Yet, there is a need to assess LWP for many species of livestock, in diverse production systems and with numerous combinations of feeds and forages to obtain a global understanding of animals' demands for water and how livestock use of water can be effectively minimized.

Peden et al. (2007) identified several strategies for increasing LWP. They include strategic sourcing of animal feeds composed of highly water productive vegetation and enhancing animal production. Many traditional animal feeding trials have been conducted previously, but they were not designed to assess LWP. This paper summarizes a methodological approach to cost-effectively using existing feeding trial data and case study results on the effects of feed composition, age and weight on LWP (Mpairwe 1998).

Methodology

In light of the need to estimate actual water productivity in cost effective way, the work was undertaken by re-analyses of feed trial data sets that had already been documented in ILRI's Debre Zeit field stations for other purposes (Mpairwe 1998).

Estimating the beneficial outputs

The beneficial outputs considered for this study are milk, meat, manure and traction. Production and values of these outputs were estimated from the experimental data and past literature values.

Animal feed water requirements

As major components of the feed, these trials were crop and crop by products and we follow procedures of Crop Water Requirement (CWR) to estimate the water requirements of animal feeds (feed crop water requirement (FCWR)) used in the experiment. Crop water requirements are normally expressed by the rate of evapotranspiration (ET). The evaporative demand can be expressed as the reference evapotranspiration (ET_o) which predicts the effect of climate on the level of crop evapotranspiration. Empirically-determined crop coefficients (K_c) can be used to relate ET_o to crop evapotranspiration (ET_c) when water supply fully meets the water requirement of the crop (Smith 2000). The value of k_c varies with crop and development stage.

Stepwise calculation of Crop Water Requirement (CWR):

$$i) \quad \text{Crop Evapotranspiration (ET}_c\text{) (mm/day) = ET}_o \text{ * K}_c \quad (1)$$

ET_o (mm) = Estimated using pan evaporation (using meteorological data obtained from D/Zeit met station)

K_c=Crop coefficient for each crop type is obtained from FAO data base (FAO 1992)

$$ii) \quad \text{Crop Water Requirement (CWR) = ET}_c \text{ * Growing period * area planted} \quad (2)$$

Computation of livestock water productivity

Livestock water productivity, (Peden et al. 2007), will depend on the livestock benefits derived from livestock to the amount of water depleted for the production of different livestock products/outputs.

$$\text{LWP} = \frac{\sum \text{Beneficial outputs}}{\sum \text{Water depleted}} \quad (3)$$

Results

Table 1. presents LWP value of dairy cows by the type of feed they were fed during the experimental period. Accordingly animals which were fed with Oats vetch+.9lablab +3.75wheat bran and maize lablab+.5 lablab +3.75wheat bran had the highest LWP value (0.64 US\$/m³). On the other extreme side, those fed with oats + vetch + adlibitum had the lowest values of LWP (0.27 US\$/m³).

Feed Type¹	FCWR	Milk	Meat	Manure	Total	LWP
	(m³)					(US\$/m³)
Maize lablab adlibitum	5441	828	688	2	1518	0.28
Maize lablab + .5 lablab	3796	872	722	3	1596	0.42
Maize lablab + .5 lablab+1.25 wheat bran	3777	966	714	2	1682	0.44
Maize lablab + .5 lablab+2.5 wheat bran	3511	1096	740	3	1839	0.52
Maize lablab + .5 lablab +3.75 wheat bran	3036	1191	754	3	1948	0.64
Maize lablab + .4 lablab	5509	867	713	2	1583	0.29
Maize lablab + .8 lablab	4779	719	744	2	1466	0.31

Maize lablab + 1.2 lablab	4025	735	775	2	1512	0.38
Oats vetch adlibitum	5279	687	722	2	1411	0.27
Oats vetch + .9 lablab	3936	907	737	2	1646	0.42
Oats vetch + .9 lablab +1.25 wheat bran	3437	992	688	2	1683	0.49
Oats vetch + .9 lablab +2.5 wheat bran	3125	1086	677	2	1765	0.56
Oats vetch + .9 lablab +3.75 wheat bran	2937	1118	775	3	1895	0.64
Oats vetch + 0.4 lablab	4989	858	722	2	1582	0.32
Oats vetch + 0.8 lablab	5150	823	756	2	1581	0.31
Oats vetch + 1.2 lablab	4451	865	735	2	1602	0.36

Table 1. Effect of feed source on livestock production and water productivity expressed as US dollars.

¹The numbers given along with the feed types (except wheat bran) in the table indicate the amount of that feed type fed as percentage of the total body weight of the animal under the experiment. However, the numbers before the wheat bran is the graded level (kg dry matter). The feed types without figures were fed adlibitum (Mpairwe 1998).

Table 2 below shows LWP by age group of cows under the feeding experiment. The result shows that there is positive relation between age and values of LWP: an increase in the age of cows' results in increase in LWP values. We found the lowest (0.34 US\$/m³) for cows less than five years and it increased to as high as 0.41 US\$/m³ for those cows in the age category of 8 years and above.

Table 2. Effects of age of dairy cows on values LWP expressed as US dollars

Age categories	FCWR (m ³)	Milk	Meat	Manure	Total	LWP (US\$/m ³)
<5 yrs	4497	782 ^a	731 ^a	2	1515	0.34
5-7 yrs	4202	894 ^b	722 ^a	2	1619	0.39
≥ 8 yrs	4263	993 ^c	759 ^b	3	1755	0.41

Probability is based on General Linear Model (GLM) procedure using t test (LSD); along columns, means with the same letter are not significantly different at p < 0.05.

In addition to improved nutritional quality, selection of improved breeds and species of livestock that are more productive or better adapted to agro-environmental conditions, improved animal health and appropriate herd structure and management are suggested as strategies to improve LWP. Table 3 demonstrates effects of weight of dairy cows on values LWP (categorised in four weight groups). The result indicated that increase in weight of animal results in increased in values of LWP: i.e. LWP value is lowest (0.32 US\$/m³) for lower weight groups (300-350).

Table 3. Effects of weight of dairy cows on values of LWP expressed as US dollars

Weight Categories (kg)	FCWR (m ³)	Milk	Meat	Manure	Total	LWP (US\$/m ³)
300-350	4519	851 ^a	604 ^a	2	1457	0.32
350-400	4131	923 ^{ab}	671 ^b	2	1596	0.39
400-450	4178	906 ^{ac}	751 ^c	2	1659	0.40
> 450	4318	920 ^d	839 ^d	3	1761	0.41

Probability is based on General Linear Model (GLM) procedure using t test (LSD); along columns, means with the same letter are not significantly different at $p < 0.05$.

In the mixed crop livestock systems of the Ethiopian highlands, the main beneficial outputs derived from livestock are not only livestock and their products, but also livestock services in terms of draught power for land preparation, transport and threshing of crops grown on the farm. LWP ranges from 0.25 to 0.39 USD/m³ and that the value obtained from a cow appears to be higher than for an ox (Table 4).

Table 4. Summary of LWP by all beneficial outputs expressed as US dollars

Type of animal	FCWR (m ³ /hd/yr)	Milk	meat	Manure	Traction	Total	LWP (US\$/m ³)
Cow	4223	908	729	2	-	1639	0.39
Ox	4344	-	574	3	517	1094	0.25

Discussion

LWP is an important issue worldwide and considered as being very low compared to CWP. About 450 m³ of water is required annually to produce feed to maintain one TLU. When animals are growing, working, stressed or lactating, they use even more (King 1983). Transpired water depleted to produce feed for animal maintenance and production can be 50 to 100 times more than what animals drink. Although this relatively small amount of quality drinking water is essential for animal health and production, drinking water is not part of water productivity because water consumed by an animal has not been depleted or lost from the agricultural system (Peden, et al. 2007).

Renault and Wallender (2000), on the basis of nutritional productivity, demonstrated that a significant part of the additional water resource to produce food for the next century population could be generated by changes in food habits. A reduction of 25% of all animal products in the developed countries' diet generates approximately 22% of the additional water requirements expected by the year 2025. Zimmer and Renault (2003) also reports a study according to which a survival diet would require 1 m³ water/cap/day, whereas an animal-product based diet needs some 10 m³ /cap/day. More common diets are ranking from about 2.5 m³ /cap/day for low animal product intake, e.g. in North Africa, to 5 m³ /cap/day for high animal product intake such as in Europe or the USA (Ayalneh et al. 2005). These data mainly comes from developed countries where the benefits from livestock are basically food products.

In sub-Saharan Africa (e.g. mixed crop livestock systems) where many benefits come from livestock, domestic animals also provide multiple services such as draught power, transport and threshing. This

multiple use, by itself, implies an increased LWP. Peden et al. (2007) also clearly indicated that LWP in sub-Saharan African can be significantly improved if farmers can adapt strategies like switching to feed sources with higher WP, using crop residues and by products as a feed, encouraging more efficient grazing, using improved breeds and heard management strategies. Our results from one case study in Ethiopia suggest that strategic feed sourcing and giving high emphasis in improving the quality of feed can help increase LWP. But at the same time, this study underlines the need for disaggregating of those strategies and has close observation on the age and weight structure of animals for effective improvements of LWP.

Conclusions and recommendations

The findings from this work indicate some strategies and technological options such as use of more water productive feed producing vegetation, better heard management (appropriate heard structure such as age and weight, etc.) that should be taken into account to enhance LWP. LWP appears to be higher in large cattle than smaller ones with in the breeds used in this study. For cows, dairy production contributes more than half of the benefits derived from them. For oxen, traction power appears to be equally important to meat production. In Africa, livestock have higher water productivity than reported in developed countries because they provide multiple benefits and much of the feed that they consume is derived from crop residues and by products that have relatively high levels of feed crop water productivity. Overall, generalizations about the inefficient use of water resources for livestock production in developing countries can be misleading. In contrast, LWP in mixed crop-livestock systems appears to compare favourably with crop production. Such generalization can be disaggregated and system specific strategies can be formulated by using existing experimental data in more cost effective way. This case study also confirms that great opportunities exist to cost-effectively assess LWP in situation where appropriate previous animal feeding trial data exist, but more case studies are needed to validate the global applicability of our research results.

1.2 Acknowledgements

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Why gender matters: reflections from the livestock-water productivity research project

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Abstract

Livestock water productivity (LWP) is becoming a major area of research. IWMI and ILRI are attempting to understand the gender implications of different interventions to increase LWP, through research funded by BMZ (Bundesministerium für Wirtschaftliche Zusammenarbeit und Entwicklung). This paper draws on research conducted in Ethiopia and Zimbabwe and also the wealth of information emerging from the Multiple Use Systems Project (CPWF Project 28 on www.musproject.net). Some of the emerging results show that technological innovations are not gender neutral, because their design, timing, and labor requirements have differential gender implications. Some technological interventions to increase livestock water productivity might result in more work for women and fewer benefits going to the women. Secondly, gender and power relationships also shape the benefit terrain, which results in differential access and control of the benefits from the improved livestock water productivity. What matters is not just improving livestock water productivity, but the type of livestock targeted. Smaller livestock are seen to be largely benefiting women, thereby improving education and health prospects of the children within poorer households more than larger livestock. Therefore improving LWP does not necessarily result in improved well-being for men, women, and children and reduce poverty at large. Gender nuanced interventions are likely to contribute toward improvements in the livelihoods of both men and women.

Media grab

Gender is central in understanding the impact of 'development' interventions for increased Livestock Water Productivity, targeting poor women and poor men.

Introduction

Gender is a central organizing principle of societies and often governs the processes of production and reproduction, consumption, and distribution. Gender roles are the 'social definition' of women and men, and vary among different societies and cultures, classes and ages, and during different periods in history. They vary greatly across the Nile Basin and sub-Saharan Africa at large. Gender-specific roles and responsibilities are often conditioned by household structure, access to resources, political stability, and ecological conditions. Gender research in rural development is therefore essential in poverty reduction and sustainability of development interventions (van Hove, undated).

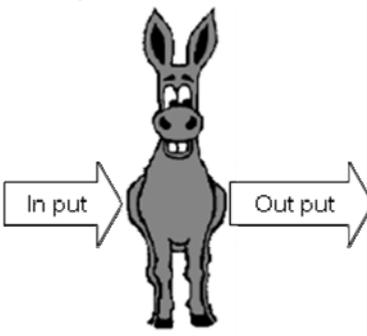
Within sub-Saharan Africa, livestock are perceived as playing a major role in poverty alleviation (Peden et al., 2007; ILRI, 2000, 2002) and environmental services. LWP is part of overall productivity of water for food production, and is defined here as the scale dependent efficiency of direct and indirect use of water for provision of livestock products and services. It includes water for production of livestock products and services and takes into account the impact of livestock on water quality, availability, and value to subsequent users (Peden et al., 2007). It needs to be viewed using a gendered lens, however, that will enable an assessment of the differential impact of the proposed interventions on poor women and men. Rural development in sub-Saharan Africa has attempted to improve the livelihoods of the poor people, but has resulted in the entrenchment of central power (Ferguson, 1990) or has not taken into account the gendered dimension of poverty. It has often only improved the well-being of well-off male-headed households, leaving poor females and males worse off (*cf.* van Hove and van Koppen 2005).

This BMZ-funded research promotes gender equity as a moral imperative in reaching the Challenge Program on Water and Food's poverty reduction and livelihood goals. It uses gender analyses and gender-balanced participation as a requirement of 'good science' (ILRI). Gender-conscious research is more likely to contribute to poverty reduction.

Conceptual framework: a gendered sustainable livelihood framework (GSLF)

This research draws upon the Gendered Sustainable Livelihood Framework (GSLF) (Figure 1), which was developed by van Hove and van Koppen (2005). This framework in Figure 1 largely borrows from the Department for International Development framework on sustainable livelihoods, which merges together DFID’s SLF with the gendered framework that was developed by Feldstein and Poats (1989) (cf. van Hove and van Koppen, 2005).

Figure 1. The Gendered Sustainable Livelihood Framework (van Hove and van Koppen, 2005).

Livelihood assets (five assets)	Costs to access assets	Access/control					Livestock as an asset Keeping livestock as a strategy/activity	Benefits /outputs or outcomes/	Access/control					Risks/vulnerability contexts= shocks, trends, seasonality/	Institutional contexts	
		M	W	H	C	G			M	W	H	C	G		Local/ community	Government or private
Natural - Water - Land - Feed							Water? Feed? Land? <ul style="list-style-type: none"> Where? How much? In what cost? (Time, labor, price?) Which mechanism helps to optimize water use? 	-Soil fertility -Biodiversity -Optimum water use								
Human - Labor - Knowledge - Skills								-Nutrition								
Physical - Water infrastructure - Services								-Traction -Transport -Energy/fuel								
Financial - Cash to purchase or pay for goods and services								-Income -Insurance -Coping								
Social - Resource sharing groups - Gifts, bride price - Cultural festivals								-Status -Social security								

Key: M = Men; W = Women; H = House hold; C = Community, G= Government

: The last two columns - Vulnerability and Institutional - help to show the different constraints and opportunities of livestock keeping in the context of other productive and nonproductive activities in the system.

In the first column, there are the five livelihoods assets: natural, human, physical, financial, and social. Examples of each of the assets are listed under the respective asset type. The second column looks at the costs to access the assets. This is further disaggregated by gender to demonstrate the costs of different interventions within the household and in the community at large.

Gendered labor contribution

This research project attempts to analyze not only the overall labor requirements of new interventions, but disaggregated along gender lines. For instance, if a new 'cut and carry' scheme is introduced, depending on the specific circumstances, it might result in increased labor requirements for women through collecting fodder for the livestock. If cattle herding was previously the responsibility of boys and men, is the result of an increased workload for the women (cf. van Hove and van Koppen, 2005). Such extra labor requirements have also to be further juxtaposed on the different types of households. *De jure* female-headed households tend to have labor constraints for their agricultural activities when compared with *de facto* female-headed households, where the male heads of household are based in urban areas and tend to send remittances that can then be used to

hire extra labor. Male-headed households tend to have more labor reserve than the two types of female-headed households (cf. ICRISAT, 2007; van Hoesve and van Koppen, 2005). It is, however, important that the intra-household assessments also look at the impact of women labor contribution in male headed households. Some studies have demonstrated that in some irrigated areas in the Awash River Basin of Ethiopia women in male-headed households were worse off than women who headed their own households and had access to irrigation plots (Aredo et al., 2006). The Access/Control column shown in Figure 1 identifies who has access and control of the input attribute. Quality of labor available is also an important issue, especially in countries in Southern Africa that have been negatively affected by HIV/AIDS. The result is a dominance of elderly and widows in rural areas. The available quality of labor is already overstretched due to caring for the sick, especially in South Africa, where the sick tend to move to rural areas when they are too weak to continue working (Mapedza et al., 2008).

Gendered control and access of benefits from livestock

The right side of Figure 1 looks at outputs, or the benefits coming from improved LWP. The benefits include income, insurance, and draft power (depending on the type of livestock). The next column–Access/Control–looks at who benefits from increased income. How does one also access increased income? Often women and children contribute most of the labor requirements, but the income distribution does not reflect that contribution. Studies by ICRISAT (2007) have demonstrated that women tend to have access and control of benefits derived from small livestock (cf. Van Koppen et al., 2005). Aredo et al (undated) further point out that marketing for large livestock such as cattle is tilted in favor of males. In such circumstances, promotion of small livestock such as goat and chicken might help reduce poverty amongst the women. The ICRISAT study also found that income controlled by women was also significantly contributing toward schooling of the children. For example, benefits such as increased milk production may not benefit women and children because the males sell the milk to buy alcohol. Children and women are worse off when their labor requirements increase without any benefits accruing to them.

The access and control of benefits terrain is also shaped by the political, economic, and institutional contexts. Laws and rules on livestock and land tenure will directly and indirectly impinge on who has access and who benefits from the improved LWP. Institutions—from local to community level—and how they are nested to national level, also has important implications in access and control of benefits by both women and men.

New innovations meant to improve LWP might also affect social relationships

Not all innovations toward improving LWP negatively affect women. If there are better forages that will result in less time spent on harvesting and collecting forages, this will be beneficial to the women. If clean water is made available for multiple use systems that include livestock and domestic requirements, this will save time previously spent collecting water for domestic, livestock, and other uses (cf. van Koppen et al., 2005). This frees the women to carry out other duties such as spending more quality time with their children and family. For the children, this might also entail more time available to play and to do their homework. Improved milk production as a result of improved fodder quality might benefit the family through improved nutrition for the family.

In Lege Dini watershed in Eastern Ethiopia, livestock productivity increased with improved water supply services. Milking livestock is a responsibility of women, and an ability to have fewer animals that yielded more milk provided women with higher incomes for reduced labor (Van Hoesve, undated). This was one of the very few sources of cash income for women in this area. They organized themselves into a milk group, where they would daily gather any surplus milk (left over after home consumption) and mix it, regardless of animal types. This milk is marketed to the nearest town, almost an hour drive, and group members rotate who goes to the market and keeps the revenue (Van Hoesve, undated). The women used this additional income for improved hygiene at the household level and for school costs (Jeths, 2006).

If women derive benefits and financial independence as a result of improved livestock water productivity, this might result in the empowerment of women beyond crop and livestock issues. Such empowerment might result in women renegotiating their position and status in the household. Such household reconfiguration will, in a small way, contribute to the increased esteem of poor women and men in sub-Saharan Africa.

This paper and associated research emphasize the following recommendations:

- Gender matters in LWP and has to be seriously evaluated.
- Development initiatives should avoid using 'labor contribution' as an indicator of empowerment and participation. It is important to note what women are getting relative to their contribution. Special attention should be given to the labor contribution by children and what the consequences are of increased or reduced workloads, e.g. enrolment in schools.

- Preconceptions about the well-being of married and female-headed households should be assessed for each context. In Ethiopia's Awash River Basin, female-headed households were observed to be well off because they had access to irrigation land.
- Impact of HIV and AIDS has to be considered in view of the labor and time requirements of the different types of interventions.
- Access and control of benefits has to be assessed. This has to be linked to the inter- and intra-household power dynamics and institutions that help alter and shape the structure of incentives, and determine who has access and control.

Conclusion and recommendations

Whilst it is important to note that improving LWP is central to improving the livelihoods of communities in rural sub-Saharan Africa, it is equally important to further evaluate what such improvements imply for different members within the household. Technological innovations are not gender neutral but their design, timing, and labor requirements will have differential gender implications for poor women, men, and children. If the household benefits, it does not mean that the welfare of all household members is improved. A gendered livelihoods approach enables a critical assessment of the winners and losers at the intra- and inter-household levels. Such an approach is informative and will enable the restructuring of the type of livestock to focus on in certain communities to get maximum benefits from interventions. Development is meant to reduce poverty for the most vulnerable. The LWP research being carried out under the auspices of the BMZ project, and building upon the earlier CPWF research, hopes to contribute toward meeting such objectives with lessons distilled from the sub-Saharan Africa region.

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Facilitating adoption of livestock water productivity interventions in crop-livestock systems

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Abstract

There is an increasing pressure on water resources in sub-Saharan Africa due to unprecedented and competing demand for water between agriculture, ecosystem services, and other uses. Various technologies and practices have been developed in the region to increase the productivity of crop and livestock systems, particularly by national agricultural research systems (NARS) and CGIAR (Consultative Group on International Agricultural Research) centers. These technologies and practices have failed to be adopted by the end-users, however, because the interventions were developed without considering the socioeconomic concerns of target communities, their systems, and their institutions. They commonly fail to respond to social preferences, indigenous knowledge, and local skills. Participatory research proved to be effective in enabling small-scale farmers and local decision-makers to identify and develop technologies, but adoption of interventions by the end-users at a wider scale remains challenging. This paper presents success factors that would help research and development actors to combine social, institutional, technological, and policy interventions to bring short-term economic benefits and long-term positive environmental services through integrated processes.

Media grab

Improving water productivity in sub-Saharan Africa requires a shift from actions merely focusing on the supply side to inclusive institutional and policy actions responding to the demand side.

Introduction

Conventional research and extension approaches that are commodity-oriented and promoting a 'linear' transfer model (research to extension to farmers) have tried to address agricultural problems facing resource-poor farmers. There is now clear evidence from adoption studies and from direct feedback from farmers, that technologies developed using this conventional approach, with limited involvement of farmers, that on-station generated technologies were not always relevant to farmers because there were few avenues to consider the socioeconomic and agroecological circumstances of the end-users.

Although livestock has a great economic and social importance for the majority of the world's poor (Parthasarathy Rao et al., 2005), improved livestock management interventions and veterinary services are rarely reaching the rural poor. Population growth, urbanization, economic growth, and flourishing markets all lead to increasing demands for animal products (Delgado, 2003), while the productivity of animals remained low. Moreover, with growing human populations, growing incomes, and changing diets, more water is needed to meet the increasing food demands (Molden et al., 2007). The current problems of water scarcity are aggravated by several factors (Gleick, 2003). There is a huge loss of water in various agricultural and nonagricultural systems, which are associated with uncontrolled evaporation, water depletion through excessive run-off, water pollution due to excessive use of chemicals, and water contamination by industrial activities. Water management interventions at farm, landscape, and higher scales are often poorly adopted and implemented, which leads to high social and environmental costs (Molden et al., 2007). Climate change puts extra pressure on sustainable water resources management (Molden et al., 2007). The increasing global importance of the livestock sector is another important factor as livestock production systems deplete, degrade and pollute enormous quantities of fresh water (Steinfeld et al., 2006). The interventions related to improved livestock-water management, however, are either not readily available for end-users or they are rarely suitable to the socioeconomic situations.

A shift is required away from actions merely focusing on the supply side or the 'hard path' (Gleick, 2003; de Fraiture et al., 2007) to actions facilitating demand for livestock and water management interventions. Appropriate policies and institutions must be developed and local communities must be involved in decision-making (Gleick, 2003; de Fraiture et al., 2007). There are three basic livestock-keeping strategies that can help achieve this (Peden et al., 2007). These are optimal feed sourcing, enhancing animal productivity, and conserving water resources. In addition, providing drinking water to livestock, especially cattle, is a proven practice that when done well can increase effective and

productive use of water. These are interventions mostly developed through approaches to solve individual system constraints, and hardly consider livestock-water interactions. Conventional approaches are usually commodity-oriented, discipline-based where the mode of transfer of technologies to farmers is assumed to be 'linear' (i.e. from research to extension then to farmers). Other factors are not considered in the linear approach. These include sociocultural, market opportunities, socioeconomic status, leadership, off-farm work, task orientation, literacy level, policy and institutional setup, which affect the adoption and dissemination of technology (Solano et al., 2006). Furthermore, most of the technologies are generated on-station through researcher-designed and researcher-managed trials. Direct feedback from farmers as well as several adoption studies (Amede et al., 2001) have clearly shown that technologies developed using this conventional approach are often not appropriate to subsistence farmers, thus leading to low adoption.

The objective of this paper is to present experiences in dissemination and adoption of interventions related to crop, land, water, and livestock management that emerged from eight case studies in Ethiopia (Amede et al., 2004). The information reported comes from a field study held by an assessment team with farmers, participating researchers, governmental and nongovernmental personnel, institution leaders, and key informants validated by recent field surveys targeting interventions related to livestock and water management.

Materials and Methods

An assessment team made up of researchers, extension personnel and NGOs was assembled to undertake the exercise. After the assessment framework was developed through a three-day facilitated workshop (by Dr J Hagmann), a process was conceived as a way to identify the elements for effective research for development. Four assessment teams, consisting of 4-5 members drawn from different disciplines and institutions, to apply the assessment framework to understand better the elements required for effective research, and the potential of PR approach in Ethiopia using a case study approach. These included project experiences from the African Highlands Initiative in Southern Ethiopia, the Joint Vertisol Project (JVP) by the International Livestock Research Institute (ILRI) in Ginchi, Participatory Research for Integrated Agro-Ecosystem Management (PRIAM) by CIAT in Nazareth, Farmers Participatory Research (FPR) Project (FARM Africa, Awassa), the Cool Season Food and Forage Legumes Project based in Holetta, and an Integrated Pest Management project based in Melkassa. The overall assessment was planned and implemented in four phases: preparation, data collection, analysis and interpretation, and report writing. Four main methods were used during the case study assessment: review of relevant documents, focus group discussions, key informant interviews and field observations. A generic checklist was iteratively developed so it could be used by all groups to extract relevant information and was based on the overall assessment framework developed during the planning workshop. Each assessment team developed its own workplan and time schedule for contacting relevant stakeholders (organizations and individuals) for discussion, field visits, gathering secondary information, data analysis, interpretation, and draft report writing. Group discussions were held with researchers, farmers, staff of districts and/or zonal Bureau of Agriculture (BoA) and other relevant stakeholders. Field observations using transect walks were made to sample sites to get first-hand information about the area in general, and the project undertakings in particular. Information obtained from group interviews was fine-tuned through key informant interviews with individuals who knew the details of the project and its implementation procedures. Review of secondary data helped to gain a general understanding of the project background, its rationale, objectives, approaches, expected outputs, and other related issues. Whereas discussions with those directly involved in implementation focused mainly on the project background, objectives, planning, and implementation procedures and to describe participatory approaches used, benefits resulted from participation, problems and challenges encountered, strengths and weaknesses, and impacts of (changes resulting from) the approaches used from the perspective of farmers, researchers, and other collaborating partners.

Results and Discussion

Targeting production systems and clients

Scaling-up of technologies beyond the contact farmers, which received continual technical and material support, remained challenging. Horizontal and geographical spread of technologies has been also limited, even with the facilitation of public institutions and NGOs. Besides unfit characteristics of technologies across agroecologies and social strata, the spread of technologies and approaches that demand collective decision and policy support (e.g. grazing land management) is very much limited. Contrasting production systems and socioeconomic categories demand diverse technological innovations and approaches to bring immediate change. Diversity in production objectives among stakeholders, for example with some households concentrating on marketable livestock-related commodities and others on food security and self-sufficiency, also required targeting of technological interventions. Resource-poor farmers, especially those far away from markets, faced difficult

decisions over the use of scarce resources in their production systems, including land, labor, nutrients, and water. Decisions on the allocation of resources were often made associated with immediate financial gains and food security, with limited assessment or appreciation of the impact of management decisions on other system components (e.g. feed production, soil fertility management). There was a need to characterize, package, and disseminate them to various recommendation domains (agroecologies, cropping systems, cultural values, system niches, and other system scenarios). Farmer-to-farmer dissemination of technologies through existing social networks—be they defined by area of residence, friendship, kinship, marriage, religion or other factors—was one successful approach (Adamo, 2001) though the reach was limited. Moreover, the production systems within this region differ in agroecology, socioeconomic, and policy dimensions as they also experienced different institutional constraints and household priorities. The interaction with research and development also varied from community to community. The important constraints were identified by the general community along with potential and relevant solutions. For instance, the major farming constraints identified by farmers in the East African highlands related to livestock and water management included shortage of livestock feed, lack of access to markets and credit, and limited access to improved varieties of forages and crops (Amede et al., 2006).

Identification of key entry points

'Entry point' is an initial action that is strategically applied to assure smooth and effective engagement with communities and institutions. Entry points were essential to build trust between the community and outside actors, arouse their interest and keep their spirit high in all case studies. Entry points had certain properties that led to the desired objectives of promoting 'win-win technologies' at farm and higher scales. These included various interventions in the form of attractive technologies, policies, and other incentives. The most apparent entry points, however, were often crop varieties, although farmers slowly shifted their engagement to water conservation measures and bund management that combined fruit trees and multipurpose forages. The type of entry points commonly determined whether farmers were keen to maintain partnerships to experiment with researchers and extensionists or not, and whether farmers were capacitated enough to try, innovate, and solve their problems without the involvement of external actors (Amede et al., 2001). Strategically, entry points must have certain properties that will lead to the desired objectives of promoting win-win technologies. These characteristics identified from the case studies were: i) of high priority, problem-solving to the community; ii) quick in bringing benefits, particularly higher household income; iii) successful, as early successes go a long way to enhance enthusiasm and trust; iv) accessible to most households, so that unequal benefits do not compromise the enthusiasm of large portions of the community; and v) technologies that are easy to multiply and manage, simple to solve and to be adopted by different sectors of the community. Selection of entry point has to be followed with capacity-building of farmers (training, provision of improved seeds and fertilizers) so that they could test and acquire the necessary skills.

Promoting linked technologies

The term 'linked technologies' was coined to define interrelated technologies applied simultaneously at plot level to render multiple benefits and facilitate adoption of technologies. The research teams employed several participatory techniques to link individual technologies to foster visible farm benefits (Amede et al., 2006). It facilitated change from commodity-oriented to a more holistic and systems approach, whereby farmers were in the forefront throughout technology development, dissemination, and impact assessment.

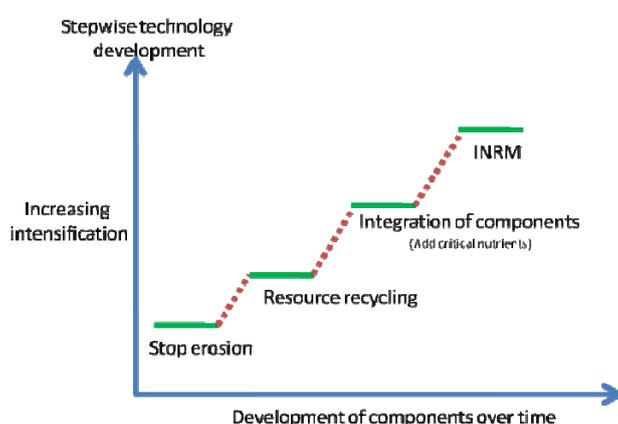


Figure 1. Step-wise integration of various technologies and approaches to improve natural resources management in the Ethiopian highlands (Amede et al., 2006).

In general, the 'linked technology' approach best enabled development workers, research organizations and recipient communities to jointly address poverty and natural resources degradation in a holistic manner. As farmers' interest gradually increased in adopting the simple entry point technologies, the research teams created access to a wider range of, and more complex and linked, technologies (Figure 1). By linking the entry point technologies with soil conservation (e.g. forage grasses and multipurpose trees), farmers in southern Ethiopia were able to get multiple benefits in the form of increased crop yield, livestock feed, and fuelwood. Further intensification was possible with more horticultural crops, production of fodder (grasses and leguminous trees and shrubs) for zero grazing, while serving soil conservation and other uses.

Strengthening linkages and partnerships among stakeholders

It was critical to create favorable linkage mechanisms among the actors to provide more options, other interventions, and expertise. This was done through holding periodic stakeholder meetings and workshops for feedback exchange and experience sharing to create a common understanding of visions, goals, and objectives. Building genuine partnerships and linkages with farmers, related organizations, and development actors (for instance, Ministry of Agriculture, input supply institutions, local organizations, and market) facilitates dissemination. Stakeholder partnerships were negotiated in such a way that each party clearly understood and fulfilled their responsibility, and were committed to work together. The commodity approach required that it be augmented with an integrated agroecosystems approach so that interrelated enterprises, heterogeneous circumstances, and innovation systems can be taken into account. This required an ability to analyze and work with systems by many development partners.

Supportive research and extension management systems and organization

Creation of a favorable policy and conducive working environment in research and extension systems played a pivotal role in the internal and external efficiency of technology dissemination processes. This was demonstrated by the establishment of researcher-farmer-extension linkage steering groups at the Ethiopian Institute of Agricultural Research. Availability of adequate resources coupled with good and visionary leadership was needed for the execution of effective extension.

Basket of technological options

There was a need to ensure sustainability of technology use by improving access to and availability of multiple technological options (e.g. annual forages with various maturity periods). The technological options were those appropriate to the needs, interests, and local conditions of the farmers. Involvement of end-users in the development of the technologies heightened the probability of appropriateness and therefore adoption.

Local organizational capacity

Facilitation of farmer organizations helped improve effective technology development and dissemination and collective action. A community change management approach was required for group facilitation in managing common natural resources (e.g. grazing land management). Organizing farmers into strong farmer research groups (FRGs) created an entry point into the community for researchers, extension personnel, and development staff to work closely together (Amede et al., 2006). Empowering the groups using participatory approaches was fundamental to enable them to meaningfully participate. Moreover, working together requires patience and respect of the communities' social values and affairs. Farmer capacities were built through training, visits, and experience-sharing discussions, and general facilitation.

Market orientation

Promotion of effective technology utilization required effective market orientation by research and by farmers. Forage and water management interventions were linked to marketable livestock enterprises. There was a need for consideration of agencies and actors associated with markets as a key stakeholder. Institutions helped farmers to identify market imperfections and incorporate the interests and priorities of stakeholders involved in marketing fields.

Community facilitation

Facilitators with appropriate skills and experience were needed to organize actors and help their groups to function. This was critical to build social capital for managing communal resources. It was also an efficient tool to reach many farmers quickly. They helped to build capacity so they can make demands, manage themselves, participate in R&D activities, and have their own activities. Farmers are empowered and their ability improved to conduct their own experiments considering resource status, wealth, age, and other stratification that might affect needs and priorities. It was crucial to document farmers' ITK and build upon it by the R&D agenda.

Conclusions

Current policies need to be adjusted to support technology generation and dissemination ensuring that large numbers of farmers have access and can use them. There was a need to foster supportive and conducive infrastructure and related policies to ensure that research, extension, and development outputs reach users. Similarly, ILRI and IWMI have recognized the need to make research more demand-driven and responsive to client needs by ensuring the participation of users in the process of agricultural technology development, and through developing the capacity and confidence of those making the demands. In general, principles and values inherent in effective dissemination of LWP interventions may include:

1. *Inclusiveness*: Different social groups of farmers should have equal access and opportunity to be part of research processes and participate in the decision-making process on communal and their own specific problems (problem differentiation).
2. *Monitoring to improve research and extension processes*: There is a need to continuously monitor progress at farm and landscape level, whether or not research is problem-driven and demand-oriented, and examine the relevance of research to the community to improve our approaches and strategies so as to deliver technical options in a sustainable manner.
3. *Trust and value indigenous knowledge and skills*: Researchers and service providers should understand systems and farmers' situations, value farmers' knowledge, and trust in farmers' potentials and capabilities (e.g. that they are experts in their own situation). This calls for building genuine partnerships with farmers and other stakeholders.
4. *Build capacity for self reliance and empowerment*: There is a need to build farmers' capacity to manage their own affairs (self reliance), improve stakeholder participation (dialogue, interactive, multiple ways), improve access to choice of technologies, create flexibility and options, improve quality of facilitation, develop a sense of joint ownership (role clarification, trust, transparency, confidence) and promote experiential learning – a way of learning-by-doing that is relevant both for researchers and farmers.

Acknowledgments

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GIS-based multicriteria decision analysis for land suitability modeling of livestock production in Tana subbasin, Ethiopia

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Abstract

Land suitability analysis is of paramount importance to identify suitable land for livestock production while causing minimum impact to the environment. This paper presents an approach of multicriteria decision analysis to generate a land suitability model for livestock in a spatial decision support platform. The following decision criteria are based on: land use, slope gradient, soil type, and rainfall availability. Spatial modeling techniques of weighted linear combination (WLC) are utilized to generate the land suitability model, wherein continuous criteria are standardized to a common numeric range, and then combined by means of a weighted average. Five suitability classes are identified with varying degrees of suitability. The spatial multicriteria analysis results revealed that about 47% of the study area is most suitable for livestock production. About 23% of the subbasin is moderately suitable for livestock production. And 2.2% of the study area is identified to be least suitable. Areas that were found to be currently not suitable are 2.7% and permanently not suitable 0.01%. The study area, Tana Subbasin, is optimally located on suitable land for livestock production, as most of the basin is covered by optimal land use cover, gentle slope, fertile soil type, and optimal rainfall availability. Nevertheless, the current livestock distribution is concentrated on marginal areas that need further intervention to improve livestock productivity.

Media grab

This study attempted to develop a land suitability model for livestock production in the Tanasubbasin in Ethiopia, using GIS-based multicriteria decision analysis.

Introduction

Livestock production contributes the highest share to Ethiopia's Agricultural GDP. Livestock play a vital role, adding to stability of farm incomes, food security, and farming systems. Livestock are kept as a form of insurance and a means of storing savings (Winrock, 1992). The emphasis given to livestock production in Ethiopia is still inadequate, however. Since the land resource is limited, proper usage could alleviate poverty in the country (Atesmachew Bizuwerk, 2005). Although livestock production is a vital component of the agricultural systems, it has so far been overlooked in integrated land and water management for food security in poverty alleviation strategies. Suitable land use is a key element for livestock production. Optimal land utilization is the most important factor in livestock production systems in sub-Saharan Africa. A GIS-based spatial decision support system represents a suitable framework for land suitability decision-making. Therefore, locating suitable areas of livestock production using GIS-based multicriteria decision analysis would provide indispensable decision support to improve livestock productivity.

In this study a pair-wise comparison method is used. This method has been tested theoretically and empirically for a variety of decision situations, including spatial decision-making Malczewski (1997). This approach is appropriate to achieve high degree spatial decision accuracy, but must be based on sound theoretical foundations. Empirical applications suggest that the pair-wise comparison method is one of the most effective techniques for spatial decision-making including GIS-based approaches.

Methods

The study area, Tana Subbasin is located south in the Amhara Regional State in the Blue Nile River Basin, which encompasses a total area of 15,054 km². In this study a pair-wise comparison method is adopted to develop criterion weights. The information is broken down to simple pair-wise comparison in which only two criteria need be considered at a time. This facilitates the weighting process, and will likely produce a more robust set of criteria weights. IDRISI software is used to implement the above method of pair-wise comparisons developed by Saaty (1977) in the context of a decision-making process known as the analytical hierarchy process (AHP). The method involves pair-wise comparisons to create a ratio matrix.

Since the complete pair-wise comparison matrix contains multiple paths by which the relative importance of criteria can be assessed, it is also possible to determine the degree of consistency that has been used in developing the ratings. The consistency ratio (CR) indicates the probability that the matrix ratings were randomly generated. Saaty (1977) indicates that matrices with CR ratings greater than 0.10 should be re-evaluated. In this study the consistency ratio calculated for the matrices is 0.04. According to Saaty (1977), this value is acceptable and the criterion weights are assigned to all the parameters.

The study resulted in mapping optimal livestock production using multicriteria decision analysis for evaluating model parameters: land use, land cover, slope, soil type, and rainfall availability. All input data layers for the MCDA are converted into a raster data model since the weighted overlay analysis environment accepts integer raster as input. Constraints of the model water bodies and urban areas are assigned a restricted value that the corresponding areas cannot be used for livestock production in the GIS based multicriteria decision analysis.

The suitability model outcomes are reclassified into six suitability classes in accordance with the FAO (1985) suitability class. Thus, S₁ indicated areas with the most suitable classes for livestock production, whereas S₂ showed areas with moderately suitable land for livestock production. Furthermore, S₃ indicated locations with least suitable class. There are two classes, that are not suitable. The first N₁ indicates locations that are currently not suitable for livestock production, whereas N₂ implies areas that are permanently not suitable for livestock production. And R represents areas restricted from the modeling.

Results and Discussion

The results indicate that areas with gentle slope, fertile soil types that are suitable for agriculture, and high rainfall are identified as most suitable (S₁) locations for livestock production in the Tana Subbasin. 46.9% of the study area is most suitable for livestock production, covering an area of 6953 km². Besides areas with moderate slope gradient, optimal rainfall availability, grassland and moderately fertile soil types are identified to be moderately suitable (S₂) for livestock production. These areas comprise of 23.3% of the study area, covering 3453.12km², which indeed is the largest in the suitability classification results. Out of the total area 2.2 % (320.8km²) are identified to be least suitable (S₃).

The suitability results suggest that 2.7% covering an area of 403.9 km² are currently not suitable (N₁) for livestock production. Areas with steep slope gradient, infertile soil type, low rainfall availability, and land use and lands cover type of shrub and woodland are identified as permanently not suitable (N₂) for livestock production. This part of the study area encompasses 0.01% with a total area of 1.32 km². In the multicriteria decision analysis, some areas such as water body, urban areas, and forests are excluded (as a constraint layer) from the weighted overlay analysis. As a result, 24.9% of the study area comprising 3696 km² is restricted (R) from the suitability modeling. Urban areas are identified as restricted due to stipulations from city administration for development of infrastructure. Similarly, freshwater bodies, especially lakes, are restricted from the land suitability analysis because of their importance for environmental sustainability of the basin. The largest part of the area, 46.9% is considered 'most suitable' for livestock production. In addition, 23% of the total area is identified as moderately suitable. Only 0.01% of the study area is permanently not suitable, which is negligible. Thus, the largest portion of the study area is identified to be optimally suitable for livestock production.

The current livestock population is highest at higher altitudes in peripheral areas of the Tana Subbasin. The density of livestock in most central parts of the study area is sparse. The concentration of denser animal population exists in the highlands. In contrast, the MCDA result (Figure 1.) shows that the central parts of the study area are optimally suitable for livestock production. The peripheral regions are relatively marginal for livestock production, since most of the evaluation criteria taken into account in the multicriteria evaluation for the peripheral regions indicated low suitability for animal production. These areas are land resources with steep slopes, infertile soil characteristics, and less rainfall availability as compared to the central parts of the study area.

As a result, the current spatial distribution of livestock production needs intervention so as to keep the land resources sustainable and maintain productivity. Any intervention plan, however, should take into account other land uses and stakeholders. Trade-offs have to be made where current land uses

possibly conflict with relocation of livestock, and the implication of such interventions should be considered.

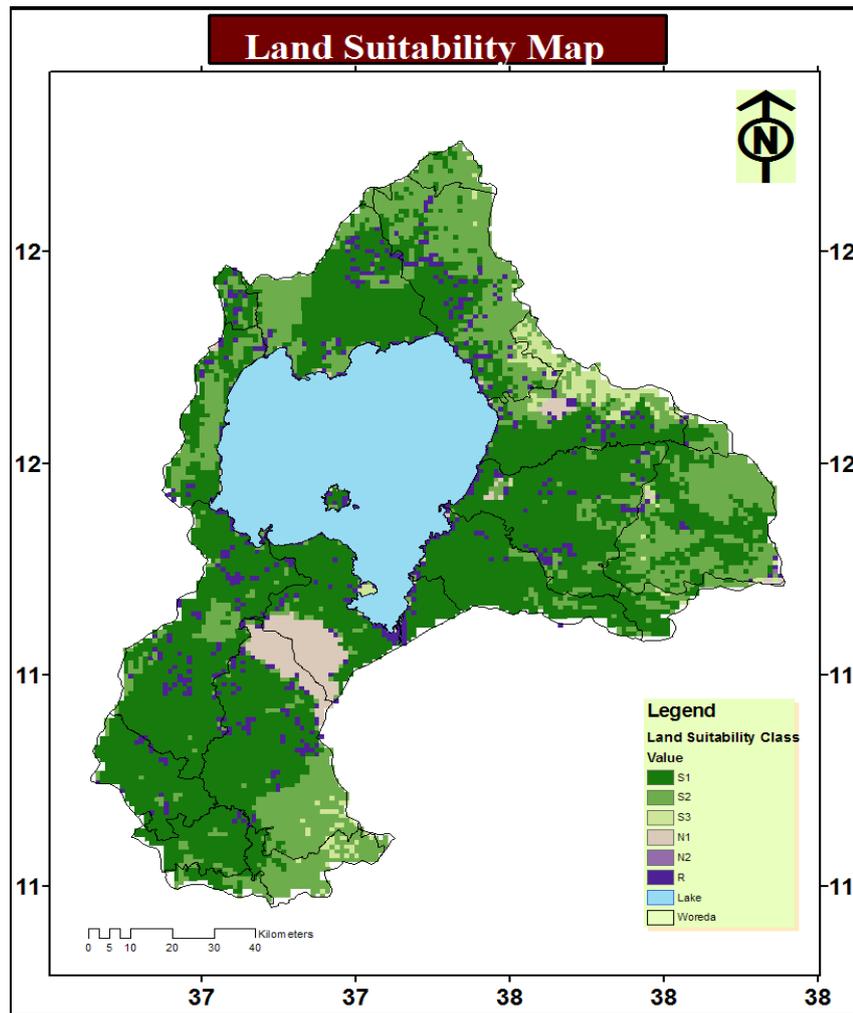


Figure 1. Land suitability map for livestock production.

Generally, based on the evaluation criteria of the weighted overlay analysis, the following are considered as constraints for livestock production: areas with steep slope, infertile soil type, inadequate rainfall, and land use/land cover.

Conclusions

This study attempted to develop a suitability model for livestock production that could support decision-making process in the Tana Subbasin of the Blue Nile River Basin, Ethiopia, using GIS-based multicriteria decision analysis. Findings suggest that larger areas of the basin are located on suitable land for livestock production. Most of the study area is covered by optimal land use/land cover, gentle slope, fertile soil type, and adequately available water for feed growth that make it highly favorable. Nevertheless, the existing spatial distribution of livestock population concentrated on peripheral higher altitudes, whereas livestock density is sparse on most of the suitable land in the basin. The current trend on livestock distribution contributes to degradation of the land resources, and low livestock productivity. Therefore, relocation of livestock production to more suitable areas based on the results of the GIS-based multicriteria decision analysis should be implemented. The practical feasibility of implementation likely depends on a range of factors that go far beyond the scope of a GIS-based multicriteria evaluation as done in this study. A multicriteria evaluation should take the trade-offs into account. Therefore one should be careful about drawing far-reaching management conclusions from the results as presented in this study, which appears to focus on livestock suitability alone. All in all, the Tana Subbasin, according to the findings, is identified as having immense land suitable for

livestock production. Thus the basin has a remarkable potential to reduce poverty and improve food security for the increasing human population in the basin.

Acknowledgment

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Response-inducing sustainability evaluation (RISE) linking agricultural practices and water productivity

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Abstract

Within the Nile LWP project, the sustainability of prevailing agricultural production practices was analyzed in four locations of the Gumera watershed of Lake Tana by using the holistic sustainability assessment tool RISE (Response-Inducing Sustainability Evaluation; <http://rise.shl.bfh.ch>). The study revealed major sustainability deficits in farm economics and social security (lack of safety nets) on the 29 farms assessed. Intensive cultivation and grazing puts biodiversity under pressure. Crop protection could be considerably improved. Soils are threatened by erosion, a problem intensified by heavy mechanical cultivation and lack of erosion control measures. Water pollution by livestock feces is a serious threat and may be reduced by proper manure storage, and preventing livestock from entering open water. Very little water is used apart from crop and fodder production. Although farmers don't perceive water scarcity, agricultural productivity of available water is low, mainly due to low yields and suboptimal water management. Any management practice contributing to increased yields will positively affect water productivity of crops and—mainly through feed production—of livestock. Soil and water conservation practices and conservation agriculture technologies may improve both yields and efficient use of available water. The RISE approach could reveal a number of intervention points where sustainability deficits can be addressed.

Media grab

Increasing crop and fodder yields through appropriate agronomic practices and soil and water conservation measures may help increase agricultural water productivity in Ethiopia.

Introduction

Sustainable production of sufficient food to feed millions of people in developing countries requires more productive use of agricultural water (Molden, 2007). This implies producing more food with less water. In the Nile River Basin, livestock are an integral and major component of agriculture, but are often overlooked in the context of water resources development. Similarly, livestock development has tended to ignore water apart from limited consideration of animal drinking requirements. The CGIAR Challenge Program on Water and Food (CPWF) has undertaken research intended to improve livestock water productivity (LWP), defined here as the ratio of the sum of the benefits of animal products and services produced to the volume of water depleted in producing these benefits. Attempts to assess LWP suggest that increasing water productivity is a key to reducing poverty (Peden et al., 2007), but agricultural practices adopted to enable this are often unsustainable. In contrast, farmers' with wealth levels may be better able to adopt LWP enhancing practices. There is a need to identify bottlenecks that make poor farmers' agricultural practices unsustainable, and to use this knowledge to establish farming enterprises that lift people out of poverty while using water and other resources more effectively and efficiently. This paper reports findings from a case study in the Gumera watershed of the Blue Nile Highlands, which assessed sustainability, of agricultural practices using RISE, a model for response-inducing sustainability evaluation (Häni et al., 2007). These results are discussed in the context of CPWF efforts to increase LWP.

Methods

RISE is an indicator-based tool developed at the Swiss College of Agriculture SHL that allows assessing the sustainability of agricultural production and trends at whole-farm level. The holistic sustainability assessment follows a systems approach and covers ecological, economic, and social dimensions (Häni et al., 2007). The sustainability evaluation is based on data collection at the farm level using a comprehensive questionnaire. Computer-aided calculation of twelve indicators identifies strengths (potentials) and weaknesses with regard to sustainability, and intervention points for

improvements are discussed with the farmer. RISE can also be used to assess groups of farms and provide information about general sustainability deficits under prevailing conditions. In large-scale studies, RISE unfolds one of its particular strengths: while information to answer research questions is collected, simultaneous assessment analysis and feedback to farmers raise awareness and stimulate improvements at the farm level. RISE has so far been successfully applied on more than 250 farms in highly diverse environments.

The sustainability of agricultural production was analyzed with RISE on a sample of 29 farms in Farta and Fogera woredas (districts), Lake Tana area, Ethiopia. The farms comprise between 0.8 and 5.3 ha of agricultural land (plus rented surfaces), and are partly irrigated. They are located at different levels in the Gumera watershed and belong to four peasant associations (Table1).

Table 1. Number and characteristics of farms assessed using RISE (Gumera watershed, Ethiopia).

Peasant association	Location	Farms assessed	Farming systems
Maynet	Upland (2850 m)	8	Mixed and dairy
Worken	Upland (2400 m)	7	1 crop only, mixed, dairy
Wareta	Lowland (1850 m)	6	Mixed and dairy
Kuhar	Lowland (1800 m)	8	Mixed

In addition to the standard RISE questionnaire some further questions on livestock diseases, type of water sources, household consumption (energy and food), distance to water sources and plots, crop diversification, and the farmers' perception of constraints and options were asked. To further deepen understanding of the context, informal interviews were conducted with various other stakeholders.

The RISE approach requires feedback to the farmers to validate analysis results, to increase awareness and understanding about sustainability issues, and to initiate measures to improve the prevailing situation where necessary in collaboration with extension. In contrast to the typical individual feedback, the analysis results were discussed with groups of farmers (one per peasant association). This prevented on one hand personalized discussion of options, and on the other hand group dynamics lead to lively discussions and exchange of experiences.

Results and discussion

Major sustainability deficits in agricultural production

The RISE sustainability analysis assesses 12 indicators that are calculated from more than 60 parameters. Although the RISE sustainability polygon (Figure 1) provides a broad overview by presenting aggregated indicator values, it is important to examine also individual parameter values because certain sustainability problems may be masked by aggregation.

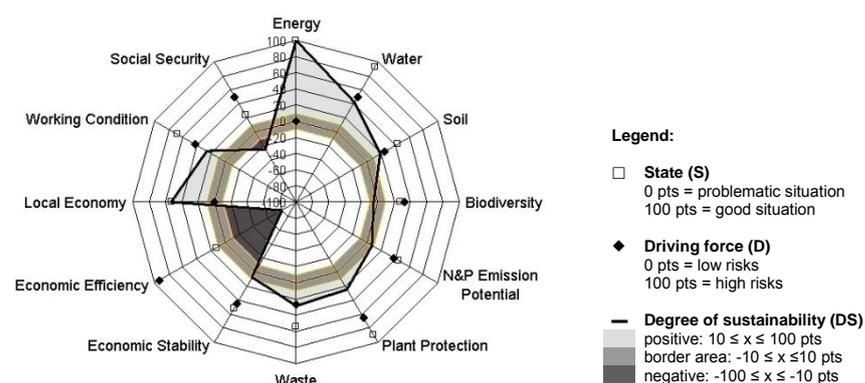


Fig.1:

Average RISE indicator values (aggregated state and driving force parameters and degree of sustainability) of 29 farms evaluated in Farta and Fogera woredas, Lake Tana area, Ethiopia.

The sustainability evaluation with RISE revealed significant deficits in farm economics on the 29 farms assessed. Most farmers mainly produce for self consumption (70% of production). Operating income from farming (including household consumption at market prices and changes in stocks) is between US\$30 and 4345 (avg. US\$1110) a year; considering interest on debts, expenses for personnel, and fees for rented land, six out of the 29 farms analyzed produce a net loss (avg. benefit is US\$730). Low and very volatile prices for agricultural products are certainly a reason for the lack of market orientation of many farmers. Since practically all capital generated remains in the region, the assessed

farms have a positive effect on the local economy—a major strength identified through the RISE assessments, although the low salaries paid don't render agriculture a very attractive métier.

Weaknesses with regard to social security in the RISE analysis are mainly related to a lack of safety nets (insurances or informal risk reduction schemes in cases of retirement, unemployment, health, accident or disability, and protection from dismissal in cases of sickness, accident, or maternity), and low potentially payable salaries (due to the low economic performance). Working conditions are satisfactory except for the lack of opportunities to gain further qualifications and the lack of vacations. Aggregated ecological indicator values calculated by RISE are not alarming but poor with regard to biodiversity and N and P emission potential. Analyzing individual parameters, however, reveals that there is ample room for improvements in various domains. A high proportion of intensively used land comprising only few natural elements that could enrich biodiversity (such as hedges) put biodiversity under pressure. Nutrient surplus and inadequate manure storage and application methods present serious pollution risks to the environment. Crop protection could be considerably improved by choosing suitable varieties and crop rotations, and by measures and practices fostering biodiversity. Soils are threatened by erosion, a problem aggravated by intensive mechanical cultivation and lacking erosion control measures (except for contour planting which is common practice). The farms use practically no external energy for agricultural production; however, 880-1260 kg dung and 2.7-3.5 t of wood are used in the farmers' households, a significant export of nutrients from the farming system.

Water availability, management, and protection

Access to water is not perceived as a problem by the interviewed farmers, although they often have to walk farther to get good quality water during the dry season. In the highlands, farmers mainly depend on springs (79%) and river water (29%), in lowlands on springs (34%), rivers (33%), hand pumps and wells (13%), shallow groundwater (13%), and tap water (7%). The farmers interviewed did not notice significant changes in water availability or quality during recent years. River water quality decreases from upstream to downstream, however. Very little water is used in livestock husbandry (apart from water for fodder production) or agricultural activities other than crop production.

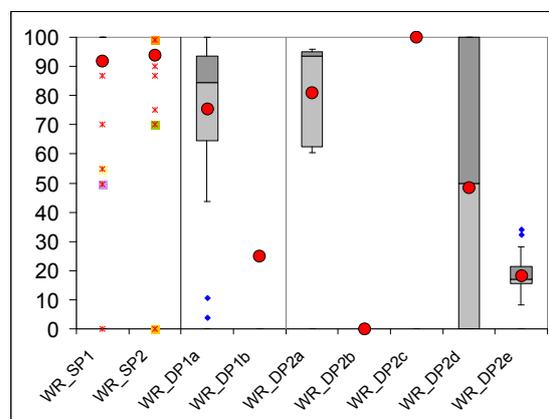


Fig.2:

RISE water parameter values of 29 farms evaluated in Farta and Fogera woredas, Lake Tana area, Ethiopia.

Parameters for calculating the water indicator:

- WR_SP1: Water availability and sources
- WR_SP2: Water quality and trends
- WR_DP1: Water use and productivity:
 - WR_DP1a: Water use and productivity in crop production
 - WR_DP1b: Water use in livestock husbandry
- WR_DP2: Risk factors for water quality
 - WR_DP2a: Water pollution by manure
 - WR_DP2b: Water pollution by silage leachate
 - WR_DP2c: Waste water production and treatment/disposal
 - WR_DP2d: Water protection by soil conservation/cultivation
 - WR_DP2e: Soil permeability (nutrients/pollutants)

Boxplot: circles denote average values

Water productivity in crop production (including green water) is low compared to other production systems (e.g. 0.03 kg wheat/m³ or 0.56 kg potato/m³). Water productivity is positively correlated with the use of irrigation that is mainly applied in potato, rice, and vegetable production. In lowlands water is generally used more efficiently than in highlands, although precipitation in highlands is lower; it is likely that significant runoff on steep slopes without soil and water conservation (SWC) measures is one reason for low water productivity in the highlands. More important for low water productivity, however, are the very low yields realized (avg. 450 kg wheat/ha or 1700 kg potato/ha) which are significantly smaller in highlands than in lowlands. It has further been observed that well-off farmers (with high incomes and greater agricultural expenditures) use water more efficiently than poorer farmers.

Water pollution by livestock feces, especially by livestock entering water bodies, is a serious issue in the project area, particularly in view of upstream-downstream relations and (human and animal) health. But also inadequate manure storage contributes to water pollution risks. Wastewater disposal is far from sustainable but does not pose a serious problem due to low wastewater quantities

produced. Implementation of measures to protect water quality by soil conservation or cultivation practices varies considerably; thus the observed problems of soil erosion also affect water quality.

Options to improve the situation

Improving yields by making better use of available resources such as water, manure, and compost could certainly improve the economic situation to a certain extent. As well, labor-related issues (e.g. by increasing low labor productivity due to scattered plots through land consolidation, or making better use of church-imposed holidays) leave ample room for improvement. Production diversification and market orientation may be fostered through cooperatives (as demonstrated by the Wareta Milk Farmer or the Kuhar Multipurpose Farmer Cooperatives) or through farmer-industry partnerships.

To improve social security through some sort of safety nets, awareness building regarding informal arrangements seems important as long as no respective policy action for formal insurance systems takes place. Furthermore, farmers should be motivated to capitalize on any opportunity for additional education and training, particularly since (due to church rules) ample time for such activities exists.

Farmers are aware of certain benefits of high biodiversity. Pressure on productive land is high (not least due to the low yields realized), however, and there is little room for ecological compensation areas and biodiversity-enhancing elements, except if they are combined with productive and protective benefits such as contour-line hedges for (fuel) wood production and erosion control. Diversification of production may not only increase biodiversity, but also allow for integrated crop and pest management by cultivating suited species and varieties, and implementing proper crop rotations. Access to appropriate seed and knowledge about market opportunities is needed to diversify production. Training may be required regarding cultivation practices for certain crops, and about the principles and practice of integrated crop management (e.g. the use of damage thresholds).

Because crop yields are very low, high stocking rates and occasional purchase of fertilizer contribute to nutrient surplus on almost all farms analyzed, although large amounts are exported from the farming system in the form of dung and wood for fuel. More effective utilization of organic fertilizers could ease this problem and at the same time contribute to better yields (with positive effects on the economic situation). Percolation and runoff from manure storage places could be reduced (by shelters and runoff collectors), which would contribute to more efficient nutrient management.

Soil erosion is a serious problem that not only threatens soil productivity but also water quality. The implementation of SWC and erosion control measures (in addition to contour planting) could protect soils from degradation, and simultaneously contribute to increased crop yields, by reducing runoff and increasing water productivity. Conservation agriculture practices (such as conservation tillage, mulching, or cover cropping) could protect soils and increase water use efficiency.

Low water productivity in crops and pastures is related to low yields and suboptimal water management. Any management practice that contributes to increased yields has positive effects on water productivity. Improved nutrient management (manure, composting), proper crop rotations, adapted varieties with reasonable yield potential, crop protection, and SWC measures may increase crop yields and thus water productivity. Such options address all three strategies for improving livestock water productivity outlined by Peden et al. (2007): Improving yields of fodder crops (including pastures) increases water productivity in feed sourcing, SWC measures conserve and make better use of water, and producing an adequate selection of feed crops enhances livestock productivity. Although many of these options also exert positive effects on other sustainability aspects (e.g. on soil conservation and economic efficiency), trade-offs are to be expected: Higher and expensive fertilizer inputs, for example, can increase pest and disease susceptibility of crops, contribute to further nutrient surplus, threaten water quality, and negatively affect biodiversity. Land degradation and low productivity are particularly obvious and widespread on common (grazing) lands. Changes in common land management (such as payment of access/use fees or a soft privatization) may be required to improve (water) productivity on common lands and better protect them against degradation.

Protecting water from pollution is important because not only livestock but also the population still depends to a great extent on surface water resources. Proper manure storage (possibly combined with wastewater treatment) will reduce pressure on water quality. To prevent livestock from entering open water courses it might be useful to divert water to watering places, possibly with overflows feeding

irrigation systems ('fertigation'). Organization for common management may be required to improve protection of water resources.

Conclusions and recommendations

Based on the identification of critical sustainability issues through RISE assessments in the smallholder farming systems of Gumera watershed, various options to improve the prevailing situation could be identified and discussed with the concerned farmers. Options to improve water productivity are mainly related to increasing yields in crop and feed production (including pasture management), since water use for other purposes in livestock husbandry is low. Complemented with SWC technologies to make better use of precipitation, such options address all three strategies to improve livestock water productivity: feed sourcing, water conservation, and livestock productivity improvement. It is also important to protect water from pollution, in particular from animal feces, to safeguard human and animal health and welfare.

Several options to improve the RISE tool have been identified. Implications related to the dependency of farmers on common property resources have to be integrated better into the tool (e.g. with regard to nutrient flows or resource degradation). Seasonality should be considered to a greater extent for more precise explanations and conclusions on water balance and water productivity. Furthermore, the integration of on-farm energy production and exports should be improved.

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An analysis of livestock production in Capricorn, Mopani and Sekhukhune districts of South Africa

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Abstract

Livestock still play a major role in most rural parts of Limpopo Province, South Africa. Some households use livestock for different purposes: draught, transportation, ceremonial, and bride wealth. In the late 1960s and 1970s most of the households in the province were livestock owners. This situation is changing as a result of migration of laborers to urban areas, poor rainfall distribution, drought, and poor access to land. During the baseline survey it was found that the majority of households in Sekhukhune district own goats (29%) compared to the other households in Mopani (15%) and Capricorn (14%) districts. Due to high climate variability in Limpopo Province, Sekhukhune district is suitable for goat production because of the poor rainfall distribution. Although Sekhukhune had a high proportion of households owning goats, they are really not making any significant contribution to the Provincial Growth Product (PGP) in the province. Goat meat is not sold in any formal market or supermarkets. Challenges facing the commercialization of livestock in rural provinces such as Limpopo are poor management of small stock and organization of farmers.

Media grab

Limpopo Province is well known for producing high-quality agricultural products. The province is rich in minerals and cultural diversity, however, two fundamental socioeconomic problems face the people: unemployment and poverty.

Introduction

Limpopo Province is situated in the northeast of South Africa and covers an area of 123,910 km², or 10, 2% of the area of South Africa. Limpopo Province is regarded as one of the poorest provinces in South Africa, with large numbers in rural areas (Oni et al., 2003; Mnisi et al., 2004). Limpopo is made up of five districts, of which Sekhukhune is the poorest. The province has a low Human Development Index, with high unemployment (48.8%), poverty (77%), and illiteracy (Statistics of South Africa, 2001 and 2003; HSRC, 2004). There is, however, general recognition amongst South Africans of the need to address problems arising from unemployment, poverty, income inequality, and disparities in access to services amongst the population (Mnisi et al., 2004, www.limpopo.gov.za/economy). The 2001 census statistics estimate that the size of the population in Limpopo Province had reached 5.2 million, 11.8% of the population of the country (Statistics South Africa, 2001). There are several reasons for keeping livestock in Capricorn, Mopani, and Sekhukhune districts, and it varies from household to household (Mnisi et al., 2004). According to Gootjes et al., (1992), some of the reasons for keeping livestock include a source of additional income and food provision. Livestock production may sometimes complement arable farming through provision of draught power and manure through enhancing the sustainability of the farming system (Mnisi et al., 2004; Raidimi et al., 2006). In some of the districts certain households are keeping livestock as part of their investment, token of status, and as security. In some instances livestock production promotes production and redistribution of wealth and may subsequently have considerable impact on rural development (Gootjes et al., 1992; and Raidimi et al., 2006).

Methods

The survey was targeted at smallholder households resident in the Limpopo River Basin. A three-stage sampling frame was used for selecting districts, villages and households to be interviewed. Households not classified as smallholder farmers were not targeted in the survey, and examples of such households include teachers, households at mini urban centers in the communal areas, as well as other civil servants.

The districts in which the survey was conducted were purposely selected. Before the interviews started with households in Capricorn, Mopani, and Sekhukhune districts, a village meeting was held with all community representatives present: chiefs, indunas, local councilors, and NGOs. Twenty enumerators (both student interns and extension officers) were trained in Polokwane and the questionnaires were tested in Turfloop village outside Polokwane town before implementation. In total 1000 households were interviewed in the districts.

The main objectives were to obtain information on:

- Livestock production in all three districts in the province.
- Ownership by gender of household head.
- The need for communal households to commercialize livestock (e.g. goats).

Results and discussion

Cattle ownership

Most households (more than 75%) in the districts did not own cattle. Sekhukhune had the highest proportion of households (24%) owning cattle, Capricorn had 22%, and Mopani 18%. Most of the households owning cattle owned a herd of less than 10. Some of the households in Sekhukhune mentioned that cattle are good livestock species because they are saleable and one gets more profit per animal. The biggest challenge in Sekhukhune, however, is the grazing land, which is decreasing due to increased pressure on the land.

Table 1. Cattle ownership by district, 2004-05 season.

	District	Proportion of households owning (%)			
		none	1 to 5	6 to 10	11 and above
South Africa	Capricorn (n=323)	78.3	10.8	6.8	4.0
	Mopani (n=340)	81.8	8.8	4.1	5.3
	Sekhukhune (n=342)	76.3	14.6	7.3	1.8

Households with male heads owned more cattle than households headed by a female in the three districts.

Table 2. Cattle ownership by district and gender of household heads for South African households, 2004-05 season.

District	Gender of head	Proportion of households owning (%)			
		none	1 to 5	6 to 10	11 and above
Capricorn	Male (n=143)	69.9	16.8	7.7	5.6
	Female (n=180)	85.0	6.1	6.1	2.8
Mopani	Male (n=166)	75.9	12.0	4.8	7.2
	Female (n=174)	87.4	5.7	3.4	3.4
Sekhukhune	Male (n=156)	71.8	16.7	8.3	3.2
	Female (n=184)	79.9	13.0	6.5	0.5

Women's responsibilities in most households were categorized as child care, cleaning, and cooking. Very few women have been farming cattle, and they have little control over it even though they are responsible for caring of livestock. Most female-headed households owned less than five cattle, with a higher proportion of households with a male head owned larger herds.

Goat ownership

Sekhukhune had the highest proportion (29%) of households owning goats, compared to Capricorn (15%) and Mopani (14%). In Capricorn and Mopani, fewer households had goats because goat meat is less preferred because is smelly. This is causing a decrease in the numbers of goats in both districts.

Table 3. Goat ownership by district 2005-06.

	District	Proportion of households owning (%)			
		none	1 to 5	6 to 10	11 and above
South Africa	Capricorn (n=323)	85.4	6.5	4.6	3.4
	Mopani (n=340)	85.6	7.9	4.4	2.1
	Sekhukhune (n=342)	71.1	14.6	9.6	4.7

Sekhukhune has a semiarid climate and vegetation that is dominated by thorny acacia bushes (Mnisi et al., 2004). This environment is most suitable for the production of goats because they are 60% browsers and tolerate dry conditions (Peacock, 1996; Mnisi et al., 2004). According to Mnisi et al. (2004), Sekhukhune has the second highest number of goats in Limpopo Province.

As was the case with cattle ownership, goat ownership was analyzed by gender of the household head. The analysis revealed that a higher proportion of male-headed households owned goats compared to the female-headed households in South Africa. The male-headed households also owned larger herds. According to Mnisi et al. (2004), goat meat and milk can produce a wide range of products, although most rural households in Capricorn and Mopani are unaware of them. Some households use goat skins as mats and also for ceremonial purposes. Goats are presently marketed live, and no slaughtering is done at official abattoirs (Mnisi et al., 2004). In Sekhukhune, for example, goat milk is getting publicity with the high rates of HIV/AIDS infection, as goat milk is believed to contain special antibodies for infected children (Mnisi et al., 2004).

Table 4. Goat ownership by district and gender of household head in South Africa.

District	Gender of head	Proportion of households owning (%)			
		none	1 to 5	6 to 10	11 and above
Capricorn	Male (n=143)	80.4	9.1	5.6	4.9
	Female (n=180)	89.4	4.4	3.9	2.2
Mopani	Male (n=166)	81.3	10.2	7.2	1.2
	Female (n=174)	89.7	5.7	1.7	2.9
Sekhukhune	Male (n=156)	66.0	16.0	10.3	7.7
	Female (n=184)	75.5	13.0	9.2	2.2

Projections suggest an increase in goat numbers for Sekhukhune, Capricorn, and Waterberg, but a reduction in the remaining districts of Bojale, Vhembe, and Mopani (Oni et al., 2003; Mnisi et al., 2004). Since 2000, Limpopo Province has been experiencing droughts in Sekhukhune, Capricorn, and Mopani. During droughts, goats suffered fewer losses than other species of livestock because of their feeding behavior (Mnisi et al., 2004). Sekhukhune had higher proportions of household-owned goats. Sekhukhune has the climate and vegetation that is suitable for goats, and goats are kept in communal households (Mnisi et al., 2004). There are several reasons why goats in Sekhukhune and in other districts are not more widely reared: poor breeding programs, poor management practices, unfavorable marketing potential for households to sell through formal markets (Mnisi et al., 2004). Results from the baseline surveys show that goats are really not making a significant contribution to income of households in Capricorn and Mopani districts because they are not being produced for the formal market.

Chicken ownership

Mopani had the highest proportion (57%) of households owning chickens compared to Sekhukhune and Capricorn. The Limpopo Provincial Department of Agriculture is distributing chickens to vulnerable communities under the poverty alleviation and enhancement of rural livelihood strategies. Such initiatives have significantly increased the proportion of households owning chickens, despite the threats from Newcastle Disease. Some of the reasons mentioned by householders in Mopani when asked why they had higher proportions of chickens included: easy to sell, easy to manage, easy to market, and there are good market opportunities.

Table 5. Chicken ownership by district, 2005-06 season.

	District	Proportion of households owning (%)			
		none	1 to 5	6 to 10	11 and above
South Africa	Capricorn	70.9	15.2	9.9	4.0
	Mopani	42.6	16.8	20.3	20.3
	Sekhukhune	63.7	18.4	12.3	5.6

Chickens are commonly owned by females with the right to dispose of them. In Capricorn, Mopani, and Sekhukhune, however, a higher proportion of male-headed households owned chickens compared to the female-headed households. As already noted on goat and cattle ownership, male-headed households owned larger flocks of chickens compared to households headed by females. In the other districts a higher proportion of male-headed households owned chickens compared households headed by females.

Ownership of other livestock

Other livestock including donkeys, sheep, and pigs, are not commonly owned in Capricorn, Mopani, and Sekhukhune. In all three districts, the main types of livestock kept include cattle, goats, sheep, donkeys, and pigs. It was noted during the surveys that most households in all three districts have lower number of pigs compared to other livestock such as cattle and goats. The reason for having lower numbers is because of the higher costs involved in feeding pigs. In Mopani and Sekhukhune, pigs are not allowed to roam around in the villages due to high chance of spreading diseases (Raidimi et al., 2006). According to Mnisi et al. (2004), these livestock are kept in the kraals in the backyards. In all three districts other livestock such as sheep and pigs are traded informally. The buyers in the village buy directly from the farming households, and as a result no commissions are charged. Generally less than 4% of households in each of the districts owned donkeys. In districts such as Mopani and Sekhukhune, donkeys are used for transport and draught. Two percent or less of households owned pigs. Sekhukhune had the highest proportion (9.1%) of households that owned sheep compared to the other two districts. Sheep in Sekhukhune are exotic, but their numbers are increasing compared to other districts.

Table 6. Ownership of other livestock by district, 2005-06 season.

	District	Proportion of households owning (%)		
		Donkeys	Pigs	Sheep
South Africa	Capricorn	2.5	1.9	4.3
	Mopani	3.5	1.5	0.0
	Sekhukhune	2.6	2.0	9.1

Sources of information on livestock technologies

Access to information on livestock issues vary between households. According to Dapaah et al. (2001) and Minsi et al. (2004), most livestock farmers exchange information amongst themselves, and allege that some of the information disseminated to them by extension officers is not sufficient. The agricultural extension officers and other farmers were identified as the most common sources of information on livestock technologies. A significant proportion of households in Capricorn (54.5%) and Sekhukhune (56.4%) did not know where to get information on livestock technologies, which indicates a huge gap in information provision. The research institutions and nongovernmental organizations were not regarded as a source of information in all three districts. In South Africa these were not identified as a source of information. This poses serious challenges to other institutions such as the Agricultural Research Council and other livestock companies in the province. The dissemination of information to most households seems to be limiting factors in the three districts. Access to information on livestock prices is critical if smallholder farmers are to fully participate in livestock markets. A significant proportion of households in the three districts identified other farmers as a common source of information on livestock prices. Radio and the print media were not identified as sources of information, although Mopani had a relatively higher proportion (12.1%) of households citing it as an important source of information. The agricultural extension officers as noted earlier were not cited by many households as a source of information on livestock prices.

Conclusions and recommendations

In Sekhukhune, for example, biophysical factors such as rainfall and soil type are considered major limiting factors to the development of agricultural production. Agricultural production in Limpopo Province was at risk due to drought and other natural disasters (Oni et al., 2003). It is not surprising to see that districts such as Sekhukhune are good for goat production. Goats can survive harsh conditions and they are easy to keep. In Capricorn and Mopani, the preferred livestock are cattle and there are also reasons why households in those districts prefer them: they fetch a good price, and they are easily saleable. Cattle adapt and cope well in Capricorn and Mopani. Most households in all three districts have lower numbers of pigs compared to other livestock, because of the higher costs in feeding pigs.

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Integration of germplasm and management for sustainable water productivity improvement in rainfed cropping

Quantifying water productivity in rainfed cropping systems in Limpopo Province, South Africa

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Abstract

This paper reports results of on-farm experimentation to quantify water productivity of maize, groundnut, and cowpea crops in the 2007-08 cropping season in Limpopo Province, South Africa. The observed crop yield and soil water and nutrient data are used to evaluate the APSIM model's performance in simulating WP and soil water balance for maize and legume crops. There was very close agreement between observed and predicted biomass, grain yield, and changes in soil water content. The model provided outputs to fill measurement gaps in water balance components of the field experimentation, thereby allowing more detailed and appropriate calculations for comparing the WP of the different crops.

Media grab

The APSIM model performed remarkably well in predicting the crop yields and water balance of major crops in Limpopo Province, making it a key analytical tool for evaluating technologies for increasing yield and crop water productivity.

Introduction

Maize production dominates the smallholder farming system in Limpopo Province of South Africa, although crop yields in these systems translate into very poor water productivity (WP)—in the order of 1-2 kg grain per mm rainfall per ha. Crop simulation analysis, supported with results from on-farm trials, suggests that WP could be increased by 50-100% if smallholder maize farmers used small doses of topdress N fertilizer and improved agronomy (Dimes and Carberry, 2008). Because the price of fertilizer has increased by more than 100% in recent times, a stronger case for expanding legume production as a means of increasing N inputs into these cropping systems is emerging. A comparison of WP for different crops and fertility management will help guide public and private sector investment aimed at improving agricultural output of smallholder farmers in the province.

Our results of on-farm experimentation to quantify WP of maize, groundnut, and cowpea in the 2007-08 cropping season are given. The observed crop yield and soil water and nutrient data were used to evaluate the performance of the Agricultural Production Systems (APSIM) model in simulating WP, yield, and soil water balance for maize and legume crops in Limpopo province.

Methods

FIELD EXPERIMENTATION

Field experiments were conducted at Tafelkop, a smallholder farming village located on the Nebo Tableland in Sekukhune District of Limpopo Province. The soils are shallow (up to 1.0 m rooting depth) loamy sands to sandy loams. The rainfall season is unimodal (October/November to March/April) with an average annual total of 500 mm.

The Grain Crops Institute and the smallholder farmer association at Tafelkop established varietal trials of groundnut and bambara nut in the 2007-08 cropping season. Separate trials were established for each legume species, with six cultivars and three replicates laid out in a RCBD design. Demonstration plots of maize (PAN6479) and cowpea (Betch White) were established with the farmer association in adjoining plots to the legume varietal trials. Replicated treatment plots of Nyanda groundnut and SB7-1 Bambara were sampled (9.1 m²) at crop maturity for stover and grain yield. Bulk samples were also taken from the maize (stover 72 m², grain 109 m²) and cowpea (36 m²) demonstration plots to

determine stover and grain yield. Groundnut and maize were sown on November 14, while bambara and cowpea were sown on December 5. Maize received 15 kg N/ha as starter fertilizer at planting, and a topdress application of 14 kg N/ha on January 14, 2008. Maize was harvested on April 29, groundnut on March 26, and cowpea on March 18.

ICRISAT monitored the trial plots for changes in soil water content during crop growth using gravimetric methods. Soil sampling commenced on December 12, 2007, in the groundnut and bambara trials. Subsequent samplings took place on February 22 (all four crop areas), March 29 (groundnut, maize, and cowpea), and May 5 (Bambara), 2008. Sampling depth intervals were 0-0.1m, 0.1-0.3m, 0.3-0.6m, and 0.6-0.9m. Three soil cores were taken at each sampling, either across treatment replicates or within the final harvest area of the maize and groundnut. Gravimetric water contents were converted to volumetric using a bulk density of 1.5 g/cm³ in all soil layers. Soils collected on December 12 were analyzed for pH and percentOC. The farm owner of the trial field recorded daily rainfall at the site.

MODEL ANALYSIS

Plant biomass, grain yield, and soil water balance of the maize, groundnut, and cowpea crops were simulated using the APSIM cropping systems model (Keating et al., 2002; Version 6.0), and model outputs were compared to observed data. Model input parameters for the maize (Pan6479) and groundnut (Nyanda) cultivars had been previously estimated (Dimes and Carberry, 2008; Ncube et al., 2008). Growth and yield of Betch White cowpea were adequately simulated using the short duration 'Banjo' cultivar description in APSIM. (As yet, there is no Bambara module in APSIM.) Dates of crop sowing and N fertilizer applications in the model were specified according to experimentation (see above). Plant populations were specified in the model according to measured populations at field harvest: maize-2.3 plants/m², groundnut-11.7 plants/m², cowpea-8.8 plants/m².

Soil parameters for simulation of the soil water and N balances in the nominated rooting depth of the soil (0.9 m) were specified as shown in Table 1. The crop lower limit of plant extractable water (LL) and the soil drained upper limit (DUL) were derived using the measured soil water contents as a guide. The plant available water capacity (PAWC) of the soil layers to the nominated rooting depth is 90 mm. The Runoff Curve Number and soil evaporation coefficients were chosen based on previous simulation studies in these environments (Ncube et al., 2008)

Table 1. APSIM input parameters used in simulation of Tafelkop experiments.

Layer Number	1	2	3	4
SoilWat parameters				
Layer thickness (mm)	100	200	300	300
Bulk density (g/cm ³)	1.50	1.50	1.40	1.40
SAT	0.250	0.270	0.300	0.320
DUL	0.140	0.155	0.176	0.185
LL15	0.052	0.064	0.070	0.081
Airdry	0.045	0.052	0.070	0.081
Swcon	0.5	0.5	0.4	0.4
CN2_bare	85			
U	3			
Cona	4			
Soil N parameters				
Organic C (%)	0.51	0.46	0.32	0.22
Finert	0.40	0.50	0.80	0.90
Fbiom	0.04	0.020	0.01	0.01
Nitrate-N (mg/kg)	3.79	1.52	0.76	0.38
Ammonium-N (mg/kg)	0.98	0.49	0.25	0.25
Soil C:N	12			
Crop parameters				
LL (maize, groundnut, and cowpea)	0.052	0.064	0.070	0.081
Kl	0.08	0.08	0.08	0.08
Xf	1.0	1.0	1.0	1.0

Soil water and N conditions at sowing of crops were not measured. The start date of simulations was therefore chosen as October 1 with the initial soil water content of layers specified at LL and starting mineral N in the profile set to 15 g NO₃--N/ha and 5 kg NH₄+-N/ha.

Only daily rainfall data were collected at the site. Daily radiation data from a nearby (within 30 km) climate station (Marble Hall, 29° 37' E, 25° 03' S, altitude 878 m), and daily temperature data from a distant site (150km) of similar altitude to Tafelkop (Polokwane, altitude 1153m), were used as climate inputs to the model, in conjunction with the measured rainfall. The rainfall record collected by the farmer, however, indicated incidences of periodic totals as daily amounts. These were reallocated or adjusted based on the rainfall distribution recorded at Marble Hall and rainfall amounts recorded at a site close by.

1.3 Results and discussion

There was very close agreement between observed and predicted total biomass and grain yield (RMSD_{grain} = 257 kg/ha, RMSD_{t_{bm}} = 436 kg/ha) of the three experimental crops grown at Tafelkop (Figure 1). There was closer agreement for predicted maize yields compared to the two legume crops, for which grain and biomass yields were slightly under-predicted. In general, however, the observed differences in plant growth and yield due to species and crop duration and the interaction of these effects and planting dates with rainfall distributions (wet December and January, dry February) were very well captured by the APSIM modelling platform used in this analysis.

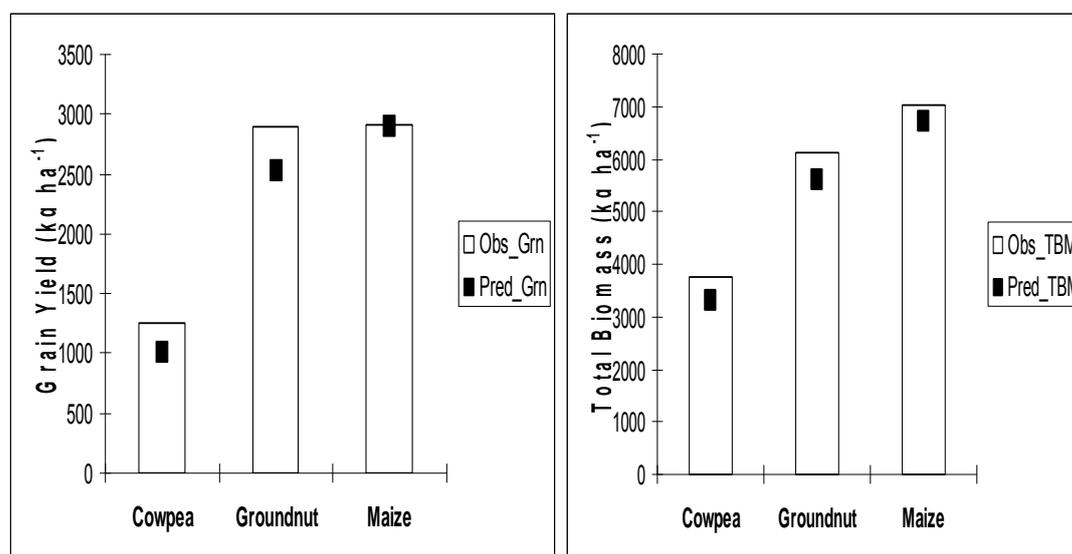


Figure 1. Observed and predicted grain yield and total biomass of cowpea, groundnut, and maize crops grown at Tafelkop in the 2007-08 cropping season.

The observed and predicted soil water contents at sampling dates in maize, groundnut, and cowpea plots are shown in Figure 2. There is close agreement between the predicted and observed soil water contents (rmsd_{t_{sw}} = 7 mm), and their distributions in the sampled rooting layers for all three crops on December 12. Similarly, the crop water use by maize and cowpea up to February 22 is well predicted by the model. This was not the case for groundnut, for which simulated soil water use by the crop below 0.3 m was noticeably overpredicted on this date.

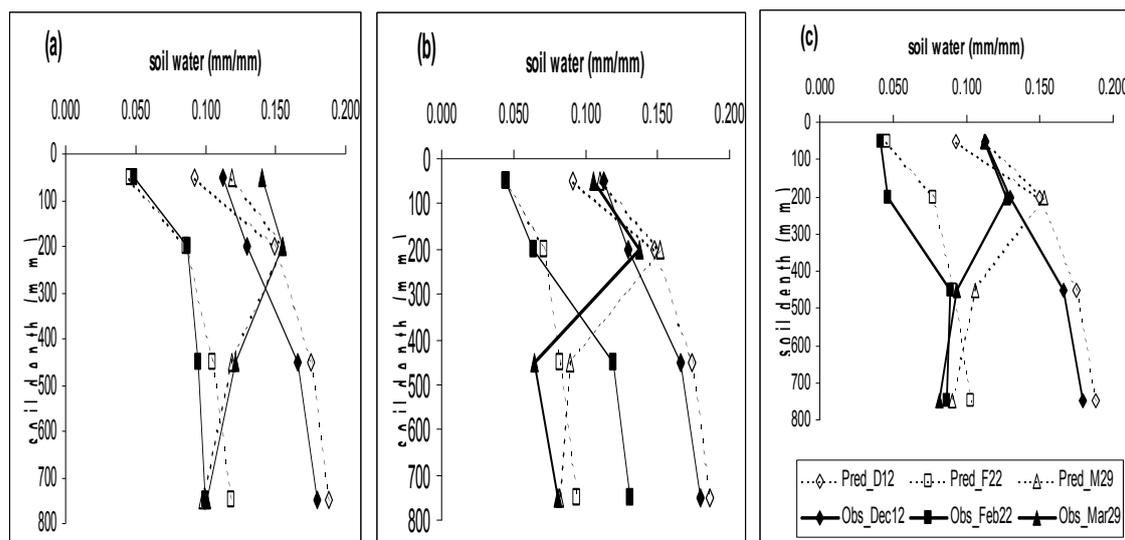


Figure 2. Observed and predicted water contents of soil layers on December 12, 2007, February 22, and March 29, 2008, under (a) maize, (b) groundnut, and (c) cowpea.

An important test of the model's performance in simulating the water balance was how well the model predicted the water content and distribution of the soil layers as measured on March 29, following the late rainfall in March. As seen in Figure 2, the observed refilling and distribution of soil water on March 29 under each crop is well predicted by the model. Overall, the performance of APSIM in predicting changes in soil water under the maize crop was most reliable ($rmsd_{tsw} = 7$ mm), followed by cowpea ($rmsd_{tsw} = 10$ mm), and groundnut ($rmsd_{tsw} = 14$ mm).

The simulated in-crop water balance (i.e. sowing to crop maturity) of the maize and cowpea grown at Tafelkop in the 2007-08 season shows runoff and soil evaporation higher than crop transpiration (Table 2). For groundnut, simulated crop transpiration comprises the largest portion of the water balance, but there is some uncertainty with this estimate given the overprediction of crop water uptake implicit in the predicted soil water contents on February 22, as seen in Figure 2b. Using in-crop rainfall in Table 2 as the reference water for assessing crop productivity in conjunction with measured grain yields (Figure 1), the calculated WP (kg grain/mm of rainfall/ha) of the three crops is maize = 6.0 kg/mm/ha; groundnut = 6.0 kg/mm/ha, and cowpea = 3.8 kg/mm/ha. Including crop water use of stored water at the time of sowing (as estimated by the model), (Δ_{sw} in Table 2), reduces the WP estimates: maize = 5.6, groundnut = 5.4, and cowpea = 3 kg/mm.ha. A notable aspect of this analysis is the very low WP of the short-duration cowpea relative to the longer duration maize and groundnut. For this above-average rainfall season, and with a distribution favoring the longer duration crops, this result can be considered to be highly season-specific.

Table 2. Simulated components of the soil water balance of maize, groundnut, and cowpea crops grown at Tafelkop in 2007-08.

Crop	In-crop rainfall (mm)	Ep (mm)	Runoff (mm)	Drain (mm)	Es (mm)	Delta_sw (mm)	Water balance (mm)
Maize	485	115	170	78	158	-35	520
Gnut	485	209	119	65	145	-53	538
Cowpea	311	101	123	86	112	-86	417
		% of water use as:					
		Ep	Runoff	Drain	Es		
Maize		22	33	15	30		
Gnut		39	22	12	27		
Cowpea		24	29	21	27		

In-crop rainfall – sowing to crop maturity.

Ep – crop transpiration; Es – soil evaporation; Drain – drainage below 0.9m

Water balance = rainfall - Δ_{sw}

Δ_{sw} = Soil water storage at crop maturity - soil water stored at sowing.

Conclusions and recommendations

APSIM's good performance in simulating the observed crop growth and yield of the three crops and the associated observed changes in soil water contents in the rooting zones is encouraging with regard to its application to quantify WP of crops in Limpopo Province.

Firstly, reliable prediction of total biomass is a prerequisite to simulation of the soil water balance. This is because simulated crop water uptake and canopy cover estimates by the crop have important feedback mechanisms on simulation of soil water balance processes such as partitioning of rainfall into runoff and infiltration, and soil evaporation. Secondly, reliable partitioning of biomass to grain yield across the species is essential in determining estimates of WP that can be used with confidence in comparing the different cropping options, from a biological yield perspective or, more particularly, on an economic basis (e.g. to take account of the high value of legume grain relative to cereal grain). Thirdly, although the only component of the soil water balance measured in the experimentation was changes in soil water storage, the good agreements achieved in predicting the different soil water distribution profiles observed over the course of the crops provide indirect evidence for having confidence in the simulated outputs for the other components of the water balance: crop water use, runoff, drainage, and soil evaporation. As a consequence, the model offers a cost-effective tool to provide reliable estimates of the water balance in these rainfed cropping systems.

Acknowledgments

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Simulated yields and water productivity of rainfed grain crops in the Volta Basin: fertilizer impact

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ABSTRACT

To explain why actual productivity and water productivity is so low in the Volta Basin, we examined variation in simulated yield and water productivity of three crops, maize, sorghum, and millet, along a transect of approximately 900 km, running from Brofoyedru (Ghana) to Bilantal (Burkina Faso). We conclude that:

Maize and other crops fail on sandy soils even in the wettest areas without fertilizer. Fertilizer produces good responses in maize yield and water productivity, but the response is increasingly risky as we move north along the transect. Because of the low planting density used, sorghum is less drought risky over the middle sections of the transect, but it responds weakly to fertilizer.

Millet seems to provide value through large production of above-ground biomass. This production seems responsive to fertilizer and resistant to drought throughout all but the most northerly part of the transect.

MEDIA GRAB

In the Volta Basin, yields of maize and other grain crops sown without fertilizer often fail on sandy soils even in wetter areas. Fertilizer dramatically reduces the risk of crop failure and could enhance food security.

INTRODUCTION

Most of sub-Saharan Africa has poor soils, with rainfall that is variable and unreliable, both within and between years. Coupled with low levels of agronomic technology, the result is low yields in rainfed agriculture, often insufficient to provide even subsistence for the rural poor. The population increases forecasted will exacerbate the problem (Millennium Ecosystem Assessment, 2005).

Soil and conservation techniques can help improve both yields and water productivity and decrease vulnerability to erratic rainfall. Field experiments (e.g. PN5 of CPWF; Bationo and Mokwunye, 1991) indicate that the use of fertilizers can also increase crop yields.

To explain why actual productivity and water productivity are so low in the Volta Basin, we present a case study in the Volta Basin to examine the yield responses to fertilizers using the DSSAT simulation crop models. We chose a North-South transect across the basin to represent the large range of annual rainfall in the region.

METHODS

SITES

The Ouagadougou meridian (1.53° W) was chosen because there was an existing set of 30 years' weather data for Ouagadougou airport, with daily measurement of maximum and minimum temperatures, rainfall, and solar radiation. These data are compared below with 99 years' data generated by MarkSim (Jones, 2003). Using Ougadougou's latitude (12.37° N) as the datum, we extended the transect south to 6.37° N and north to 15.37° N, at intervals of 1.5° latitude, or about 160 km. Each site was named for the nearest town (or village) contained in the MarkSim shape file for African towns (afrtowns.shp) (Table 1).

Table 1. Nearest towns/villages to the sites on the Volta Basin transect.

Nominal latitude ($^{\circ}$ N)	Location	Latitude ($^{\circ}$ N)	Longitude ($^{\circ}$ W)	Mean annual rainfall* (mm)
6.37	Brofoyedru	6.24	1.52	1480
7.87	Fiakwasa	7.77	1.35	1260
9.37	Chutadi	9.36	1.51	1160
10.87	Nakong	10.80	1.43	1100
12.37	Ouagadougou	12.37	1.53	840
13.87	Bourzanga	13.68	1.55	610
15.37	Bilantal	15.29	1.56	440

*Calculated from the 99-years' data generated by MarkSim.

Annual rainfall decreases and daily mean temperature and diurnal temperature range during the rainy season increase from the south to the north on the meridian transect (Figure 2). Moreover, rainfall distribution changes from bimodal in the southernmost sites (Brofoyedru and Fiakwasa) to unimodal at Chutadi, becoming more strongly unimodal farther north. The atmospheric evaporative demand increases with increasing temperature with a gradient from south to north.

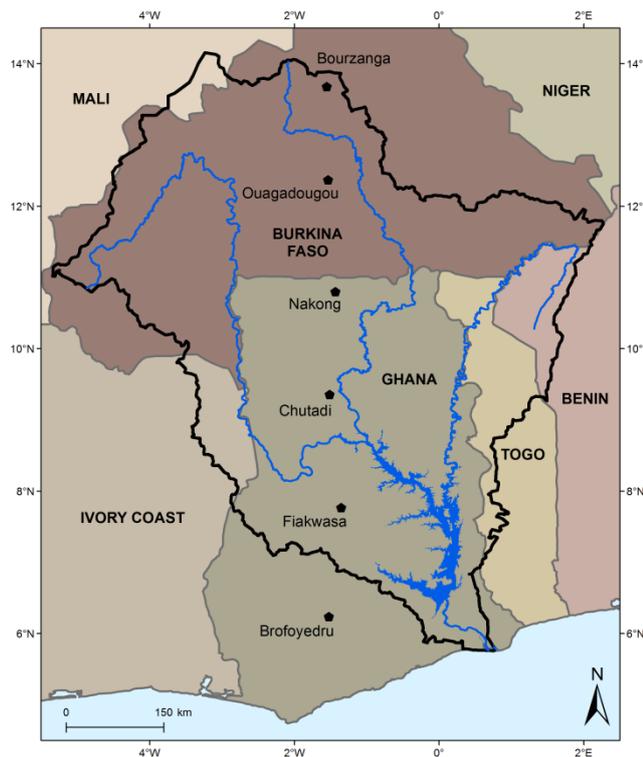


Figure 1. Map of the Volta Basin showing the transect, the sites, and the named locations.

SIMULATION MODELING

Simulation modeling allows us to identify problems in agronomic management, rainfall distribution, and soils that limit crop performance. We accordingly simulated yields of maize, millet, and sorghum at the seven sites across the transect. A brief description of the model chosen, the Decision Support System for Agrotechnology Transfer models (DSSAT), follows.

DSSAT consists of a suite of crop simulation models (Jones et al., 2003), including most cereals. The simulation uses a daily time step, although some processes, especially those related to photosynthesis, are simulated on time steps as short as one hour. The model requires input of daily data of rainfall, maximum and minimum temperatures, and solar radiation. The user specifies the appropriate agronomic management to be applied (crop variety, sowing density, row spacing, seed rate, fertilizer application, and other factors such as irrigation and pest damage, which we did not include). Sowing date can be specified, or automatic sowing is allowed when a specific amount of soil water is available within a window of sowing dates.

The DSSAT model requires soils data with a minimum of drained upper limit, lower limit, saturated water content, and a 'root growth factor' for each layer in the soil profile. We used data for nine soils in Niger from the WISE database (Batjes, 1995), modified for use with crop simulation models (Gijssman et al., 2007).

Examination of the output data of the simulations showed that the yield probability curves fell into three distinct groups, broadly according to soil texture (Table 2). The subsequent data reported are for the grouped soils.

Weather data

We used climate data for each site from the WorldClim data set, with a resolution of 30 arcseconds (about 1 km at the equator) as input to MarkSim. We generated 99 years' weather data for each site using MarkSim (Jones and Thornton, 2000).

Agronomic considerations

After experimenting with many combinations of automatic sowing, the final protocol we chose was to start all simulations on 1 January, and to trigger sowing when there was 60% of 30 mm of available soil water (ASW) in the profile. The date after which sowing was allowed was set at 16 March at Brofoyedru, and half a month later for each 1.5° latitude northward progression, culminating with 16 June at Bilantal.

Seeding rates for all three crops were set at 3 plants/m² in 1-m rows, which approximates those used in the basin where mixed crops (e.g., sorghum and niebe or bissap) is a commonly used risk-avoiding sowing method.

Table 2. Summary of the soils for Niger in the WISE database (Batjes, 1995) used in the Volta Basin meridian transect.

Soil (WI_xxNEnnn) ¹	SCS Family	Texture	Soil depth (cm)	ASW ² (mm)	Depth to hold ~30mm ASW (cm)
Soil group 1					
LV007 ³	Haplic Luvisol	Sand	140	98	45
AR016	Ferralic Arenosol	Sand	201	123	50
LX014	Haplic Lixisol	Sand	201	123	50
Soil group 2					
AC008 ²	Haplic Acrisol	Sand	201	165	40
AC012	Haplic Acrisol	Loamy sand	201	168	35
AC009	Haplic Acrisol	Sand	211	171	40
Soil group 3					
LX011	Plinthic Lixisol	Loamy sand	201	189	30
PT010	Eutric Plinthosol	Sandy loam	201	202	30
FL015	Eutric Fluvisol	Clay loam	196	172	25

¹The WISE code; xx is the code for the SCS family, NE is for Niger, and nnn is the WISE sequence number.

²ASW, available soil water.

³The soil code in the form xxnnn.

Since we have no basis for creating genetic coefficients for the cereal germplasm grown in the Volta Basin, we chose a pragmatic approach. We chose the same millet variety used in the example for the ICRISAT Nohemy station in the DSSAT distribution package. It presumably reflects the characteristics of the germplasm grown in Niger, and, in the absence of better information, is likely to be similar to that grown in the Volta. The maize variety was one listed by the West African Seed Growers' Association and for which the genetic coefficients were defined in the DSSAT package. The sorghum variety chosen was Hegari, a variety of West African origin. The fertilizer treatment was also chosen pragmatically as a low-level application that might be used to determine response to fertilizer. Phosphorus was simulated, but examination of the simulation output data showed that it had little effect.

RESULTS

Water productivity of grain yield

The salient features for the seven sites, three crops, three soil groups, and two fertilizer levels are (Table 3).

Table 3. Water productivity (50% probability for the 99 years tested) for simulated grain crops grown with and without fertilizer on a 9-degree transect on the meridian of Ouagadougou (1.53°W) in the Volta Basin, West Africa, using the DSSAT4 crop simulation package. Units are kg grain/m³ water.

Soil group	Crop					
Soil group 1	Millet (kg grain/m ³ water)		Sorghum (kg grain/m ³ water)		Maize (kg grain/m ³ water)	
Fertilizer	N0P0	N45P13	N0P0	N45P13	N0P0	N45P13
6.37° N	0.09	0.39	0.17	0.46	0.45	1.00
7.87° N	0.17	0.35	0.28	0.45	0.37	0.90
9.37° N	0.17	0.37	0.30	0.46	0.39	0.89
10.87° N	0.13	0.37	0.24	0.41	0.32	0.85
12.37° N	0.18	0.34	0.32	0.40	0.39	0.72
13.87° N	0.06	0.21	0.13	0.37	0.20	1.00
15.37° N	0.12	0.17	0.24	0.36	0.28	0.50
Soil group 2	Millet		Sorghum		Maize	
Fertilizer	N0P0	N45P13	N0P0	N45P13	N0P0	N45P13
6.37° N	0.38	0.68	0.44	0.46	0.80	1.25
7.87° N	0.35	0.51	0.44	0.41	0.69	1.15
9.37° N	0.35	0.55	0.45	0.46	0.76	1.15
10.87° N	0.35	0.61	0.42	0.44	0.72	1.14
12.37° N	0.35	0.54	0.40	0.41	0.63	0.99
13.87° N	0.19	0.33	0.37	0.41	0.50	1.25
15.37° N	0.17	0.21	0.34	0.37	0.47	0.61
Soil group 3	Millet		Sorghum		Maize	
Fertilizer	N0P0	N45P13	N0P0	N45P13	N0P0	N45P13
6.37° N	0.44	0.74	0.41	0.42	0.87	1.21
7.87° N	0.37	0.52	0.42	0.40	0.76	1.10
9.37° N	0.37	0.56	0.41	0.41	0.82	1.11
10.87° N	0.42	0.66	0.40	0.40	0.83	1.09
12.37° N	0.38	0.54	0.36	0.36	0.73	0.96
13.87° N	0.22	0.39	0.37	0.37	0.54	1.21
15.37° N	0.18	0.19	0.33	0.33	0.52	0.62

Maize

Maize has high WP in the coastal zone (latitude less than Chutadi, 9.366° N). Three of the sandy soils in the absence of fertilizer have low WP in at least 50% of years because of substantial leaching of N before sowing. By the latitude of Ouagadougou (12.37° N), WP has fallen dramatically. At this latitude and further north, the leaching effect is substantially less, as might be expected.

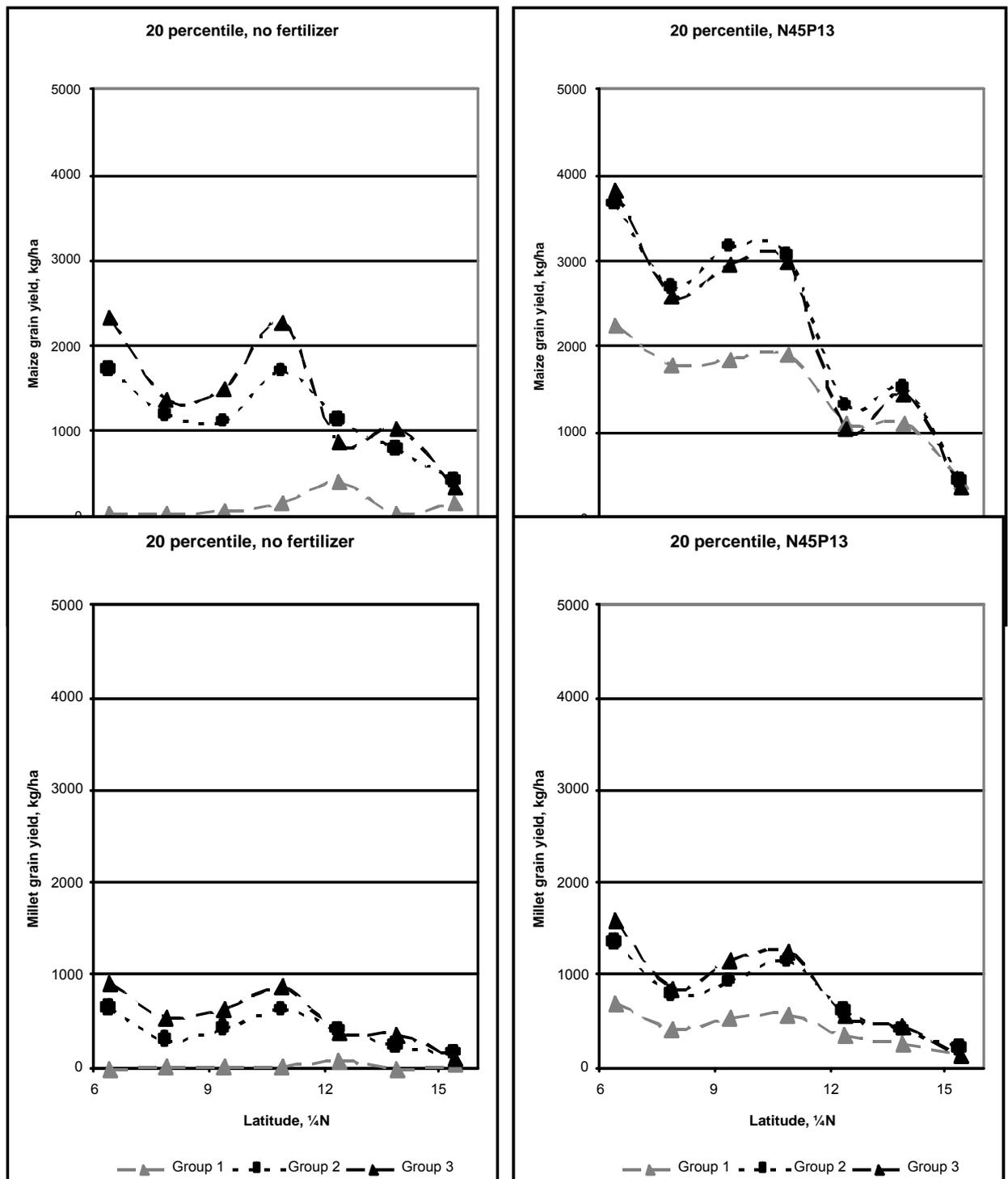


Figure 2. Risk as estimated by the 20 percentile of cumulative yield probability for simulated grain crops grown with and without fertilizer on a 9-degree transect on the meridian of Ouagadougou (1.53°W) in the Volta Basin, West Africa, using the DSSAT4 crop simulation package.

At Brofoyedru (6.37° N) there is a substantial effect of fertilizer, which greatly improves the performance on the sandy soils. By the latitude of Ouagadougou (12.37° N) there is still some fertilizer response, but it is undoubtedly not economic. Further north, the fertilizer response is only in the minority of years.

Millet

Millet overall has much lower WP than maize, such that at latitudes where maize grows it would not be the crop of choice in terms of WP. However, its advantages occur in terms of forage production,

especially in lower rainfall environments of Ouagadougou and further north. The same effect of N leaching occurs on three sandy soils.

Sorghum

In all cases, because of the low sowing density, sorghum gives very low WP at all latitudes, with no response to fertilizer, but with much lower risk than either maize or millet, even at the higher latitudes. Clearly, 3 plants/m², which the sowing density that farmers in the Basin use, is a risk-avoidance strategy. Yields are low, but reliably so, and farmers' investment in the crop is minimal.

Grain yield

The cultivated area of the main crops varies from north to south in the Volta Basin, with millet and sorghum progressively decreasing to the benefit of maize and tubers. This shift results from farming strategies, where the rainfall distribution takes its place.

The graphs (Figure 2) of the 20 percentiles demonstrate how the degree of risk increases from south to north on the transect, between the soil groups, and that fertilizer greatly lessens risk, especially on the group 1 (sandy) soils. The effect is much more pronounced with maize than for millet. Fertilizer had little effect in reducing the risk with sorghum (data not presented), principally because the low plant densities used already constitute a risk avoidance strategy.

Millet seems to provide value through large production of above-ground biomass (data not presented). This production seems responsive to fertilizer and resistant to drought effect throughout all but the most northerly part of the transect.

CONCLUSIONS

Yield potential decreases greatly from south to north, with sandy soils having much less yield potential than the others. Actual yields and WP are both well below their potential. Fertilizer can increase both but it gets increasingly risky toward the north.

Simulated water productivity for grain yield declines from south to north because of the higher evaporative demands associated with higher temperatures. Fertilizer substantially increases water productivity at lower latitudes, but it becomes less effective at higher latitudes.

Our results confirm that yields can be improved with fertilizers, without increasing the risk of crop failure for farmers. Fertilizers would help in providing self sufficiency if a policy to develop food crops production and markets in the basin countries is put into action.

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Efficient rainwater harvesting and nutrient management for high crop productivity in Volta Basin

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Abstract

In the Volta Basin crop productivity is low due to erratic and unpredictable rainfall, and poor soil fertility. To improve crop productivity promising technologies of integrated soil, water and nutrient management, namely the Sahelian Eco-Farm (SEF), and tied ridging were evaluated in Ghana in partnership with farmers. The SEF combined the use of Acacia trees (*Acacia coli*), microcatchments or half moons, and high value trees (*Ziziphus mauritania*) planted inside the half moons, and sorghum and cowpea planted in rotation or continuous system. The half moons served as soil and water conservation structures to channel and retain water around the *Ziziphus* trees. Acacia prunings were incorporated in the cropped areas. Sorghum grain yield was increased by rotation with cowpea compared with continuous sorghum system, inside and outside the SEF. Yields were not significantly influenced by introducing trees into the cropping system. Cowpea did not appear to benefit from rotation until the fourth year. *Acacia coli* had rapid growth and survived the dry seasons. Water harvesting using tied ridging increased yield (by up to 20%) and water productivity of maize and sorghum, and there was a consistent trend for this effect to be enhanced when fertilizer was applied, and the enhancement was significant in one out of three trials.

Media grab

In-field rainwater harvesting (tied-ridging) and fertilizer application increased crop and water productivity, and the response to fertilizer tends to increase with tied-ridges.

Introduction

Food production in the Volta Basin is characterized by rainfed subsistence agriculture, low use of external inputs, and low and declining soil fertility. More than half of the basin is semi-arid with annual rainfall ranging between 150 and 1100 mm. The rainfall is monomodal and erratic with wide seasonal variations of up to 20% or more (Kasei, 1988). The two conditions of erratic rainfall and low soil fertility are the most important limitations to agricultural productivity in the area, with perennial food deficit in most of the countries within the basin. To increase food production in the basin, these two key conditions need to be addressed. Traditional cropping systems have sustained food production over the years though at low levels. In evaluating the traditional cropping systems, Dakora and Keya (1997) concluded that legume-cereal rotations were far more sustainable than intercropping systems. Organic and mineral fertilizers have been shown to improve cereal yields in the basin (Schlecht et al., 2006; Fosu et al., 2004). Although fertilizer application consistently improves crop production, the results of tied-ridging have not been consistent. In addition, the combined effect of tied-ridges and soil fertility amendment has not been widely tested. An integrated soil, water, and nutrient management approach holds promise to managing erratic rainfall and low soil fertility in sub-Saharan Africa. The objectives of the work presented here were to evaluate an integrated crop management system within the Sahelian/Savannah Eco-Farm (SEF) system developed by ICRISAT, and the interactions between tied-ridging and fertilization on crop production in the Volta Basin.

Methods

Two experiments were conducted at Navrongo and Tamale in Ghana. The systems tested were: (1) crop rotation (continuous sorghum, continuous cowpea, and sorghum-cowpea rotation) within and outside a Sahelian/Savanna Eco-Farm (SEF) system over 4 years (2004-07), and (2) tied-ridging and fertilizer application in 2006 and 2007.

The SEF, which was conducted on-station at Navrongo, combines the use of *Acacia coli*, microcatchments, or half moons, high value trees such as *Ziziphus mauritania* planted inside the half moons, and sorghum and cowpea planted in rotation or continuous, each year in a RCBD with three replicates. There were two rows of *A. coli* and one row of *Z. mauritania* in each plot of 15 x 30 m. The half moons installed within grassed contour bunds served as soil and water conservation structures to channel and retain rainwater around the *Ziziphus* trees. *Acacia coli*, a drought-resistant leguminous tree, was pruned annually after 2 years, and incorporated at the time of land preparation within the cereal and legume plots.

The tied-ridging was tested on-station (at Nyankpala) and on-farm (farmer managed, at Tamale) in Ghana and compared open ridges and tied-ridges without or with fertilizer (N₆₀P₃₀K₃₀ kg/ha) using maize and sorghum as test crops. The tying was done 6 weeks after planting at 0.8 m intervals. The trial design on-station was a 2 x 2 factorial arranged in a RCBD with three replicates. On-farm, each farmer served as a replicate and the plot size was 10 m x 10 m.

Results and discussion

Integrated cropping system

Over the 4 years, there was no effect of the SEF on crop yield (Table 1), i.e. there was no yield loss as a result of reduced crop area or competition for water, nutrients, and light by the trees. Yields within or outside the SEF were similar each year for sorghum and cowpea in respective rotations. In the continuous system, sorghum grain yield was similar in all systems in the first year, but after 2 years (i.e. the first sorghum crop after cowpea), yield of continuously cropped sorghum was significantly lower than yield of sorghum grown in rotation with cowpea (yield reduction of about one-third).

As for sorghum, there was no effect of the SEF on yield of cowpea grown continuously or in rotation with sorghum (Table 2). In the 4th year, there was a significant effect of rotation on cowpea yield, with around a 50% increase in yield of cowpea grown in rotation with sorghum in comparison with continuous cowpea (Table 2). The mean cowpea yield over the experimental period was below 1 t/ha.

In the SEF, *Acacia coli* grew rapidly and survived the long dry season probably partly due to the water storage from the half moons. In 2006, the firewood obtained from *A. coli* pruning was 3.6 t/ha, and in 2007 it was 3.1 t/ha, valued at US\$78.1 and 62.0, respectively. The *Ziziphus* fruit harvested in 2007 was 96 kg/ha. The harvest from these trees is additional benefit to the SEF system. Incorporation of the *A. coli* prunings in the SEF plots did not improve sorghum and cowpea yields over the No-SEF system (Table 1 and 2). This may be due to the slow decomposition observed for *A. coli* leaves (data not included).

Table 1. Effect of integrated cropping system on sorghum yield (t/ha) at Navrongo, 2004–07.

Treatment	2004	2005	2006	2007	Mean
SEF + sorghum ^f in rotation with cowpea	2.21	-	2.04a	-	2.13
SEF+ sorghum continuous	2.15	1.28	1.37b	1.33	1.54
No SEF + sorghum in rotation with cowpea	2.14	-	2.15a	-	2.15
No SEF+ sorghum continuous	2.02	1.72	1.48b	1.31	1.63
SEF +cowpea ^y in rotation with sorghum	-	1.81	-	1.41	1.61
No SEF +cowpea in rotation with sorghum	-	1.77	-	1.52	1.65
LSD	NS	NS	-	NS	-

^fSorghum begins rotation; ^yCowpea begins rotation.

Table 2: Effect of integrated cropping system on cowpea yield at Navrongo, 2004–07.

Treatment	2004	2005	2006	2007	Mean
SEF +cowpea ^y in rotation with sorghum	0.80	-	0.81	-	0.81
SEF+ cowpea continuous	0.86	0.54	1.01	0.52	0.73
No SEF +cowpea in rotation with sorghum	0.71	-	1.09	-	0.90
No SEF+ cowpea continuous	0.64	0.79	0.98	0.48	0.72
SEF + sorghum ^f in rotation with cowpea	-	0.59	-	1.19	0.89
No SEF + sorghum in rotation with cowpea	-	0.76	-	0.84	0.80
LSD	NS	NS	NS	0.44	-

Tied-ridges and fertilizer application

On-station at Nyankpala, there was no interaction between tied-ridging and fertilizer rate on maize grain and stover yield in 2006 (Table 3). Water harvesting had no effect on maize biomass or yield production. There was, however, a highly significant effect of fertilizer application on grain and stover yield. The highest water productivity was obtained when fertilizer was applied (Tables 3 and 4).

Table 3. Effect of water harvesting on maize yield at Nyankpala (on-station) 2006.

Treatment	Grain yield (t/ha)	Stover (t/ha)	Water productivity (kg/mm)
Water harvesting			
No tied ridging	1.1	2.4	2.0
Tied ridging	1.5	3.1	2.7
LSD	ns	ns	
Soil amendment			
No fertilizer	0.48	1.2	0.87
N ₆₀ P ₃₀ K ₃₀	2.13	4.3	3.84
LSD	0.07	0.14	
P>F			
Wat-h	0.18	0.2	
Soil-a	0.0001	0.0001	

Wat-h x Soil-a	0.32	0.34
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Wat-h = water harvesting; Soil-a = soil amendment.

On farmers' fields also, there was no fertilizer by tied-ridging interaction effect, but there were significant effects of water harvesting and fertilizer on maize grain yield and of fertilizer on stover yield (Table 4).

Table 4. Effect of water harvesting on maize yield at Tamale (on-farm) 2006.

Treatment	Grain yield (t/ha)	Stover (t/ha)	Water productivity (kg/mm)
Water harvesting			
No tied ridging	0.81	2.3	1.5
Tied ridging	0.97	2.4	1.7
LSD	0.14	ns	
Soil amendment			
No fertilizer	0.46	1.9	0.8
N ₆₀ P ₃₀ K ₃₀	1.33	2.7	2.4
LSD	0.40	0.23	
P>F			
Wat-h	0.03	0.32	
Soil-a	0.004	0.006	
Wat-h x Soil-a	0.26	0.78	

In 2007, a significant water harvesting by fertilizer interaction effect was observed on sorghum yield at Navrongo (Figure 2). In other words, there was a greater response to fertilizer in the presence of tied ridges.

Tied-ridging on-station at Nyankpala in 2006 was conducted on slightly sloping land (about 2.7% slope), which was gravelly on the surface. The slope, in addition to the expected low water retention of the soil, may have accounted for the beneficial effect of tied-ridging in 2006, when the rainfall distribution was poor (Figure 1). The response to tied-ridging in 2007 was contrary to expectation given the high rainfall (860 mm from July to October) experienced in the area. The water productivity was 0.9, 1.1, 1.5, and 2.4 kg/mm of rain for control, TR-F, NTR+F, and TR+F, respectively (see Figure 2 for definition). The effect of tied-ridging may have been important in minimizing the effect of terminal drought as the rains stopped abruptly in Navrongo in 2007.

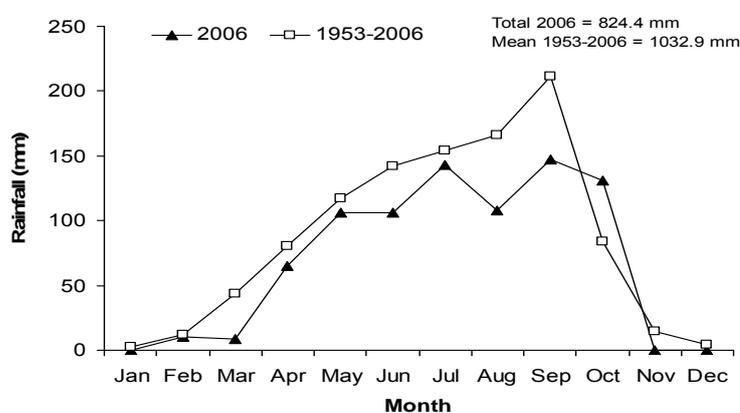


Figure 1. Rainfall in 2006 and long-term mean (1953-2006) at Nyankpala.

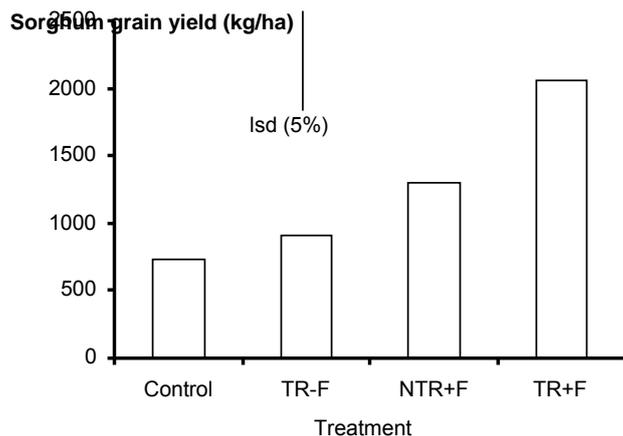


Figure 2. Effect of tied-ridge on sorghum yield at Navrongo, 2007
 TR = tied-ridge; F=NPK 60-30-30 kg/ha, control=No tied ridging, no fertilizer.

Conclusions and recommendations

Crop rotation is an important component of integrated soil fertility management. SEF has potential for diversification of smallholder cropping systems, but its benefits need to be further demonstrated. A complete picture of the productivity of the integrated cropping system can be assessed only after economic analysis. Water harvesting with tied-ridges under fertilization enhances water productivity and crop yields. Tied-ridge appear to be more effective when there is slope and the water-holding capacity of the soil is low. Further research on different slopes, soil types, climate conditions and time of tying are needed to establish the conditions under which tied-ridges are most effective.

Acknowledgments

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Improving crop productivity and farmer income using fertilizer microdosing and the warrantage system in the Volta Basin

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Abstract

In the Volta Basin, poor soil fertility and low water availability are the major constraints to crop production. Fertilizer microdosing technology involves application of small quantities of fertilizers in the planting hole. It increases fertilizer use efficiency and yields while minimizing input costs. Recognizing that liquidity constraints often prevent farmers from intensifying their production system, the 'warrantage' or inventory credit system helps to remove barriers to the adoption of soil fertility restoration. Fertilizer microdosing was tested in partnership with 32 farmers in Navrongo and Tamale, Ghana. Farmer field schools (FFS) were established at Kandigah in Kassena Nankana District of Upper East Region, Ghana, where 21 farmers were trained in microdosing. In Burkina, microdosing resulted in an increase in yield of 25-40% compared to controls. Warrantage was implemented in Ziga and Saala in Burkina Faso from 2005-2007, with a major emphasis on the training of farmer associations. In Ghana, microdosing increased maize yields by more than 50% compared to the controls. By using the warrantage system, farmers increased the value of their grain stocks by 42 % in Ziga and 21% in Saala.

Media grab

Microdosing combined with a warrantage system increases rainwater productivity and farmer revenue, and gives farmers better access to credit.

Introduction

Most of the people in the Volta Basin are resource-poor farmer families relying on rainfed agriculture for their livelihoods. Temporal and spatial variability of rainfall results in high risks for farmers. Intensive cultivation of farmlands with low external inputs has led to a significant decline in soil fertility, resulting in low agricultural productivity, which is the main cause of poverty and food insecurity. Efficient use of fertilizers combined with good market management of agriculture products may help farmers to achieve food security and improve livelihoods. This paper presents the results of a combination of the microdosing technology with improved crop varieties to increase cropland and water productivity and fertilizer efficiency. It also presents an innovative approach for increasing farmer's incomes through the warrantage system. Microdosing experiments in farmer's fields as well as in farmer's field schools (FFS) included a range of fertilizer formulas in Burkina Faso and Ghana research areas. The warrantage system was applied to give farmers the opportunity to access credit, to generate revenues from dry season economic activities, and to facilitate acquisition of inputs.

Methods

Fertilizer microdosing experiments

The demonstration tests consisted of two plots per farmer, each plot measuring 0.25 ha (2500 m²). Each technology was repeated by four farmers. Treatments consisted of the farmers' practice (control) and one 'improved' technology on each farm. The earlier recommended broadcasting system of fertilizer application is about 100 kg/ha of compound fertilizer (NPK = 15:15:15 for Ghana, and 14:23:14 for Burkina Faso), whereas the fertilizer microdosing involves 4-6 grams per hill of compound fertilizer (NPK) corresponding to 40-60 kg compound fertilizer/ha, or 2 grams of sulfate of ammonia (SA) per hill (20 kg SA/ha). Farmers used their own densities in the control plots, but were requested to follow the recommended densities in the microdosing plots, with guidance from the field technicians. Plant densities under farmer practice varied between 5000 and 6000 hills/ha whereas the recommended densities in the microdosing plots ranged from 10,000 to 20,000 hills/ha. The same planting date was recommended for treatments and control, to be done when the soil was moist enough for germination of seeds. The farmers weeded as needed, in some cases on the advice of field

technicians. Harvesting was done by the farmers under the supervision of field technicians. Data collection was done by the field technicians.

In Ghana, experiments were carried out on farm with 20 farmers in 2005 and 2006. Treatments included microdosing, recommended fertilizer rates, and no fertilizer, using improved varieties of sorghum (Kapaala) and maize (Obatampa) and farmers' varieties. The microdose rate was 60 kg/ha of NPK (15:15:15) plus 60 kg/ha of sulfate of ammonia (SA) using 2 g NPK + 2 g (SA)/hill at planting, whereas the recommended rate is 240 kg NPK 15-15-15/ha using 8 NPK g /hill + 4 g SA/hill.

The following treatments were compared:

- T1: Improved variety with microdose.
- T2: Improved variety with recommended fertilizer rate.
- T3: Farmer variety + micro dose.
- T4: Farmer variety with recommended fertilizer rate.
- T5: Farmer variety with no fertilizer (Control).

In Burkina Faso during the cropping seasons in 2005-2007, four microdosing formulations were tested with 32 farmers each year in their fields to select the best formula for improved varieties of the main crops in the study regions: maize (Espoir) continuously cropped in Saala village in the southwest, and sorghum (Kapelga) grown in rotation with cowpea (K VX.39-2D-5X) in the north (Ziga village).

Apart from the control, all fertilizer treatments were tested in the presence of water harvesting measures (stone rows (cp) and zai). The micro dosing formulations were:

- NPK: 14:23:14 at 60 kg/ha on all crops corresponding to 8.4 kg N/ha and 13.8 kg P/ha.
- Urea: 40 kg/ha on sorghum and 60 kg/ha on maize, corresponding to 18.4 and 27.6 kg N/ha.
- BP (Burkina phosphate rocks): 200 kg/ha for all crops corresponding to 21.7 kg P/ha.
- Organic matter (OM): 2.5 t/ha for all crops.

The treatments are described below:

- Tech1 = cp + Zai + OM.
- Tech2 = cp + Zai + NPK+ urea.
- Tech3 = cp + Zai + OM + urea + BP.
- Tech4 = cp + Zai + OM + urea + BP +NPK.
- Tech5 (control): farmer practice (no fertilizer, no water harvesting).

Rainwater productivity (RWP)

RWP was calculated at Ziga in 2007 using the total rainfall (Rain) between planting and harvest and grain yield:

$$RWP = \frac{Yield}{Rain} \text{ (kg/mm/ha)}$$

Rainfall data were collected from rain gauges installed in each farmer demonstration field. Data were analyzed by ANOVA using the general linear model (GLM), and the software package SPSS (Statistical Package for the Social Sciences).

Warrantage

The methodology to implement the warrantage system in Saala and Ziga was based on Participatory Learning and Action (PLA) methods. Participatory Rural Appraisal (PRA) and a literature review were undertaken in 2005 to characterize the two sites in terms of socioeconomic status: infrastructure, internal and external relationships between farmer organizations, and development partners (public, private, and NGO). Infrastructure included farmers' product storage capacity and quality.

Sensitization sessions with the target public and training sessions were organized to establish memoranda of understanding (MOU) with partners in both villages. Sensitization sessions involved meetings with the target groups, financial institutions, development partners, NGOs, and the project manager group. The training curriculum included explaining the warrantage credit system, warrantage function and monitoring, revenue generating activities, and management and market organization. Warrantage was implemented in the two villages in 2005 and 2006. Its impact was evaluated from the induced benefits, the income generating activities (IGA) management, and farmers' capacity building through economic analysis and an impact study.

Description of the sites

In both sites, rainfall varies in time and space. Mean rainfall is about 800 mm/year in Navrongo and Saala. In Ziga, mean annual rainfall is around 650 mm. Rainfall has high spatio-temporal variability in all locations. In addition to rainfall limitations, soil characteristics determine land use, crop productivity and small farmer livelihoods in the Volta Basin. The major soils of the Navrongo area belong to the Tanchera association and consist mainly of Puga series (Eutric Plintisol), Tanchera series (Endoeutric-Stagnic Plintisol), Pu Series (Eutri Gleyic Regosol), Kupela series (Eutric Gleysol) and Berenyasi series (Gleyic Arenosol). The soils are mainly loamy sand and sandy loam on the surface. Bulk density ranged from 1.7-1.9 mg/m³ and total porosity of the topsoil was 34-37%. Organic carbon was 0.5-0.7% and saturated hydraulic conductivity (*Ks*) at the surface was 4.5 mm/h. Soils in Ziga are eroded soils overlying gravelly material. In Saala, the soils are lixisols overlaying sandy-clayey material, and luvisols overlaying clayey material. These soils have low organic C and total N contents because of low biomass production and a high rate of decomposition (Mokwunye et al., 1996). N and P are limiting nutrients in all site soils.

In Ziga and Saala, trading is based on the local market system. Markets are held every 3 days and distances vary from 10-70 km. Farmers have no access to credit for revenue-generating activities and agricultural investments (fertilizers, pesticides, insecticides). Agricultural products are sold at very low prices during the harvesting period (October, November) for cash for social needs such as school fees. Later on in the dry season (April, May), prices increase and traders make higher profits from farmers out of their products.

Results and discussion

Yields

There was a consistent trend toward higher yields of all fertilizer treatments in comparison with farmer practice at all locations. In 2005 at Nyankpala, there were significant, large yield increases with all fertilized treatments in maize, but for sorghum the yield increase was only significant with the highest (recommended) amount of fertilizer hum, at Nyankpala in 2005 (Figure 1). Conversely, sorghum and cowpea responded significantly to all fertilizer treatments averaged over 3 years at Ziga in Burkina Faso, while maize was less responsive (Figures 2, 3). At Saala in year 2, maize yields were very low as a result of flooding early in the season followed by a very dry season. In Ghana, maize yields increased many-fold over the control for all fertilizer treatments, while in Burkina there was an increase of at least 25% in cereal yields and 39% in cowpea yield with the technologies compared to the controls. Tabo et al. (2006) found that microdosing optimizes nutrient use efficiency, while Zougmore et al. (2004) found that the combination of water harvesting technologies and fertilizer improved water and nutrient use efficiencies and thereby increased crop yield.

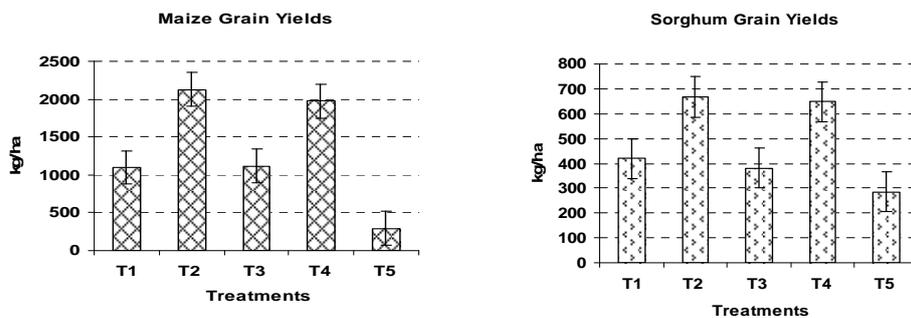


Figure 1. Yield of maize and sorghum at Nyankpala (Ghana) 2005. Error bars are least significant differences at p=0.05 (Lsd).

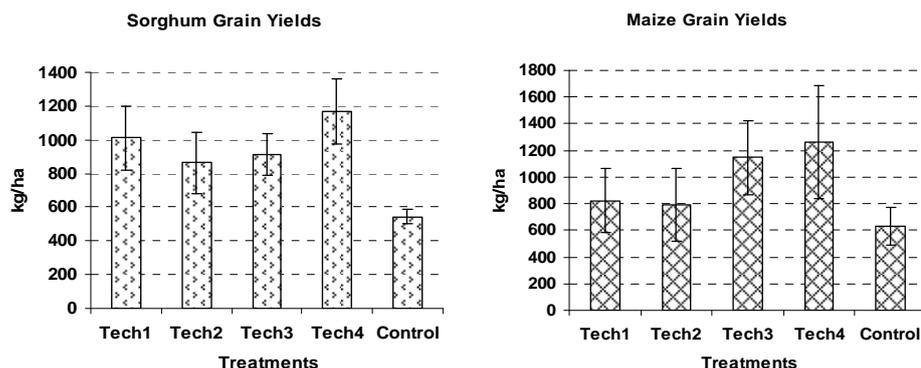


Figure 2. Sorghum and maize means yields (averages 2005-2007) per technology as compared to farmers practices in Ziga (Burkina Faso). Error bars are standard errors

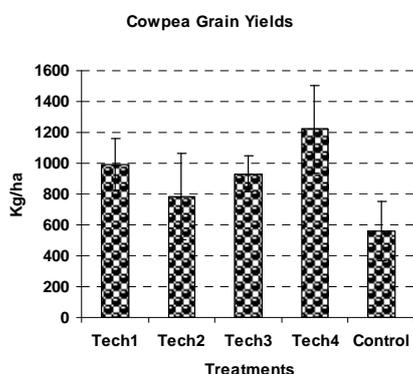


Figure 3. Cowpea mean yields (averages 2005-07) per technology as compared to farmers practices in Ziga (Burkina Faso). Error bars are standard errors.

Rainfall water productivity

In 2007 at Ziga, rainwater productivity was significantly higher on Tech 4 than Tech 1 and the control plots, for sorghum and cowpea (Figure 4). Tech 3 and Tech 1 are intermediate between the control and Tech 4 in terms of amount of fertilizer. The combination of water harvesting technique with mineral and organic fertilizers improved water productivity compared to the farmers' traditional practice (control).

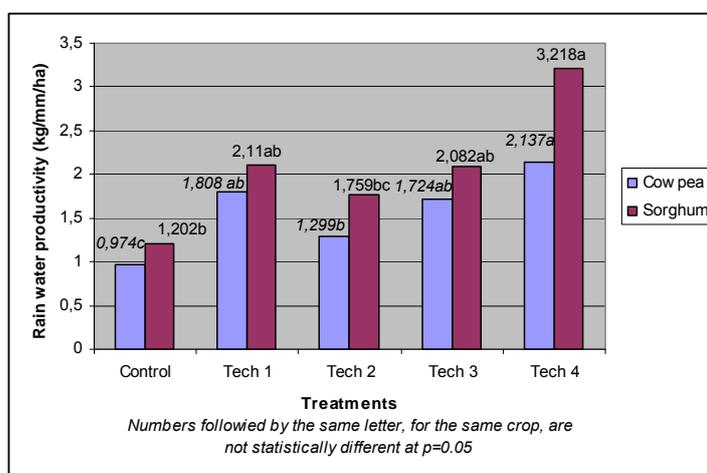


Figure 4. Rainwater productivity (kg/mm/ha) for cowpea and sorghum per treatment at Ziga, 2007.

Warrantage results

In each village a storage house of at least 30 t was identified. Nevertheless, partnerships between farmers, extension services, and NGOs were poorly developed due to lack of consultation and lack of financial means. Therefore, the project research approach was appreciated by farmers and all partners. Indeed, at both villages, a tripartite MOU was established between a decentralized financial institution (the Direction Régionale des Caisses Populaires), the village farmers' organization, and INERA through Project CPWF5. The protocols describe the role of each of the partners in the warrantage system as well as the conditions for farmers to access credit and its reimbursement. One-hundred farmers from the two villages were trained in different aspects of credit and market management. This resulted in farmer's capacity-building in terms of decision-making for better agricultural product management, credit handling, and income generation. Each village formed its own management committee comprising a credit manager, a stock manager, and a warehouseman/storekeeper.

The quantity of warranted products is given in Table 1. There were more product types in Saala than Ziga. Crops are more diversified in Saala due to higher annual rainfall and higher soil fertility. In 2006 the quantities of products involved in the warrantage increased compared to 2005: by 35% in Ziga and by 495% in Saala. This shows the increasing interest of farmers in the warrantage system. The

number of farmers involved in the credit, however, decreased in Ziga, while in Salla it increased (by 19%). This was due to the late credit release in Ziga (February instead of December).

Table 1. Nature and quantities of products in 2005-2006 (1) and 2006-2007 (2) for warrantage (in kg).

Site	Year	White Sorghum	Red Sorghum	Millet	Maize	Rice	Ground nut	Cowpea	Soybean	Sesame	Total	Increasing Rate (%)
Ziga	1	1 312	-	-	-	-	5 600	656	-	-	7 569	
	2	2 112	-	96	-	-	6 776	1 168	-	-	10 154	34
Total		3 424	-	96	-	-	12 376	1 824	-	-	17 720	
Saala	1	-	256	-	944	30	-	64	-	-	1 295	
	2	-	384	-	3 296	2 340	1 260	272	32	96	7 682	493
Total		-	640	-	4 240	2 370	1 260	336	32	96	8 974	

Table 2. Number of producers warranting their agricultural products for credit acquisition.

Site	Period	Producers who warrant their products	Producers who accessed credit
Ziga	Dec 2005-May 2006	32	0
	Dec 2006-June 2007	31	20
Saala	Dec 2005-May 2006	21	0
	Dec 2006-June 2007	25	09

The total amount of credit for income generating activities (IGA) is shown in Table 3: about 461,000 and 636,000 CFA (US\$1300 and 1800), respectively, in Saala and Ziga. Diversification of IGA in both sites demonstrates the farmers' capacity in understanding market systems for cash flow. In Ziga, IGA included: sheep and cattle fattening, trading (cereals, cowpea, leather, and livestock), local transformation (snacks, local beer (dolo), cooking ingredients). In Saala activities included fattening (pigs, small ruminants), butchery and trading (cereals, cigarettes, batteries). At both sites, credit was totally reimbursed in May before the bank released the stored products to the farmers. The warrantage system improved farmers' incomes in two ways: (1) product value increased during the storage period by 3-4 times the initial value; (2) IGAs ensured cash activities during the dry season. Overall benefit of 42% in Ziga and 21% in Saala are shown in Table 3.

Table 3. Evaluation of 2006-2007 warrantage operation benefits in CFA francs ('000).

Site	Value at storage	Credit requested	Value in May	Additional value	Pledged savings	Bank Interest	Bank fees	Storage fees	Gain	Benefit in %
Ziga	684	636	929	244	107	23.3	26.4	12.4	289	42.3
Saala	512	461	671	158	0	26.8	13.6	9.72	108	21.1

For the first 2 years, the benefits of the warrantage system went mainly to social expenses: school fees, marriage (Ouedraogo et al., 2007). It was used also for seed and fertilizer acquisition. An economic impact study is ongoing to identify the destination and use of warrantage benefits.

Conclusion

In Ghana and Burkina Faso, the technologies developed with farmers increased sorghum, maize, and cowpea yields. The warrantage system helped improve the farmers' livelihoods. Efforts are being made by the farmers' associations to set up input shops that will be linked to their warehouses and their savings and credit schemes.

Acknowledgments

This paper presents findings from PN5 'Enhancing rainwater and nutrient use efficiency for improved crop productivity, farm income and rural livelihoods in the Volta Basin,' a project of the CGIAR Challenge Program on Water and Food. We would like to thank all collaborators and partners for their efforts in participating in this research in Ghana and Burkina Faso. We wish to express our sincere gratitude to the reviewers for their comments and suggestions to improve the paper.

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Incorporating gender analysis in assessing the needs, opportunities and benefits from research and technology development for salt-affected rice areas: a case in Eastern Uttar Pradesh, India

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Abstract

In eastern Uttar Pradesh, sodicity is a major problem in rainfed areas grown under rice. The problem is more severe during the dry season, preventing farmers from growing a second crop of rice. Aside from sodicity, farming households are faced with drought and submergence that result in low rice yields. To address these problems, the International Rice Research Institute (IRRI) in collaboration with Narendra Deva University of Agricultural Technology (NDUAT) initiated research in eastern Uttar Pradesh, India, under CPWF Project 7 'Development of Technologies to Harness the Productivity Potential of Salt-Affected Areas of the Indo-Gangetic Plains and Mekong Delta' in 2004. The project conducted baseline socioeconomic surveys, including gender analysis, ²in assessing the needs and constraints in rice productivity, as well as opportunities for improving the livelihoods of men and women farmers. A pretested structured questionnaire was used in conducting farm-household surveys at selected villages with sodic problems. Based on the results of the surveys, women's labor participation in rice farming is highest among the marginal and small farming households who belong to the lowest rung of the social ladder. Women from lower caste farming households with nonsodic lands contributed 63% to total labor inputs in rice production, while those with sodic lands provided 59%. Most of these women are illiterate and face several constraints to increasing rice productivity, such as lack of access to seeds of varieties tolerant to sodicity, and lack of knowledge on nutrient management practices. To overcome these constraints, the project deliberately involved women and men in technology evaluation and dissemination.

Salt-tolerant lines/varieties and nutrient management technologies (use of pressmud³, pressmud+zinc sulfate, and *Sesbania*³) were validated by men and women farmers on their own fields. Focus group discussions revealed the benefits derived by women in participating in the project activities such as: a) increased crop yields; b) gained confidence in applying knowledge on new rice varieties and in expressing their opinions regarding new technologies; and c) recognition as farmers.

Media grab

This work demonstrates that the inclusion of women in the project led to increased crop yields, improved their confidence in applying new knowledge on new rice varieties, improved skills in nutrient management, and enhanced their recognition as farmers.

Introduction

In India, the area affected by salinity is about 8.5 million ha, and eastern Uttar Pradesh has 1.29 million ha area affected by sodicity. Uttar Pradesh is one of the largest states where agriculture and rice production, in particular, is the main livelihood of the rural population. Due to erratic rainfall distribution, sodicity, soil micronutrient deficiencies, and productivity of major crops such as rice, wheat, and other crops (pulses and oilseed) are low. Most of the farmers are resource-poor with marginal landholdings (<1 ha). Farmers who have supplementary irrigation sources are few, and the high cost of diesel is a major constraint to crop productivity. Resource-poor farmers living in stress-prone rice environments rely heavily on family members, especially the women in performing rice production and processing operations, livestock management, and expenditure-saving activities. Social and cultural norms that are biased toward men, however, deprive women of new knowledge and technologies required for ensuring food (rice) under stress-prone environments. A study by FAO (1997) also shows that only 5% of agricultural extension services reach women. It is also true that development programs generally do not consider social and gender factors.

To address these problems, IRRI and NDUAT initiated a collaborative research project in 2004 on the development of technologies to harness the productivity potential of salt-affected areas of the Indo-

² Gender analysis has become the commonly accepted term for analyzing gender roles and intra- and inter-household dynamics. It asks the questions: 'who does what activities, who has access to and control of resources' in identifying needs, constraints and opportunities for poor women. Gender analysis is also used within farming systems, and applying that analysis to decisions about agricultural research and development activities that can benefit women.

³ Pressmud is a byproduct of sugar which came from nearby factory sugarcane'

³ Sesbania refers to crops that are used as green manure. Pressmud and sesbania are effective in enhancing soil fertility and rice productivity in sodic soils.

Gangetic Plains and Mekong Delta in 2004. This project is part of the Challenge Program on Water and Food (CPWF) Project 7. The project seeks to enhance land and water productivity of rice-based cropping systems in salt-affected areas by integrating genetic improvement and management strategies that are environmentally sustainable and socially acceptable. Thus the initial step in the research process was to develop a systematic understanding of the agroecological, social, and cultural circumstances of the target sites. This paper focuses on how gender analysis was used in assessing the needs and opportunities from research and technology development for salt-affected rice areas in selected villages in Eastern Uttar Pradesh, India. Although several studies have focused on the significant contributions of poor women and their constraints in sustaining rural livelihood in India (Agarwal, 1985; Veepa, 2007; Krishnaraj, 2007), case studies that demonstrate how women farmers were included in participatory research and how they benefitted from their participation are few (Paris et al., 2008b; Ramprasad, 2008). Our effort emphasizes that involving women as partners and simultaneously building their capacities as farmers are prerequisites to any research activity intended to enhance benefits to farmers.

Methods

During 2005-06, three representative villages in sodic lands in the Faizabad district were selected for this study. These villages are Dhamthua (village A), Lodhe Ka Purwa (village B), and Leela ka Purwa (village C). These villages were selected based on the following criteria: 1) large area affected by sodicity; 2) rice is the major crop grown during the wet season; and 3) farmers do not adopt rice technologies for sodic soils, i.e. varieties tolerant to sodic soils and nutrient management. For the purpose of the study, villages B and C were combined as they had the same salinity level (from moderate to severe).

Of the 98 farm households in the three villages (Dhamthua-49, Lodhe ka Purwa-19 and Leela ka Purwa-30), 50 were included in the surveys. These households were selected using the following criteria: (a) must have rice land affected by sodicity (more than 50%); (b) should grow rice as the main crop in *kharif* season; and (c) willingness to cooperate in the project. A pretested structured questionnaire was used for the household surveys. Principal males and principal females (decision-makers) were interviewed. The questionnaire included information on age, education, and occupation of male and female family members, farm size, income, plotwise information on land use, inputs and outputs, rice varieties used, and gender division of labor in rice production. Qualitative information on the perceptions on proposed innovations was also obtained. The project introduced new rice lines and released varieties tolerant to sodicity along with improved nutrient management such as use of sesbania and pressmud to reclaim the soils. The project involved men and women farmers as key sources of information on rice varieties, indigenous crop management practices, and as farmer cooperators in evaluation of innovations on their fields.

Results

Study areas

The selected villages were located 45-48 km from the District headquarters and 5-8 km from the NDUAT campus. Soils are mostly sodic ranging from neutral to severe. Agroclimatic conditions are normal with four seasons: summer and rainy (March to October), winter and spring (November to April). The important cropping seasons are *kharif* (wet), *rabi* (dry), and *zaid* (April to June). The average annual rainfall is less than 1000 mm. The selected areas are prone to drought because of the variability of the monsoons during the cropping season. The major cropping pattern of the area is rice-wheat, rice-potato, rice-pea + mustard, sugarcane-wheat, rice-oilseed and pigeon pea (in upper fields). Animal production is an integral component of the farming systems. Farmers with animals and with access to supplementary irrigation grow green fodder in *kharif* and *rabi* season.

Characteristics of farming population

On average, the principal males are 47 years old and principal females are 40. Both share farming responsibilities. Each farming household has 5-9 family members. There is wide disparity in education attainment between adult males and females. In Village A, all the principal females are illiterate; and in Village B and C, the principal females attended school for only 2 years. Despite the free education offered by the government for girls, the high illiteracy rates among adult women are due to the lack of awareness on the importance of education, discrimination against girls, traditional attitudes on the future roles of women in the society, and responsibilities on the girl child in the household and on the farm that prevents them from attending school. The disparity in literacy rates among the young population (6-15 years old) no longer exists. All male and female children in all social groups from the sample households across the villages attended school. This reduction in the discrimination against girls is due to increased awareness of the importance of education as an escape from poverty, and free education provided by the government for each child in the village. The government provides mid-day meals, free education, free books, scholarship for primary and secondary levels, and free education for girls up to college level.

Size of farm holdings

All sites were dominated by backward and scheduled castes (lower caste) households that are mostly marginal (0.4 ha) and small (1.3 ha). The upper caste households have fairly larger farm sizes averaging 2.6 ha. The upper caste households generally rent out their lands to lower caste landholders because of management problems and the high cost of cultivation.

Sources of income

Farming households diversify their income portfolio due to risks in farming. Family members are engaged in crop, livestock, off-farm and non-farm activities. Female family members from the lower caste work as hired laborers in other farms within the village and have less access to non-farm income outside the village. Most households, however, have one or more male adults who are engaged in non-farm employment. Male adults either work in adjacent villages, in the city as daily laborers, or as seasonal or long-term migrants. Other non-farm activities are either as day laborers or permanent employees in government or the private sectors.

Gender division of labor in rice production

Based on the results of the surveys, women's labor participation in rice farming is highest among the marginal and small farming households who belong to the lowest rung of the social ladder. These findings are similar in other salt-affected areas in eastern Uttar Pradesh (Paris et al., 2008a). In rice cultivation, female laborers (either as family, exchange or hired basis) do all major activities, including pulling of seedlings in the seedbeds, carrying the seedlings to the main fields, transplanting, weeding, harvesting, and threshing (manual). Gender analysis undertaken through in-depth studies in two villages in India revealed that adoption of new technologies enhanced task specialization where activities were performed exclusively by a particular gender in order to optimize available household labor resources (Kollie and Bantilan, 1997). The findings revealed that gender roles were segregated into type of work and into market and domestic activities, where men gain greater control over market-related activities and women over the domestic realm.

Female family members among households who have non-sodic lands contribute 63% to total labor inputs in rice production, and those with sodic lands provide 59%. Women among the upper caste farming households do not work on the fields. Among the upper caste households, landowners usually hire more women than men to work on their fields. These women belong to the small and marginal farming and landless households. Aside from women's labor participation in rice production, they provide labor in rice postharvest such as seed cleaning, selection, and storage. They also prepare rice into many rice products. In wheat production, plowing and threshing are mechanized. Men are mainly responsible for irrigating fields, broadcasting seeds, applying chemical fertilizer, while women do the weeding and other crop operations.

Participation in farm-related decision-making

Traditionally, the principal males or male heads of households dominate in household and farm-related decision-making. In situations wherein the principal males are away for a longer period of time, however, the principal females are left behind to work or supervise field activities. The breaking down of joint families into nuclear households also compels women to take on more farm responsibilities. They become *de facto* heads of households as farm managers. Principal females of nuclear families have more decision-making power in farm-related activities compared with women where the principal males are present.

Needs, opportunities, and farmers' feedback on technological innovations

Farmers evaluated several salt-tolerant varieties and nutrient management technologies. Salt-tolerant varieties Usar Dhan 3, CSR 23, and CSR 30 were evaluated by farmer cooperators on their own fields. Aside from salt-tolerant lines/varieties, farmers validated nutrient management technologies (use of pressmud, pressmud+zinc sulfate, and sesbania) on their sodic lands. Farmers like Usar Dhan 3 and CSR 23 because they are of medium duration. These varieties fit nicely in the time window for rice-wheat cropping systems. Usar Dhan 3 and CSR 23, which are of medium duration, are suitable for the upland and medium lands where other crops such as wheat, potato, and pulses, can be grown during the *rabi* season. This variety has good germination and tillering ability (20-25 tillers from 2-3 plants).

Farmers with assured irrigation (underground tubewells) preferred sesbania green manuring as well as pressmud technology. Poor farmers without irrigation, however, showed their preference for the pressmud technology. Farmers were also convinced and agreed on the benefits of the pressmud technology in improving soil fertility, since they obtained higher yields of rice and the succeeding wheat crop in *rabi* season from the same plot in which pressmud was applied in rice fields during wet season. Farmers also observed the benefits on sesbania on the succeeding wheat crop, but the effect was lower than pressmud technology. Some farmers said that 'We have been cultivating sodic fields for several years but we never got such a bumper harvest of rice.'

Women's perceptions on the benefits of their participation in project activities

Focus group discussions with women revealed the following benefits in their participation in the project activities: (a) increased crop yields; (b) improved confidence in applying new knowledge on new rice varieties and improved skills in nutrient management; and (c) enhanced recognition as farmers.

Increased crop yields

Farmer cooperators, men and women, who used pressmud and sesbania revealed that during the last 2-3 seasons, rice and wheat yields increased by 30-50% in their fields. Before the project, they left the fields fallow due to sodicity. Before the project, most of the farmers were not able to manage the field because of high labor and material costs. Thus farmers are willing to apply sesbania and green manure on their sodic plots because they are cheaper than chemical fertilizer. As mentioned by the women: 'Previously seeds did not germinate in our sodic plots; now we have better yields. We will ask our husbands to bring pressmud from the sugarmill so that we will continue to have good yields.'

Gained confidence in applying knowledge on new rice varieties and in expressing their opinions regarding new technologies

Before the project, women engaged in rice farming were rarely consulted by scientists. In this project, women farmers were deliberately invited as cooperators in participatory varietal selection, focus group discussions, and field days. Their opinions with regard to new varieties and introduced crop management practices were elicited along with the men. Thus after involving them in the project, the women gained confidence in applying their knowledge on new rice varieties and in expressing their opinions regarding new technologies. The women cooperators mentioned that improved soil health increased the crop yields of rice and wheat, thus increasing their food security as well as their income. Due to low yields, their production was just enough for their consumption. Now they are able to sell some of their crops.

They mentioned that salt-tolerant variety CSR 23 is good for sodic soil in terms of duration, plant height, threshability, milling recovery, taste, and for puffed rice. Straw is also preferred by animals. Usar Dhan 3 is high yielding (>3 t/ha) and of medium duration, with long slender grains with bright appearance. It is also suitable for sodic land, but cooked rice taste is inferior. Duration is important because farmers want the variety that fits into their cropping system. Early rabi crops are grown as succeeding crop after rice. Farmers preferred short to medium duration varieties to escape the terminal drought, particularly in the flowering stage. Farmers' existing varieties Sarjoo52 and NDR359 performed better than earlier in those plots where CNRM technologies were introduced. 'We are happy that male scientists are asking our opinions in rice or other crop cultivation and appreciating our suggestions.'

Recognition as farmers

The inclusion of women as farmer-cooperators in focus group discussions and farmer-managed trials led to the recognition of their roles as farmers/food producers. As mentioned by women farmer cooperators, 'This is the first time that scientists talked to us and provided us with information on how we can increase crop production on sodic soils. Although we had been working in the fields for a long time, we did not realize that there are new methods in farming and new seeds of varieties that can survive in sodic soils. Now we are hopeful that we can increase our rice yields. Now that we attend field days and planning meetings, we feel that we are now recognized as farmers rather than laborers in our farms. Ensuring that our family will have something to eat today and tomorrow will mainly depend on us.' Other women said that 'Earlier we only worked as laborers in our field. We believe that we are destined to be poor and can only contribute by doing heavy work. However, by joining the project we have increased our knowledge and we can now help our husbands in making decisions related to crop production. Thus we feel that our status also improved.'

Conclusions and recommendations

In this CPWF project, baseline socioeconomic surveys, including gender analysis, were conducted to identify gender-differentiated constraints to crop productivity in salt-affected environments. Men and women were involved in farmer-participatory testing of stress-tolerant varieties, and associated nutrient management technologies such as green manuring with sesbania and use of pressmud. These technologies were refined, validated, and out-scaled to reach their end beneficiaries, including men and women farmers. Men and women were given instructions on how to apply these technologies and then test them on their own fields. Women benefitted by producing increased crop yields, applying knowledge on new rice varieties and in expressing their opinions regarding new technologies, and enjoy their new recognition as farmers/food producers not as farm laborers.

Biological and social scientists should continue to work together to include not only men but also women as end users and potential beneficiaries of research projects. Our project will continue to enhance the capacities of NARES partners in including men and women in farmer participatory approaches in varietal selection and validation of nutrient management technologies. The inclusion of both men and women farmers in rice research and technology development will bring hope for a better life to the disadvantaged families, especially the women, whose livelihoods depend on rice.

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Germplasm and management strategies for enhancing productivity of salt-affected areas

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Abstract

The productivity of salt-affected coastal and inland areas is seriously hindered by salt stress, and disproportionately affects poor farmers. Our work involves identification of rice and non-rice crops and varieties tolerant to salt stress; unraveling the underlying mechanisms of tolerance, transferring tolerance into suitable varieties, and evaluating them in partnership with farmers. Conventional and modern breeding strategies are used including the development and use of molecular markers, to greatly speed the breeding process. Through a network of germplasm exchange, breeding lines were selected by seven NARES in three river basins, and numerous salt-tolerant lines were either released as varieties for commercial use or promoted for release as in India, Bangladesh, and Vietnam. Affordable integrated crop, nutrient, and other natural resources management practices, including soil sodicity/salinity mitigation strategies, were developed in association with salt-tolerant material. These strategies include proper seedling nursery management, integrated use of organic, inorganic, and bio-fertilizers, water management, and the use of cheap amendments such as 'pressmud,' are being validated and out-scaled through farmer participatory approaches. Use of tolerant varieties also helped reduce the amount of gypsum required to reclaim sodic soils to only 0.25 of the recommended levels. Effective cropping patterns were developed through adjusting the cropping calendar, which became feasible with the availability of short-maturing salt-tolerant varieties. Through partnership with ICRISAT and ICBA, new non-rice crops were introduced for the dry season where freshwater resources are scarce, and in areas where salinity is too high, rice-shrimp/fish systems were evaluated. These interventions demonstrated enormous potential for enhancing land and water productivity and farmers' income in salt-affected areas.

Media grab

There is enormous potential to improve food security and livelihoods for millions of the world's poorest people struggling to survive on salt-affected soils, through the adoption of simple and affordable management strategies combined with salt-tolerant crops.

Introduction

High salt stress is an ever-existing and worsening problem, progressively degrading lands and resulting in low productivity in over 20 million ha in coastal and inland Asia. Coastal salinity, caused by seawater intrusion and shallow saline water tables, is severe during the dry season, while flooding in the monsoon season limits cropping to rice. In inland areas, saline and sodic soils are widespread and progressively expanding because of improper water management. Rice is suitable for rehabilitating salt-affected soils because it can grow under flooding and has high potential for genetic improvement. But rice productivity in salt-affected areas is low and could be raised by 1–2 t/ha, providing food for millions of the poorest people and making use of some of the least exploited land and water resources.

The project objective is to enhance land and water productivity of rice-based cropping systems in salt-affected areas, by integrating genetic improvement and management strategies that are environmentally sustainable and socially acceptable. Building on past research accomplishments, the project uses science-based and impact-oriented approaches to develop interventions that are

appropriate to local farmers' conditions. Both conventional and modern breeding tools are being used to accelerate the development of salt-tolerant crop varieties, which are being evaluated with matching crop and natural resource management practices within a farming systems' context. Furthermore, opportunities are being explored for increasing crop intensity and diversity to improve farmers' incomes and livelihoods.

Methods

Most of the germplasm shared with partners through this project was generated at IRRI; however, some lines generated by NARES partners were also included in the different testing networks. Detailed descriptions of the approaches used in the generation of this germplasm, and in the selection and dissemination of adapted material at particular sites, and its subsequent participatory evaluation and feedback are presented elsewhere (Gregorio et al., 2002; Lang et al., 2008; Salam et al., 2008; Singh et al., 2008a). Examples of the approaches used for the development and validation of crop and nutrient management practices are summarized in Singh et al. (2008b) and Ram et al. (2008), and on crop intensification in Mahata et al. (2008). Both breeding lines and management practices are evaluated in target areas jointly by farmers and local researchers using participatory varietal selection (Salam et al., 2008).

Conventional approaches for introducing improved varieties have had limited success in unfavorable ecosystems in Asia, such as in salt-affected areas, mainly because of the complexity and coexistence of multiple stresses, variable farmers' preferences, and site-specific adaptation requirements. To accelerate the development and adoption of new varieties, integrated approaches were followed using conventional and modern breeding tools, and involving beneficiaries in evaluation and validation of new elite breeding lines. Developing broadly adapted varieties is more viable for these areas because abiotic stresses are particularly variable and complex, and growing conditions are too risky to persuade farmers to invest in inputs. In most cases, superior performance of genotypes under experimental conditions does not guarantee similar performance in farmers' fields, and occasionally farmers reject genotypes that yield well in the field if they do not satisfy their specific preferences. In view of these difficulties, the project uses participatory varietal selection (PVS), where farmers take part in varietal screening and adaptation testing, to accelerate adoption (Salam et al., 2008), using germplasm from breeding networks such as the International Network for Genetic Evaluation of Rice (INGER), particularly its International Rice Soil Stress Tolerance Observational Nursery (IRSSON). Salt-tolerant lines were selected based on adaptation and consumer preferences and sent to each partner institution each year. Promising lines were selected through PVS trials, and some were released or promoted for release as varieties in various countries.

Proper crop and nutrient management options were also being developed, particularly for the new varieties. On-farm trials were conducted in most of the project sites using salt-tolerant varieties and selected nutrient management options involving various combinations of green manures, chemical, organic, and bio-fertilizers, and local industrial by-products such as 'pressmud,' a by-product of the sugarcane industry. Successful strategies are being evaluated and out-scaled in partnership with farmers.

Results and discussion

Germplasm development and dissemination

In most areas, farmers increased their paddy yield from < 2 t/ha to >3.5 t/ha using improved varieties and management. In some situations, these technologies made the difference between a failed crop (zero yield) and a yield of 2-3 t/ha. As a result, neighboring farmers were also encouraged to adopt these new varieties. The success of the PVS model was recently witnessed by the release of BRRIIdhan 47 as the first salt-tolerant variety for the dry season in coastal Bangladesh (Salam et al., 2008). In addition, numerous lines with substantially higher levels of tolerance were identified including four varieties introduced from Vietnam into Bangladesh, some of them with >1 t/ha of yield advantage over the current popular varieties (Salam et al., 2008). In coastal Vietnam, some varieties were developed that can yield 4-5 t/ha under salt stress of 6-9 dS/m, and which are now being out-scaled (Lang et al., 2008). Significant progress was also made in developing varieties adapted to the inland saline and sodic soils as in Lucknow and Faizabad in UP, India. Varieties such as CSR30, an aromatic fine-grain, salt-tolerant variety, and CSR23, recently became popular among farmers. Introducing PVS increased the adoption rate and helped in soliciting feedback from farmers to devise better breeding strategies and customized breeding materials. When combined with appropriate management strategies, the next generation of tolerant rice varieties will contribute substantially toward increasing and sustaining rice production in these fragile ecosystems.

Previous work at IRRI identified several salt tolerance quantitative trait loci (QTLs), including *Salto1*, a major QTL on chromosome 1 (Ismail et al., 2007). *Salto1* was fine-mapped and is currently being introgressed into a number of popular varieties including IR64, BRRIIdhan 28, and BR11. This helps to greatly shorten the breeding cycle (from 6 to 10 years to ~2.5 years) and increase the chances of adoption by introducing tolerance into popular varieties. Efforts were also devoted to the collection and evaluation of landraces at each site as prospective sources of new tolerance traits for use in breeding.

Management strategies

These studies showed that an approach combining integrated nutrient management with improved salt-tolerant rice varieties could substantially increase and sustain productivity in salt-affected areas because tolerant varieties are more responsive to inputs that enhance yield or mitigate the stress. An example of this is the response of salt-tolerant varieties to different nutrient managements under field conditions, where substantial increase in yield was recognized over farmers' varieties and practices (Figure 1). Another example is observed on alkaline soils in Utter Pradish, India, where the use of tolerant varieties resulted in considerable reduction in gypsum requirement for the reclamation of these soils. Use of tolerant varieties alone reduced the gypsum requirement to only 0.25 of the recommended level, with similar effectiveness on soil reclamation. This practice is particularly important in being affordable to farmers, and with the current decline in gypsum supply and increased cost. Integrating the use of 'pressmud,' which is rich in organic matter, sulfur, and zinc, with salt-tolerant rice varieties substantially improved rice productivity on sodic soils. This technology was further validated in farmers' fields across several villages in sodic soils of Eastern Uttar Pradesh. Improved rice varieties such as Usar 3, Sarjoo 52, CSR23, CSR30 and NDRK5083 showed a yield advantage of 1-4 t /ha in sodic soils with pH range of 9.2 (moderately sodic) to 10.5 (highly sodic). Basal application of 10 t/ha of pressmud resulted in an additional 30-60% increase in grain yield on farmers' fields and also improved soil health through reducing the pH. This further allowed crop intensification, where farmers started growing 2-3 crops of rice and non-rice crops each year (Ram et al., 2008).

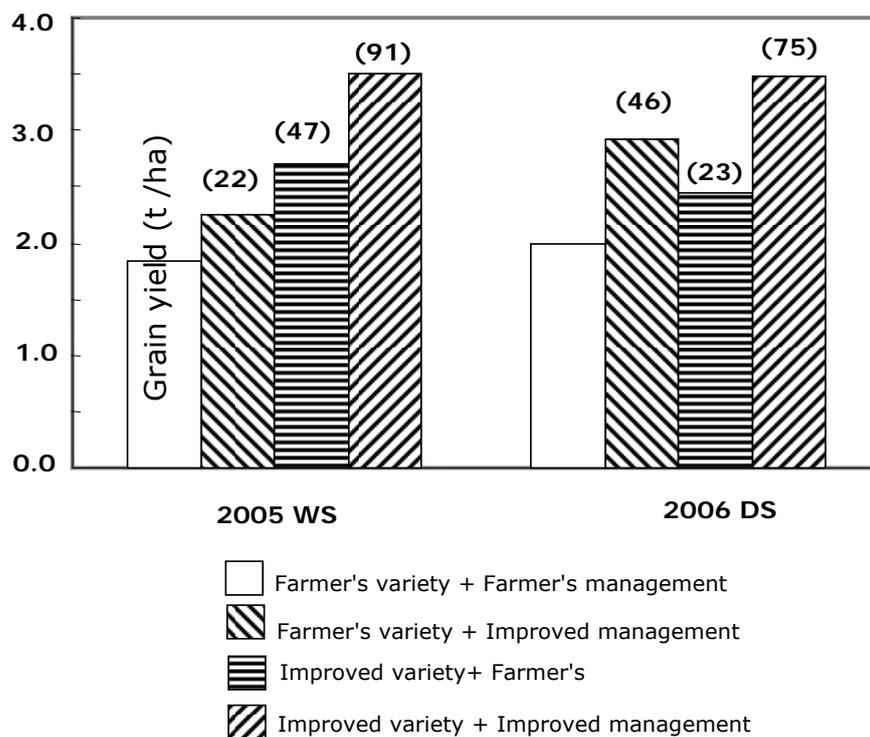


Figure 1. Yield improvement through the use of improved management practices and salt-tolerant rice varieties at the farmers' field in coastal Orissa, India. The numbers in parentheses indicate the percentage increase in yield obtained over that of farmers' varieties and management practices.

Cropping intensity and diversity

Coastal saline areas are mostly mono-cropped with rice during the wet season. This is mainly because of the lack of proper crops and varieties and knowledge of alternatives for the dry season. In coastal Orissa, India, numerous non-rice crops were evaluated during the dry season over a few years, including sunflower, *Basella*, watermelon, chilli, pumpkin, peanut, tomato, bitter gourd, and okra, under medium and high salt stress. In most cases, all crops performed well under medium salinity, while only few crops such as sunflower and *Basella* produced reasonable yields under high salinity. Across seasons and salinity levels, watermelon, chilli, pumpkin, and sunflower were the most promising dry-season crops based on rice yield equivalent, net return, and water productivity. In Vietnam, new cropping patterns involving high-yielding, short-maturing rice varieties for less saline

areas with ample fresh water during the dry season, non-rice, high value crops such as soybean and peanuts for areas where fresh water is scarce, and rice-aquaculture systems for areas where salinity is high during the dry season, were evaluated. The introduction of short-maturing rice varieties coupled with water harvesting and proper management of irrigation water enabled doubling the cropping intensity and annual grain yield in South Bangladesh. Apparently, considerable opportunities exist for diversification of rice-based systems in saline ecosystems. Farmers' responses to adoption of the new non-rice crops are encouraging and demand for seed is increasing rapidly in these areas.

Conclusions and recommendations

In this project, greater emphasis was devoted to germplasm enhancement through: 1) development and use of molecular tools to speed up breeding; 2) strengthening the capacity of local breeding programs; and 3) exchange and testing of new varieties and breeding lines of rice and non-rice crops. Through these efforts, adaptive high-yielding breeding lines were identified and some were released as varieties. Good progress was made in the collection and evaluation of landraces from salt-affected areas in different countries as new sources of tolerance. ICRISAT and ICBA contributed new upland crops and varieties suitable for salt-affected areas, including food and forage crops, doubling the cropping intensity in some of the project areas. Non-rice crops such as sunflower, chilli, watermelon and okra, sweet potato, peanuts and soybean, are now being promoted in areas with limited water availability for the dry season, and most farmers have reported good harvests. Rainwater harvesting is effective for expanding the cropping area during the dry season in coastal ecosystems. The project also developed efficient management and low-cost reclamation technologies to maximize the performance of tolerant crop varieties. The benefits of combining improved salt-tolerant rice varieties with matching management practices were demonstrated through on-farm trials, giving substantial increases in yield. Expansion of rice and non-rice crops during the dry season is now possible for the first time in Orissa and some parts of Uttar Pradesh, India, South Bangladesh and Vietnam, with significant increase in food availability, employment and income. More efforts are needed to ensure that these technologies are further refined, validated, and out-scaled to reach their ultimate beneficiaries. Greater attention should be paid to these unfavorable salt-affected areas to explore and exploit their enormous potential for better system productivity for the millions of poor people who struggle to survive in these areas.

Acknowledgments

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Is the Quesungual System an option for smallholders in dry hillside agroecosystems?

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Abstract

The Quesungual Slash and Mulch Agroforestry System (QSMAS) is a smallholder production system with a group of technologies for the sustainable management of water, soil and nutrient resources in drought-prone areas of hillside agroecosystems of the sub-humid tropics. QSMAS integrates local and technical knowledge and provides resource-poor farmers with an alternative to the non-sustainable, environmentally unfriendly slash and burn (SB) traditional production system. The main objective of this study was to determine the key principles behind the biophysical resilience of QSMAS and its capacity to sustain crop production and alleviate water deficits on steeper slopes with risk of soil erosion. Activities included the evaluation of QSMAS performance compared to the traditional slash-and-burn system in terms of water dynamics (including crop water productivity), nutrient dynamics, and greenhouse gas fluxes (including global warming potential). Results indicate that the application of the four principles behind QSMAS productivity and sustainability (no slash-and-burn, permanent soil cover, minimal disturbance of soil, and improved fertilizer practice), has positive effects on the soil-plant-atmosphere continuum, soil quality, and on landscapes and the environment. Validation in Nicaragua and Colombia underpin the potential of QSMAS to enhance support for livelihoods in vulnerable rural areas.

Media grab

An improved indigenous agricultural production system may be adaptable to replace the non-sustainable, environmentally unfriendly slash-and-burn system traditionally used by resource-poor farmers in hillside sub-humid tropical regions.

Introduction

The Quesungual Slash and Mulch Agroforestry System (QSMAS) is a smallholder production system with a group of technologies for the sustainable management of water, soil, and nutrient resources in drought-prone areas of hillside agroecosystems of the sub-humid tropics. QSMAS is an indigenous production system identified by technicians and then improved in collaboration with local farmers, resulting in a suitable option to replace the slash and burn (SB) traditional system. QSMAS is being practiced by resource-poor smallholders in southwest Honduras to produce major staples (maize, bean, sorghum), where the system has been successfully adopted by over 6,000 resource-poor farmers on 7,000 ha.

Widespread adoption of QSMAS has been driven by its biophysical and socioeconomic benefits at multiple scales ranging from farm (increased crop-water productivity, food security) to landscape (better amount and quality of available water, resilience to extreme water deficits and to excess water) (Ayarza and Welchez, 2004; TSBF/CIAT, 2003). Adoption of QSMAS has contributed to improved livelihoods of the rural poor through increased water resources and food security in sub-humid hillside areas, while maintaining the soil and plant genetic resources for future generations. The main objective of the work described in this paper was to determine the key principles behind the

biophysical resilience of QSMAS by defining the role of the management components of the system and QSMAS' capacity to sustain crop production and alleviate water deficits on steeper slopes with high risk of soil erosion.

Methods

The performance of QSMAS was studied in southwest Honduras, within the Lempa River upper watershed department (district) of Lempira, from 2005 to 2007. Mean annual (bimodal) precipitation is ~1400 mm falling from early May to late October, with a long dry season of up to 6 months. Field plots were established in April 2005 for the comparison of five main treatments (replicated on three different farms): QSMAS of three different ages (<2, 5-7 and >10 years old), the traditional SB system, and secondary forest (SF) as reference. The four production system treatments (QSMAS of different ages and SB) were split in order to apply a fertilizer treatment (addition vs. no addition). Studies included: monitoring and analysis of soil water dynamics, crop yield and water productivity, nutrient (N and P) and soil organic matter dynamics, greenhouse gas (GHG) fluxes, global warming potential (GWP), energy⁴ sustainability index and ecological footprint index.

Water dynamics were evaluated through the assessment of infiltration, runoff and soil water availability during the rainy and dry seasons of 2007. Water infiltration and runoff were evaluated through rainfall simulation for 30 minutes using two intensities (80 and 115 mm/ha). Soil water content was evaluated through soil sampling at three depths (0-10, 10-20 and 20-40 cm). Susceptibility of the soil to erosion was determined in erosion plots (5 m length x 1.5 m width) over 3 years. Soil losses were determined through the comparison of the indices of soil erodibility K-USLE [(t/ha.h)/(MJ.mm)] and Ki-WEPP (kg/s/m⁴), corresponding to the Universal Soil Loss Equation (Wischmeier and Smith, 1978) and to the Water Erosion Prediction Project (Nearing et al., 1989), respectively. Nutrient losses through erosion were quantified by determining total contents of N, P, K, Ca and Mg from samples of eroded soils. Water quality was assessed through the determination of NO₃⁻, NH₄⁺, P, PO₄³⁻ and soluble solids in samples collected 45 days after planting (DAP). Both eroded soil and water samples were collected in the erosion plots in 2007. Crop water productivity (CWP), expressed as kg of grain produced per m³ of water used as evapotranspiration, was calculated using the crop yield and soil water data obtained in 2007 and by estimating the evapotranspiration according to the method of Penman and Monteith (FAO, 1998).

Measurements for the study on nutrient dynamics included: (1) decomposition of and nutrient release from biomass of trees, shrubs, and annual crops, using the litterbag technique (Shanks and Olson, 1961); (2) N aerobic mineralization (NH₄⁺ and NO₃⁻ + NO₂⁻), determined by mineralization of the whole soil (Anderson and Ingram, 1993); (3) partitioning of soil total P following a shortened sequential P fractionation (Tiessen and Moir, 1993, after Hedley et al., 1982); (4) size-density fractionation of soil organic matter (SOM) in the soil (Meijboom et al., 1995; Barrios et al., 1996); and (5) nutrient partitioning of crop biomass.

GHG fluxes including N₂O, CH₄ and CO₂ were determined using the closed chamber technique, with 16 sampling dates from July 2005 to July 2006. Global warming potential (GWP) was determined using CH₄ and N₂O fluxes, and C stocks in soil (soil organic carbon) and in tree biomass. GWP values were extrapolated to the region where QSMAS is practiced and were projected in time considering land use change. An energy evaluation was conducted to quantify resource use and system sustainability, using data from plots and relationships (energy input per unit of energy output) reported in other studies.

Results and discussion

During the rainy season, SB had the lowest infiltration (29.8 mm) and highest runoff (12.0 mm). In contrast, QSMAS >10 years had the highest infiltration (38.5 mm) and lowest runoff (4.8 mm). SF had the highest infiltration (43.9 mm) and lowest runoff (1.6 mm) during the dry season. SB system again showed the lowest infiltration (41.9 mm) and highest runoff (2.4 mm), while QSMAS 5-7 and QSMAS >10 years had higher infiltration (44.3 and 43.9 mm, respectively), and lower runoff (0.91 mm). SB had lower infiltration and higher runoff than QSMAS, during both the rainy and dry seasons.

In the rainy season available soil water (0-40 cm) varied between 0.09 and 0.104 m/m, with QSMAS <2 and QSMAS 5-7 showing higher values than SF (by 16 and 10%, respectively). In the dry season the amount of available water varied between 0.11 and 0.127 m/m in SB and QSMAS <2, respectively. The mean value of available soil water content (0-40 cm soil depth) in QSMAS systems was significantly greater than that of SB system (Figure 2), suggesting increased availability of water for crop growth. These improvements in QSMAS were related to changes in soil porosity due to increases in mesoporosity (30%) and macroporosity (19%), and decreased the soil bulk density. This increased the plant available soil water storage capacity and availability of water for crops in the dry

⁴(defined by H.T. Odum (1996) as the total solar equivalent of available energy that is needed directly and indirectly in making a product, good or service).

season, and increased the capture of rainfall at the beginning of the rainy season.

The highest soil loss occurred in 2005, and was highest in SB followed by QSMAS and SF (Figure 1). The same trend was observed in 2006 and 2007. Soil losses from SB were 5.6 times greater than the average losses from the three QSMAS treatments, and 22 times greater than the losses from SF. Using the rainfall simulator, higher indices of soil erodibility were also observed with the SB system in both seasons, while SF presented the lower indices. As expected due to higher soil loss, the SB system had greater nutrient losses (kg/ha) of N (9.9), P (1.3), K (6.9), Ca (22.8) and Mg (24.2). Similarly, as QSMAS lost less soil it also had lower nutrient losses. SF presented the lowest losses (kg/ha) of N (1.7), P (0.2), K (1.2), Ca (2.6) and Mg (2.7).

Water quality was poorest in SB system, with highest content (mg/L) of total P and PO_4^{3-} (2.30 and 0.29, respectively), and best in QSMAS >10 (0.18 and 0.25, respectively). In the same way, SB system had the highest values (mg/L) of NO_3^- and NH_4^+ (7.97 and 0.70, respectively), while QSMAS 5-7 showed the lowest content of NO_3^- (6.13) and QSMAS >10 of NH_4^+ (0.24). Highest soluble solids (mg/L) was observed with QSMAS 5-7 (183.3), and lowest with QSMAS <2 (83.3). SF presented values (mg/L) of 0.65 for P, 0.43 for PO_4^{3-} , 4.73 for NO_3^- , 0.92 for NH_4^+ , and 25.0 for total soluble solids.

Crop water productivity (CWP, kg/m^3) for maize was greatest in fertilized systems of QSMAS <2 (0.48) and least with QSMAS >10 (0.18 kg/m^3) (Figure 3). In plots with no fertilizer application, the highest CWP was observed with QSMAS <2 (0.26) and the lowest with SB (0.10). In both fertilized and nonfertilized systems, CWP for common bean was greatest in QSMAS <2 (0.32 and 0.27 kg/m^3 , respectively) and least with SB (0.10 and 0.07 kg/m^3). Fertilization increased CWP for both maize (by 92%) and common bean (by 23%). These results may reflect adequate available soil water during the maize crop in the rainy season, when precipitation was higher than evapotranspiration (ET). In the case of common bean, available water content in the soil decreased from flowering to physiological maturity, with lower precipitation than ET and therefore with a negative water balance. Under these conditions, QSMAS showed greater available water content in soil that resulted in greater grain yield and CWP.

Total soil N content was not different among land use systems (LUS) within each year. Trends across the years, however, showed that the content of N decreased with time in the SB system while it increased in QSMAS (with the highest increase in QSMAS >10) and in SF. The comparison of total N in SB system vs. QSMAS <2 (with a similar period under production) and SF (the natural condition which is disturbed for the establishment of either QSMAS or SB), suggest that the use of SB can drive rapid reduction of this nutrient in the landscape while QSMAS maintains and even increases the pool of N from the moment the system is established. Over the 3 years, potential N mineralization (N-min) was not different between LUS. The study on P dynamics showed different trends in SB and SF, with SB showing an increase in the organic (Po) pool and QSMAS increasing its inorganic (Pi) pool. In terms of P availability, over the years the average size of P pools relative to total P were: available P (AP) 12% of total P, moderately available P (MAP) 29%, and residual (not available) P (RP) 59%. The RP pool tended to increase and MAP and AP pools tended to decrease over time in the SB system relative to SF, while QSMAS (average of <2 and >10 years old plots) exhibited the opposite tendency (Figure 4).

The similar behavior in N-min and P available pools among production systems is a positive finding, because it implies the following: (i) QSMAS is as good as SB as a source of N and P, even though in QSMAS their content is more a result of biologically mediated process than of an accelerated process that drives immediate availability of nutrients, such as burning; and (ii) QSMAS performs consistently over time, suggesting that this form of management may provide a sustainable source of N and P. Additionally, at similar rates of N-mineralization, the N balance in SB system is expected to be less positive than in QSMAS, considering that yearly SB has lower additions of N (no fertilization and fewer sources of biomass) and higher losses of N through burning (volatilization losses of ammonia and wind-related losses of ash) than QSMAS.

Results from the study on GHG emissions showed that QSMAS and SF were CH₄ net sinks, with values (mg CH₄ /m²/year) of -102 and -36, respectively. The only CH₄ net source was SB, with 150 mg CH₄ /m²/year. All LUS were found to be N₂O and CO₂ sinks, resulting from natural processes (SOM decomposition) and from management (fertilization). QSMAS presented a much lower GWP (10.5 Mg Equiv. CO₂) than SB system (40.9 Mg Equiv. CO₂) (Figure 5). SF had a very low GWP (1.14 Mg Equiv. CO₂). According to land use change trends, when projecting GWP to the region where QSMAS is practiced and using a 20-year time horizon, we estimate a decrease of 0.10 Tg Equiv. CO₂. Higher C stocks in soil and tree biomass indicate a gradual accumulation of C in SF and QSMAS >10. In the energy evaluation major differences were observed in the eroded soil variable, with higher values in the SB system. SF and QSMAS had less environmental impact than SB as noted in the Environmental Loading Ratio with values of 0.63, 0.14, and 0.02, respectively. SB presented the higher Ecological Footprint Index. Sustainability Index values were 34.8 for SB, 135.6 for QSMAS, and 4123.8 for SF.

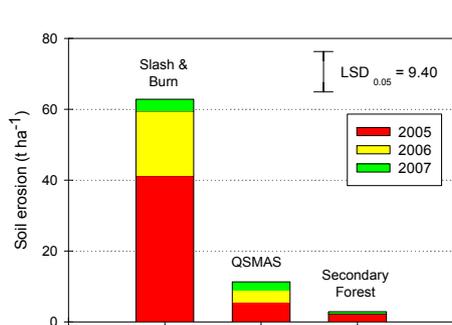


Figure 1. Accumulated soil losses in three land use systems in 2005. QSMAS value is the average of three different

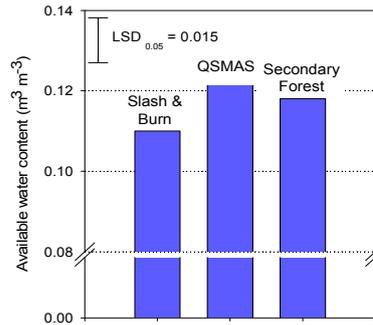


Figure 2. Average available soil water content in the dry season of 2007. QSMAS value is the average of three different ages.

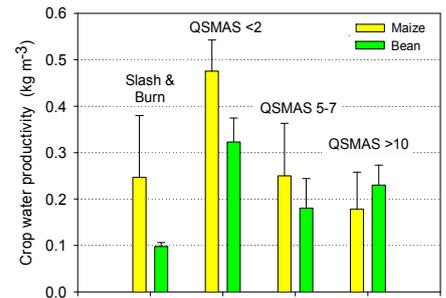


Figure 3. Crop water productivity in two land use systems (mean of treatments with and without fertilization). LSD_(P>0.05) are 0.14 for maize and 0.10 for common bean.

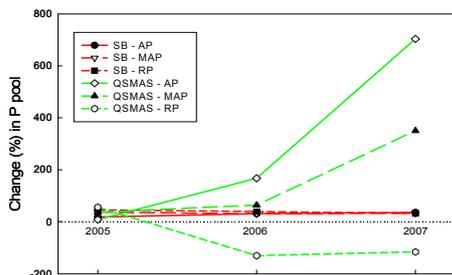


Figure 4. Changes on P pools in soil from SB without fertilization and QSMAS (average of fertilized QSMAS plots of <2 and >10 years old) in relation to the SF.

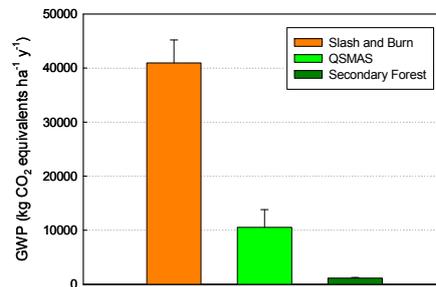


Figure 5. Global Warming Potential (GWP) in a 20-year scenario of three land use systems in Lempira, southwest Honduras.

Conclusions and recommendations

The improved knowledge and understanding of the QSMAS system and the results from field studies lead to the following general conclusions:

- The set of technologies responsible for the success of QSMAS can be synthesized in four basic principles that contribute synergistically to its superior performance: (1) no SB, through the management of natural vegetation; (2) permanent soil cover, through the continual deposition of biomass from trees, shrubs, and weeds, and through crop residues; (3) minimal disturbance of soil, through the use of no tillage, direct seeding, and reduced soil disturbance during agronomic practices; and (4) efficient use of fertilizer, through the appropriate application of fertilizers.
- Management practices based on the key principles result in increased C synthesis and accumulation, accelerated nutrient cycling, and improved crop water productivity in a resilient production system, thereby enhancing support for livelihoods through water-efficient and soil-conserving technologies in vulnerable rural areas.
- Experience in on-farm participatory validation suggests that QSMAS will be readily accepted and adopted by smallholders in similar agroecosystems, and it also will receive strong support from local authorities and policy makers.

Acknowledgments

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Is soil carbon sequestration part of the bundle of ecosystem services provided by conservation agriculture in the Andes?

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Abstract

The positive role that conservation agriculture (CA) has on ecosystem services in the Fuquene watershed (in the Andes of Colombia) derives from better soil water retention, sediment retention and water infiltration located in the Andes. Soil carbon retention could be, however, an additional soil ecosystem service inside the 'bundle' of services provided by CA in this watershed. The objective of this research was to compare soil organic carbon (SOC) content and its stability in different soil aggregate sizes under traditional tillage and CA (reduced tillage, green manuring, permanent cover) in a potato-based production system. Soil organic matter (SOM) and SOC contents were not significantly increased with CA, and the stability of carbon was lower in production systems with these practices. This was explained by lower soil moisture with traditional practice, and by the naturally high OM content and deep A horizon (~0.2 g/g, 72 cm A horizon) of these soils. Although the stability of carbon was not increased, the CA practices are ensuring the nondisruption of aggregates that has a positive effect on water-related soil characteristics such as porosity, hydraulic conductivity, and soil moisture.

Media grab

In the Andes conservation agriculture practices ensure soil aggregate protection against mechanical breakdown reducing the probability of emitting C to the atmosphere and improving water movement throughout the soil, which favors the volume of stream flows.

Introduction

Much of the world's carbon is held in soils (more than 41%) and another significant part is in the atmosphere, as carbon dioxide (20%). Soil disturbance for crop production is, however, reducing soil carbon and augmenting the atmospheric carbon pool. Golchin et al. (1995) classifies light fraction soil organic carbon (SOC) into free particulate organic carbon and occluded organic carbon. Bremer et al. (1994) found that the SOC light fraction is a sensitive indicator of management-induced effects on SOC.

SOC accumulation to some degree depends on the amount of soil disturbance. Disrupting macroaggregates exposes the microaggregate carbon pool to decomposition (Bajracharya et al., 1997). Management systems involving high C inputs and reduced tillage should favor C storage directly by reducing aggregate breakdown and by enhancing SOM-mediated aggregation (Angers, 1992; Carter, 1992; Beare et al., 1994).

Conservation agriculture (CA) is one of the management systems practiced in the watershed of Fúquene Lake, located in the valleys of Ubaté and Chiquinquirá, north of Bogotá, Colombia. These practices were introduced to reduce erosion from potato farms on very steep slopes, which is causing sedimentation and eutrophication of the lake. This lake provides potable water to more than half a million people downstream. Although the benefits of reduced sediments and increased net income of farmers are recognized (Rubiano et al., 2006), there are no studies about the impact of these practices on soil carbon protection.

The objective of this research, therefore, was to determine carbon content and its stability in stable soil aggregates in two different systems (traditional tillage vs. CA). To achieve this, the protected carbon in soil micro- and macroaggregates was measured using sonication techniques. The hypotheses were that with CA: (1) soil organic matter content is increased; (2) the stability of carbon contained in aggregates is increased; and (3) the SOM (and the SOC) is more stable in smaller size fractions of aggregates.

Methods

Two potato production systems (traditional tillage, CA with minimum tillage with incorporation of green manures and permanent plant cover for 7 years) were compared at six sites (three sites per system) within the Fuquene watershed. The soils are Andisols and are classified as Lithic Hapludands (IGAC, 2000). The sites were selected with the same characteristics in terms of: (1) landscape position; (2) land cover; (3) slope; and (4) rainfall intensity. At each site, two pits were dug, soil horizons were identified, and three soil samples were taken per soil horizon. Fresh samples were segregated and classified by size using dry-sieving with a nest of sieves with 5, 2, 1, 0.5 and <0.5 mm screen size. Additional samples were taken to measure saturated hydraulic conductivity, soil moisture, porosity, and bulk density. In general, three horizons were found in the profiles with average thicknesses of 72 cm (horizon I, top), 21 cm (horizon II), and 56 cm (horizon III, bottom).

Soil organic matter content of each aggregate size class was extracted using a sonication procedure (North, 1976; Six et al., 2001). Through this procedure, some of the SOM in the aggregates was extracted while the rest of the SOC remained in the aggregates even after sonication. The organic matter extracted from the aggregates by sonication was called AOM (aggregate OM) as it contained fine organic matter from inside aggregates. Organic matter remaining in the same particle size class after sonication was termed particulate organic matter (POM). Different levels of energy were applied to see how AOM and POM are affected by the degree of disruption. The AOM and POM were measured through the loss on ignition procedure, and %AOM was calculated as percentage of total SOM (AOM+POM). All SOM measurements were converted to estimates of SOC concentration by multiplying by the Van Bemmelen factor of 0.58 (Lal et al., 1998). It was expressed as percent of total organic matter in each sample.

Data analyses

The effects of production system on %AOM and SOC were analyzed using analysis of variance (ANOVA) with soil horizon, type of management practice and aggregate size fraction as fixed effects. Differences were considered significant at $p < 0.05$. There were significant effects of horizon and size fraction on %AOM and SOC. Therefore further statistical analysis was done separately for each size fraction and horizon. A post hoc comparison procedure with the Tukey-Cramer adjustment was used. The SOM and AOM values were correlated to physical soil characteristics using a linear model.

Results

Soil organic carbon concentration and tillage systems

The average concentration of SOC in the soil profile was not significantly affected by the management system, and averaged 0.12 g/g with CA and 0.09 g/g with traditional tillage. SOC was significantly higher in the top horizon (0.13 g/g) than in the deepest horizon (0.05 g/g).

Aggregate stability and SOM content

As the ultrasonic energy applied to the soil increased, more aggregates were destroyed, increasing the amount of AOM removed (Table 1). The effect of size fractions on % AOM was highly significant ($p < 0.01$). The 5 mm fraction released significantly less organic matter than the smallest size fraction (0.5 mm).

Table 1. Average values of AOM for different aggregate size fractions.

Aggregated Organic Matter (AOM) (%)		
Size fraction (mm)	Average	Tukey group
0.5	99.4	a
1.0	95.3	ab
2.0	87.1	ab
5.0	83.2	b

Note: Inside the same column, averages with the same letter are not statistically different.

There was no significant size fraction x tillage system interaction for the AOM. However, %AOM was higher in the 2 and 1 mm size fractions under CA than with traditional tillage (Figure 1). Also, %AOM was higher in the horizon II and III with CA than with traditional tillage, but with similar values in horizon I (Figure 2).

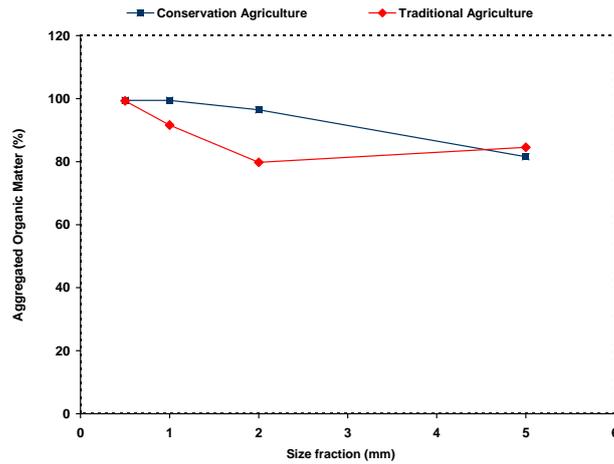


Figure 1. Effect of size fraction on %AOM.

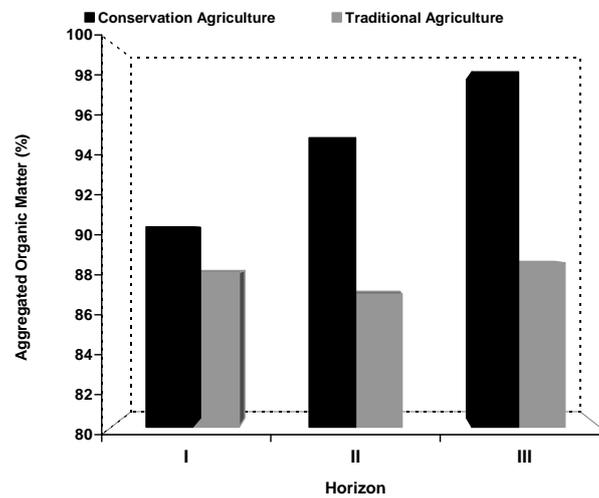


Figure 2. Effect of horizon on %AOM variable.

AOM, SOM, and physical soil characteristics

Simple correlation analyses using a linear model showed that, for CA, aggregate organic matter (g/g) was negatively correlated with the aggregate size (5 mm) ($p < 0.01$; Figure 1) and positively correlated with soil moisture ($p < 0.05$; data not shown). Also, there was a positive correlation of total organic matter (g/g) with hydraulic conductivity, total porosity, and macroporosity in conservation and traditional agriculture treatments (data not shown). The soil moisture and hydraulic conductivity were higher in CA. The average soil moisture for the soil profile in CA was 52% while in traditional agriculture it was 39%. The average hydraulic conductivity was 12 cm/h in CA soil profiles and 5 cm/h in traditional agriculture.

The total organic matter was negatively correlated with bulk density in conservation and traditional agriculture systems. In general, bulk density had a negative correlation with saturated hydraulic conductivity, total porosity, macroporosity, and soil moisture.

Discussion

SOM and SOC contents

The soils of the study sites are Andisols and according to IGAC (2000) are classified as Lithic Hapludands. The high concentration of organic carbon is in line with the high organic matter concentration characteristic of Andosols.

The accumulation of organic matter in these soils is determined by the environmental conditions of the *paramo* ecosystem, which is characterized by low temperatures and high plant biomass (pastures) inputs and low decomposition rates. The lack of significant differences between SOC concentration in CA vs traditional agriculture sites may reflect the difficulty of detecting small changes in SOM against such a high background level, even after 7 years of CA in these soils. The high accumulation of OM in these soils is reflected in the large depth (mean 72 cm) of horizon I. Also, the capacity of these high organic matter soils to store further C may be near maximum. Finally, the lack of significant differences between the production systems may be due to the fact that in the traditional tillage system, potato is rotated every 2-3 years with 2-3 years of pastures (average of 2.7t DM/ha/year). Therefore the benefits of CA could be more related to nutritional benefits, reduction of runoff, and improvement of water movement in the soil profile rather than change in SOC per se (see below).

Aggregation and SOM stability

The results showed no effect of production system on aggregate stability of organic carbon stability in the aggregates, rejecting the second hypothesis. In fact, the aggregates from CA in horizons II and III, and from the 2 and 1 mm size fractions, released more organic matter than the equivalents from the traditional system.

The higher stability of traditional agriculture soil aggregates may result from greater drying of the soil than under CA. Soil moisture was higher in CA sites, especially in horizons II (63 vs. 44%) and III (48 vs. 32%). In Andisols, the presence of minerals such as ferrihydrate and allophone results in irreversible hardening when the soil is dried beyond a certain level (Maeda et al., 1977); the drier the soil, the stronger the aggregates. Other authors have also found that the strength of the bonds between organic materials and mineral particles decreases with increasing water content, resulting in lower stability (Reid and Goss, 1982; Perfect et al., 1990; Gollany et al., 1991; Caron and Kay, 1992 cited in Lal et al., 1992). However in the CA sites the risk of releasing that SOC contained in aggregates is low because of the use of minimum tillage.

While it is recognized that microaggregates protect SOC (Six et al., 2000), we found that in these soils the trend was counter to the third hypothesis, as OM in aggregates of 5mm size fraction was more stable than in the smaller fractions. Similar results were obtained in Spodosols of Florida where the highest strength was obtained in macroaggregates (Sarkhot et al., 2005). This trend is less apparent in horizon III, which could be related to the fact that the content of clay is higher in deeper horizons, making the OM more strongly attached to the microaggregates (the average percentage of clay content in horizon III was 39%, in horizon II 32%, and 19% in horizon I).

The percentage of OM released after applying higher amounts of energy (11.7-15.4 kJ) was high on most soil samples (>80% of total organic matter), and only 17.4% of soil samples released <80% of the total organic matter of the samples. This means that most of the organic carbon is in the aggregate pool and the remaining is POM. This result is in line with other studies that have found that 90% of SOM was located within soil aggregates (Jastrow et al., 1996). This highlights the importance of conserving the aggregation of these soils and reducing its mechanical breakdown by tillage or soil erosion. It is worth noting that this sonication procedure measures the stability of aggregates to mechanical breakdown and does not indicate the susceptibility to microbial breakdown.

Conclusions and recommendations

In Andisols of this Colombian watershed, CA practices had a negligible effect on SOM and SOC concentration. This may be due to the already high SOM content in these soils. In these soils, the benefits of CA (minimum tillage and permanent cover) are related to improving soil characteristics important for increasing infiltration and storage and reducing runoff and erosion, such as hydraulic conductivity, porosity, and bulk density. Probably it also contributes to increased nutrient availability and to reduced soil runoff. In addition, CA practices did not increase SOM stability in aggregates, which may be related to the higher soil moisture in the CA system. It is important to note that CA

ensures that the accumulated OM is not released from aggregates as soil disturbance is minimal in this system.

Since more than 80% of the total organic matter is contained in the aggregates it is important to avoid the disruption of aggregates by mechanical forces in these *paramo* soils. Also the importance of macroaggregates for SOC stability is important in these soils, even more than microaggregate stability, contrary to our initial expectations.

Finally, there is a need to apply the same methodology to explore the effects of CA on SOM and SOC content and its stability in other type of soils with lower COM and with different clay contents.

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Simulating sorghum yield response to mineral fertilizer in semi-arid northern Ghana

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Abstract

In the past, farmers used long fallow periods to restore soil fertility of their fields. This practice has now given way to continuous cropping of the same fields thereby leading to low crop yields. There is therefore a need to evaluate various options of improving soil fertility and crop productivity. In our work, the Decision Support System for Agrotechnology Transfer (DSSAT) was used to assess the yield response of sorghum to varying levels of mineral fertilizers in Navrongo, northern Ghana. DSSAT predicted well the effects of the varying levels of mineral fertilizers on total biomass and crop yields, with an internal efficiency of the model (E1) of 0.63 and 0.69, respectively. Application of 40 kg N/ha in the homestead yielded the best value-to-cost ratio, whereas 80 kg N/ha¹ produced the highest value to cost ratio in the bush farms. Yield projection into 2035 showed that the amount and distribution of rainfall poses a higher risk to efficient use of mineral fertilizer on soils with low organic matter (bush farm) content than to soil with higher (homestead) content of organic matter. Also, food security can only be assured by using inorganic fertilizer and organic matter.

Media grab

The use of organic matter and mineral fertilizers and supplementary irrigation are critical for continuous food production on sandy soils in smallholder farming systems.

Introduction

In the semi-arid region of Ghana in the Volta Basin, poor soil fertility is one the most limiting factors to crop production, along with low water availability due to erratic and poorly distributed rainfall. This is further aggravated by the soil texture, which is mainly sandy (average 70% sand). Farmers have small fields surrounding the house, known as homestead fields, and larger fields farther away called bush fields. The homestead fields receive limited amounts of animal manure from the homestead. Traditionally, farmers practiced bush fallow as a way of restoring soil fertility in the bush fields after cultivating them for some years. This has, however, now given way to continuous cropping due to growing pressure on land, thereby degrading the soil. The practice has rendered the soil poor in fertility, hence farmers are forced to restrict the cultivation of cereals to the homestead where they can provide limited amounts of animal manure and the bush farms are cultivated mainly with legumes. Sorghum is an important crop in the study region due its ability to withstand drought, among other desirable features. Cultivars used by farmers are the locally adapted ones that are less responsive to mineral fertilizer application. The cultivar (ICSV III) used in this study is an improved one that responds to mineral fertilizer. DSSAT was the crop simulation model (CSM) used in the study, which sets out to assess the yield response of sorghum to mineral fertilizer and to assess the sustainability of grains in light of the erratic rainfall pattern for two different fertilizer management practices.

Materials and method

The study was conducted at Navrongo, in the semi-arid portion of the northern part of Ghana (10° 15" and 11° 10" N and 0° and 1° 0" W). Experiments were set up under two management regimes; the homestead, which benefits from some amount of organic manure, and the bush farm, where no manure is applied and which is also characterized by annual bush burning. The sorghum variety ICSV III (a pure-line cultivar developed at ICRISAT Asia center) was used as the test crop. Data collected on sorghum grown under limited water and nutrient stress on two different planting dates in farmers' fields were used to calibrate the DSSAT CSM for the study area. Data collected for model calibration included grain yield, total biomass, and phenological data (days to flag leaf stage, days to flowering). To evaluate the performance of the model, two experiments were set up on the July 12 and 26, 2005: one in the homestead and the other in the bush farm. Sorghum was sown by direct dibbling at about 5 cm depth, 0.75-m row spacing, and 12 plants/m². Four levels (0, 40, 80, and 120 kg/ha) of inorganic N fertilizer were applied in a randomized complete block design. Treatments were replicated seven times in the homestead and four times in the bush farms. Data on grain and biomass yield collected from these experiments were used to evaluate model performance.

Model description and application

The DSSAT CSM utilizes data from soil, weather, and crop management practices. Details of the model can be found in Jones et al. (2003) and Ritchie et al. (1998). The model was used to assess the sustainability of grain sorghum production as affected by the variation in seasonal weather patterns. Fifteen years of weather data (1990–2004) for the study area were used to project over a longer period, and to assess the impact of the distribution of weather pattern on long-term crop production on given scenarios.

Statistical analysis

RMSE and modified coefficient of internal efficiency (E_1) were used to assess model performance.

$$RMSE = [n^{-1} \sum (Yield_{Calc} - Yield_{meas})^2]^{0.5}$$

$$E_1 = 1 - \frac{\sum_{i=1}^n |Observed_i - Simulated_i|}{\sum_{i=1}^n |Observed_i - Mean_{obs}|}$$

The sustainable yield index (SYI) suggested by Singh et al. (1990) was used to assess the sustainability of the two management systems (homestead and bush farm).

$$SYI = (Y_a - \sigma) Y_m^{-1}$$

where Y_a is the mean yield, σ the standard deviation, and Y_m is the maximum yield obtained under each set of management systems. Also, cost benefit analysis of using fertilizers in each of the management systems was undertaken.

Results and discussion

Table 1. Performance of the model.

Sorghum grain yield response to different fertilizer rates was reasonably predicted by the DSSAT–CSM with an internal efficiency of 0.63 and a RMSE of 0.44 t/ha. Total biomass production was also well predicted. A comparison of observed and simulated values of both grain and biomass indicated no significant differences ($p = 0.05$). The E_1 values obtained for both management systems were above 0.6 (Table 1). The RMSE were also low and comparable with those of Mavromatis et al. (2001) in their study on developing genetic coefficients for CSM with data from crop performance trials.

Location	Grain		Total biomass	
	RMSE (t/ha)	E_1	RMSE (t/ha)	E_1
Homestead	0.23	0.68	0.60	0.71
Bush farm	0.37	0.62	0.65	0.69
Overall	0.44	0.63	0.90	0.69

The amount and distribution of rainfall poses a higher risk to efficient use of mineral fertilizer on both management systems, with the risks being higher in the bush farm soil with lower organic matter content, as opposed to the homestead soils that are relatively enriched by the annual application of manure.

Table 2. Summary statistics of grain yield projected over 30 years period

The use of inorganic fertilizer to produce sorghum was economically feasible in both the bush farm and the homestead, with the latter being more economical. Sustainability indices of the various management scenarios as influenced mainly by changing weather pattern over 30 years are shown in Table 2. The highest SYI (0.84) was obtained in the homestead management system where 40 kg N/ha mineral fertilizer was applied. The least sustainable management system ($SYI = 0.36$) was the bush farm where no fertilizer was applied over the simulation period.

Scenarios	Mean	Stdev	Max	Min	SYI
Bush farm 0 kg/ha	0.71	0.264	1.2	0.3	0.36
Homestead 0 kg/ha	1.48	0.256	1.8	1.0	0.67
Bush farm 80 kg/ha	2.86	0.316	3.2	2.0	0.79
Homestead 40 kg/ha	3.16	0.220	3.2	2.2	0.84

Sustainable management practices, however, imply more than maintaining yields (Bhattacharyya et al., 2008; Lynam and Herdt, 1989) hence AE, which provides information on the efficiency with which fertilizers are used, was also examined. Applying 40 kg N/ha in the homestead was more agronomically efficient than applying 80 kg N/ha in the bush farm (Figure 1). This is indicated by the consistently higher AE values illustrated in the figure. Regression analysis for the two data sets shows an increasing trend (slope = 0.077, $r^2 = 1.4 E2$) in grain yield over the long term for the homestead production, whilst that for the bush farm remains relatively stable (slope = 0.008, $r^2 = 4.0 E4$). Differences in AE between the two systems can also be attributed to differences in soil organic matter (soil fertility), which positively influences the soil chemical and physical properties that are necessary

for crop production. Though AE index is not recommended for comparisons between the two different systems due to differences in their inherent soil properties (Dobermann, 2005), it brought out the differences in the efficiency of using in organic fertilizer in this study. The relationship between total rainfall over the growing season and AE was poor in both systems ($r^2 = 7 \text{ E-}06$ and $r^2 = 9.8 \text{ E-}03$ in the bush farm and homestead, respectively). The differences in grain yield within each management system can be attributed to the distribution of rainfall over the growing season as initial soil conditions (nutrient and water) were the same for each season. The risk of lower sorghum yield due to variability in rainfall is higher in the bush farms (CV = 37%) than the homestead (CV= 17), hence, to improve grain production in this region, organic matter is indispensable. The risk of lower yields over the simulation period was reduced by the application of fertilizers in both systems (with fertilizer application, CV of 37% reduced to 11% in the bush farm, and from 17 to 7% in the homestead). This phenomenon could be explained by the fact that prolonged crop phenology associated with low fertilizer predisposes critical plant developmental stages to coincide with drought conditions.

Conclusions

Sorghum grain yield in response to fertilizer was well predicted by the DSSAT-CSM. Sustaining food security in this area requires investment in organic matter and mineral fertilizer. The AE of using fertilizer in the homestead is higher than in the bush farm. Also, applying 40 kg N/ha fertilizer in the homestead produced grain yields similar to application of 80 kg N/ha in the bush farm. Low soil organic matter content of sandy soils increases the risk of low crop yield; hence, there is the need for conscious effort to increase soil organic matter content particularly of sandy soils.

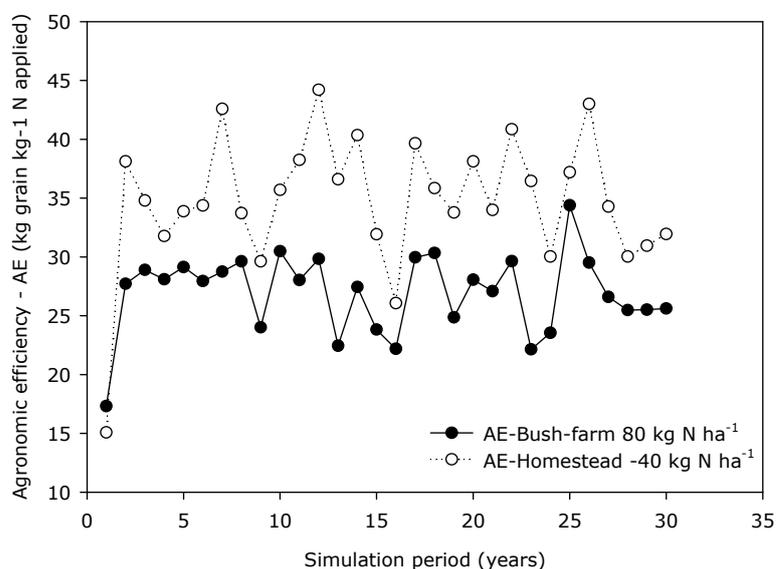


Figure 1. Influence of weather pattern on the efficiency of fertilizer use in two management systems.

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Improving water and land productivity through technology integration in saline sodic soils of the Indo-Gangetic Basin

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Abstract

Nearly 100 M ha of agricultural lands are affected by soil salinity and alkalinity globally, of which about 22 M ha are in Asia and 11 M ha in India alone. Approximately 10 M ha of agricultural land is lost annually due to salinization and water logging, endangering food security of the ever-increasing world population. Salt-affected soils are highly degraded and encompass a variety of complexities including high pH, high soluble salts, deficiency and toxicity of one or several micronutrients, and poor water-holding capacity leading to low productivity. These soils have immense productivity potential, however, which can be harnessed through proper technology intervention. Even a modest improvement of yields in such soils can ensure food security of millions of hungry and impoverished people.

Sodic soil reclamation is successful using inorganic amendments like gypsum and pyrite, but these amendments are expensive and not easily accessible to many poor farmers. We explored the possibilities of integrating 'pressmud,' an easily accessible organic by-product of sugar factories and rich in sulphur and zinc, with salt-tolerant rice varieties to improve the productivity of sodic soils. This technology was successfully validated in farmer's fields across several villages in target hot spots of sodic soils in Eastern Uttar Pradesh. A farmer participatory approach was followed for technology validation and to ensure adoption. The promising rice varieties preferred by the farmers were Usar 3, Sarjoo 52, CSR23, CSR30, and NDRK5083 which produced yields ranging between 1-4 t/ha in soils having a pH range of 9.2 (moderately sodic) to 10.5 (highly sodic).

Improvement of rice yields of 30-60% was reported by farmers by the basal application of 10 t/ha 'pressmud' along with normal recommended doses of fertilizers in highly sodic soils (pH 9.5-10.2). Basal application of pressmud was done 10 days prior to transplanting followed by 5 cm water ponding. Pressmud application increased rice yield through increase in biomass, ear bearing tillers, and grain fertility. Soil health also improved as evident from better fertility and lower soil pH at harvest and during subsequent years. Sodic soils which were unable to sustain even a single good rice crop became highly productive land within 2-3 years, with two to three crops per year. Improving sodic land productivity through natural resource management may also improve water productivity, farmer's economy, and livelihood.

It is concluded that pressmud could be a cost effective and easily accessible technology within the reach of rice farmers, and can effectively be used to improve the productivity of sodic soils by integration with salt-tolerant rice varieties. This will also ensure the food security and improve the livelihood of poor farmers living in the Indo-Gangetic Basin of India.

Media grab

The use of sugar mill waste (pressmud) combined with improved (salt-tolerant) varieties can provide food security for millions of poor farmers trying to subsist on poor and non-productive sodic lands.

Introduction

Uttar Pradesh is one of the largest and most populous states in the Indo-Gangetic Basin (IGB) of India. Agriculture is the main activity of the impoverished poor people of this area, and rice-wheat is the main cropping system. The soil of Uttar Pradesh is mainly alluvial and productive, but about 1.3 M ha are affected by soil salinity and sodicity, especially in the eastern part of the state. These soils have several inherent problems including high pH, low organic carbon and nitrogen, poor hydraulic conductivity, zinc and iron deficiency, and poor microbial activities that render them highly unsuitable

for cultivation. Even under rainfed conditions, subsurface soil always remains waterlogged and anoxic-inducing accumulation of toxic metabolites that adversely affect root respiration and growth (Ponnamperuma, 1972; Setter and Waters, 2003). Iron, aluminium, and manganese accumulate to toxic levels in waterlogged duplex soil of Australia (Khabaz-Saberi et al., 2006). Reclamation of these soils for cultivation using chemical amendments is an expensive and time-consuming process which the poor farmers of these areas cannot afford. A number of soil reclamation projects have been launched by the U.P. Bhumi Sudhar Nigam, Lucknow, primarily to bring 'C' class (barren-no crop) sodic soils under cultivation. They succeeded in their mission of reclaiming such soils but these benefits did not reach many small and marginal landholders of B (mono crop) and A (double crop) class sodic soils.

Rice is the only crop that can be grown in highly sodic soils with proper management skills. Incorporation of organic materials such as crop residues, green-manure crops, pressmud, and water hyacinth have been advocated to improve soil organic matter, structure, and water infiltration, and decrease pH. These provide safeguards against adverse effects of salinity and sodicity (Swarup, 1981, 1988, 2004). Farmers mostly grow traditional rice varieties and use farmyard manure (FYM) for soil reclamation. This is a slow process and may take several years to ameliorate these soils. Lack of irrigation facilities also limits the ability to harness sodic soils for crop production. Salt-tolerant varieties along with soil amendments could be suitable technologies for bringing such saline and sodic soils under cultivation. Recently a few salt-tolerant varieties have been developed, but have not reached most of the farmers. Gypsum and pyrites are the most effective soil reclamation agents, but they are expensive and beyond the reach of the poor farmers. Pressmud, a byproduct of sugar factories, is readily available and less expensive (US\$50-60/ha) compared to gypsum (US\$375-400/ha), and can also be used as organic amendment for sodic soil reclamation. As part of the Challenge Programme on Water and Food (CPWF), we explored the possibility of using pressmud and salt-tolerant varieties together to harness the sodic soils of eastern Uttar Pradesh.

Methodology

The pressmud technology along with salt-tolerant varieties was validated in Dhamthua and Parua Khas villages of Faizabad and Deeh village of Sultanpur districts during 2005, 2006, and 2007 wet seasons. The soils of these villages are predominantly sodic with high pH values ranging between 9.0 and 10.0 and poor soil fertility. Small and marginal farmers with sodic land were selected for technology validation and farmers provided with 5 kg of seeds of tolerant rice varieties and pressmud @ 10t/ha. Soil samples were collected prior to pressmud application and at harvest, and analyzed for various soil parameters including pH.

Composition of pressmud

Pressmud is a byproduct of sugar factories and contains several nutrients that are quite useful in improving health and productivity of sodic soils (Table 1). It contains about 1% calcium oxide, and reclaims sodic soil by replacing Na⁺ from the soil complex. It also has 10% sulfur which forms sulfuric acid and lowers soil pH. In addition, it supplements sulfur supply of the plants and enriches the soil with organic carbon and nitrogen, leading to better soil structure and growth and yield of rice.

Table 1. Nutrient composition of pressmud.

S.N.	Constituents	Values-%
1.	Nitrogen	1.0-1.2
2.	Zinc	0.025-0.027
3.	P2O5	2.5-3.2
4.	K2O	1.5-1.8
5.	CaO	1.0-1.2
6.	Sulfur	10-12
7.	Organic carbon	10-15

Pressmud application and transplanting

The trials were conducted at the main experiment station of Narendra Deva University of Agriculture and Technology, Kumarganj, Faizabad, India, and also in farmers' fields in target areas. Pressmud @10t/ha and zinc sulphate @20 kg/ha were thoroughly mixed in the topsoil (0-15 cm) 10-12 days prior to puddling and transplanting, and 5 cm water was continuously ponded in the fields. Thirty-five to forty day-old seedlings were planted. The trials at farmers' fields were managed by the farmers under the overall supervision of the researchers. All agronomic practices and fertilizer applications

were done by the farmers themselves. Different farmers applied different levels of fertilizers depending upon their financial situation and fertilizer availability. Data on yield and yield traits were recorded by the researchers at the time of harvest in collaboration with the farmers.

Results and discussion

Usar3 (salt tolerant) and Sarjoo52, a widely grown high-yielding variety, gave higher yields than the local varieties. Application of pressmud and zinc increased plant height and productive tillers per hill (data not presented), total biomass, total and fertile grain number per panicle, and increased partitioning of biomass into grains. All these traits positively contributed to grain yield. The yield improvement with pressmud and zinc application ranged between 18 and 39% in the salt-tolerant variety Usar3 and 22-29% in popular variety Sarjoo52 (Table 2). This led to a net profit of about Rs.4000 per ha (US\$100) per rice crop from a degraded sodic soil. A decrease in soil pH after rice harvest and an increase in fertility level (Tables 3 and 4) were additional benefits that were reflected in higher yields of the succeeding crops.

Table 2. Effect of pressmud in combination with zinc sulphate on yield and yield traits of rice genotypes. (data are mean \pm standard deviation from three experimental fields over 3 years at Main Experiment Station Kumarganj, Faizabad, U.P.).

Treatment	Total biomass-t/ha		Grain yield-t/ha		Grain fertility-%		Harvest index-%	
	Usar3	Sarjoo 52	Usar 3	Sarjoo 52	Usar 3	Sarjoo 52	Usar 3	Sarjoo 52
Control	7.29 \pm 0.22	6.84 \pm 0.37	2.91 \pm 0.14	2.65 \pm 0.25	89	90	40	39
PM	8.50 \pm 0.35	7.85 \pm 0.30	3.48 \pm 0.12	3.05 \pm 0.20	93	92	41	39
PM+ Zn	9.25 \pm 0.26	8.50 \pm 0.35	3.77 \pm 0.08	3.42 \pm 0.19	95	94	41	40

Control= No soil amendment, PM= Pressmud @10t/ha, Zn= Zinc sulphate 20kg/ha

Table 3. Effect of pressmud application on characteristics of sodic soils at Main Experiment Station, N.D. University of Agriculture and Technology Kumarganj, Faizabad, India (data are mean \pm standard deviation from three experimental fields over 3 years).

S.N.	Soil characteristics	Before pressmud treatment	After harvest
1	pH (1:2)	9.2-9.5 \pm 0.15	9.0-9.1 \pm 0.10
2	Electrical Conductivity- dS/m (1:2)	0.9-1.2 \pm 0.16	0.5-0.7 \pm 0.06
3	Organic carbon (%)	0.3-0.4 \pm 0.05	0.45-0.55 \pm 0.05
4	Hydraulic conductivity (cm/hr)	0.2-0.3 \pm 0.05	0.4-0.5 \pm 0.05
5	Zinc (ppm)	1- 3 \pm 1.0	5- 8 \pm 1.5
6	Available N (mg/ ka)	43.0 \pm 1.52	68.0 \pm 1.82
7	Available P mg/ kg)	15.4 \pm 0.43	15.0 \pm 0.59
8	Available K (mg/kg)	49.3 \pm 0.60	52.7 \pm 0.7

To disseminate the benefits of this technology among the poor farmers of salt-affected areas, it was evaluated in farmer's fields in target villages of Faizabad and Sultanpur districts of Eastern Uttar Pradesh. A participatory approach was adopted in which pressmud and salt-tolerant varieties were provided from the CPWF project and the rest of the operations and inputs were applied by the collaborating farmers.

About 30 farmers evaluated the technology over 3 years in their sodic lands with soil pH ranging from 9.2-10.2. An average yield advantage of 0.5-0.8 t/ha (16-30%) relative to the untreated control was obtained due to pressmud application. The benefits were greater in soils with higher pH, where rice crops in untreated plots were very poor due to high plant mortality. The net profit ranged from Rs.500

to 3500 per ha (US\$13-88) from a single rice crop, from the lands that normally remained barren, and which the farmers were earlier reluctant to cultivate due to highly degraded soil.

Table 4. Evaluation of the beneficial effects of pressmud on rice yields in farmers' fields on sodic soils in Eastern Uttar Pradesh (Data are mean \pm standard deviation from 30 farmers fields over 3 years).

Variety	No of farmers	Average grain yield (t/ha)		Yield increase due to pressmud (%)	Grain fertility range (%)		Soil pH range
		Control	Pressmud (10 t/ha)		Control	Pressmud (10 t/ha)	
Usar 3	16	2.62 \pm 0.62	3.39 \pm 0.61	30	50-75	66-89	9.3-10.2
Sarjoo 52	5	2.70 \pm 0.14	3.15 \pm 0.32	16	74-85	90-93	9.2-9.6
CSR 23	5	1.83 \pm 0.41	2.35 \pm 0.39	28	65-80	75-88	9.4-10.0
NDRK 5083	4	2.70 \pm 0.14	3.48 \pm 0.15	29	75-88	83-90	9.2-9.5

The noteworthy benefit is the improvement in soil health within 2-3 years, which normally would have taken several years through traditional approaches. Farmers were overwhelmed by seeing good crops of rice and wheat within three years in fields that they thought could never become productive. Consequently, the pressmud technology became popular among the collaborating farmers and was also appreciated by other farmers who visited the experimental fields during field days organized yearly before harvest. The farmers of the other villages possessing sodic lands were also interested in participating in this project. We are now upscaling the technology in other districts of eastern Uttar Pradesh with similar ecosystems in order to harness the productivity potential of saline sodic soils.

Conclusion

The beneficial effects of pressmud application on sodic soil health and productivity are of paramount importance for the poor farmers of Uttar Pradesh in the Indo-Gangetic Basin of India. Assuming an average yield advantage of 20% over the existing rice yield of 2.5 t/ha, an estimated gain of about 0.5 million of paddy annually will be achieved from only 50% of the area of the sodic lands (presumed to be under rice cultivation) in Uttar Pradesh. This additional rice yield may ensure food security and improve the livelihood of the farmers of Uttar Pradesh, one of the most populous and impoverished states in India. Concerted efforts are needed, however, by the national and international agencies to provide timely inputs and other resources such as irrigation and fertilizers to realize the maximum benefits from the technology. Government and nongovernment extension agencies should also come forward to disseminate this technology to the remote salt-affected areas that still do not have access to modern information technology.

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Breeding salt-tolerant rice varieties in Vietnam

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Abstract

Accumulation of salt in the soil leads to reductions in crop and livestock productivity. Saline soils in Vietnam are estimated to cover about 1 million ha. Rice is predominantly grown in these areas and improving salt stress tolerance in rice is one of the most important objectives of Vietnamese breeding programs. Molecular markers combined with selective genotyping were used to map quantitative trait loci (QTLs) associated with tolerance to salt stress. Salt-tolerant cultivar AS996 was crossed to IR50404 and 229 recombinant inbred lines (RILs) were developed by single seed descent. Another backcross population, IR64/OMCS2000//IR64 was developed and 217 BC₂F₂ lines were analyzed. A highly significant association with salinity tolerance was detected at the SSR locus RM223 on chromosome 8. Furthermore, the genotypes of 93 varieties were determined at RM223 giving an accuracy of > 95% in identifying salt-tolerant plants. RM223 was subsequently used for selecting tolerant plants while developing OM4498, which was recently released as a variety in Vietnam. The results of the germplasm survey of the BC₂F₂ line will be useful for the selection of parents for use in breeding programs aimed at transferring these genes from one genetic background to another through marker assisted selection.

Media grab

Use of advanced technology is making it possible to greatly speed up the incorporation of salt tolerance into locally adapted, high-yielding rice varieties.

Introduction

Rice (*Oryza sativa*) is sensitive to salinity, which affects one-fifth of the irrigated land worldwide. Progress in breeding to enhance salinity tolerance has been slow due to limited knowledge about the genetics of tolerance, the complexity of the several tolerance mechanisms involved, inadequate screening techniques, low selection efficiency, and poor understanding of the interactions of salinity with the environment. Through recent developments in molecular marker analysis, it is now feasible to analyze both simply inherited and quantitative traits, and then identify individual genes controlling the trait of interest. Molecular markers can now be used to tag quantitative trait loci and to evaluate their contribution to the phenotype by selecting for favorable alleles at these loci using marker-assisted selection (MAS) to accelerate genetic improvement. Advanced backcross analysis can be used to evaluate mapped donor introgressions in the genetic background of an elite recurrent parent. For rice, QTLs for salt tolerance have been identified using microsatellites (SSRs), with 108 markers used for analysis of recombinant inbreds derived from the cross between the varieties Tesanai and CB (Lang et al., 2001). We investigated the genetic basis of salinity tolerance using SSR markers, and analyzed mapping populations developed from two crosses: IR64 with OMCS2000 and IR50404 with AS996. The main objective was to identify microsatellite markers linked to salinity tolerance with phenotyping done under greenhouse conditions. A second objective was to test whether introgression of the identified QTLs into some lines will enhance tolerance of salt stress in the field.

Material and methods

Two populations were developed. The first involved AS996 (salt-tolerant) and IR64 (sensitive) with 96 BC₂F₂ lines derived from these parents. The second involved a backcross of IR64 with OMCS2000. The promising BC₁ plants were selected for desirable phenotypic traits and backcrossed to IR64 to generate BC₂ plants. About 219 BC₂F₂ were screened for salt tolerance at 12 dS/m using Yoshida nutrient solution (Gregorio et al., 1997). Salinization of the nutrient solution started 3 days after germination at 3 dS/m and then increased by 3 dS/m at 3-day intervals until it reached 12 dS/m, which was maintained through to the end of the experiment. Seedlings were rated for their salinity tolerance at 16 and 18 days after the imposition of salt stress. The solution was changed every 5 days and the pH was adjusted daily to 5.0. Agronomic characteristics such as plant height, panicle length, tiller per hill, spikelet per panicle, and grain yield were investigated and compared with those of the

control plants at maturity. Three replications were used per line. Analysis of variance and mean comparisons of the data from saline field conditions were carried out.

Genotyping of BC₂F₂ families using microsatellite markers

DNA was extracted using the CTAB method (Lang, 2002), and used for PCR reactions to evaluate the fragment patterns of each marker. Amplification products were obtained using RM223 forward: 5'-ACAGTATCCAAGGCCCTGG-3', and backward 5'-CACGTGAGACAAAGACGGAG-3' primers. To construct the SSR map and to assign the particular linkage groups to chromosomes, a set of previously identified polymorphic SSR markers was used. Linkage groups were ordered using MAPMARKER (Lander et al., 1987) and reconfirmed using the 'GROUP' > program. Map units (cM) were derived using the Kosambi function (Kosambi, 1944). QTL analysis was performed using single-marker linear regression following Tanksley (1993). The presence of the marker allele associated with salt stress tolerance was coded 1 and the allele associated with sensitivity was coded 0. The data were analyzed using MAPMARKER and interval analysis was conducted with MAPMARKER/QTL for QTL detection with the threshold for declaring a QTL for protein of LOD > 3.0.

Results and discussion

Phenotypic variation in salinity tolerance

The phenotypic responses to salinity among the BC₂F₂ families are shown in Figure 1. A continuous distribution of growth was observed in this population indicating quantitative inheritance. For shoot dry weight (SDW) and root dry weight (RDW), large variations were noticed in the population. RDW ranged from 45 to 110 mg and SDW ranged from 200 to 350 mg.



A: EC = 0



B: EC = 12 dS/m

Figure 1. Screening for salt tolerance in BC₂F₂ at seedling stage at EC 0 (left) and 12 (right) dS/m.

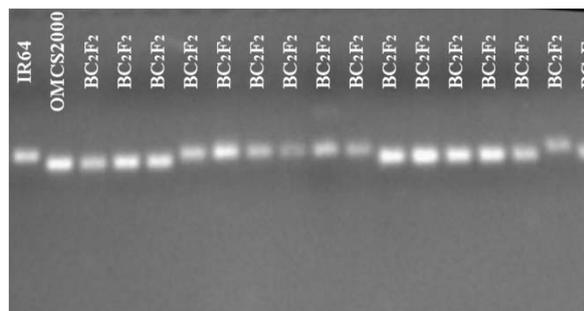


Figure 2. PCR products of BC₂F₂ population from IR64/OMCS2000, with primers of RM315 marker.

Polymorphism of SSR markers and marker segregation

Initially, the parents were surveyed for polymorphism using a set of 150 microsatellite markers. About 38 markers were identified as polymorphic between IR64 and OMCS2000, and 47 markers are polymorphic between IR50404 and AS996. The overall level of polymorphism between the two parents was 23.7%, which is too low for AS996, despite the large morphological differences between these parental lines.

For the cross of IR64/OMCS2000, 95% of the selected SSR markers were polymorphic in the parents IR64 and OMCS2000. The BC₂F₂ population was evaluated using 34 SSRs, and 98% of the markers were homozygotes and 2% were heterozygotes. Allele frequencies were 47.6% IR64 and 51.58% OMCS2000. For the IR50404/AS996 cross, 92% of the SSRs were polymorphic. The BC₂F₂ population was evaluated using 44 SSRs, and 97.5% of the markers were homozygotes and 2.5% were heterozygotes, with allele frequencies of 55.5% IR50404 and 37.5% AS996.

Construction of genetic linkage map

Grouping of markers was carried out by a two point linkage analysis with a LOD score of 4 and a recombination fraction D of 0.3. For the BC₂F₂ population from the cross of IR64/OMCS2000, 34 markers were used to construct a framework map and a total length of 148.6 cM was recovered for two chromosomes, 1 and 8 (Figure 3). Two QTLs were significantly associated with tolerance, one on chromosome 1 at marker RM315 and the other on chromosome 8 at marker RM223.

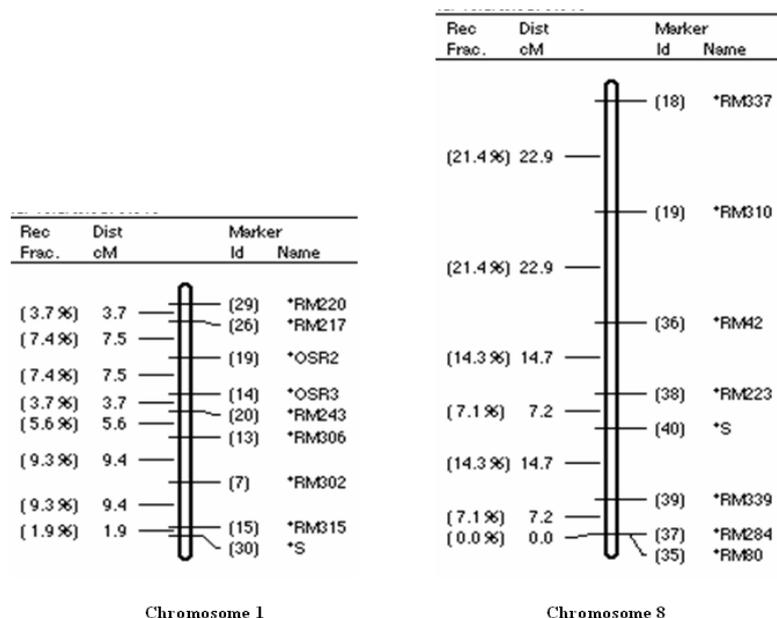


Figure 3. Microsatellite linkage map of rice chromosome 1 and 8. The markers were mapped in the indica/indica IR64/OMCS2000 BC₂F₂ population.

Marker-assisted selection for salt tolerance

Major quantitative traits loci (QTLs) underlying many agronomically important traits have been mapped, allowing the integration of biotechnology with the conventional breeding to speed the development of modern high-yielding varieties. Currently, the use of MAS for simply inherited traits is gaining increasing importance in breeding programs. In this study, about 217 BC₂F₂ lines from the cross IR64/OMCS2000/IR64 were analyzed and regression analyses based on SSR allele class differences were performed. Highly significant associations were detected at the SSR locus RM223 on chromosome 8. This marker was then used to select breeding lines possessing this locus and the results showed an accuracy of more than 95% in identifying tolerant plants. This marker was successfully used in the development of OM4498 from the cross IR64/OMCS2000/IR64, which was released as a new variety in 2007 in Vietnam. Beside the two major QTLs on chromosomes 1 and 8, few minor QTLs were also detected at other loci.

Conclusions

This study identified QTLs associated with seedling survival under salt stress conditions and provides a starting point for examining the effects of the underlining genes in rice. The study provided detailed information on the relative importance of genomic segments and could increase our understanding of the genetic basis of salt tolerance once the genes involved were identified. Further, studies are needed to confirm the contribution of these two QTLs to salinity tolerance under field conditions and in different genetic backgrounds.

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Evaluation of agronomic management practices for enhancing chickpea yield in Karkheh River Basin in Iran

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Abstract

Development of chickpea cultivars with high and stable yields and with suitable characteristics for different environments and for autumn and spring planting is very important for improving water productivity in rainfed agriculture. The objective of this research was to compare autumn and spring planting with advanced chickpea genotypes in farmers' fields in Merek and Honam watersheds. Three improved varieties and a local check were in a randomized complete block design with four replications during two years (2005-07). The results of a combined analysis of variance for sowing date showed that autumn planting produced significantly higher yields than spring planting. Higher productivity in autumn planting in comparison to spring planting is due to higher water use efficiency. A significant difference was also found among the genotypes; Arman and Azad with 1499 and 1373 kg/ha produced the highest yield under autumn planting. Also Azad and the local check with 760 and 751 kg/ha produced the highest yield under spring planting. Economic analysis showed that the research recommendations (fall planting, improved agronomic management and improved varieties) had higher net benefits than the farmers' methods. Water productivity analysis indicated that genotypes in autumn planting had higher economical water productivity than spring planting in both watersheds.

Media grab

Planting chickpea in fall instead of spring can more than double the water productivity of rainfed chickpea cultivation in Karkheh River Basin.

Introduction

Legumes are an excellent source of good quality protein in the diets of people and they are also valuable as animal feed. Legumes also increase and sustain the productivity of soil and when grown in rotation with cereals, and reduce chances of build-up of diseases, insect-pests and weeds for the following cereal crops (Sabaghpour 2004). Iran ranks fourth in world in chickpea production, after India, Pakistan and Turkey. Average chickpea productivity in Iran is 400 kg/ha. Most farmers grow chickpea in marginal areas in spring. Due to lack of rainfall during flowering, podding and seed filling, terminal drought stress is a major abiotic stress affecting chickpea productivity in Iran (Sabaghpour et al, 2006). Low productivity is also due to the use of local varieties with low yield potential and poor agronomic practices such as broadcast sowing, use of a furrow turning plough for covering the seed, low seed rate (about 16 seeds/m²) and unsuitable planting dept. The local chickpea varieties are harvested by hand because of prostrate growth habit, resulting in high harvesting cost.

The majority of the chickpea crop in Iran (95%) is planted under rainfed conditions. The rainfed yield for chickpea is about 34% less than that of the irrigated area. This indicates that improving moisture conservation in rainfed areas may improve the rainfed yield. Singh and Hawtin (1979) reported that winter-sown chickpea gave higher seed yield than the traditional spring-sown chickpea. Saxena (1980) studied the effect of successive delays in date of sowing from autumn, through winter, spring and reported a linear reduction in the yield as sowing was delayed. The results of research station experiments showed that autumn planting had 72-79 percent higher yield than spring planting in Kermanshah and Lorestan due to higher water use efficiency (Sabaghpour 2004).

Studies conducted at ICARDA, Syria revealed that the winter-sown crop is prone to damage by ascochyta blight and cold, both of which can be avoided by spring sowing (Hawtin and Singh 1984). Thus, lack of blight- and cold- tolerant cultivars has been the major reason for growing spring-sown chickpea. Reddy and Singh (1990) studied the relationship between ascochyta blight severity and yield loss in winter sown chickpea for three years at ICARDA. They found less than 10% yield loss in disease-resistant lines, compared with a loss of more than 80% in susceptible ones.

The agronomy of chickpea cultivation including date of sowing, seed rate, method of sowing, plant population, weed control, method of harvesting and high potential chickpea lines with resistance to ascochyta blight and cold tolerance has been researched and recommendations have been developed for different areas. The objective of this study is to evaluate improved chickpea varieties and agronomic management under dryland conditions in the Karkheh River Basin in cooperation with farmers and to compare the economic aspects of the research recommendations versus the conventional methods.

Material and methods

Experiments were conducted during the 2005-06 and 2006-07 growing seasons in cooperation with farmers in Merek Watershed in Kermanshah Province and Honam Watershed in Lorestan Province. A split plot design with four replications was used, with date of sowing as the main plot and variety as the subplot. The research recommendation (autumn planting) was sown on 10 and 13 December 2005 in Merek and Honam, respectively, and on 14 and 29 November in 2006. Varieties were planted by planter with suitable seed rate (30 plants/m²). For the conventional method (spring planting) agronomic practices were the current procedures used by the farmers. Seed was broadcast on 11 and 15 March 2005 in Merek and Honam, respectively, and similarly on 16 and 19 March in 2006. Three improved varieties (Hashem, Arman and Azad) and a local check were planted in 2500 m² plots. Hashem, Arman and Azad are resistant to ascochyta blight, tolerant to cold and have an erect growth habit for mechanical harvesting. Each farmer field was considered a replication. Plots were fertilized with 30 kg P₂O₅ /ha and 20 kg N/ha. Data were recorded for number of days to emergence, 50% flowering, and maturity, plant type, reaction to ascochyta blight and fuzarium wilt diseases, number of pods per plant, plant height, 100 seed weight, and seed yield. Weeds were controlled by hand weeding. The autumn-sown crop matured by late June and was harvested by combine. The spring-sown crop matured by early July and was harvested by hand. No insecticide or fungicide was used to control insect pests and diseases. Water productivities were computed based on the seasonal rainfall for each watershed, considering that only one crop is grown per season.

Results and discussion

The results of the combined analysis of variance for two years in Merek and Honam watersheds showed that there was a significant difference between environments. The results showed that interactions of environment × date of sowing, genotype × environment and date of sowing × genotype were significant at 1% level of probability. Interaction of date of sowing × genotype × environment was not significant (Table 1). Autumn planting (research recommendation) produced 85% higher yield than spring planting (conventional method). The results of the pooled analysis of this study indicated that there was a significant difference between the research recommendation and the conventional method at 5% level of probability (Table 1). Sabaghpour (2006) reported that autumn planting had significantly different higher yield compared to spring planting due to benefit of winter rainfall and low evapotranspiration, as temperatures are low when the crop approaches maturity. This allows optimum vegetative growth, development of higher yield potential, and higher water use efficiency. Significant differences were found among the genotypes at 1% level of probability (Table 1).

Table 1. Combined analysis of variance for grain yield in Merek and Honam watersheds for the 2005-2007 cropping seasons.

Source of variation	Degree of freedom	Mean square	P
Environment (Env.)	3	1270770	<0.001
Methods (Date of sowing)	1	10140200	<0.05
Env. × Date of sowing	3	911793	<0.01
Error	12	102536	
Genotype	3	677385	<0.05
Genotype × Environment	9	178707	<0.001
Date of sowing × Genotype	3	601404	<0.001
Date of sowing × Genotype × Env.	9	24799	<0.1
Error	72	37743	
Total	127	217300	

Improved varieties Arman and Azad with 1499 and 1373 kg/ha produced significantly higher yields than the local variety at 1% level of probability for autumn planting in Merek and Honam (Table 2). For spring planting, the local check and Azad varieties with 760 and 751 kg/ha produced higher yields than the other varieties in both watersheds (Table 2).

Table 2. Agronomic characteristics for autumn planting in Merek and Honam in 2005-2007.

Genotype	PT ^a	DM ^b	PH ^c	100 SW ^d (g)	AB ^e	Yield (kg/ha)	Relative yield %	Class ^f
Autumn planting								
Hashem	E	191	41	25	3	1088	115	B
Arman	E	181	40	28	3	1498	158	A
Azad	E	178	38	31	3	1373	145	A
Local check	SE	181	28	30	5	947	100	C
Spring planting								
Hashem	E	116	36	27	3	490	64	B
Arman	E	106	33	28	3	654	86	A
Azad	E	104	35	29	3	751	99	A
Local check	SE	103	25	32	4	760	100	A

^a PT= Plant type, ^b DM= days to maturity, ^c PH= Plant height, ^d 100 seed weight, ^e AB= Ascochyta blight, ^f letters indicate significantly different yields at the 5% and 1% probability level for each planting date.

Economic analysis showed that the research recommendation resulted in a net income of \$880/ha, as compared with \$412/ha for the conventional method (Table 3). In Honam watershed rainfall for the 2005-06 season was 540 mm and 572 mm in 2006-07. Water productivity analysis indicated higher rainfall water productivity (kg/m³, \$/m³) under fall planting than under spring planting in both watersheds. The results for Honam watershed are presented in Table 4. The water productivity for fall planting (0.27 kg/m³) was twice as high as for spring planting (0.13 kg/m³). Similar results were obtained for Merek watershed. Arman and Azad are resistant to ascochyta blight and are suitable for mechanical harvest. Therefore, these are superior varieties for autumn planting for both sites.

Table 3. Economic comparison of research recommendation (fall planting) and conventional method (spring planting) of chickpea production in Honam and Merek watersheds.

Methods	Gross income (\$/ha)	Expenses (\$/ha)	Net income over check (\$/ha)
Conventional	613	201	
Research recommendation	1127	247	468

Table 4. Water productivity of different chickpea genotypes in Honam watershed during 2005-07.

Genotype	Season	Yield	Yield	WP ^a	WP	EWP ^b	EWP
		Autumn planting kg/ha	Spring planting kg/ha	Autumn planting kg/m ³	Spring planting kg/m ³	Autumn planting \$/m ³	Spring planting \$/m ³
Hashem	2005-06	1451	481	0.27	0.09	0.16	0.05
Arman	2005-06	2058	588	0.38	0.11	0.22	0.06
Azad	2005-06	1880	721	0.35	0.13	0.20	0.08
Local check	2005-06	1364	800	0.25	0.15	0.15	0.09
Hashem	2006-07	1159	643	0.20	0.11	0.12	0.07
Arman	2006-07	1847	1053	0.32	0.18	0.19	0.11
Azad	2006-07	1447	723	0.25	0.13	0.15	0.07
Local check	2006-07	857	653	0.15	0.11	0.09	0.07

^a WP= water productivity, ^b EWP= economic water productivity

Conclusions and recommendations

Autumn planting had significantly higher yield than spring planting due to the benefit of winter rainfall and low evapotranspiration, as temperatures are low when the crop approaches maturity. This allows optimum vegetative growth, development of higher yield potential, and higher water use efficiency. The improved varieties Arman, Azad and Hashem produced significantly higher yield than the local variety at autumn planting in Merek and Honam. With spring planting, the local check and Azad produced higher yield than other varieties. Economic analysis showed that the research recommendation was more profitable than the conventional method. Water productivity analysis indicated that genotypes in autumn planting had higher economic water productivity than spring planting in both sites. Arman, Azad and Hashem are resistant to ascochyta blight and erect growth habit which are suitable for mechanical harvest in comparison to local check. Therefore, Arman, Azad are superior varieties for autumn for both sites. Azad variety is resistant to ascochyta blight, erect

growth habit and large seed size. Therefore, this variety and local check are suitable for spring planting for both sites.

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Land suitability evaluation in Merek Watershed, Karkheh River Basin

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Abstract

Merek Watershed is located in the Upper Karkheh River Basin in Iran. The annual mean air temperature is 14.1 °C and the annual rainfall is about 458 mm. The aim of this research was land suitability evaluation for main crops in the study area. The methodology was based on a simple limitation method. Climatic suitability in the study area for rainfed cultivation shows that due to rainfall limitation, wheat and barley are marginally suitable, chickpea is moderately suitable and sugar beet, maize, alfalfa and clover are not suitable for rainfed cultivation. Considering no water limitation, climatic suitability for irrigated cultivation is highly suitable for wheat, barley, and chickpea and moderately suitable for sugar beet, maize, alfalfa, and clover due to temperature limitations. Map units on the mountains and hills are not suitable for crops due to topography. Map units on the plains show that P1111 is marginally suitable for rainfed wheat and barley with precipitation limitations, moderately suitable for rainfed chickpea and marginally suitable for irrigated wheat, barley chickpea, maize, sugarbeet and alfalfa, due to calcium carbonate limitation. Map unit P1121 is highly suitable for irrigated wheat, barley, chickpea, and sugarbeet and moderately suitable for maize, alfalfa and clover and moderately suitable for chickpea, due to calcium carbonate limitation. Map units P1131, P1132 and P1133 are moderately suitable for irrigated wheat, barley chickpea, sugar beet, maize, alfalfa and clover, due to calcium carbonate limitations.

Media grab

Due to inadequate rainfall, Merek Watershed is marginally suitable for rainfed crops, but irrigation will make the watershed highly suitable for wheat, barley, and chickpea.

Introduction

Traditional systems of resource management and land husbandry are being abandoned, and soil and environmental degradation are proceeding rapidly over large areas of the world. An alternative approach is essential (FAO, 1990). This approach can be land evaluation. Land evaluation is the process of assessment of land performance when the land is used for specified purposes. It involves the execution and interpretation of surveys and studies of landforms, soils, climate, vegetation, and other aspects of land in order to identify and compare promising kinds of land use in terms applicable to the objectives of the evaluation. To be of value in planning, the range of land uses considered should be limited to those relevant within the physical, economic, and social context of the area considered, and the comparisons should incorporate economic considerations (FAO, 2007).

Land evaluation deals with two major aspects of the land: physical resources such as soil, topography, and climate, and socioeconomic resources such as farm size, management level, availability of labor, market position, and other human activities. The former are relatively stable properties, while the latter are much more variable and dependent on social and political decisions (Sys et al., 1991a). The principal objective of land evaluation is to select the optimum land use for each defined land unit, taking into account both physical and socioeconomic considerations, and the conservation of environmental resources for future use. Detailed objectives can vary considerably according to the purpose and scale of land evaluation (Sys et al., 1991a).

Land suitability is the fitness of a given type of land for a defined use. The land may be considered in its present condition or after improvements. The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses (FAO, 1976). The aim of this research was land suitability evaluation of Merek Watershed for wheat, barley, chickpea, sugar beet, maize, and alfalfa, based on climate, soil and landscape characteristics. The methodology is based on a simple limitation method (Sys et al., 1991b), which forms the basis of the FAO land evaluation framework.

Methods

Determination of growing period

The usual start of the growing period and the likely end of the rains can be determined graphically or can be calculated using a linear or parabolic interpolation technique based on rainfall and evapotranspiration data. The same applies to the start and end of the humid period. The end of the growing period is determined by the number of days that are required to consume 100 mm of water after the likely end of rains. In this study growing period was determined based on a graphical method (Sys et al., 1991a).

Land suitability classification

The limitation approach suggests five level scales in the range of limitations, where the "severe" level is used when the property is marginal. The different levels in the degree of limitation are defined as follows:

- No limitation: The characteristic (quality) is optimal for plant growth.
- Slight limitations: The characteristic is nearly optimal for the land utilization type, and affects productivity not more than 20% with regard to optimum yield.
- Moderate limitations: The characteristics have moderate influence on yield decrease; however, benefits can still be made and use of land remains profitable.
- Severe limitations: The characteristic has such an influence on productivity of land that the use becomes marginal for considered land utilization type.
- Very severe limitations: The characteristics not only decrease the yields below profitable levels, but may totally prohibit the use of the soil for the considered land use.

The limitation levels could be expressed as land classes. This means that for each land characteristic or quality, one can define: S1, very suitable; S2, moderately suitable; S3, marginally suitable; N1, unsuitable but susceptible for correction; N2, unsuitable and not susceptible. In this case, no or only slight limitations define the S1 level, moderate limitations the S2 levels, severe limitations the S3 level, and very severe limitations the N1 and N2 levels. The definition of the classes can be done using the simple or maximum limitation method. Application of the simple limitation method implies that requirement tables have to be produced for each land utilization type, such as crop requirement tables from Sys et al. (1993).

The methodology suggests in the first instance evaluation of the climatic characteristics (rainfall, temperature, relative humidity, and radiation) with the aim of the determining one class level to be introduced in the total evaluation. The class level of the climatic characteristics corresponds with the lowest class level of all four climatic characteristics. Land classes are defined according to the lowest class level of only one or more characteristics.

Results and discussion

Determination of growing period

The growing period in the study area starts November 5 and ends April 25 (155 days). The humid period starts November 27 and ends March 2 (71 days) (Figure 1).

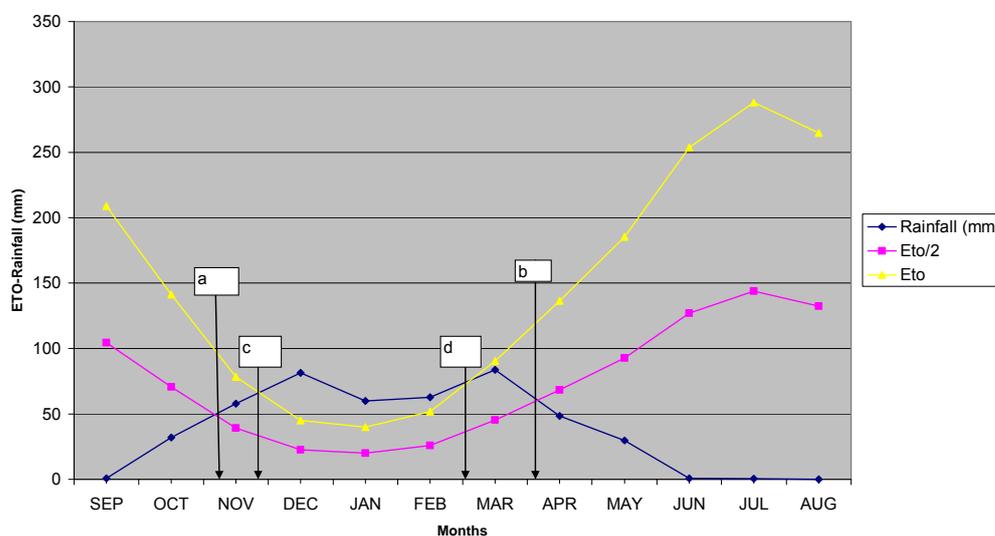


Figure 4. Growing period curve of study area: start of growing period (a), end of growing period (b), start of humid period (c), and end of humid period (d).

Land suitability classification

Climatic suitability for wheat and barley shows that due to low rainfall during the crop cycle and low rainfall during the ripening stage, the watershed is marginally suitable for rainfed wheat and barley and is highly suitable for irrigated wheat and barley. Similarly, the watershed is moderately suitable for rainfed chickpea and is highly suitable for irrigated chickpea. Climatic suitability for sugar beet shows that due to very low rainfall during the crop cycle, it is not suitable for rainfed sugar beet but is highly suitable for irrigated sugar beet. Climatic suitability for maize shows that, because of very low rainfall during the crop cycle, the watershed is not suitable for rainfed maize, but is moderately suitable for irrigated maize, due to the minimum temperature. Climatic suitability for alfalfa shows

that, due to very low rainfall during crop cycle, it is not suitable for rainfed alfalfa, but is moderately suitable for irrigated alfalfa due to mean temperatures.

Land suitability for these crops shows that 1401 ha of the area (6%) are highly suitable, 10,549 ha (44%) are moderately suitable due to gravel limitation, and 2134 ha (9%) are marginally suitable due to calcium carbonate limitation. A total of 8842 ha (37%) are unsuitable due to topography, and 56 ha are not suitable due to gravel limitation.

Since land suitability considers climate, soil, and landscape, the final land suitability for irrigated crops for different map units in the study area (Figure 2) are summarized as follows:

Map units Mo211, Mo212, Mo311, Mo312, Mo321, Mo322, Mo332, HI111, HI121, HI221, and HI231, due to topography limitations are not suitable for wheat, barley, chickpea, sugar beet, maize, alfalfa, and clover in the study area.

Map unit PI111 is marginally suitable for rainfed wheat and barley with precipitation limitation, moderately suitable for rainfed chickpea due to low rainfall during the crop cycle, and marginally suitable for irrigated wheat, barley chickpea, maize, sugar beet, and alfalfa due to calcium carbonate limitation.

Map unit PI121 is marginally suitable for rainfed wheat and barley with precipitation limitation and moderately limitation for rainfed chickpea due to low rainfall during crop cycle and highly suitable for irrigated wheat, barley chickpea, and sugar beet and moderately suitable for maize, alfalfa and clover due to rainfall limitation and moderately suitable for chickpea due to calcium carbonate limitations.

Map units PI131, 132, and PI331 are marginally suitable for rainfed wheat and barley with precipitation limitations, and moderately suitable for rainfed chickpea due to low rainfall during the crop cycle, and moderately suitable for irrigated wheat, barley, chickpea, sugar beet, maize, alfalfa, and clover due to calcium carbonate limitation.

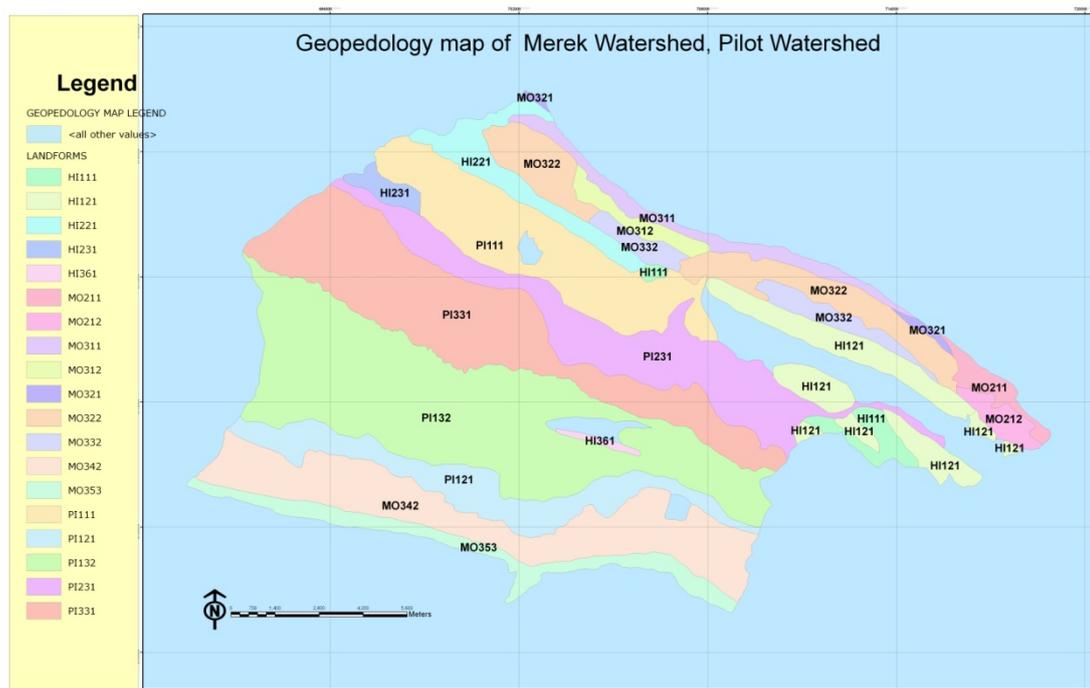


Figure 2. Map units distribution in the study area.

Conclusions and recommendations

Climatic suitability for rainfed cultivation shows that Merek Watershed is marginally suitable for wheat and barley, moderately suitable for chickpea, and not suitable for sugar beet, maize, alfalfa and clover. The main landscape and soil limitations in the study area are topography and calcium carbonate. Climatic characteristics cannot be improved, except low rainfall, which can be compensated for by irrigation. Soil and landscape characteristics such as soil physical and chemical characteristics cannot be changed, and the subclasses that have such limitations such as calcium carbonate will remain without change in the future. Topography limitations, if slight or moderate, can be improved by leveling the lands for crop cultivation.

Acknowledgments

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Effect of *Azotobacter* and *Azospirillum* on the yield of wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) in Kermanshah and Lorestan, Iran

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Abstract

To reduce farmers' dependency on mineral fertilizers, to increase water use efficiency, and to increase households' incomes, participatory on-farm research trials to test the effect of the inoculums of *Azotobacter* and *Azospirillum* on the yields of wheat and barley were conducted in the upper catchments of Karkheh River, Iran, in 2005-06 and 2006-07. In 2005-06, grain yield of inoculated irrigated wheat increased by 11%, while the yields of rainfed barley increased by 36% compared to the untreated control. In 2006-07, inoculation of irrigated wheat significantly increased grain yields from 3656 to 4536 kg/ha. The risk for a randomly selected farmer not to obtain a determined yield target was always lower for the inoculation treatment than for the control. Grain yields of inoculated rainfed wheat increased by 11% on average. Adaptability analysis revealed that the yield increase was independent from the farmer's location, hence the technology is robust and yield increases remain constant with improved environmental conditions. The probability that the *Azotobacter* treatment outperforms the untreated control at a randomly chosen farming environment in Merek was 73%. The marginal costs for the inoculation treatment were low and equivalent to about 14 and 27 kg grain per hectare for rainfed and irrigated wheat or barley, respectively. These preliminary results suggest that inoculation of wheat and barley are low-cost and environment-friendly options with low agronomic and economic risk for farmers to increase yields, water productivity, and income.

Media grab

Biofertilizers *Azotobacter* and *Azospirillum* can increase water productivity of rainfed and irrigated cereals in the dry areas, and have been quickly adopted by farmers in the Karkheh River Basin.

Introduction

The main sources of income in the rural areas of the Karkheh River Basin rely on crop production and animal husbandry. Crop production is dominated by wheat and barley. In 2006, the irrigated land comprised only 8% and 24% of the total arable land in Merek, Kermanshah province, and Honam, Lorestan province, respectively. The total wheat area was 44% in Merek and 49% in Honam. Barley was grown on 9% of the arable land in Merek and on 22% in Honam. Crop yields are generally low. Mean grain yields of irrigated wheat, rainfed wheat, and rainfed barley in Honam are 3750, 1350, and 1500 kg ha, respectively. In Merek, the situation is similar, with average yields of 4500, 1500, and 1200 kg ha for irrigated wheat, rainfed wheat, and rainfed barley, respectively. Therefore, any crop improvement will have a substantial impact on farmers' livelihood. At the same time, increased yields would also have a positive impact on a more efficient use of the scarce water resources.

At present, the government in Iran is heavily subsidizing mineral fertilizers for wheat, and offers guaranteed prices to achieve the national policy on self sufficiency for wheat. Besides environmental concerns of the use of high rates of chemical fertilizers, agricultural subsidies put a considerable burden on Iran's economy. Biofertilizers are inoculums of soil-borne beneficial organisms. Research on biofertilizers in Iran began in 1995 when the Soil Biology Research Division was added to the Soil and Water Research Institute (Khavazi et al., 2005). Today, emphasis is put on plant growth regulating bacteria, microorganisms that are capable of increasing the rate of plant growth by direct or indirect mechanisms. Secretion of vitamins and amino acids, auxins, and fixing atmospheric nitrogen by *Azotobacter* and *Azospirillum* are among the direct mechanisms of increasing root development and plant growth (Radwan, 2002; Khavazi et al., 2005; Akbari et al., 2007). Secretion of siderophores and hydrogen cyanides and antibiotics that control some plant diseases are additional effects of improving the growth rate and yields of plants such as wheat and barley (Khavazi et al., 2005). Recent studies have even detected synergistic effects of plant growth promoting rhizobacteria (such as *Azospirillum* and *Azotobacter*) and *Rhizobium* on nodulation and nitrogen fixation of legumes (Tilak et al., 2006). The current study aimed to investigate the effect of *Azotobacter* and *Azospirillum* biofertilizer on crop yield, water use efficiency, and households' incomes in farmer-managed trials at various locations in the upper catchments of Karkheh River Basin.

Methods

From 2005 to 2007 farmer-managed on-farm trials were conducted under rainfed conditions in two pilot sites of the Upper Karkheh River in southwest Iran: Merek plain in Kermanshah and Honam in Lorestan province. The participatory nature of the research approach required a simplified experimental design with only one test plot (*Azotobacter* treatment) and one control plot at each farmer's location. One part served as a control without *Azotobacter* and *Azospirillum* inoculation, and the other part was planted with either wheat or barley seeds inoculated with *Azotobacter* and *Azospirillum*. Wheat and barley seeds were inoculated with *Azotobacter* and *Azospirillum* by spraying 'Nitroxin' over the seeds (1.5 liters per 100 kg of seeds).

Sixteen interested farmers opted to test *Azotobacter* and *Azospirillum* inoculants on rainfed wheat, 22 farmers on irrigated wheat, and seven farmers on rainfed barley in two sites. Farmers were allowed to use their own cultivar, sowing density, and management practices. In both years, local collaborators recorded grain and straw yields at harvest in July for each farmer by taking 10 subsamples, 1.0 m² in size, from both plots. Subsamples were cut at soil surface, and threshed separately with a mechanical thresher. Water productivity (WP) was calculated based on yields and rainfall data recorded by the meteorological stations in the respective sites and years.

Where sufficient data were available, the paired data sets were also used to assess the adaptability of the *Azotobacter* treatment to the productivity level of each farmer's location. To this end, for each farmer's location the yield mean (MEAN) of both treatments, defined as $[0.5 (Y_{Azo} + Y_{ctrl})]$, was computed as environmental index. The yields of each individual treatment were plotted against the environmental index and linear regressions were calculated. Interpretation of the results followed those described by Hildebrand and Russell (1996).

Larger data sets were also used to assess the risk of either technology to fall below a critical yield level. Where normality of data was given, the probability that the yield γ of this technology falls below a critical level λ in a randomly chosen environment j was calculated by

$$Pr(\gamma_j < \lambda) = \Phi[(\lambda - \mu) \sigma^{-1}], \text{ (Eskridge, 1990)}$$

where Φ is the cumulative distribution function of the standard normal distribution, μ is the mean yield of the technology, and σ is the standard deviation.

For a direct comparison of the *Azotobacter* technology with the farmers' practice, the probability of one system outperforming the other one was calculated by:

$$Pr(D_j > 0) = \Phi[\delta (\sigma_D^{-1})], \text{ (Eskridge and Mumm, 1992)}$$

where D_j is the yield difference between the two technologies in a randomly chosen location, Φ is the cumulative distribution function of the standard normal distribution, $\delta = \mu_1 - \mu_2$, μ_1 and μ_2 are the mean yields of the two technologies, and σ_D is the standard deviation of the difference D_j .

Economic risk analysis was based on net returns per treatment. Since the main interest was in treatment differences, only the return and cost factors differing among treatments were taken into account.

Results

In the 2005-06 season, *Azotobacter* and *Azospirillum* inoculants increased grain yields of irrigated wheat from 8346 kg/ha to 9265 kg/ha, a difference of 11%. The average net return difference between the *Azotobacter* and the untreated control treatment was 1.9 million Rials (US\$211) per hectare (± 0.72 million Rials). In the same season, rainfed barley yields increased by 36% from 2356 to 3197 kg/ha when seeds were inoculated with *Azotobacter* and *Azospirillum*. This was equivalent to an increase in WP from 0.44 to 0.59. The average net return difference between the two treatments was 1.8 million Rials (US\$162) per hectare (± 0.38 Rials). In 2006-07, the *Azotobacter* and *Azospirillum* treatment increased grain yields of irrigated wheat from 3656 to 4536 kg/ha in Honam. The adaptability analysis revealed that yield differences varied among locations and significantly increased with improved productivity levels (environmental index) of the farm site. Hence, there was an above-average yield response with higher environmental index. The risk analysis discovered that regardless of the critical yield of choice, it was always more likely to achieve that yield level with the *Azotobacter* than with the control. For instance, there was a 71% risk for the control to fall below a yield level of 4000 kg/ha while the corresponding risk for the *Azotobacter* treatment was only 30%. Comparing the two treatments, there was only a 13% risk that the *Azotobacter* was outperformed by the control treatment, if grain yield was the parameter.

The marginal costs for the *Azotobacter* application in irrigated wheat were equivalent to only 40 kg of grain per hectare. The economic risk of *Azotobacter* application to be outperformed by the control was only 14% and therefore similarly low as the agronomic risk. The inoculants also increased grain yields

and WP of rainfed wheat and barley in the same year, but due to the high variability between sites and the low number of participating farmers, the high differences were not significant. Yield increases were detected, however, at all farming locations, and in rainfed barley, yields; and WP even doubled as affected by *Azotobacter* inoculation. The marginal costs for the *Azotobacter* application in rainfed wheat or barley were equivalent to only 21 kg of grain per hectare. The net return difference between *Azotobacter* treated rainfed wheat and the untreated control and between rainfed barley and its control was 0.89 million Rials (US\$99) per hectare (± 0.47 million Rials) and 2.96 million Rials (US\$328) per hectare (± 1.01 million Rials), respectively. In Merek, where the inoculants were tested for the first time during the 2006-07 season, *Azotobacter* treated rainfed wheat yields increased on average, but only moderately, from 1314 to 1457 kg/ha. This was associated with an increase in WP from 0.21 to 0.24. Moreover, the adaptability analysis showed similar yield increases regardless of the environmental index. The probability to fall below a critical yield level was always higher for the control treatment than for the *Azotobacter* treatment, but the risk difference between the two treatments was never higher than 15%. Moreover, there was a 27 and 30% risk of the *Azotobacter* treatment to be outperformed by the control treatment, respectively, when yield and net return were the criteria. The average net return difference between the *Azotobacter* and the control treatment were only 0.27 million Rials (US\$30) per hectare (± 0.14 million Rials).

Based on data of the provincial agricultural service centers, in 2006-07 farming households in Honam cultivated 2.2 ha irrigated wheat, 5.9 ha rainfed wheat, and 3.7 ha rainfed barley. If *Azotobacter* is adopted on all the fields, the household income would increase by US\$2232 per year. In Merek, an average household cultivated 0.6 ha irrigated wheat, 5.1 ha rainfed wheat, 0.15 ha of irrigated barley and 1.05 ha of rainfed barley during the 2006-07 season. The sole adoption of *Azotobacter* on rainfed wheat could increase household income by 1.36 million Rials (US\$151) per year.

Discussion

Azotobacter and *Azospirillum* significantly increased wheat and barley yields in both years and in irrigated land as well as in rainfed crops. The Merek experiment in 2006-07 showed that the biofertilizers significantly increased rainfed wheat yields and the increase was independent from the environmental index, hence regardless of the productivity level at a given farmer location, such an increase can be expected. The situation in Honam was different. Although the inoculation treatment increased irrigated wheat yields on average by 24%, the obtained difference depended on the farmer's location. With increasing environmental index, the yield difference between the two treatments also increased, while in poorer environments the difference diminished. The environmental conditions with respect to soils, elevations, and slopes in the Merek watershed, which comprises a long and wide even valley, are more homogeneous (De Pauw et al., 2008), which accounts for the lower variability of the yield difference between *Azotobacter* inoculated and untreated wheat. In contrast, the Honam watershed is more diverse, which explains the significant farmers' fields' effects. The effect of the inoculants on wheat was less pronounced than the effect on barley.

In 2005-06, the biofertilizer treatment increased irrigated grain yields by 11% in Honam, while the yields of rainfed barley increased by 36%. In the following year, grain yields of irrigated wheat increased by 24%, while rainfed barley yields doubled. These differences in response are suggested to be an effect of the fertility level of the soils and the fertilizer application. Wheat, and in particular irrigated wheat, is grown on the most fertile soils and receives the highest amounts of mineral fertilizers. On the contrary, rainfed barley is grown on the most marginal soils with low inherent fertility, on gravel-rich hilly land, and receives little attention and no mineral fertilizers. This observation is supported by other researchers (Rai and Gaur, 1988; Ali et al., 2005). The stronger effect of the biofertilizer on barley compared to wheat is especially important for poorer households, who often have no access to the more fertile soils in the center of the valley and to irrigated land.

Inoculation of wheat and barley seeds with *Azotobacter* and *Azospirillum* was also a suitable entry-point technology for the PTD approach of the project. The technology is relatively simple and easy to apply for farmers; it is cheap; and it does not require major changes of the farming system or the management practices. Over a wide range of farming environments, it proved to be superior compared to the common farmers' practice, and it poses a low economic risk of failure. The increasing number of farmers asking for the technology proves the suitability for farming households in the upper catchments of Karkeh River Basin in Iran. The economic analyses revealed that the *Azotobacter* technology has a high potential to increase farm household income and, therefore, may serve as an option to reduce poverty.

Conclusions and recommendations

Azotobacter and *Azospirillum* inoculants are well adapted technologies to dry mountainous areas of the Karkheh River Basin. The biofertilizers significantly increased wheat and barley yields and net returns. Moreover, there was a low economic risk for the *Azotobacter* treatment to be outperformed by the control treatment. The technology is cheap, easy to handle, does not change major parts of the farming and cropping system, and is easily available. Therefore, it can serve as a strategic component

for farmers to cope with the harsh environments and to increase livelihood resilience in Upper Karkheh River Basin and in similar areas.

Acknowledgments

This paper presents findings from PN24 'Livelihood Resilience in dry areas,' a project of the CGIAR Challenge Program on Water and Food.

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Water productivity estimates in the Volta Basin, West Africa

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Abstract

An attempt to estimate integrated water productivity (WP) in the Volta Basin is presented, including rainfed crops, livestock, and fisheries. WP for cereals and tubers have been derived from national statistics and rainfall. WP for livestock and for fisheries in Lake Volta, however, could not be estimated properly as the water consumed or depleted by these activities could not be estimated properly.

Media grab

The water productivity concept could be applied to agriculture production but not to gathering activities such as fisheries or transhumant livestock keeping in the Volta Basin.

Introduction

Because agriculture is the main consumer of water at the global level, and considering the general increase in water scarcity, increasing the production per unit of water has been identified as one of the world's most serious problems requiring urgent attention. Other limiting factors can be considered, however, and lead to other indicators: availability of land area, labor availability, energy, and financial inputs. Water efficiency or water productivity (WP) is one form of agricultural efficiency that may be analyzed, with the objective of a reduction in the water consumption by agriculture while maintaining or increasing production. It has been developed mainly for irrigated crops, for which it is a robust measure of the ability of agricultural systems to convert water into food (Le Houérou, 1984 ; Molden et al., 2003). It seems useful to extend the concept to include other types of livelihood support, such as mixed cropping, pasture, fisheries, or forests, and to define actionable goals of agricultural water management for poverty alleviation (Kijne et al., 2003; Cook et al., 2006; Hussain et al., 2007). If water productivity could be applied to all rural activities, and especially to the array of food production, then a common matrix would allow comparisons of the different productions within a single system of units and help in water allocation policies. The possibility of such an approach was tested on the Volta Basin (West Africa) during the Basin Focal Project-Volta.

The Volta Basin is a transboundary area of 394,100 km², which lies mainly in Ghana (42%) and Burkina Faso (42%), while Benin, Togo, Côte-d'Ivoire, and Mali share the remaining 16%. Our work focuses on the upstream Burkinabe and the downstream Ghanaian parts of the basin.

The upper part of the Volta Basin lies in semiarid Burkina Faso, and the rivers flow toward the more humid Ghana. The priority in Burkina Faso is to develop water conservation, with numerous small dams and some medium size reservoirs. Lake Volta, in the lower part of the basin, was created to generate hydropower at Akosombo (1,020 MW). It is a high priority for Ghana.

In the basin, rainfed agriculture is by far the dominant cropping system, being practiced on more than 95 % of the cultivated area. The different uses of water in different parts of the basin set the scene for the need of some consultation processes for water allocation, in a context of climate change and a population increase of 2.5 to 3 % per year (Andah et al., 2004; de Condappa et al., 2008). The water productivity approach can help in identifying which types of production make the best use of the available resource, and where improvements can be made.

Water productivity

Water productivity is defined as output per unit of water depleted. Output may be measured in terms of the amount or value of crops or livestock produced or (at least in principle) the value of water in domestic, urban, industrial, hydropower or environmental uses. Water is considered to be consumed or depleted when it is unavailable for further use, for example, when it is evaporated or transpired, or polluted to the point where it can no longer be used.

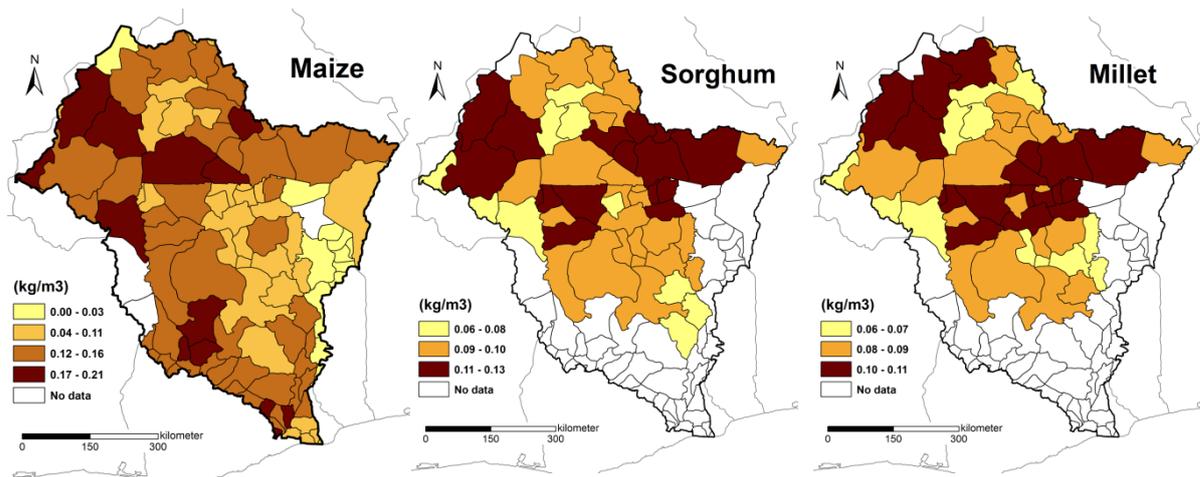


Figure 1. Field scale water productivity for maize and sorghum in the Volta Basin. Map generated by BFP Volta with data from Ministry of Food and Agriculture, Ghana (MOFA), and by the Ministère de l'Hydraulique, de l'Agriculture et des Ressources Halieutiques of Burkina Faso (MAHRH), mean values for 1992-2000. Rainfall from Climate Research Unit (Lemoalle, 2008).

Water productivity of food crops Basin scale

Water productivity at the basin scale was estimated as the amount of food crop production (in the Ghana and Burkina Faso parts of the basin) divided by the amount of rainfall received by the total corresponding area (a), and by the cultivated area only (b). The related figures are: WP(a) food crop calculated for total area : 51 kcal/m³ for the year 2000. WP(b) food crop calculated for cultivated area only : 466 kcal/m³ for the same year. In the Volta Basin, WP(a) is quite low. This is largely because of the small area devoted to crops relative to the area of savannah or grasslands, or nonarable lands. Most water is depleted through evapotranspiration in uncultivated areas. At the basin scale, crop water productivity would increase if a larger proportion of arable land in the basin were to be cultivated. WP(b) is also low, because of poor soils, low inputs, rain variability, and low technology. The farmers' strategy is to maximize their work power and to reduce the risk of failure, not to improve water productivity.

Field scale

Water productivity at the field scale was estimated as yield divided by the volume of rainfall received by the cultivated area. Crop water productivity is generally higher for maize than for sorghum or millet. Mean values for crop water productivity were 0.15 kg/m³ (± 0.05) for maize, 0.10 kg/m³ (± 0.03) for sorghum, and 0.08 kg/m³ (± 0.03) for millet. The spatial distributions in the Volta Basin of field-scale water productivity for maize and sorghum are shown in Figure 1.

Relationships between maize, millet, and sorghum yields and annual rainfall were analyzed. Maize yields were found to be partly correlated with annual rainfall, with a strong dispersion ($R^2=0.2$). In other words, maize yields tend to be higher where rainfall is more favorable. No such correlations were found between sorghum or millet yields and annual rainfall ($R^2=0.05$ and $R^2=0.03$, respectively).

Water productivity was found to be partly correlated with rainfall for sorghum and millet ($R^2=0.3$), but not for maize ($R^2=0.06$). The water productivity of sorghum as a function of annual rainfall is represented in Figure 2.

These relationships may be explained as follows: in the northern part of the basin, maize yields are constrained by inadequate moisture, while in the southern part of the basin, maize takes advantage of higher rainfall levels and yields more. Higher rainfall leads to higher yields, so water productivity (yield divided by rainfall) is relatively flat across the basin. In contrast, yields for sorghum and millet do not increase as rainfall becomes more abundant. This means that water productivity for these crops declines in wetter areas. These crops are less able than maize to take advantage of increased moisture to produce higher yields, but their yields do not decrease as much as that of maize in drier areas or in drier years.

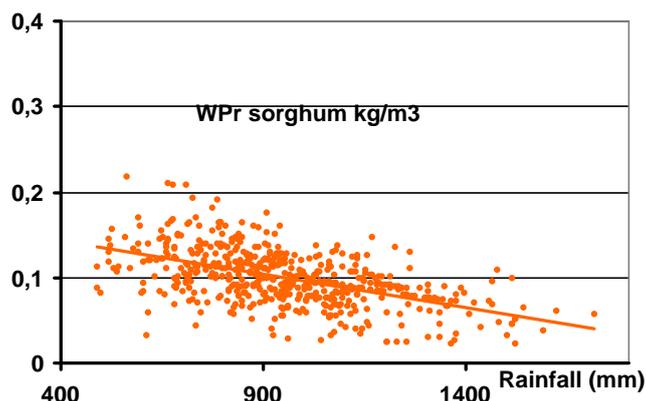


Figure 2. An example of the biased relationship between rainfall and water productivity: water productivity of sorghum as a function of annual rainfall. Data from MHARH and MOFA and CRU rainfall (Lemoalle, 2008).

WP of livestock and fisheries

Water productivity has been introduced mainly as an indicator of irrigation performance. The concept applies when some volume of water, or some area of rainfall, is dedicated to a productive use. It applies to agriculture, not to a gathering activity. Fishing is typically a gathering activity. Livestock production can be typically an agricultural activity in industrial countries, but can also be partially a gathering activity in developing countries with free access to rangeland.

If fisheries are considered, either in the ocean or in inland water bodies, the water is not dedicated nor consumed for fish production. Fisheries are gathering activities and no denominator can be identified for WP computation. Some marginal WP, however, can be estimated on some occasions if some water is dedicated to improve the fishery. This can occur for ecological flows in rivers or in order to increase the inundated area of a floodplain, and thus its total production. In both cases, an increase in fish catch ΔP can be associated with some water volume ΔW , dedicated to this increase. The marginal water productivity is $\Delta WP = \Delta P / \Delta W$.

In most industrial countries, a specific area is dedicated to fodder and feed production for the cattle. If these are rainfed, the rainfall over this specific area is the denominator of the livestock WP. The virtual content of the other elements of the cattle feed may also be computed. The consumption for watering the animals is a very small fraction of the feed water content. In semiarid tropical environments, the cattle mostly feed on wild rangeland which is often not delineated. It is therefore difficult to estimate the rain water which has allowed the growth of the fodder.

WP of other productions

The other main productions using water are cash crops (mostly rainfed), and hydropower from lakes Volta, Bagré, and Kompienga. These productions are best qualified by their economic returns (in US\$). The water used for hydropower is more difficult to estimate. The hydrologic budget can be computed for a hydroelectric reservoir, with the net evaporation loss from the lake surface used in the WP denominator. It should, however, be considered that the services that can be provided by the water below the dam are not identical to the services provided by the same water at the reservoir surface, e.g. for irrigation at an intermediate altitude. The services provided by (blue) water do not seem to be taken into account in the WP approach.

Conclusions

The concepts of WP and of virtual water have proven useful in focusing on the question of the sustainability of water use by agriculture worldwide, although agricultural WP indicators do not always capture the full range of benefits and costs associated with water use (Hussain et al., 2007). Consideration should be given in particular to the overall benefits or value of water at various levels for larger growth and poverty alleviation impacts, considering the sustainability of the systems.

Water productivity is largely scale and context specific. For example, the organic rich drainage water of a fish pond may be considered as consumed in some instances, if delivered to a river, but may be regarded as useful water if it is to be used for irrigation. The WP of the fish pond changes considerably

according to the use of its drainage water, and to the scale considered (fish pond alone, or fish pond plus irrigated field).

Although WP seems well adapted to basin scale analyses, it may not apply equally to all the various activities in a basin. Gathering activities, as opposed to agricultural activities, are not properly taken into account, except when marginal WP can be involved. Gathering activities are typically fishing and livestock rearing in wild rangeland.

At the farm or family scale, resilience to natural variability, especially to unreliable rainfall, is a dominant component of the family strategy in semiarid environments. This applies equally to rainfed cultivation and to livestock rearing where minimizing the risk does not always result in increasing WP.

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Effect of conservation agriculture on the soil biochemical characters in semi-arid area of north China

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Abstract

A study on microbial biomass C (MBC) and N (MBN) content and soil enzyme activities (dehydrogenase, acidic phosphatase, β -glucosidase, and urease) under different tillage systems was carried out for a 4-year experiment in a semi-arid area of north China. Two different tillage systems were compared: conservation agriculture-zero tillage with straw mulching (CA), and conventional tillage with the crop residues removed (CT). Soil analyses were performed on samples collected at four depths (0-5 cm, 5-10 cm, 10-20 cm, 20-30 cm). Zero tillage significantly increased crop residue accumulation on the soil surface. In general, higher organic matter content, MBC, MBN and enzyme activities were found in the more superficial layers of soil under CA than under CT. Biological properties showed a pronounced decrease with increasing soil depth for both tillage systems. Conservation agriculture was the more effective practice for improving soil chemical and biochemical qualities.

Media grab

Conservation agriculture (reduced tillage with straw mulching) improves soil chemical and biochemical qualities.

Introduction

Soil biochemical characteristics such as soil organic matter (SOM) content, soil microbial biomass and soil enzyme activity are important indicators of soil health. Tillage and residue management have a direct effect on soil biochemical characteristics. Soil organic matter distribution, nutrient cycling, and microbial activity are usually influenced by the type and the degree of soil tillage (Salinas-Garcia et al., 2002). Research has shown that soil organic matter and soil microbial biomass and activity respond to crop and soil management practices such as tillage and residue incorporation (Kaiser and Heinemeyer, 1993). Traditional extensive tillage (moldboard plowing with residues removed or burnt) often causes a rapid loss of SOM leading to a decrease of soil biological activity and impairment of chemical properties over time. The efficiency of conservation agriculture (CA) (zero or reduced tillage with residues retained) to reduce soil erosion and improve soil quality is universally recognized. Numerous studies have shown that decreasing tillage intensity or increasing the amount of surface residues on the soil surface result in higher organic C and N and improved soil quality (Heeman et al., 1995; Soon et al., 2001).

Soil degradation is a concern in semi-arid areas of north China due to serious soil erosion, especially on crop lands where conventional tillage practices have resulted in moderate to severe soil erosion. Numerous studies in this region have shown that conservation tillage can increase soil moisture, reduce wind erosion and increase crop yield (Wang et al., 2007), but most of the research has focused on changes in soil physical and chemical properties to date. In contrast, information on the effects of CA on biological processes such as soil enzyme activities, which mediate nutrient cycling and influence their acquisition during active crop growth stages, is limited. The purpose of this study was to determine the effects of different tillage systems and residue management on the dynamics of SOC, microbial biomass characteristics and soil enzyme activity, and also the effects of soil enzymes on soil microorganism activity and nutrient cycling in a semi-arid area of north China. We hypothesized that a CA system would have a positive effect by increasing SOM and soil fertility and enhancing soil microbial functionality.

Materials and methods

Site characteristics description and experimental design

The experiment was carried out in Shouyang County, Shanxi Province, China (37°32'-38°6'N, 112°46'-113°26'E) at 1300 m above sea level. The location has a semi-arid warm temperate continental climate with a mean annual precipitation of 474 mm, most of the rain falling between July and September. Evaporation is 1714 mm and exceeds rainfall throughout the year. The mean annual

temperature is 8.14 °C, mean annual sunshine is 2679 h, and mean length of the growing period is 130 days. The soil is classified as Cinnamon soils. The main crops are maize, millet, and sorghum.

The experiment was started in 2004 and compared two tillage/residue management treatments (called 'tillage' treatments for simplicity): CT+RM–conventional tillage (CT)–30 cm deep moldboard plowing, with all crop residues removed for fodder (RM), and a CA treatment ZT+RK–zero tillage (ZT) with the residues kept (RK) on the soil surface after harvest (standing in the field). The plot area was 380 m² (19 m×20 m). No disease or insect pest controls were applied. Urea (300 kg/ha) was applied as top dressing in the jointing stage of maize every year. Maize was planted each year in late May.

Soil sampling

Soil sampling was carried out in October 2007 (after harvesting maize) – collected using a 5 cm diameter coring tube from 10 locations in each plot. The soil was divided into layers of 0-5, 5-10, 10-20, and 20-30 cm and respective layers from within each plot were composited. After carefully removing the surface organic materials and fine roots, each mixed soil sample was divided into two parts. One part was air-dried for the estimation of soil chemical properties and the other part was sieved through a 2 mm screen and incubated at 25°C for 2 weeks to enable uniform rewetting and to stabilize microbial activity after the initial disturbances.

Soil chemical and biological properties analysis

Soil organic matter (SOM) was determined by wet oxidation (Black, 1965) and the percentage of organic carbon was calculated by applying the Van Bemmelen factor of 1.73 (Piper, 1950). Soil total nitrogen (STN) and total phosphorus (STP) were measured using the method of Bao (2000). Microbial biomass C and MBN were estimated by fumigation–extraction (Brookes et al., 1985; Vance et al., 1987). Soil enzyme activities (dehydrogenase, β-glucosidase, alkaline phosphatase, urease) were determined by the method of Wu et al. (2006).

Statistical analysis

All statistical work was done using the SPSS 11.0 for Windows. One-way ANOVA was used to analyze means, to least significant difference at the 5% level.

Results and discussion

Soil organic carbon (SOC), soil total N (STN), and soil total phosphorus (STP)

Soil tillage greatly affected soil chemical properties, and values declined with depth in all treatments. CA increased SOC content by around 10% in the 0-5 and 5-10 cm layers, but had no effect in deeper layers (Table 1). This was probably due to increased carbon input from residue retention (Brevik et al., 2002).

Table 1. Soil profile chemical properties under different tillage systems.

Indicators	Tillage treatment	Depth (cm)			
		0-5	5-10	10-20	20-30
Soil organic carbon (mg/g)	ZT+RK	15.3*	14.6*	13.1	11.7
	CT+RM	13.7	13.4	13.6	12.2
Soil total nitrogen (mg/g)	ZT+RK	6.93*	6.28*	5.17 *	3.88
	CT+RM	5.76	5.44	4.23	3.52
Soil total phosphorus (mg/g)	ZT+RK	0.83*	0.78	0.68	0.66
	CT+RM	0.76	0.74	0.71*	0.65

*Symbol identifies significant difference between treatments in the same soil layer at the 5% level.

Soil total N showed the same trend as SOC in relation to different tillage treatments. In the 0-5 cm layer, STN under CA was increased by 18.9% compared to CT, while in the 5-10 cm layer, STN was increased by 7.4% (Table1). Below 10 cm, the STN differences were not significant.

Soil total P under CA was 8.6% higher than under CT in the 0–5 cm layer (Table 1). In the 10–20 cm soil layers, the STP content was 10.2% lower under CA than under CT. In the 5-10 and 20–30 cm layers, the difference was not significant. Long-term zero tillage management commonly leads to a stratification of available P in soils (Zibilske et al., 2002). The topsoil accumulation of P in CT+RM is attributed to the limited downward movement of particle bound P in zero tillage soils and the upward movement of nutrients from deeper layers through nutrient uptake by roots (Urioste et al., 2006).

Soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and enzymatic activities

Microbial biomass C and N were significantly affected by both soil depth and tillage system. MBC varied from 136 to 312 mg/g in CA and from 120 to 166 mg/g under CT (Table 2). MBN varied from 25 to 64 mg/g in the soil under CA and from 26 to 47 mg/g under CT. In the 0-5 and 5-10 cm soil layers, MBC and MBN were significantly higher under CA than CT. In the 0-5 cm layer, microbial biomass C and N were 88 and 73% higher under CA than under CT. Microbial biomass C and N decreased with soil depth, more so under CA. Soil subjected to CA accumulates crop residues and organic C in the surface layers, providing substrates for soil microorganisms near the soil surface. As a consequence, the soil microbial biomass and various soil microbial processes increase in surface soils under CA (Roldán et al., 2007).

Table 2. Soil profile biological properties under different tillage systems. MBC = microbial biomass carbon, MBN = microbial biomass nitrogen.

Indicators	Tillage treatment	Depth (cm)			
		0-5	5-10	10-20	20-30
MBC (mg/g)	ZT+RK	312*	218*	152	136
	CT+RM	166	138	130	120
MBN (mg/g)	ZT+RK	64*	45	37	25
	CT+RM	47	36	32	26
Dehydrogenase (mg TPF/ kg.24h)	ZT+RK	45*	26	22	5
	CT+RM	37	28	25	14
Alkaline phosphatase (mg PNP/ kg.h)	ZT+RK	475*	351 *	310	209
	CT+RM	289	228	217	112
β -glucosidase (mg PNP/ kg.h)	ZT+RK	353*	316*	270	186
	CT+RM	257	203	199	107
Urease (mg NH ₃ / kg.h)	ZT+RK	13	12	11	8
	CT+RM	10	10	9	8

*Symbol identifies significant difference between treatments in the same soil layer at the 5% level.

Since dehydrogenase activity is only present in viable cells, it is thought to reflect the total range of oxidative activity of soil microflora, and consequently may be considered to be a good indicator of microbial activity (Nannipieri et al., 1990). Tillage system had significant effects on soil dehydrogenase activity (Table 2). The dehydrogenase activity ranged from 5.2 to 44.8 mg TPF/kg.24h in the soil under CA and from 13.8 to 36.8 mg TPF/ kg.24h under CT. Zero tillage resulted in a significant increase in dehydrogenase activity at the 0-5 cm layer. In the 5-30 cm depth, there was no significant difference in dehydrogenase activity between treatments CA and CT. Other authors have reported similar results under no tillage or conventional tillage under semi-arid conditions (Madejón et al., 2007).

The phosphatases are a broad group of enzymes that hydrolyze esters and anhydrides of phosphoric acid. Tillage treatment had a significant effect on alkaline phosphatase activity (Table 2), particularly in the 0-5 and 5-10 cm soil depths, where CA significantly increased it by at least 53.7% compared to CT. In the 10-30 cm depth, values for both treatments were similar. Kremer and Li (2003) showed that phosphatase activity in soils under organic management was greater than under conventional management.

The β -glucosidase activity varied from 186 to 353 mg PNP kg/1 in the soil under CA and from 107 to 257 mg PNP/ kg.h under CT (Table 2). Averaged across the depths, β -glucosidase activity under CA was 46.7% higher than under CT. β -glucosidase, an enzyme already reported as an early indicator of changes in soil properties induced by tillage systems (Ekenler and Tabatabai, 2003), catalyzes the hydrolysis of various β -glucosides during the decomposition of organic materials. This fact could indeed explain the increase in β -glucosidase initially observed as a result of CA with straw cover treatment.

Conclusions

Four years after the tillage treatments commenced in semi-arid north China, there were significant treatment effects on soil chemical properties, microbial biomass, and soil enzymatic activities. SOC, TN, and TP in the topsoil (0-10) were greater under the CA system (zero tillage with residue retention on) than under conventional tillage with residues removed. The CA system promoted surface accumulation of crop residues and was more effective in improving soil biochemical quality than the conventional tillage system. The beneficial effects of CA on soil quality were more noticeable in the surface (0-10 cm) than below. In addition, the microbial biomass and enzyme activity showed higher sensitivity to soil management practices than the chemical properties. These variables might be useful soil quality indicators once their critical values have been determined for different conditions.

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Introduction of salt-tolerant wheat, barley, and sorghum varieties in saline areas of the Karkheh River Basin

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Abstract

Salinity is a major problem in irrigated areas of the lower Karkheh River Basin (LKRB) where high groundwater level has compounded the situation. Use of salt-tolerant genotypes, such as high-yielding salt-tolerant wheat, barley, and sorghum varieties, is a potential short-term consideration to address the growing salinity problem in the area. In a field study, we evaluated seven wheat genotypes, six barley genotypes, and eight sorghum varieties (four lines and four hybrids) in individual experiments at Dasht-e Azadegan. The experiments were arranged as randomized complete block designs with three replications during 2005-2008 for wheat and barley and 2006-2007 for sorghum experiments. Results of the wheat experiments showed that Sistan, Kavir, and Bam had the highest yields (4.7, 4.5 and 4.4 t/ha), while Verinak produced the least (3.2 t/ha). Based on the results of the barley experiment, On-4 (3.3 t/ha) and M 81-19I (3.0 t/ha) produced the highest grain yield. For sorghum, KFS4 (104.2 t/ha) had the highest fodder yield for 2 years among pure lines. For hybrid varieties, Speedfeed (117.0 t/ha) had the highest fodder yield for the first year, but in the second year Jumbo produced the highest yield with no significant differences with Speedfeed and Sugargraze. Considering that 90% of the planted area in this region under cereal cultivation has an average yield of 2 t/ha, the introduction of high-yielding salt-tolerant varieties could have a positive impact on total crop production and water productivity.

Media grab

Yield increases of up to 50% are possible through the use of salt-tolerant crop species in the irrigated areas of the Karkeh River Basin.

Introduction

Salinity and waterlogging co-exist in the lower reaches of several river basins throughout the world, affecting agricultural production and the livelihoods of the affected communities (Wichelns and Oster, 2006). The same applies to the lower Karkheh River Basin (LKRB) of Iran. Efforts being made to overcome salinity and waterlogging problems consist of engineering solutions such as installation of a drainage system to manage the drainage effluent generated by irrigated agriculture. This is a long-term strategy, however, as drainage installation is expensive. The areas under salt-affected and waterlogged soils are expanding because of inappropriate on-farm water and soil management. Selection and cultivation of high-yielding salt-tolerant varieties of different crops is a potential interim strategy to fulfill the needs of the communities relying on these soils for their livelihoods (Ayers and Westcot, 1989).

Many crops show intraspecific variation in response to salinity, including wheat (Kingsbury and Epstein, 1984, 1986; Parida and Das, 2004). Barley is one of the most salt-tolerant crop species, but there are also wide variations among its genotypes under saline conditions (Royo and Aragues, 1999). Sorghum is moderately salt-tolerant (Maas et al., 1986). Generally, substantial genotypic differences exist among sorghum cultivars in response to salinity stress (Sunseri et al., 2002; Netondo et al., 2004). The objective of this study was to compare yield of some salt-tolerant wheat, barley, and sorghum varieties in the saline areas of LKRB.

Methods

This study was conducted at Dasht-e Azadegan in Khuzestan Province during 2005-2008. Dasht-e Azadegan is located in the LKRB and lies between 31° 04' 35" to 31° 51' 39" N and 47° 46' 34" to 48° 35' 12" E. Wheat, barley, and sorghum genotypes were examined in separate experiments.

Wheat crops were grown in 4 × 7 m plots with each plot containing 18 rows of each genotype. The rows were spaced 0.2 m apart. Prior to sowing triple super phosphate was mixed into the top 0.25 m of soil at a rate of 115 kg P/ha. To assure adequate N fertility throughout the experiment urea was added at the rate of 150 kg N/ha. Herbicides were applied to control weeds whenever necessary. The salt-tolerant genotypes were Bam, Akbari, Sistan, Kavir and Roshan. The local wheat cultivars were Chamran and Verinak.

The treatments for barley experiments were two cultivars (Afzal and Reyhan) and four barley lines (Karon × Kavir, M80-9, M-81-19, and On-4). Barley rows were spaced 0.2 m apart with sowing density of 350 seeds/m². Each plot was 4.0 m × 6.5 m, so that 18 rows of each genotype were sown in every plot.

Wheat and barley genotypes were sown in November 2005, 2006, and 2007. To determine grain and straw yield of wheat and barley genotypes, a 3 m² area was harvested from the center of each plot.

In the sorghum experiment, the treatments included four hybrid varieties (Speedfeed, Sugargraze, Jumbo, and Nectar) and four pure lines (KFS₁, KFS₂, KFS₃, and KFS₄). Each plot was 6.0 m long and 1.8 m wide and contained 6 rows, which were spaced 0.3 m apart.

At four occasions during the experiments (planting, stem elongation, flowering, grain filling) soil samples were taken to a depth of 0.9 m for salinity measurement of saturated extracts.

All experiments were laid out in a randomized complete block design with three replications. The data collected were subjected to variance analysis using SAS software. Statistical differences among the means were determined using Duncan's new multiple range test.

Results and discussion

Root zone salinity

Crops were irrigated during the growing season with irrigation water diverted from Kharkheh River. Salinity of the river water was around 1 dS/m. The relatively good quality of irrigation water leached the salts, which were deposited in the soil during the fallow season as a result of high evaporative demand and high water-table level. As shown in Fig 1, crops were affected by salinity during the growing season in addition to other environmental stresses (waterlogging and end of the season heat stress).

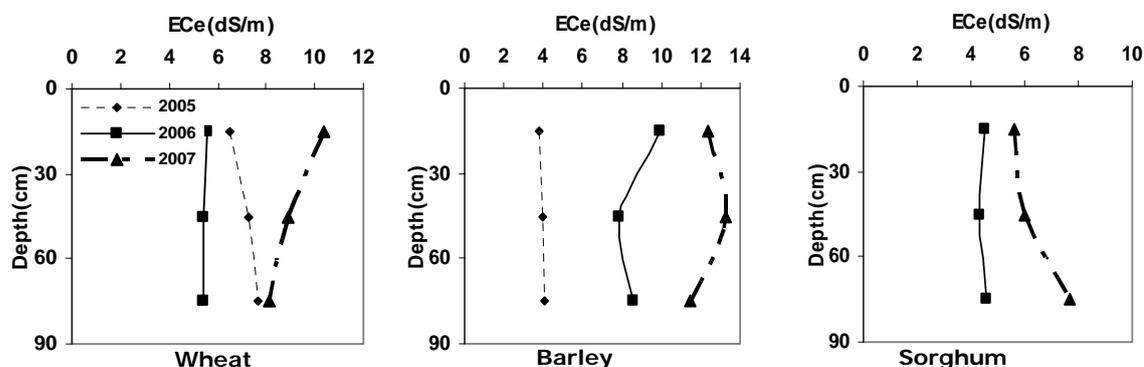


Figure 1. Average soil salinity for different growing seasons.

Wheat

Statistical analysis of combined grain yield for 3 years showed that yield performance of the genotypes varied significantly. Among the genotypes, Sistan and Verinak produced the highest and lowest grain yield, respectively, regardless of the year. The mean grain yields of Sistan, Kavir, Bam, Chamran, Roshan, Akbari, and Verinak were 4.7, 4.5, 4.4, 4.3, 4.1, 3.9, and 3.2 t/ha, respectively. Comparison of mean grain yield of genotypes in each year showed that Sistan produced the highest grain yield except in 2005-2006 (Table 1). The mean grain yield of Sistan for the whole experiment was 11 and 47% more than Chamran and Verinak (local varieties), respectively. Verinak showed the lowest grain yield compared to the other varieties for 3 years.

From the present study, it appears that all genotypes have the same main stem leaf number, and the same phenology except for Verinak (data not shown). In spite of this, Sistan, Kavir, and Bam showed higher yield than the others. There are many genetic factors that affect grain yield under saline

conditions, such as the number of tillers and leaf area duration (Hay and Walker, 1989). The number of tillers per plant for Sistan, Kavir, Bam, Chamran, Roshan, Akbari, and Verinak were 4.0, 3.0, 3.5, 2.2, 4.1, 3.7, and 2.0, respectively. In fact, salt-tolerant genotypes produced more tillers than the local varieties. Roshan produced the most tillers during the growing season, but it lodged at the end of the season and its grain yield was markedly reduced. The other very important factors affecting grain yield under stressed conditions are leaf area and the duration of the grain filling period. Field observations showed that varieties like Sistan, Bam, and Kavir had the highest ground cover and longest grain filling period. This allows for more mobilization of soluble carbohydrates from other parts of the plant to the developing grains. Short grain filling period could be a factor causing low yield in some varieties such as Verinak.

Barley

Combined analysis of variance showed that On-4 produced the highest and Afzal the lowest grain yields regardless of the year. The mean grain yields of On-4, Reyhan, M80-9, M81-19, Karon x Kavir, and Afzal were 3.3, 3.1, 2.8, 3.0, 2.9, and 1.7 t/ha, respectively (Table 2). The barley genotypes produced the same grain yield each year except for Afzal. High-yielding barley varieties are always tall plants. Thus a variety that has a strong stem and does not lodge in the field can produce the highest grain yield (Hay and Walker, 1989). Field observations showed that lodging percentage for On-4, Reyhan, M80-9, M81-19, Karon x Kavir, and Afzal were 0, 20, 3, 0, 10, and 55, respectively. Therefore, based on the results of grain yield and lodging percentage, On-4 and M81-19 could be considered as new barley genotypes for the LKRB.

Table 1. Comparison of mean grain yield for wheat genotypes during 2005-2008.

Genotypes	2005-2006	2006-2007	2007-2008
Kavir	4.1a	3.9ab	5.4ab
Roshan	3.8ab	3.7ab	4.6bc
Bam	4.5a	4.2a	4.6bc
Akbari	3.2bc	3.2bc	5.4ab
Sistan	3.9ab	4.3a	5.7a
Chamran	3.8ab	4.0a	5.0b
Verinak	2.7c	2.9c	4.1c

Means followed by the same letter were not significantly different (Duncan's 5%).

Table 2. Yield comparison of barley genotypes during 2005-2008.

Genotypes	2005-2006	2006-2007	2007-2008
Reyhan	3.3a	3.6a	2.5ab
M80-9	2.6b	2.9ab	3.0a
M81-19	3.4a	3.4a	2.3bc
On-4	3.6a	3.3a	3.1a
Karon x Kavir	3.2ab	2.9ab	2.7ab
Afzal	1.0c	2.2b	1.7c

Means follow by the same letter were not significantly different (Duncan's 5%).

Sorghum

KFS₄ produced the maximum fresh matter of 100.7 t/ha in 2006, followed by KFS₂ and KFS₁, with 92.7 and 86.3 t/ha, respectively, which were not significantly different. A minimum of 66.9 t/ha fresh matter was observed for KFS₃ in 2006 (Table 3). Again, in the second year (2007), the maximum fresh matter was measured for KFS₄, at 107.7 t/ha.

For hybrid varieties, Speedfeed produced the maximum fresh matter yield of 117.0 t/ha in the first year, followed by Sugargraze, Nectar, and Jumbo, which were in the same Duncan's group with 89.3, 81.9, and 70.2 t/ha, respectively (Table 3). In the second year, Jumbo produced the highest fodder yield with 130.4 t/ha followed by Speedfeed (124.6 t/ha) and Sugargraze (120.7 t/ha), which were not significantly different. Nectar hybrid variety had the lowest fodder yield in the second year. The highest dry matter yield of 23.6 t/ha was measured for KFS₄, followed by KFS₂ and KFS₁, with 22.8 and 20.6 t/ha, respectively in first year, which were not significantly different. KFS₃ produced minimum dry matter of 17.0 t/ha among lines in the first year. KFS₄ produced the highest dry matter yield of 30.1 t/ha in the second year, again followed by KFS₃ (27.7 t/ha) with no significant difference.

Dry matter production of Speedfeed, Sugargraze, and Jumbo hybrid varieties differed significantly in the first year (Table 3). The highest total dry matter yield of 28.3 t/ha was measured for Speedfeed. Sugargraze and Nectar produced the next highest dry matter (22.3 and 18.7 t/ha). Total dry matter of both varieties was not significantly different in the first year. Jumbo had the lowest hybrid dry matter yield of 17.1 t/ha in 2006, and the highest yield of 32.6 t/ha in the second year. Combined analysis of dry matter showed that Speedfeed produced the highest dry matter yield for the two years of 30.5 t/ha (data not shown).

Table 3. Comparison of fresh and dry matter yield for sorghum lines and hybrids.

Line	First year(2006)		Second year(2007)	
	Fresh matter yield (t/ha)	Dry matter yield (t/ha)	Fresh matter yield (t/ha)	Dry matter yield (t/ha)
KFS ₁	86.3 a†	20.6 ab	83.2 c	23.9 c
KFS ₂	92.7 a	22.8 a	100.2 ab	27.4 b
KFS ₃	66.9 b	17.0 b	95.4 b	27.7 ab
KFS ₄	100.7 a	23.6 a	107.7 a	30.1 a
Hybrid				
Speedfeed	117.0 a	28.3 a	124.6 a	32.6 ab
Sugargraze	89.3 b	22.3 b	120.7 a	30.1 bc
Jumbo	70.2 b	17.1 c	130.4 a	34.7 a
Nectar	81.9 b	18.7 bc	96.0 b	27.5 c

†Means comparison were made separately for lines and hybrid.

Conclusion and recommendations

Crop production in the lower areas of the Karkheh River Basin is impaired by highly saline soil and water resources and waterlogging conditions. At present, the crop varieties used by farmers are not adapted to the prevailing soil conditions, and significant improvements in production could be realized by introducing salt-tolerant varieties. Based on the results of this study, varieties such as Bam, Sistan, and Kavir for wheat, On-4 and M81-19 for barley, and KFS4 and Speedfeed of sorghum, were found to be more tolerant than the others and could be considered as potential substitutes for the present varieties under saline (also waterlogging) conditions of LKRB.

Acknowledgments

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Marketing small packs of fertilizer in Limpopo Province, South Africa

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Abstract

It has been asserted that resource-poor farmers do not buy fertilizers because they are unable to afford the large-size packages, and that farmers could sustainably increase the use of fertilizer if smaller (more affordable) packages were made available to them. Therefore, SASOL Nitro, Progress Milling, Limpopo Department of Agriculture, Agricultural Research Council, and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) collaborated to supply different-sized packs of fertilizers, especially ammonium nitrate, to farmers in Limpopo Province, and to monitor its use. This was done over three seasons—2004-5 to 2007-8. Small pre-packed fertilizer packs were supplied to the Province by Sasol Nitro through Progress Milling—a private food processing and inputs supply company. Progress Milling then distributed the packs to its depots (over 100) located in communities throughout the province. This paper reports on the outcome and experiences from the project (CPWFPN1) aimed at assessing whether farmers could sustainably increase the use of fertilizer if more affordable packages were made available to them. Generally, fertilizer in South Africa is packed in 50 kg bags. On average, a 50 kg fertilizer bag of compound fertilizer would cost R242 (equivalent to US\$30). Sasol Nitro packed the fertilizers into 10 kg and 20 kg packages which cost R48 (US\$6) and R97 (US\$12), respectively, and ensured that it was available to farmers at all Progress Milling depots. Most of the first-time fertilizer users opted for smaller packs because they could experiment with less risk, and lower costs.

Media grab

Supplying fertilizer in small packs has improved fertilizer access for poor smallholders in Limpopo Province, South Africa.

Introduction

Agricultural production in sub-Saharan Africa is hampered by low use of inputs such as improved seeds and mineral fertilizers, low inherent soil fertility, and nutrient-depleted soils in much of the continent (Henao and Baanante, 2006; IFPRI, 1999; Mwangi, 1996). Millions of smallholder farmers suffer poverty and hunger because they are unaware of the correct inputs required to achieve subsistence yields from increasingly depleted soils. To achieve yield gains needed to meet food requirements of the rapidly growing population, Africa must significantly increase its current low levels of inorganic fertilizer use and intensify its production systems. African farmers, however, have little access to fertilizers and cannot always afford them. In response to various constraints faced by farmers, a consortium of partners—ICRISAT, Limpopo Department of Agriculture (LDA), SASOL Nitro, Progress Milling, and Limpopo Agricultural Strategic Team (LIMPAST)—teamed up to design a program aimed at providing fertilizer of various pack sizes to a selected number of Progress Milling depots. This initiative builds on a 2-year LDA-supported experiment and trials with farmers on improved soil and water management technologies. The trials included microdosing, which is precision (through time and space) application of small doses aimed at maximizing returns from small investments in fertilizers. The principle underlying provision of small packs is to make fertilizer affordable to many who cannot meet the full cost of the traditional 50 kg bags—creating convenient access to farmers as the fertilizer would be sent to a depot close to them. This program is aimed at laying a foundation for a rapid uptake of fertilizer through increased participation of the private sector.

From 2004-2007, the consortium worked together to improve access to fertilizer by packaging fertilizer into smaller packs and improving deliveries to local distribution depots owned by Progress Milling—a more than 50-year-old company operating in Limpopo Province. Progress Milling has over 100 depots in the province. Its core business is to process locally produced crops and to supply agricultural inputs. Progress Milling collaborates with SASOL Nitro (which manufactures the fertilizers), and PANNAR, in the supply of inputs. When farmers deliver grain to the depots, they have three options: leave it there for storage for sale at a future date; exchange with a milled bag of

grain of the same weight and pay a small milling fee; or sell to Progress Milling straight away. Progress Milling has gained the confidence of the farmers as a secure market as well as a secure source of food, since farmers can collect milled grain at any time of the year as long they have delivered grain to the depot.

Methods

Qualitative and quantitative data were obtained from various sources through desk reviews (secondary data) and from primary data obtained through field work designed and implemented by the research team. Two household surveys were carried out to obtain the primary data subsequently used to address the research questions. The preliminary survey was held in 2005-06 and 75 farmers were interviewed in the first round. The target group consisted of farmers who had bought fertilizer for the farming season 2005-06. A reconnaissance survey covering Progress Milling depots preceded this survey. It focused on depots that had sold small-pack fertilizer to assess the state of the depots (Minde and Pedzisa, 2008). The 13 depots were selected randomly out of 73 depots in the province that had a record of having received fertilizers for the season under reference. In addition, selection for inclusion was based on there having been on-farm trials on fertilizers around the depot. Agricultural extension officers who were within the vicinity of the depots were interviewed as part of the reconnaissance survey and they also assisted in the survey.

A larger and more in-depth farmer survey was carried out in 2006-07 targeting 180 randomly selected farmers consisting of 120 buyers and 60 nonbuyers. The main instrument used for data collection was a questionnaire, while descriptive statistics were the main analytical technique. After preliminary drafting of the questionnaires, the instrument was critically examined and fine-tuned before commencement of fieldwork.

Results and Discussion

Findings from the preliminary survey confirm that the more experienced farmers were not necessarily experienced in fertilizer use, because 20% of the sample farmers only started using fertilizer in 2005-06 season, thereby constituting first-time users. Inherent household characteristics such as age, farming experience, and household size are not significantly different between buyers and nonbuyers. Cattle ownership is high among nonbuyers but the subsequent quantities of cattle manure used on maize are lower among nonbuyers (Minde and Pedzisa, 2008). The income of buyers of fertilizer will be expected to be higher because they get additional income from crop sales. The most common source of income, however, for smallholder farmers in Limpopo Province is the government pension grant, disability grant, and child grant for children below 14 years—posing a challenge to new technologies since they need to provide appreciable additional income to be adopted. The landholding between buyers and nonbuyers is not significantly different. Education is an important factor in distinguishing buyers from nonbuyers, and it is hypothesized that education enlightens so that farmers are better able to appreciate new technologies as they come. Moreover, it is these educated farmers who are always targeted by extension officers for trials and training. The compounded effect will result in educated people appreciating and hence using fertilizer more compared to those who are not educated. The extension meetings are more widely attended by buyers than by nonbuyers, because these farmers need to learn and consult more with local extension officers.

Fertilizer use increases the yield of cereals, and this can be confirmed by the yield differentials between buyers and nonbuyers. When the season is good as it was in 2005-06, the difference in yield was highly significant. In 2006-07, however, which was a bad season, the yield difference was only significant at the 10% level. Only 35% of the respondents used soil fertility enhancements other than mineral fertilizers such as chicken and cattle manure. Chemical fertilizers are applied solely to maize, except for the irrigation schemes where they specialize in horticultural crops. Different methods were used to apply fertilizer depending on whether it was basal fertilizer or top-dressing. Targeted application methods were commonly used to apply the fertilizers. Spot application of top-dressing fertilizer using a bottle top is a technique referred to as microdosing, and this was deliberately promoted by ICRISAT in Zimbabwe as well as South Africa, particularly in Limpopo Province.

Buyers of fertilizer had much higher incomes and years of education (Table 1), and slightly larger landholdings. Their crop yields were at least double those of nonbuyers, and they participated more often in extension meetings. Buyers and nonbuyers of fertilizer were similar in terms of average age (58 years), farming experience (17 years), cattle ownership (7 per household), and quantity of manure used (1000 kg/household each season).

Table 1. Distinguishing characteristics of buyers and nonbuyers.

Descriptive variable	Buyers	Nonbuyers	t-value
Age (years)	59.36	58.45	0.604
Farming experience (years)	17.59	16.39	0.500
Schooling (years)	6.08	4.0	3.292**
Household size	6.74	6.31	0.803
Land holding (ha)	1.63	1.37	1.178*
2005/06 cereal production	2303.48	1074.78	3.197**
2006/07 cereal production	619.48	291.24	1.867*
Number of extension meetings	4.34	2.04	3.231**
Number of cattle owned	6.9	7.3	-0.173
Quantity cattle manure applied to maize (kg)	1486.52	1190.37	0.977
Annual income	26,327.74	15,317.51	1.848*

*10% level of significance

**5% level of significance

Source: ICRISAT Survey data 2007.

Most farmers (60.3%) bought fertilizer from the local Progress Milling depot for the cropping season 2006-07 than from any other source. The other sources of fertilizer included urban wholesalers, local and distant retail shops, as well as the local depot of a competitor company called Northern Transvaal Koopeative (NTK.) The initiative of supplying fertilizer through Progress Milling depots was born of a private-public partnership that strengthened over the year, and saw more fertilizer supplied through local depots. The opening up of local depots resulted in fertilizer being available to the smallholder farmer thus addressing the access constraint. Amongst the households in the survey sample, farmers who bought fertilizer from urban wholesalers were declining in number, whilst those who sourced fertilizer from the local depot were increasing in number over the 3 years (Figure 1).

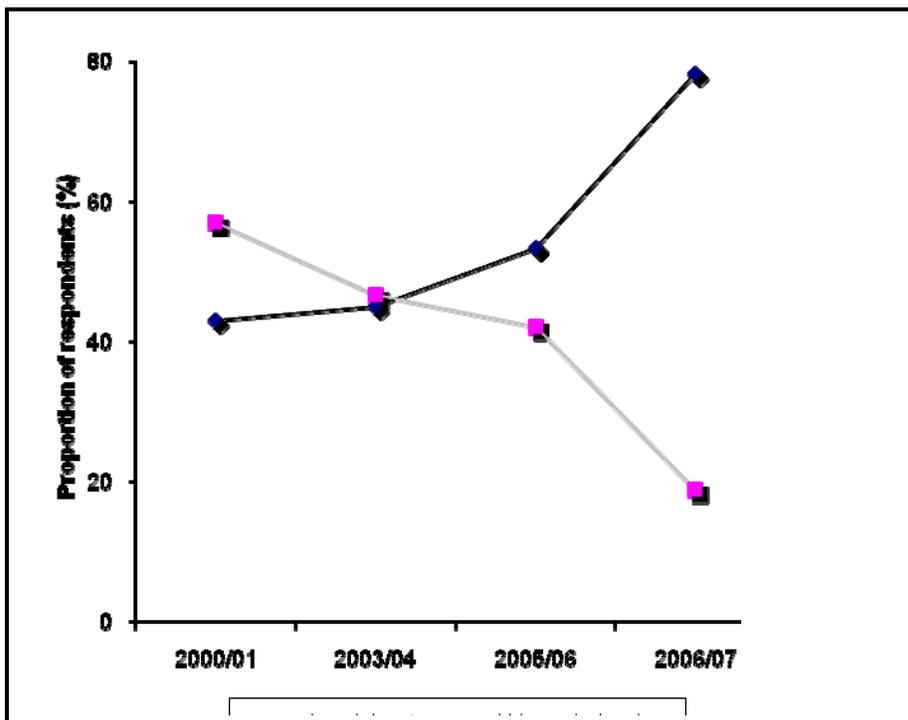
The total investment outlay required to buy a 10-kg pack is five times less than the investment required to buy a 50-kg bag. The investment required to buy a 50-kg bag might be equivalent to the price of a goat, whereas the cost of a 10-kg bag would be the same as the price of a chicken. The price per unit, however, between a small pack and the 50kg pack is not very different. Farmers were still paying the same price per kg for the pack size they bought for the two fertilizer types (Table 2). The cost of fertilizer per kg could not have influenced the farmer's decision to buy small packs, but it is the total investment required to buy a particular pack size.

Table 2. Average price of different pack sizes by fertilizer type 2006-07.

Fertilizer type	Price per unit (Rand)		
	10-kg packs	20-kg packs	50-kg packs
CAN/LAN	30.5	61.00	151.23
NPK (2.3.2)	33.3	65.00	150.01
Price per kg of NPK (2.3.2)	3.33	3.25	3.00

Source: ICRISAT Survey data 2007.

It was revealed that, though Progress Milling local depot provided fertilizer to many farmers (44%) in the past 5 years, urban wholesalers were the most popular option supplying fertilizer to almost 55% of the farmers. Over time, Progress Milling local depot captured most of the fertilizer customers. Within the past two seasons, Progress Milling has dominated the fertilizer market for smallholder farmers with a market share of 78% (Figure 1). This is because of the convenience to the farmers of having fertilizer closer to their homestead. Urban wholesalers provided the cheapest fertilizer as expected, because wholesalers buy direct from the manufacturer and sell in bulk. It would seem that the 50-kg bags provided a cheaper option of buying fertilizer for the farmers but there is a hidden cost. By virtue of volume and weight of the 50-kg bag added by the distance, it becomes inevitable to pay for transport. All the farmers who bought the 10-kg packs did not pay the transport cost because they carried the fertilizer by head.



A small number of farmers have received training and conducted trials but these seem to be on the increase in Limpopo Province. Farmers are learning about banding and spot application as ways of applying fertilizers. At least 80% of the nonbuyers have never attempted to use fertilizer. The most important reason cited by farmers was that fertilizer was too expensive and therefore unaffordable. The second constraint was lack of information about availability and use of fertilizers.

Characteristics of buyers

Farmers were characterized into those with experience in fertilizer use, and those without experience. The experienced group was subdivided into those who regularly apply fertilizer, and those who occasionally apply fertilizer. Most farmers with experience in fertilizer use and who consistently applied fertilizer purchased 50-kg packs of fertilizer (Figure 2). On the other hand, some farmers with experience in fertilizer use who use fertilizer only occasionally usually purchased smaller packs. Their use of fertilizer was irregular depending on whether they had money, whether they considered their soil to be fertile enough, or whether they preferred to use manure. First time fertilizer users only purchased small packs. These were generally poor farmers who could not afford the larger 50-kg bags and who were still in the learning phase about fertilizer use. These farmers also owned smaller plots or were involved in backyard vegetable gardens.

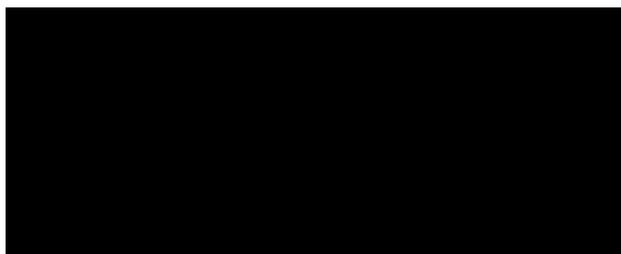


Figure 2. Fertilizer pack size preferences of different fertilizer users.
Source: ICRISAT Survey data 2007.

First-time users of fertilizers opted for smaller 5-kg packs while consistent users bought larger packs (Figure 2). The relatively more use of large packs could also be that smaller packs may not have been abundantly available at the time and place of buying to enable farmers to have a choice. About three-quarters of farmers who bought the 10-kg pack have less than 5 years of using fertilizer. The remainder has between 5-10 years of fertilizer use experience. More than half of the farmers who bought 20-kg bags are fairly new in the practice of using fertilizer. It can be noted that the majority of those buying 50-kg packs have quite some experience in using fertilizer of between 5 and 10 years. One possible inference here is that first-time users of fertilizer who are still experimenting buy the small packs (especially the 10-kg packs). Farmers who have been using fertilizer for many years are likely to buy the 50-kg packs because they have gone beyond the trial stages. Small packs therefore provide an essential starting point for using chemical fertilizers.

In terms of purchases of fertilizers, 50-kg packs dominated the fertilizer sales in the survey areas (Figure 3). This could be associated with the unavailability of small fertilizer packs at the required time. Affordability was the most popular reason for buying small-pack fertilizer, followed by poverty, which is strongly related to affordability (Figure 4). This result also demonstrates that smallholder farmers are considerate of the cost implications of production.

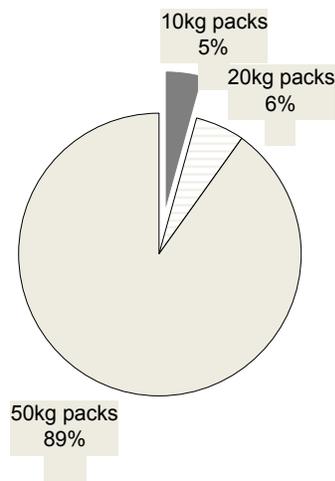


Figure 3. Farmer purchases by pack size in the survey area for 2006-07.
Source: ICRISAT Survey data 2007.

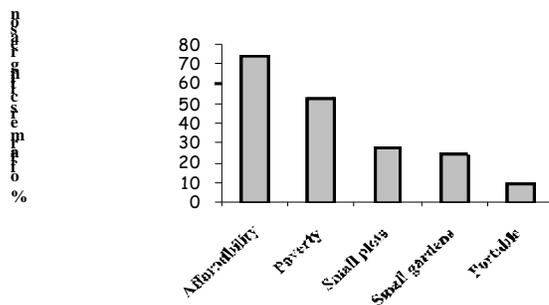


Figure 4. Reasons for buying small pack fertilizer.
Source: ICRISAT Survey data 2007.

Fertilizer use by crop

Most of the 20- and 50-kg packs were used for maize production, while the 10-kg packs were used for maize and vegetable production (Figure 5). Fertilizer use for vegetables was almost entirely from small packs.

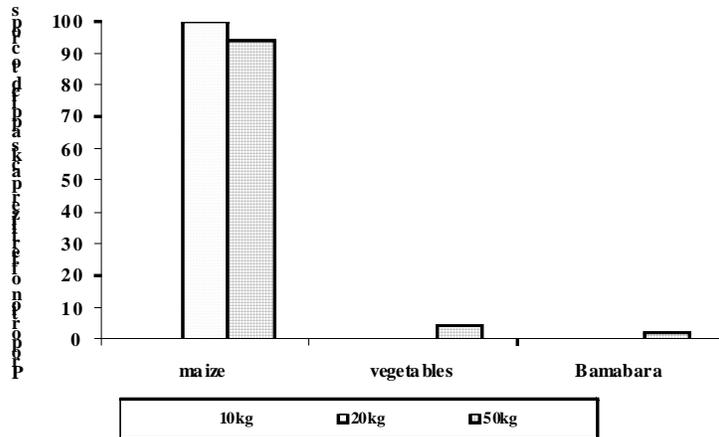


Figure 5. Uses of fertilizer packs in 2006-07.
Source: ICRISAT Survey data 2007.

Most farmers used spot application (i.e. applying the fertilizer directly at the base of plant) rather than broadcast or banding (Figure 6). Farmers who purchased small-pack fertilizers used spot application methods more frequently than farmers who used banding or broadcasting. This confirms that they were considerate of the cost of fertilizer and thus ensured that the application was most efficient.

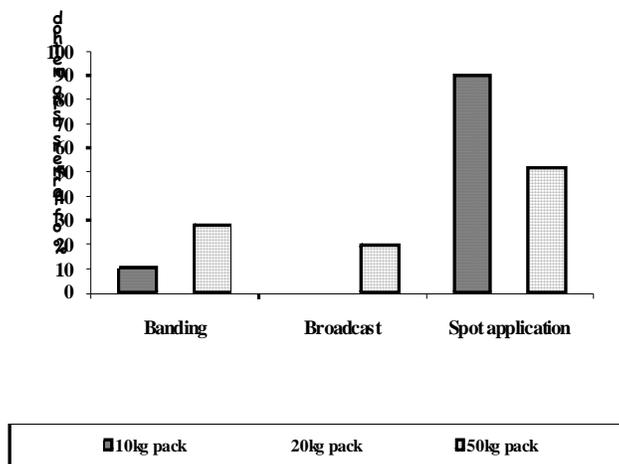


Figure 6. Fertilizer application methods.
Source: ICRISAT Survey data 2007.

In general, smallholder farmers in the area were skeptical about inorganic fertilizers. Farmers cited the following reasons for avoiding using chemical fertilizer: fertilizers are expensive, there is a risk of burning crops especially under moisture stress, and there is a preference for organic manures.

Conclusions and recommendations

The distinction between nonbuyers and buyers of fertilizer could only be explained in terms of annual income earned, the education level attained, size of landholding, number of extension meetings attended, as well as the levels of cereal production in any given year. The factors that determine pack size preference were not clear from this study, because the sample was skewed toward those who bought the 50-kg bags. A closer analysis revealed that among those who bought the 10-kg packs were inexperienced in fertilizer use. The farmers were trying fertilizer for the first time or were second-time users. Seasoned farmers who use fertilizer consistently bought 50-kg bags. This, therefore, implies that there is a market for small-pack fertilizer among the first-time users. Cash resources did not come out as a constraint as hypothesized. There is not enough evidence to conclude that farmers who bought the small packs were cash constrained. On the contrary, these farmers fell into the third quartile of the income ranking.

The place for small packs in smallholder agriculture needs to be further investigated and ascertained using a balanced sample with farmers who have equal access to all pack sizes. Demonstration trials and training in microdosing can enhance the use of small packs for the purposes of experimenting as a stepping stone to increased fertilizer use. Farmers who have stopped using fertilizer because of financial constraints can resume through purchase of small packs that are affordable. The public-private partnership between ICRISAT, LPDA, SASOL Nitro, and Progress Milling, has managed to improve fertilizer access to smallholder farmers in Limpopo Province. The partnership is still to improve the capacity of smallholder farmers to use fertilizer through training and hosting of on-farm trials, and improving access to fertilizer at the village level is critical because few villagers' stock fertilizer—farmers buy from the nearest town, paying extra for transport. It is paramount to build the private sector capacity for input supply in rural areas as well as supply small packs through community-based retail shops. Furthermore, policy reforms are necessary to create well functioning fertilizer markets and reduce transaction costs.

Acknowledgments

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Catalysing collective action in water management and scaling up and out in multiple use systems

Empowering communities to co-manage natural resources: impacts of the *Conversatorio de Acción Ciudadana*

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Abstract

Community participation is recognized as an essential part of equitable and sustainable watershed management, however, meaningful participation is difficult to achieve when communities are unorganized, unaware of their legal rights and responsibilities, and lacking the information, education and confidence necessary to interact with other more powerful stakeholders. The *conversatorio de accion ciudadana* (CAC) is an innovative methodology for empowering communities to participate actively and effectively in the governance and management of natural resources. This paper presents the results of three CACs conducted in the Colombian watershed between 2005 and 2007. The experiences are analyzed based on participant observation, process documentation, and an *ex post* evaluation. The three CACs led to over 75 specific commitments on the part of authorities to improve conditions in watersheds. Important human and social capital impacts were also documented, as well as changes in relations between communities and institutions.

Media grab

In one day, empowered communities negotiated over 75 concrete commitments from public and private institutions to improve environmental and social conditions in three Colombian watersheds.

Introduction

It is widely recognized that effective and equitable watershed management requires the participation of all relevant stakeholders. Since upstream land use affects downstream water quality and quantity, downstream residents may suffer (or benefit) as a result of actions of those living upstream (Swallow et al., 2006). Regulation is one way to manage potential conflicts, but the high costs of monitoring and enforcement means that compliance is often low. In theory, stakeholder participation in watershed management can be a solution to these challenges. If stakeholders are involved in the decision-making, they are more likely to reach agreements that are mutually acceptable and therefore respected (FAO, 2006). In practice, the power inequities between different stakeholder groups often make it difficult for them to interact on a level playing field.

The *conversatorio de accion ciudadana* (CAC) is a politico-legal mechanism for achieving meaningful participation by civil society. It is based on the idea of civil society and authorities conversing in familiar terms about issues of importance to both, and arriving at agreements for action. The methodology, which consists of three phases—preparation, negotiation, and follow-up—is designed to address the inequities in power and information between communities and government institutions that often prohibit communities from exercising their constitutional rights to participate and to hold their representatives accountable.

Developed by Asdes (La Corporacion Asesoría para el Desarrollo) a Colombian NGO, and first implemented with support from WWF-Colombia in the late 1990s (Beardon, 2008), the CAC's point of entry is the Colombian constitution and the rights and responsibilities that citizens are entitled to but often do not know how to use. Training in concrete legal instruments that ordinary individuals can use to obtain information or compel government agencies to fulfill their obligations in a timely manner is accompanied by efforts to build social capital and improve people's knowledge of their natural resources. While the focus is on the community, training courses are also offered for public servants since in reality many of them are also unaware of their roles and responsibilities under the constitution, especially in relation to citizen participation.

The three pronged (environmental, social, and legal) capacity building or 'preparation' phase culminates in a one-day public meeting to which communities invite representatives of the authorities whose mandates include the key social and environmental issues identified by the communities in the preparation phase. A structured negotiation takes place leading to signed agreement by representatives of institutions to undertake specific actions to improve social welfare and natural resource management. In the follow-up phase of the CAC, community representatives ensure that institutions comply with their commitments.

CACs were conducted in three Colombian watersheds between 2004 and 2007 (these dates cover preparation and negotiation phases since the follow up is ongoing), two under the Scales project (Fuquene, October 2005-February 2007) and Coello (December 2005-May 2007), and one led by WWF and partners (Güiza, October 2004-October 2006). This paper assesses the impacts of the processes and identifies lessons for improving and scaling-up the methodology.

Methods

The information presented in this paper comes from a variety of sources including project documentation and direct observation of the processes and interaction with participants. In 2007, the Scales project commissioned an external review of the three CAC processes (Cantillo and Gonzalez, 2008a, b, c, undated) The evaluation methodology consisted of five steps or 'Moments': (1) Definition of scope and focus of the study with the project partners; (2) Reconstruction of the experience, again with the main partners; (3) Analysis of secondary data; (4) Collection of primary data, including interviews with participants from the communities, representatives of institutions, and elected officials in the watershed; and (5) Analysis.

Results and discussion

While all followed the same general methodology, each CAC was implemented in a slightly different way due to differences in the lead organizations, the social, political, and biophysical contexts, the available resources, and the level of support from organizations like ASDES and WWF. Why these differences occurred and how they affected the outcomes form part of the discussion of impacts. The types of impacts considered are: (1) Agreement signed on the day of the meeting; (2) Human and social capital impacts among participants from communities; (3) Relationships between communities and public institutions. Impacts on poverty and the environment are not addressed since these are of a long-term nature, however, implications for these kinds of impacts can be inferred from the shorter-term impacts that are presented.

Signed agreements

The CAC in Güiza, held on October 28, 2006, was the best attended. In addition to the institutional representatives, the state governor and two mayors were in attendance. The relatively high profile of the Güiza CAC is likely due to the fact that the first and only other CAC ever implemented had been held in the same region several years earlier. Also, the meeting was held in the state capital rather than in the watershed itself, due to security concerns relating to Colombia's armed conflict. Thirty agreements were signed with 13 institutions including municipalities, the environmental authority, and departments such as health, agriculture, and planning (Cantillo and Gonzalez, 2008c). Though most agreements were nonmonetary, a total of more than US\$1.7 million was committed for activities such as watershed planning, water and sanitation, health, and agriculture.

The CAC in Fuquene was held on February 28, 2007, in the regional capital, Ubaté. Eleven institutions attended, however, organizers were somewhat disappointed by the turnout since mayors did not attend and several sent representatives without authority to make commitments. Unlike in Güiza, in Fuquene there had been no prior experience with CACs, relatively little work on community organization prior to initiating the process, and no history with WWF or ASDES on which to build. Thus Fuquene, in spite of its advantages in terms of accessibility and security relative to Coello and Güiza, was in some ways the most difficult of the three environments. Nonetheless, 25 agreements were signed with 10 institutions (Cantillo and Gonzalez, 2008a). More than US\$13 million was committed for a range of activities including water treatment, conservation of protected areas, and productive projects with communities, however, 85% of this was from a federal emergency aid package that was announced after damaging floods in April 2006, but had been slow to be disbursed.

In Coello, the CAC was held on May 10, 2007, in the state capital of Ibagué, which is located within the watershed. Attendance was relatively good, including institutional representatives, elected officials, and even members of the

general public. Thirty agreements were signed with 14 institutions. A total of US\$600,000 was committed, less than in the others but as in the case of Güiza, the funds represented 'new' commitments for actions to be initiated in the current fiscal year, in this case for the purchase of land in environmentally sensitive parts of the watershed.

The total Scales project investment in the two CACs it supported was approximately US\$150,000 to cover staff time and logistics. To fully cost the CACs we would need to estimate both the partners' contributions—significant in Coello and Güiza—and the considerable time invested by the communities. The return on that investment would include not only the money committed on the day of the CAC, but also the nonmonetary commitments to implement policies and programs, or in some cases to involve communities explicitly in decision-making processes, which arguably could lead to much greater economic benefits over the long term.

Human and social capital impacts on participants

The CACs appear to have had major impacts on the human and social capital of the participants (Cantillo and Gonzalez, 2008a, b, c; Fujisaka, 2008; Participatory video). Baseline information is not available on human and social capital levels prior to the project, so the assessment is based on what was observed by project implementers over the course of the project and what the participants themselves say. In the Scales-supported CACs, an explicit attempt was made to target poor communities (Johnson et al., 2007), however, within those communities participation in the project activities was voluntary so those who chose to be involved are likely to have been among the more educated, innovative, or socially active people in the target communities. In Güiza, most of the CAC participants had previously been involved in a WWF-led course and were known to be people with leadership skills and an interest in environmental issues.

The specific interventions that the CACs undertook to increase human capital included training on legal rights and how to exercise them; hands-on analysis of environmental issues such as water quality, soil erosion or loss of biodiversity; workshops on identifying and analyzing problems and formulating solutions; and, especially for those who were 'questioners' in the CAC itself, coaching on how to formulate questions, arguments, and counter-arguments, and how to speak in public.

In some cases such as Fuquene, the main contribution to social capital occurred when participants from different communities came together to do training activities. Fundación Humedales developed a series of games to demonstrate legal and environmental concepts to people with low levels of formal education. In Coello, the coordinators were able to undertake activities such as a regional Water Forum, and the Coello Expedition, in which 40 people from all parts of the watershed spent 4 days following the river from its origin in the *páramo* to its outlet, learning first-hand about the watershed and about each other. In the evaluations, participants mentioned these events as having been important opportunities to learn about the watershed issues and to gain an understanding of the challenges faced by people living in other parts of the watershed.

In both Scales communities, economic games were conducted both as a research activity to understand better the factors that support or inhibit collective action in watersheds, and as a development activity in which watershed residents participate as 'players' in 'games' or scenarios designed to reflect the actual incentives people face when deciding how to use resources that have both individual and social costs and benefits (Cardenas and Ostrom, 2004). The games made explicit some of the reasons behind the lack of cooperation that many people observe, and generated discussion on how to address the problem. The consensus, however, from the communities was that they could have been better articulated into the CAC process.

In all cases, changes in human and social capital were observed and were documented through interviews, including increased skills, knowledge, and confidence (Cantillo and Gonzalez, 2008a, b, c; Fujisaka, 2008). Concrete applications by individuals of legal instruments such as *tutelas* or *derechos de petición* led to the resolution of personal and community problems, providing benefits to participants and perhaps more importantly building confidence and commitment to the CAC process. In Fuquene, a two-decades-old conflict between two communities about access to a water source in which the municipality had long denied responsibility was resolved when participants in a CAC training were able to compel a revision of the case, which led to a reversal of the mayor's position and a commitment to build necessary infrastructure to allow the downstream community to access the water.

Impacts were observed in all three sites, however, where education levels were low, progress was slower and methodologies had to be adapted to make them accessible. In Fuquene, fewer people benefited since budget constraints prevented inclusion of more communities—Fuquene and Guiza focused on three municipalities while

Coello covered six—and limited the number of times the full group could meet. Interviews conducted with non-participants say that knowledge of the CAC declines as distance from the process increases (Fujisaka, 2008) which suggests that spillover benefits are likely to be small, at least in the short run. Political violence in Coello and Guiza also reduced participation of some people in the process.

Changes in relations between communities and public institutions

As a result of the process, some community members have changed their perceptions of institutions and vice versa. Many community participants previously had a negative perception of public institutions, fueled in part by their perceived inaccessibility. As a result of the CAC experience, they have gained confidence in dealing with institutions, and in some cases have gained greater understanding of and sympathy for the constraints that the institutions themselves face in trying to carry out their obligations.

Representatives of institutions experienced similar changes in perceptions of the communities. According to several representatives interviewed as part of the evaluation, prior to the CAC, they often viewed communities as uninformed and hostile. As a result of the CAC, that perception changed to one of seeing the communities as constructive partners with whom institutions could collaborate to achieve shared objectives. This occurred not only with public sector institutions, but also with private sector ones such as the USOCOELLO irrigation district, which provides water to one of the major commercial agricultural zones in Colombia in the lower part of the Coello watershed.

Impacts at the level of institutions seemed to be greater in Coello than in Fuquene, where the limited prior interaction with the institutions led some to feel that they were 'put against the wall' in the CAC. There was more criticism in Fuquene than Coello on the part of the institutions, however, one representative acknowledged that some of this was due to the fact that some of the institutions in the Fuquene were particularly ineffective and untransparent and therefore felt threatened by the community's insistence that they comply with their responsibilities.

Conclusions and recommendations

The CAC methodology, as implemented in three Colombian watersheds between 2005 and 2007, led to 76 concrete commitments on the part of institutions to make improvements in welfare on watershed residents and the management of watershed resources. An assessment in late 2007 showed that compliance rates were relatively high, especially in the communities that had stronger follow-up processes. The CAC methodology also had significant human and social capital impacts on community members who participated, and led to changes in the ways that communities and institutions perceive each other, in some cases, moving from antagonism to respectful collaboration. While estimating an economic rate of return is beyond the scope of this assessment, relative to the size of the investment made in carrying out the CACs, the impacts appear to be large, indicating a high rate of return.

The main lesson from this experience is that a CAC takes time. The Scales project initially estimated that the preparation phase would take 3-6 months, when in reality it took a year and a half and even then had it not been for the Scales project deadlines, more time could have been used to properly prepare the communities and make the institutional contacts. Resource limitations were a part of this, but the main explanation was simply that the methodology was being applied in the local contexts by the local partners for the first time so it was difficult to estimate the time needed. The methodological guide being produced by the WWF and partners will provide more detail to organizations interested in implementing the methodology to permit them to plan accordingly.

In addition to the dedication of sufficient time and resources, perhaps the most critical determinant of success is the presence of a committed local organization with experience in community organization. In Fuquene and Coello the lead NGOs were relatively local in their scope prior to the CAC, but were interested in working at higher scales to address watershed issues. As such, both succeeded in increasing the recognition at the watershed scale and increased their visibility.

Scales project partners had experience in Fuquene and Coello prior to the initiation of the Scales project. In Fuquene, the experience was more of a research nature, and as a result there was more information and analysis available on the environmental and socioeconomic issues in the watershed. In Coello, experience had a research and a community development component and this appears to have provided a stronger base for the CAC.

Another key lesson was to link early with the public institutions to be invited to the CAC, since involving them in the process seems to lead to more meaningful participation in the negotiation phase. This is important both for public and private sector actors. In neither CAC, did the major private sector actors—e.g. dairy and potato farmers in Fuquene or rice farmers and CEMEX in Coello—play a major role. The basic CAC methodology is focused on communities and public institutions, however, the private sector is increasingly important in watershed management and innovative ways of engaging them need to be explored.

Finally, the impacts of the CAC will be larger and will likely be more widely distributed if more community members can be involved. A core team will always lead the process, however, so more emphasis can be put on having them share progress and seek feedback from their communities. Increasing the presence of the general public at the CAC itself will also make it clear to the public institutions that the people asking questions have the support of their communities.

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Sustainable resource management: an institutional perspective

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Abstract

Government policies on water and forest resource management both in Nepal and India are sector oriented. Although forest and water users groups in Nepal are more influential compared to their counterparts in India, due to customs and usufruct rights, independent management of resources still occurs in both countries. Since the needs of other users are rarely taken into account, the functional linkage among resource users, mainly the forest and water users groups in the watershed, is weak. Many areas are challenged by inequitable access to productive resources and benefit sharing within and across the users group. This is also due to the lack of an institution that facilitates integrated natural resource management (INRM). To address the institutional gap for resource management with a holistic approach, the research project facilitated the creation of a platform to encourage user group interaction by enabling them to present their views and interests, and to learn from the experiences of each other. The platform is expected to strengthen relationships with local organizations, government agencies and other external organizations for expanded and integrated activities on land and water management. Ultimately, the platform could evolve to act as up-scaled institutions for INRM at catchment level.

Media grab

Up-scaling of existing resource management institutions is necessary for CBINRM at catchment level.

Introduction

Poor rural women and men face critical food security and livelihood challenges, particularly in marginal upper catchments of the Nepal and Indian Himalayas. Restricted access to often-degraded water, land, and forest resources combined with low productivity of open-access resources result in seasonal or permanent out-migration leading to the loss of traditional knowledge, labor for management, and community solidarity to address resource degradation. Functioning models of Community-Based Natural Resource Management (CBNRM) seem to work for a single critical resource, e.g., forest. Examples of more integrated approaches tend to be found only at a small scale, in one or just a few communities. Yet communities need to manage multiple resources, particularly forests and water, and also have to address resource competition issues with other communities, e.g., upstream/downstream resource use and availability. An action research project was implemented to contribute to enhanced sustainable livelihood opportunities and reduced vulnerability for poor rural people in upper catchments in Nepal and India, through improved understanding of existing linkages or limitations among institutions for integrated natural resource management.

The objective of the study was to analyze forest- and water-based livelihoods opportunities and constraints through the lens of institutional dynamics exhibited by various resource management groups and institutions at the sub-basin level. This study attempted to understand:

- What are the institutional roles of each of the resource user groups in the management of natural resources?
- How are these user groups linked to each other in contributing to resource management?

Methods

The study was carried out at Begnas, and Hilaugad, Western Nepal, and Uttarakhand, India, watersheds (Figure 1). A review of the literature on the existing policy, legal, and institutional frameworks for Natural Resources Management (NRM) in Nepal and Uttarakhand, India, was done (Boje and Wolfe, 1989; and CGIAR, 2000). A reconnaissance survey was conducted for the selection of a micro watershed and its communities for detailed study. During the reconnaissance survey, transect walks were conducted along different routes in the basin area to gain insight into the sociophysical features and natural resources of the basin. Key information on the villages, farming system, water uses systems, local resource use patterns, livelihoods, and the institutional framework for

resource management were collected through informal discussions with the local community. This was followed by household surveys, focus group discussions, and measurements during the field study. At the end of the reconnaissance survey, a one-day workshop was organized to initiate dialogue with local users on research activities. For the purposes of the study, six and five villages in Begnas and Hillaugad watersheds were selected from the upper, middle, and lower reaches of the watersheds.

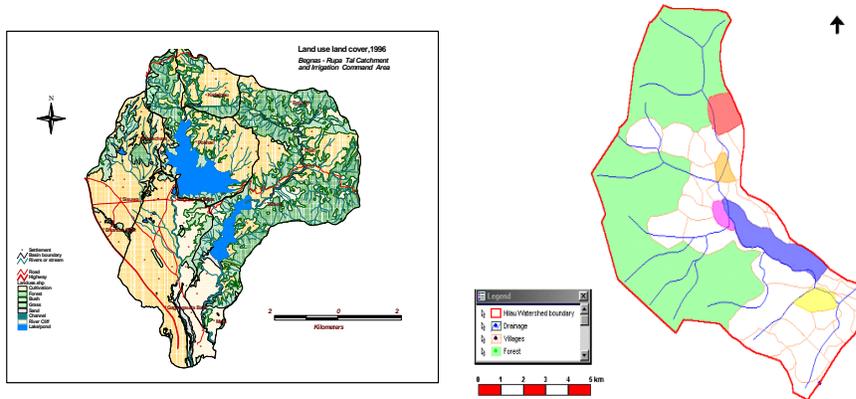


Figure 1. Begnas-Rupa Watershed, Nepal, and Hillaugand Watershed, India.

Results and discussion

Nepal

The review of policy, legal, and institutional provisions in relation to the integrated natural resources management (INRM) indicated that these are sector oriented and contain overlaps and contradictions. Therefore, it generates a disconnect among organizations and encourages vertical and horizontal disintegration rather than integration. This is because the sectoral line agencies have vertical linkage with local stakeholders, and their activities are guided by relevant sectoral policies. The ownership right of the water is vested with the government, although customary water-rights are recognized.

From field observations, it was revealed that the livelihood of the people with respect to resource management is based on agriculture. The people in the upper watershed are poor in comparison to the downstream users. One of the reasons is insufficient availability and poor management of farmer managed irrigation systems (FMISs). This is due to the traditional land-based water rights practices and inability to mobilize adequate resources for the improvement of infrastructure. The improvement in the infrastructure and redefining the existing water rights could provide benefits to the farmers. But due to lack of linkage with the external agencies, because of their informal nature, they have not been able to access external support needed for infrastructure improvement. Another important factor is that the upper watershed is the source of water to the Begnas irrigation system and the drinking water scheme serving the downstream towns. Likewise, the Forest Users Groups (FUG) are formally organized and have been managing forest that is community owned. Households in the community have access to forest products, mainly the firewood. Organizationally, they are strong, but their linkage with other institutions downstream is nonexistent. There is no linkage between the local forestry institution (CFUG) and local water institution (WUA) in terms of managing resources.

Though several water user groups are functioning downstream, the irrigation users group of the government-supported irrigation system Begnas Irrigation System and the fishers group who raise fish in the lake, are the important users in terms of obtaining benefit from the environmental services from the forest and water management. But, functional linkage among them is weak, as each of the user groups is trying to maximize the benefit from the lake without making substantial contributions for its sustenance. In such a situation, quite often, conflicts arise within and among the institutions due to their diverging interests. The interest of various resource user groups is reflected through their organizational undertakings. As far as water delivery at the system level is concerned, it was assumed that users could manage the internal water distribution on their own in an equitable way without needing external input. This assumption is not turning into reality, mainly because of lack of resources and inadequate communication among users. As a result, in many water use systems, water distribution has remained inequitable leading to several types of water use conflicts. Thus, improvement in governance and actualization of equitable and reliable delivery of water at the system level are prerequisites for functional linkages at the basin level.

The resource users recognize the water-forest (upstream–downstream) linkage although it is not clearly visible and users are unable to identify and establish this. One of the mechanisms for this linkage is to establish that the benefit downstream is due to the action of upstream users' and the cost/benefit needs to be ascertained. This

would facilitate the introduction of Environmental Services Fees (ESF). Besides, the enforcement of ESF is not possible without an intermediary who plays the role of mediator between the resource users upstream and downstream. Foremost of all, the users need to acknowledge and accept the concept of ESF, which is quite new to them. Establishing such linkages at the basin level would be possible only when the governance at the system level is improved to enable users' equitable access to and benefit from resources. In this respect, a holistic approach of catchment management in consultation with relevant stakeholders can create a win-win situation for all of them. This is not happening due to lack of relevant policies that delineate the roles and responsibilities of both external and local organizations in common property resource management. This clearly points to a need for integrated management of resources in the catchment.

In order to address the problem for CBINRM, this research project facilitated the formation of a platform, with representation from resource users, local institutions, and other stakeholders who were directly or indirectly affected by resource management in the catchment. The platform has been officially registered with relevant government agencies, and has acquired legal recognition. It is expected that users could learn from the experiences of each other, and some of the experiences should be shared among them for better resource management. For this, the users group could strengthen relationships with local institutions, government agencies, and other external institutions for expanded mandates for integrated activities on land and water management. Ultimately, the platform could be facilitated to act as up-scaled institutions for integrated natural resource management at catchment level.

Uttarakhand, India

Ownership rights of water is vested with the state government; there is no explicit formulation on customary rights. In 2004-05, the Uttarakhand government circulated a draft State Water Policy document in which a clear statement regarding ownership, control, and rights over water resources was missing. As a result, local communities and institutions could have had only a limited role in the various aspects of water resource management, viz., ownership, planning, development, use, and maintenance of the resources and systems. While the draft seemed to recognize a need for involving the local communities, even going to the extent of saying 'A paradigm shift towards participation of local community in management of water resources should be done,' the nature of the 'paradigm shift' had not been spelled out. Instead, the emphasis is on management of schemes installed by the line departments, rather than on decentralized governance of water resources. The civil society organizations actively mobilized public opinion against the derogatory move by organizing well-meaning debates. This thwarted government's move to sneak in the policy framework through the back door, and activists demanded ownership and first use rights over the natural resources.

In the past few decades, in order to incorporate an element of decentralized governance, the government had encouraged, established, and fostered institutions at the grassroots level in the rural areas, especially the formation of Van Panchayats (institutions of local self-government). Even though such institutions continue to proliferate, the sense of ownership by the community is lacking. Van panchayats are perceived as a government exercise. They are not demand driven, and the user's role is not explicitly spelled out, so the participatory management is in question. The 73rd Amendment of the Constitution has cast a Constitutional imperative on all the State Governments to come up with an appropriate Panchayat Raj Act detailing meaningful democratic devolution of functions, functionaries, and funds. Specifically, it empowers States to endow panchayats with such powers and authority to enable them to function as institutions of self-government, and goes on to list Water Management, Minor Irrigation, and Watershed Development as subjects under the jurisdiction of panchayats. It also envisages transfer of power to forest self-governing bodies.

From the field study it was observed that the irrigated lands have only modest productivity and community forests are degraded. Presently, there are serious implications for community-based natural resource management, especially in the era of massive shifts of livelihoods from agriculture to off-farm employment. This process of shifting of the primary source of income from agriculture to non-farm employment has reduced incentive for the rural communities to participate in various activities required to manage common property resources. Even the field studies indicate that families were not interested in offering voluntary labor for community activities such as the management and maintenance of community irrigation systems. As state control through legal, policy, and administrative provisions over natural resources has grown in the past, the local communities have become alienated. The rural communities now do not display sufficient interest in any initiative taken by the government. Most of the institutions for resource management are dysfunctional. The people do not show ownership of development programs or processes, though some voluntary organizations are working to alter this situation. Thus it becomes naturally imperative that there is a need to improve the condition but which can only become possible through community management. For this there will have to be a felt urgency to reestablish the traditional arrangements whereby the people not only enjoyed ownership of the natural resources but also managed the affairs in a sustainable manner.

To address the weak institutional base for INRM at the catchment level, this research project facilitated the formation of a 'platform,' with representation from resource users, local institutions and other stakeholders who were directly or indirectly affected by resource management in the catchment. The effectiveness of the 'platform,' however, will be known from its future activities. A comparison of the situation in Nepal and India revealed that both water and forest user groups in Nepal are organizationally strong compared to India, largely due to the policy and legal support. Therefore, the representatives to 'platform' in Nepal were from the respective user groups, whereas in the case of India the representatives were selected from a large number of users. Whether this makes a difference in their functioning is yet to be seen, as they have just started.

CONCLUSIONS AND RECOMMENDATIONS

Historically, users at the local level have protected, managed, and made beneficial use of the available natural resources for their livelihood. Therefore, the local users invested their resources in the development and management of natural resources with locally available technology. The FMIS and guls are the typical example of this collective action in Nepal and India, respectively. Over a period of time these natural resources became an important source of revenue for the government and therefore, government-introduced control mechanisms through various measures. Gradually, the government took over the ownership rights of these resources and usufruct rights were given to the users. Based on the discussions above in Nepal and India, the following conclusions could be drawn and are important in the context of INRM.

In Nepal, there are various stakeholders for the management of natural resources with formal and informal organizations, and among them forest and water users group are quite strong. In practice, all the user groups are working independently and have little interaction with each other in terms of natural resource management. There exist inequities in access to resource use and benefit from it to users within and across the resource users. This inequity is an obstacle for the integrated approach, and needs to be addressed. Developing an appropriate compensation mechanism for the positive outcome of the activities of the upstream users would be helpful in establishing upstream-downstream linkage.

Likewise, the resource management pattern in India indicates lack of strong policy, legal, and institutional support to encourage users to organize themselves for the management of the resources. Besides, the declining share of income from agriculture and related activities compared to the income from off-farm employment is also the reason for less interest in natural resource management. The users, however, recognize their role in managing natural resources, and that all users' groups wish to work in an integrated manner. The external stakeholders in this respect can play an important role for the integrated approach by facilitating the processes. The 'platform' concept has been introduced to facilitate INRM at the local level through users' participation in Nepal and India.

Recommendations

A legal framework clearly defining the customary right, usufruct right, and statutory right needs to be developed in both countries to address the issues on roles and responsibilities of various stakeholders, along with issues on intersectoral or interbasin resource management. The emerging equation between local elected institutions and the users groups in resource management needs to be taken into account.

Institutionally, the functioning of the 'platform' needs to be helped for some time to come as it learns to handle its responsibilities independently.

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**Effects of companion modeling on water management:
comparative analysis across five sites in Bhutan and Thailand**

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Abstract

The transdisciplinary companion modeling (ComMod) approach for adaptive renewable resource management aims to facilitate knowledge integration, collective learning, creative negotiation, and institutional innovation about concrete problems faced by communities. In this paper, we compare the effects of different ComMod processes on collective water management at five sites located in northeast and northern Thailand, and west-central Bhutan. At the three highland sites, agricultural commercialization leads stakeholders to review the local water management rules, while in northeastern Thailand land/water management dynamics are interlinked with labor migrations and the market integration of farming activities. The main effects of the ComMod processes at these sites are analyzed based on a common framework focusing on the stimulated processes of individual and collective learning, communication, negotiation, and coordinated action. The following effects are documented: individual learning about the current situation, increased awareness of a collective problem, understanding each other's perceptions, reaching a common agreement on the problem, exploration of new water management rules, implementation of new practices, and institutional innovation. The discussion focuses on how methodological choices made in the implementation of ComMod influenced the observed effects. The factors contributing to, or limiting, the achievement of institutional innovation are underlined, in particular the role of the local institutional context and the possibility to establish interinstitutional dialogue among multiple levels of organization are highlighted. Finally, we point out the need for specific monitoring and evaluation procedures adapted to such highly interactive and adaptive processes.

Media grab

ComMod, a pragmatic methodological approach, facilitates communication between social hierarchies relaxing the conflict situation and strategizing water management issues.

Introduction

Traditionally a public good not to be expropriated, 'Water' has become a highly contested renewable resource as a valuable part of cultural identity worldview. This has resulted from the pressure of diverse users and declining clean water, compounded by the breakdown of social fabrics due to globalization vis-à-vis commercialization. As seen by the changing and conflicting stakeholder role from relevance of issue to their ability to influence, further makes it a multidimensional problem. Within the complexity of multiple socioecological systems, modeling approaches offer pragmatic means to enhance the better understanding and strategizing of water management issues.

The contrasting problems associated with water use and management in different sites across Thailand and Bhutan provide a unique methodological challenge (Bousquet et al., 2005). Developing a common understanding among stakeholders to harness collective decisions can achieve longer lasting influences and impacts. Companion modeling (ComMod) approach facilitates dialogue and shared learning through collaborative multiagent modeling and simulation activities developed during the past 10 years by a group of researchers (Trébuil et al., 2008). Its methodologies rely on iterative coupling of role-playing games (RPG) and agent-based models (ABM), ComMod is an approach making use of evolving simulation models in a collaborative and integrative way to understand

complex systems and facilitate stakeholders collective decision-making processes when sharing a common resource (Bousquet et al., 2005).

In recent years, four sites in Thailand (Mae Salaep, Mae Hae, and Nam Haen, upland catchments in Chiang Rai, Chiang Mai, and Nan provinces, respectively, and Lam Dome Yai in the rainfed lowlands of Ubon Ratchathani), and one in the highlands of west-central Bhutan (Bousquet et al., 2005) have been testing the use of the ComMod approach to examine different water management issues, and to develop methodologies to enhance adaptive management capacities of the community by inducing experiential and explorative learning (Barnaud et al., 2006). This paper presents a brief comparative analysis of ComMod effects on water management.

Contexts

The five sites provide a very strong contextual diversity for applying the ComMod approach (Barnaud et al., 2006). To give a better insight into the sites in relation to water management issues, a simple framework (Table 1) is used to compare and contrast the cases. The principal focus in all sites is associated with water management concerns from plot to catchment level, which has evolved over generations. The problems are legitimate, however demand to address the issues have not always come from farmers (or stakeholders). In two cases (Nam Haen and Lam Dome Yai) it has been researchers addressing the problems based on the opportunities and experiences from research.

Table 1. Characterization of ComMod for water management contexts at the different sites.

Topics/Sites	Lingmteychu (L)	Mae Salaep (MS)	Nam Haen (NH)	Lam Dome Yai (LDY)	Maehae (MH)
Problem	Irrigation water sharing for rice cultivation	Irrigation water sharing in cash cropping	Forest conservation in upper catchment	Water and labor management in rainfed lowland rice	Shortage and unequal access of water
Scale of the problem	Seven villages	One Akha village (48HH)	Two Mien villages	Eleven households	Fourteen Villages
Age and evolution of the problem	Since the settlement and increasing conflict	Recent / rising due to more cash cropping	Recent /establishment of new national park	Since the settlement & rising with mobility	Since 2005
Severity of the problem	High for 7 villages	Low to medium, rising	Severe for small farms	Low	High
Researchers-stakeholders linkage	Since 1987	Several years of on-farm research	No previous collaboration	Several years of on-farm research	Since 2002
Origin of demand and legitimacy	Downstream communities. Highly legitimate	Villagers after previous ComMod activities; good legitimacy	Researcher to local devpt. agency & village leaders; low legitimacy	Researchers, low legitimacy	Local watershed management officer & local dev. agency
Opportunities/incentives to act	Increased access to irrigation water	Decentralization policy & allocation of financial resources	New park: redefinition of rules for accessing NTFPs	New plan for more investments in water infrastructures	Emerging regulation to equitable water sharing
Potential of ComMod in these contexts	Approach for learning and communication	Villagers already aware of ComMod and ask for more	Poor communication & information sharing	To enhance a joint understanding of the water – labor issue	Weak communication & need to facilitate collective action
Key development question	Sharing irrigation water & foster community cooperation	Inequity in decision-making about water & power relations	Public awareness & communication about the new national park	Water availability and labor migration management	Strengthening of local institutions
Key research question	Can ComMod facilitate better understanding and communication in resolving water sharing conflict?	Can ComMod facilitate the emergence of new equitable water sharing rules?	Can ComMod facilitate information sharing and consultation between stakeholders?	Can ComMod enhance understanding of the water management – labor migration interaction?	Can ComMod support improved water sharing & better understanding of resource management
Specific ComMod objectives	Understand decision-making in sharing irrigation water	Set up a consultation mechanism on irrigation water sharing	Improve communication among stakeholders	Integrate and produce new knowledge	Use ComMod & tools with different stakeholders

The diversity of stakeholders and their stake presents a challenge. Categorizing the stakeholders according to their relative influence (*control on outcome of issues*) and importance (*need to resolve the issue*) (Figure 1), indicates the position of farmers (small-majority) highest in importance and lowest in influence. Thus the actual control of the issue lies with other stakeholders for whom the issues may not be as pressing as it is to a farmer. It is the diversity of the stakeholders, power relations, and conflicting interests that provide a basis to establish key development objectives of awareness building, strengthening social capital, and networking; and key research objectives to test ComMod for better understanding, networking and institution building.

INFLUENCE	High	Block Development Office (L) District (L/MH) TAO President Community Leader (MH)	Royal Forestry Department (NH)	Farmers (LDY) Chief of National Park
	Medium	Local Development Agency (MH) Large farmer (NH) Research Team (NH) Village Network (MH) Watershed Management Com (L/MH)	Village Headman (NH) TAO Representative (NH)	Early Settlers (L) Large farmers (MH) TAO Representative (MH)
	Low	Research Team (L/MH/LDY/MS) National Park staff Local Highland Dev. Agency (MH)	Medium farmers (NH)	Small farmers (L/MS/MH/NH) Late Settlers (L) Medium farmers (MS/NH)
		Low	Medium	High
		IMPORTANCE		

Figure 1. Diversity of stakeholders and their relative role in water issues at five sites.

Process

ComMod uses different tools such as RPGs, ABMs, geographical information system (GIS), participatory mapping, etc. Within a ComMod process, tools are used iteratively to build up learning their use in the proceedings. These tools can be used in different ways to associate them depending on the context, objectives, and dynamics of a given ComMod process (Trébuil et al., 2008). In five test sites, the processes have been adapted to suit the situation. As represented in Figure 2, the process started with problem identification and analysis, and sensitization of stakeholders about ComMod in all sites. Studies addressed complex ecosystem issues (soil erosion in Mae Hae and Mae Salaep, hydrological dynamics in Lam Dome Yai, park-people interaction, and water sharing in Lingmuteychu).

Conceptualization of RPGs was done in a participatory way by using real situations and simplifying the problem context. While the ABMs were conceptualized based on previous RPGs in all sites, except in Mae Salaep and Nam Haen, hybrid gaming ABMs were used. Conception and implementation of RPGs and ABMs were iteratively done in all sites and with no definitive order (Figure 2). In all cases CORMAS simulation platform was used to implement the ABMs and simulate scenarios that were presented and discussed with the stakeholders.

Following the validation of scenarios, stakeholders make decisions for next steps, which often leads to the next cycle with a higher-level problem or a new problem altogether. For instance, farmers mobilized for a tea plantation in Mae Salaep from a simple water sharing problem of two villages in Lingmuteychu watershed. This led to the need for a watershed management committee, new NTFP harvesting rules, and livestock-forest interactions as the new issue in Nam Haen, and forest-arable land management to water conflict in Mae Hae from an initial issue of land use change.

The process promotes stakeholders to develop common action plans benefiting the community as in Lingmuteychu and Mae Hae as an off-shoot from the usual loop. Implementing the common action plan has lessened the tension on water sharing, instituted watershed management committees, and acquired donor funds to implement collective plans in Lingmuteychu.

The spiral within the RPG and ABM network represents continuous iteration between model and reality-enhanced incremental advances in collective understanding of the different viewpoints (D'Aquino et al., 2002). Such iterations used in all sites efficiently promoted knowledge integration in a collective learning process. Thus in all sites 2-3 cycles have been completed with every cycle opening up new frontiers and learning experiences.

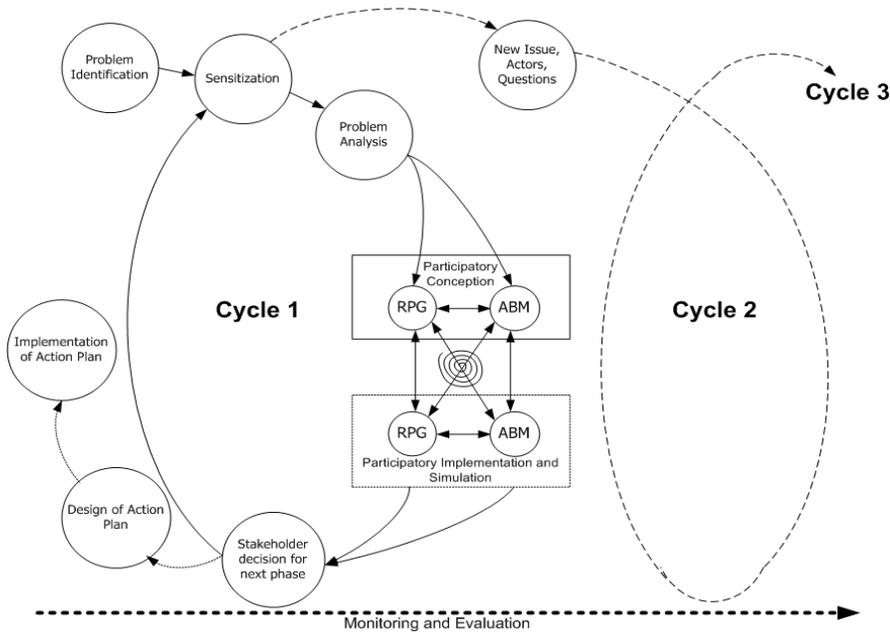


Figure 2. Schematic representation of a companion modeling process.

Diversity of effects

The effects of ComMod process in all sites have been diverse and tangible. To analyze effects over five sites, a simple framework based on experiences of the researchers is used (Figure 3). The foremost effect has been the acquisition of new knowledge on discovering farm dynamics in Mae Salaep and Lam Dome Yai, resource sharing as a key to community cooperation in Lingmutychu, and ecological dynamics in Mae Hae and Nam Haen. It is also evident that knowledge acquisition is at individual, collective, and institutional levels, which leads to subsequent changes. Acquired knowledge helped in better collective understanding and awareness of the situations. For instance, severity of complexity became clearer in Lingmutychu, Nam Haen, and Lam Dome Yai, while people became aware of opportunities for collective management in Mae Hae and Mae Salaep. Such awareness at individual and collective level engages people to collective learning leading to a series of changes.

Individual interviews of players in all case studies and monitoring of ComMod process using Most Significant Change approach and Logbook method revealed that in all the cases there was a distinct display of changes in perception, behavior, decision-making, and practices. Change in perception from neglect and isolated in dwindling resource situation changed with new knowledge and understanding, to confident, well connected and confidence to negotiate resource management. People in Lingmutychu started discussions on water issues openly beyond the village. Solidarity extended from kinship to community level, and resource-poor voices were heard in Mae Salaep. A contrasting behavior was observed, however, as people in Mae Hae participated in the consultative process, whereas in Nam Haen people who freely accessed forest chose to stay away from the process. Behavior change was broadly in terms of communication, networking, and engagement. Change in decision-making and practices from individualistic to collective mode supported emergence of adaptive mechanisms in most cases, except in Nam Haen. Overall the effect of these changes was on the evolution of the initial problem from simple to complex and more legitimate, that impacted their livelihood.

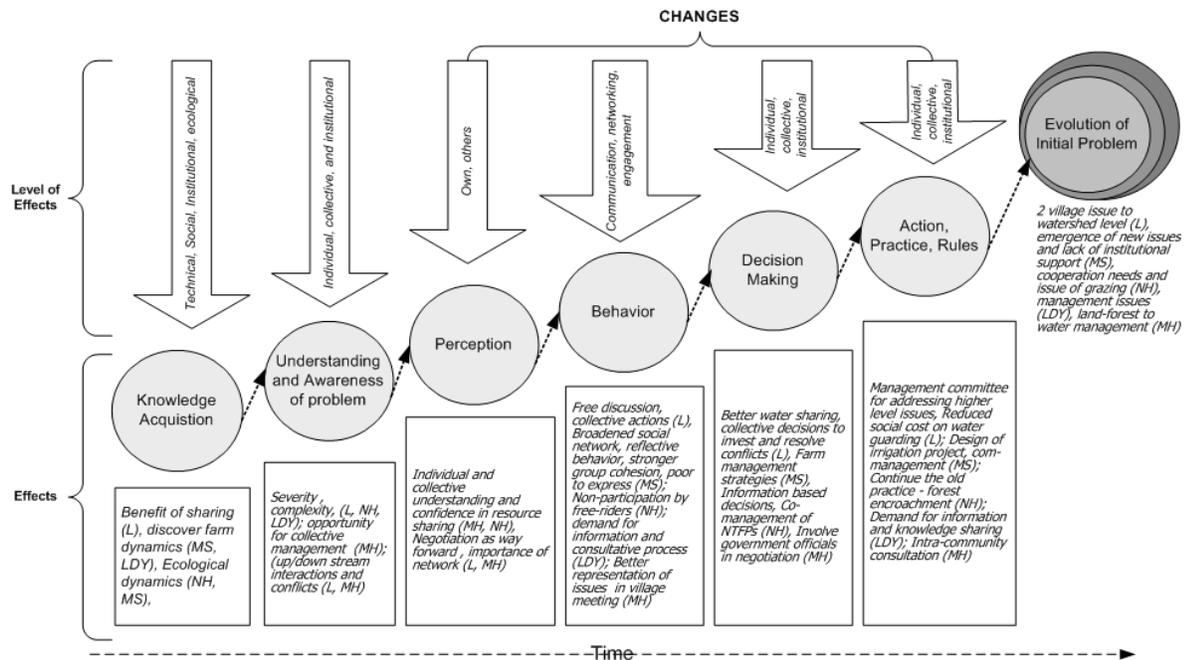


Figure 3. Diversity of effects and impacts generated by ComMod process.

Discussion

The five case studies in diverse socioeconomic and agroecological situations offer a wealth of experiences in using companion modeling approach. Some of the potentials and limitations of the approach are illustrated below:

Potentials:

- In a situation where communities lack knowledge to appreciate effects of their actions, ComMod process provides a suitable methodological approach to support knowledge acquisition at individual, collective, and institutional levels. It also facilitates behavioral changes leading to adaptive mechanism, a principal strategy to adjust in a dynamic ecosystem. The model and scenarios allowed people to step out of their real setting thereby enabling stakeholders to realize the problems. While it takes time (multiple cycles in case studies) ComMod creates space for integrating knowledge and viewpoints leading to trust in relationships between stakeholders.
- RPG in all five cases was confirmed to be a neutral communication platform that allows heterogeneous groups of stakeholders to participate in the process without comprehending their social status. RPG in conjunction with MAS modeling opens up pathways to networks of reciprocity and collective management, thus leading to construction of social capital.
- The use of different tools, agrarian system analysis (Trébuil and Dufumier, 1993), RPG and MAS Modeling (Bousquet et al., 2002), GIS (Trébuil et al., 2005), RPG (Gurung, 2005) in different case studies with no definitive structure shows its flexibility to apply. Particularly the use of RPG and ABM alternatively displays the adaptability of approach depending on the context.

Limitations:

Whilst ComMod promotes a neutral platform for knowledge integration, communication, and exploration of adaptive mechanisms, there are some weaknesses that can be improved during the process:

- The effects of ComMod processes are sequential, as it opens areas of understanding and or intervention from small to bigger. Further, the indifferences (social inequities, exclusion, sanctions) that may be induced by opening up the hidden rules of society and experiential learning, a mechanism to closely monitor the change process, will help in explaining the dynamics of change. The use of most significant change (MSC) technique and logbook in many sites proves to be useful tool to monitor.
- As ComMod process empowers people with information and knowledge, people (small proportion of population) who become involved in the process think and act collectively, which does not correspond to

- the bigger group who did not participate in the process. This fragmentation undermines the strength of the ComMod process. Thus a method to up/out-scale the effects is a prerequisite.
- ComMod, as any participatory process, generates ideas and plans to improve, however, without a commensurate policy and institutional environment to implement the action plans, aspirations quickly die and further breaks down the social trust and fabrics. Lingmuteychu case is a good example where policy and institutional environment supported the outcome of process, making a difference to people's livelihood, while this did not occur in Thailand. Thus local groups need support from legal structures for entitlements and legitimizing the change.
 - In all cases, there is no demonstration of how institutions at different levels can be linked for dialogue. The inability to link grassroots to higher level institutions often has become a critical hurdle in four sites in Thailand.

Conclusion

In five diverse case studies representing a complex socioecological-political domain where natural resource is highly contested, an iterative process supporting integration of stakeholder perspectives for collective learning and exploration of future strategies become a pragmatic methodological approach. The iterative process with flexibility in application facilitated collective learning and negotiation for resource sharing and management. With the ability to integrate viewpoints of heterogeneous stakeholders, ComMod opens several windows for interventions. Rather than conceiving it as a temporary and merely exploratory process, the principal challenge is how to enhance the ownership of the development process and legitimacy by local stakeholders. Furthermore, the involvement of stakeholders having greater influence on the issue from the initial stage still remains a challenge. While the process can empower voices less influential, the outcome has minimum impact on the governance system and institutions. A challenge remains on how the process can motivate people and institutions to partake in the process and legitimize the outcome. The approach working with small groups of RPG players heightens the understanding and expectation of small groups, leaving them as a privileged few in a majority of those who do not believe in the predictions of those who participated in the process. Thus the use of hybrid gaming ABM of Nam Haen promotes involvement of more stakeholders and communication at a higher social hierarchy. At the same time, it is imperative to institute monitoring procedures that can keep track of evolutions at different levels.

Acknowledgments

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Community-level multiple-use water services: MUS to climb the water ladder

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Abstract

The Challenge Program on Water and Food (CPWF) project PN28 developed and tested 'multiple-use water services' ('MUS'). This approach to water services takes multiple water needs of rural and periurban communities as the starting point for planning and designing new systems or rehabilitations. By overcoming the administrative boundaries between single-use sectors, MUS contributes more sustainably to more dimensions of well-being than single-use approaches: health, freedom from drudgery, food, and income. The action-research took place in 25 study areas in eight countries in five basins. The project brought global, national, intermediate level, and local partners together who were champions of MUS at the time. At the community level, the project identified generic models for implementing MUS. This was done through pilot-implementation of innovative multiple-use water services, and by analyzing de facto multiple uses of single-use planned systems. At the intermediate, national, and global level, the project's 'learning alliances' engaged in the wide upscaling of these community-level MUS models, with the aim of establishing an enabling environment to provide every rural and periurban water user with water for multiple uses. This paper presents some of the project findings.

Media grab

Multiple use water services (MUS) improve health, freedom from drudgery, food, *and* income considerably more effectively and sustainably than conventional single-use 'domestic' or 'irrigation' water services.

Introduction

Multiple users take water from multiple sources and use and reuse it for multiple purposes. This reality is obvious for rural and periurban water users at the local level. When they develop water themselves, they do so for multiple uses. Moreover, infrastructure that is designed for a single use, e.g., 'domestic water' or 'irrigation water' is de facto used for multiple purposes by communities. Similarly, at the highest levels, water professionals who provide bulk water supplies or manage national or basin-level water resources are well aware of the integrated nature of water resources and their multiple sources, uses, and users. This straightforward insight, however, is lacking at the community and household level. At this level, water professionals from each water sector carve out one particular end-use, which becomes the mandate and structuring principle of the entire sector. Other water uses, even by the same user taking water on the same site from the same source, are ignored. In externally supported water development and storage, this blindness is strongest for storage, conveyance, and use at homesteads and at the community or sub-basin level. This is the gap that the 'multiple-use water services' or MUS project attempted to fill.

The project developed, tested, and upscaled an alternative approach to water services at the household and community level. MUS is defined as water services planning and design of new systems or rehabilitations that start with people's multiple water uses and reuses and needs at their preferred sites within communities. By accommodating for multiple uses, multiple livelihoods benefits are achieved, in particular freedom from drudgery, health, food, and income. These benefits contribute directly or indirectly to all Millennium Development Goals. Hence, compared to conventional single-use water services approaches, MUS contributes more effectively to rural development, gender equity, and, if well targeted, poverty alleviation.

Methods

At its start in 2004, the MUS project brought those partners together who were pioneering MUS approaches at the time. Encouraged by CPWF's call for innovative partnerships, the project included representatives from the domestic and productive water sectors, and scientists and implementers. Working in five CPWF benchmark basins, each of the global lead partners chose their national and intermediate-level partners and selected sites for case studies, again according to the criterion of being a MUS innovator. Thus, IRC International Water and Sanitation Center became the basin coordinator for the Andean (Bolivia and Colombia) and Limpopo basins (South Africa and Zimbabwe); IDE International Development Enterprise coordinated MUS project activities in the Indus-Ganges Basin (India and Nepal); Khon Kaen University and the Farmer Wisdom Network led the MUS project in the Mekong Basin (Thailand); and IWMI led the project in Ethiopia in the Nile Basin, and was the lead partner. Twenty-five

study areas were selected (either one or more communities or a group of adopters of a similar technology). This selection process gave a wide diversity in partners and contexts, which allowed exploring diverse perspectives on MUS. In 19 study areas, 'MUS by design' was piloted. In six sites (all from the domestic sector), de facto multiple-use systems were studied. The project partners encompassed all four main categories of water services providers: water users with self-supply, private providers, NGOs, and governments. Also, the three main technology groups were covered: private homestead-based technologies; communal systems with single-access points; and communal systems with distribution networks to public standpipes or homesteads. Socioeconomic conditions varied from low-income Ethiopia to middle-income South Africa. Hydrological contexts ranged from 300 mm average annual rainfall in Maharashtra to up to 2200 mm in Nepal.

Across all sites, the first objective was to establish generic, field-tested, and convincing models of MUS at household and community levels. The second objective was to widely upscale these models in order to reach, ultimately, all rural and periurban people with water services that meet both domestic and productive water needs. So the challenge was to create an enabling environment at intermediate, national, and global levels that responds adequately to communities' multiple water needs. This institutional innovation was taken up by 'learning alliances.' In each country the national MUS partner forged horizontal and vertical exchange with other water service providers in the local study area and at the intermediate, national, and global levels. These learning alliances raised awareness about community-level MUS models and through 'learning by doing' they induced institutional changes toward an enabling environment, which continued beyond the project life. As the MUS partners driving this process encompassed all four categories of service providers, insights in upscaling were generated from these different perspectives.

In order to structure the action-research and allow for global comparison and generic conclusions, a 'MUS conceptual framework' was developed at the start. For this, the team identified the conditions, or principles, that should be in place if MUS were to work at the community level and if MUS were to be upscaled at intermediate, national, and global levels (Van Koppen et al., 2006). Learning how to realize those conditions was the focus of research. At community level, the principles were: livelihood-based planning and design of water services, appropriate technologies, adequate financing, equitable institutions, and sustainable water resources. At the intermediate level, these were: participatory approaches, coordinated long-term support, and strategic planning for further MUS innovation. At the national level, the principles were: decentralization of support and enabling policies and laws. This paper synthesizes some findings, conclusions, and recommendations. Over 100 of the project's national outputs, international publications, and two books are available and forthcoming at www.musproject.net.

Results

Models for community-level MUS

Table 1. Relationship between technologies and water use in selected study areas.

Country	Technology	Range of average daily water use (lpcd)	Levels
Ethiopia	Communal piped systems with very scattered standpipes	8-17	Basic domestic
South Africa	Communal piped systems with scattered standpipes	30	Basic MUS
India	Communal piped systems with frequent standpipes	40 (design supply)	Basic MUS
Zimbabwe	a. communal boreholes with hand pumps b. individual shallow wells with windlass and buckets c. individual shallow wells with rope-and-washer pumps	a. 10-15 b. 60-70 c. 80-90	a. basic domestic b, c. intermediate MUS
Bolivia	a. tankers b. piped distribution systems with household connections	a. 30 - 40 b. 60 - 80, with exceptions up to 140	a. basic MUS b. intermediate MUS
Nepal	Communal piped systems with frequent standpipes	137-225 (design supplies)	high MUS
Colombia	a. Communal piped systems with household connections (rural communities) b. Communal piped systems with household connections (periurban communities)	a.190 - 250, with some cases much higher b.76-118	a. High MUS b. intermediate MUS
Thailand	Farms with ponds and other sources	80-1,000	Intermediate - high MUS

With regard to the principles of livelihood-based services and affordable technologies, a strong link was found between people's multiple water uses for livelihoods at and around homesteads and water availability as captured, conveyed, and stored through technologies. This link is shown in Table 1. Water-dependent productive activities that increase in number and size with higher water availability included small and large livestock keeping, trees, crops and vegetable irrigation, crafts, and small-scale food and other enterprises. This finding confirmed the project's hypothesized 'multiple-use water ladder.' This is a critique on the conventional 'service ladder' in the domestic sector, which assumes that when water quantities available at or near homesteads increase up to 100 liters per capita or more per day (lpcd), this is only used for more drinking, sanitation, cooking, cleaning, bathing, and laundry. Instead, the MUS project proposed a ladder that reflected all water uses for livelihoods, distinguishing basic domestic (less than 20 lpcd), basic MUS (20-50 lpcd), intermediate MUS (50-100 lpcd), and high-level MUS (more than 100 lpcd) (Van Koppen and Hussain, 2007).

The far-reaching policy implication of this finding is that water services that aim at meeting people's livelihoods needs at and around homesteads should double or triple the conventional design norms in the domestic sector of 20-30 lpcd for domestic uses only (for Sub-Saharan Africa or South Asia). Instead, 50-100 lpcd or more is required to ensure that services meet people's livelihood needs so they can 'climb the multiple-use water ladder.'

Increasing water availability requires incremental expansion of one type of technology (e.g. through better lifting devices), jumps from one type to another, or further combinations. Such incremental investments make economic sense, especially for intermediate-level MUS (50-100 lpcd). Systematic cost-benefit analyses of various case studies of the MUS project and other cases were conducted by Winrock, IRC and IWMI and sponsored by the Bill and Melinda Gates Foundation. They showed that total incremental investments in hard- and software to 'climb the water ladder' can be repaid in 6-36 months (Renwick, 2007).

With regard to the other principles (financing arrangements, equitable institutions and water resource availability), many challenges were similar to those in conventional domestic or productive water services. One unique feature of MUS, however, concerned equity notions for water sharing under scarcity. Homestead-based multiple uses were small-scale compared to a relatively few large users, most of whom use water beyond homesteads. Under scarcity, basic domestic needs were prioritized and, after that, minimum water supplies for both domestic and small-scale productive uses for all. Thus, within communal systems, the risk of overuse by the few was mitigated by pricing, institutional, and technical measures. Within areas with limited water resources, for example in water-scarce Maharashtra, homestead-based multiple uses by all were seen as higher priority than sugarcane farming by the few. In national water legislation, as in Thailand, the MUS project partners ensured that small-scale multiple uses were better prioritized over commercial users.

When moving from homestead-to community-level water development, another typical MUS finding was that synergies can be forged if river intakes, storage, and conveyance structures are holistically designed and incrementally improved for shared water provision, whether to homesteads or fields. Failing to build upon prior community-level abstraction, storage, and conveyance infrastructure for any use leaves unmanageable 'spaghettis' of layers of infrastructure.

Innovation and upscaling: creating a supportive environment for MUS

At intermediate, national, and global levels, project partners initiated learning alliances that started creating an enabling environment for MUS at intermediate, national and global levels. In all countries, the *visible* and *documented* successful performance of community-level MUS in sufficient cases to allow for some generic validity appeared vital for awareness creation. There were also many differences between the learning alliance processes in the respective countries. They were primarily related to the different starting points of each category of water service providers that drove the upscaling process. The strengths and weaknesses in realizing the three principles for upscaling MUS at the intermediate level, from the angle of the each of water service provider categories, are given in Table 2.

These findings show that the different water service providers brought different strengths to upscaling MUS at the intermediate level. Collaboration according to those strengths appeared effective and most sustainable and upscalable through local government. Highest-level policymakers were approached and appeared receptive in Nepal, Thailand, South Africa, and to some extent in Colombia and Zimbabwe. They started supporting community-level MUS through policymaking and providing direct support without strings. At the global level, a dozen of domestic and productive water sector organizations and IWRM agencies increasingly recognize the merits of MUS and strengthen collaboration, for example during the World Water Forums of 2006 and 2009.

Table 2. Strengths and weaknesses in realizing principles for upscaling MUS by category of water service provider

Category of water service provider	Principles for upscaling at intermediate level		
	Participatory planning	Coordinated long-term support	Strategic planning for upscaling

Self-supply Thailand (Farmer wisdom network) South Africa (Water for Food Movement)	Multiple water needs obvious; High own contributions in cash and kind; Own experimenting, mutual learning and knowledge generation.	Expansion based on mutual help with limited resources; Needs-based soliciting of external support; Sustainability of movement uncertain.	Strategic alliances at highest policy levels for influencing policy and support for roll-out.
Private service provider Bolivia (Agua Tuya)	Multiple water needs obvious; Market-driven.	Providing holistic support for higher sales; private business' outlook of medium-term growth.	Market-driven roll-out limited; linking with municipality.
NGOs Ethiopia (CRS) Nepal (IDE) Zimbabwe (various)	Responsive to multiple water needs; High own contributions in market-driven technological innovation, but otherwise limited.	Poverty relief or technological innovation driving coordinated support for multiple water uses; Short-term, project-bound.	Strategic alliances with local service providers and government at all levels for uptake of innovations and sustainable after-care of technologies.
Local government Bolivia Nepal, South Africa (with NGOs)	Responsive to multiple water needs; Elected representatives, but possibly politicized. Some own contributions.	Balancing between top- down sector-based frames and bottom-up needs-based integrated funding and service delivery; Permanent presence.	Developing generic methodology for integrating multiple water needs in local planning; Influencing national policy and guidelines.
Government/ parastatal domestic sector Colombia (with university) India (with NGO)	Top-down single-use and single-site planning; unable to prevent <i>de facto</i> multiple uses; limited contributions by users.	Supporting a single use at homesteads only; Short-term, project bound.	Lobbying at national level to increase design norms and address water quality issues; Awareness raising about livelihoods benefits of <i>de facto</i> multiple uses; Promoting immediate multiple uses of 'domestic' services planned for future expansion.
Government productive sector Learning alliance members	Top-down single-use planning biased to large- scale systems; Unable to prevent <i>de facto</i> multiple uses; limited contributions by users.	Prioritizing a single use or productive uses in agricultural zones, with 'add-ons' for better access (e.g. washing steps) Short-term, project-bound.	Lobbying at national level to support small-scale productive uses, also at homesteads; Awareness raising about livelihoods benefits of <i>de facto</i> multiple uses; Promoting efficient productive water use (drip kits)

Conclusions and recommendations

The MUS project identified and tested new models for meeting the multiple water needs of people in rural and periurban areas. These multiple-use water services improve health, freedom from drudgery, food, and income more effectively than conventional single-use water development. Counter-productive bureaucratic water sector boundaries are dissolved into one common agenda: to plan and design new systems or rehabilitations according to people's multiple water needs at preferred sites, starting with providing 50-100 lpcd to homesteads. At the level of one or more communities, communal abstraction, conveyance, and storage is embedded in holistic spatial layout. Specialization remains needed on health impacts, point of use water treatment, synergies, and conflicts regarding use-specific water requirements, for example, increasing productivity of water, or market linkages. Such use-specific specialist knowledge, however, is to support this common agenda instead of replacing it by systems designed for one single-end use at one specific site only.

This agenda appeared evident for water users' self-supply and private service providers. MUS project partners found NGOs and local government at the direct interface with communities also increasingly responsive to their integrated water needs. The same holds for a number of highest-level policymakers and global organizations. Indeed, proponents agree that this agenda is not rocket science but people's logic. Hence, the most relevant question for further upscaling to reach, ultimately, every citizen with appropriate services is: why do sector-based services, in particular in government and its related education systems, continue?

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Collective action in water management through regional networks: Critical reflections from M-POWER experiences

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ABSTRACT

Disputes and contests over allocation of benefits and burdens from multiple users and uses of water often persist because of difficulties in finding ways to get different social actors to recognize each other's rights and responsibilities. In the regional and trans-boundary settings like the Mekong region, state interests, diplomatic norms, weak regional institutions, and partial democratization, can make collective action dependent solely on state-led initiatives especially problematic. This paper critically reflects on the experiences of a regional network of organizations and individuals contributing to the Mekong Program on Water Environment and Resilience (M-POWER). M-POWER focuses on the added-value and limitations of a network for collective action at regional as well as more local levels. We identify several different mechanisms that may be of wider significance to evaluating the policy and practice influence of networks in water resources development and management, such as regionalizing an issue for individuals to raise concerns about trans-boundary impacts. Networks are also important for rapid mobilization of knowledge inputs as well as the more reflective sharing of experiences and tactics. Finally, networks also have some major limitations, in particular, the efforts needed to maintain them while not detracting from the effectiveness of contributing members.

MEDIA GRAB

Organized but informal networks play a vital role in the governance of water in the Mekong Region complementing, informing, and challenging intergovernmental processes.

INTRODUCTION

The existence of international agreements, water regulations, and policies alone does not ensure that water governance is transparent, accountable, and fair. Just because the Mekong River has an organization, the Mekong River Commission, which looks specifically after the lower part of the basin, does not imply that everything is 'taken care of.' Some consider the MRC as the place to take all transboundary water governance issues; experiences elsewhere suggest it is unwise to look for panaceas in water institutions (Meinzen-Dick, 2007). National interests, political and economic factors, have sometimes sidelined the MRC (Dore, 2003). International institutions are important for cooperation (Keohane et al., 1994), but they are not sufficient.

International agreements are often disconnected from national legislation and procedures. National water regulations and policies on paper may not reflect actual practices when it comes to evaluating, deciding, and implementing new water resources development projects. Multilateral and bilateral banks and foreign investors often have better access to national governments than the citizens of the countries that could benefit or otherwise be affected by water projects. Public monitoring and scrutiny are needed. Informed critiques and analysis of alternatives need to be forwarded and discussed in the public domain (Conca, 2006). This is not always simple for individuals in a region where democratic institutions are in 'the making' without peer support and encouragement. One way forward is through regional networks.

Sometimes it takes initiatives and interventions from a third party to move polarized situations forward. In the regional and transboundary settings like the Mekong region, state interests, diplomatic norms, the weak regional institutions, and partial democratization, can make collective action dependent solely on state-led initiatives especially problematic.

This paper is based on the experiences of M-POWER (www.mpowernet.org) (Mekong Program on Water, Environment and Resilience), a regional network that sits at the boundary between research and action. As an epistemic community (Haas, 1992) it is helping develop capacity within the region to conduct scholarly research on

governance problems. As an actor engaged in facilitating dialogue activities, policy analysis, and public commentary, its members are often drawn into the political process as well.

Networks are thought to have value in building relationships, fostering trust, and coordination of activities. But they also place time and resource demands on members and can raise questions about identity and representation. Not enough is known about their functions and influence in water governance; this paper is a contribution to improving such understanding.

METHODS

This paper reflects on the ways M-POWER has engaged with water politics in the Mekong region. Information comes from annual meeting reports, previous technical progress reports, and scholarly publications of the network people. All five authors are members of networks and cannot be considered independent researchers. This has the advantage of insider knowledge and the limitation of possible biases. Some findings draw on a survey of M-POWER stakeholders conducted by one of us (AC).

RESULTS AND DISCUSSION

M-POWER network: Collective engagement and collaboration

Over the past few years, a substantial network of individuals and organizations has contributed to the development of M-POWER program. It was started around 2004 as a loosely organized network of like-minded scholars working on water governance issues in the Mekong region. Over the period it turned out as a regional research network actively engaged in water governance related research, organizing and facilitating dialogues, and lobbying for influencing policy decisions through collective efforts of the various actors. The ultimate goal of M-POWER is improved livelihood security, and human and ecosystem health in the Mekong region through democratizing water governance.

M-POWER Steering Committee (SC) governs overall development of the program by providing strategic advice to the coordination unit. SC is the cohort of researchers actively engaged in water governance issues in the Mekong region in various ways. Collective decisions of SC are crucial for the functioning of M-POWER and having overall policy impact in the region. The action research program is organized around empirical comparative studies and cross-cutting governance themes (Figure 1). Detailed distribution of ongoing research, especially under fellowship program, is given in Table 1.

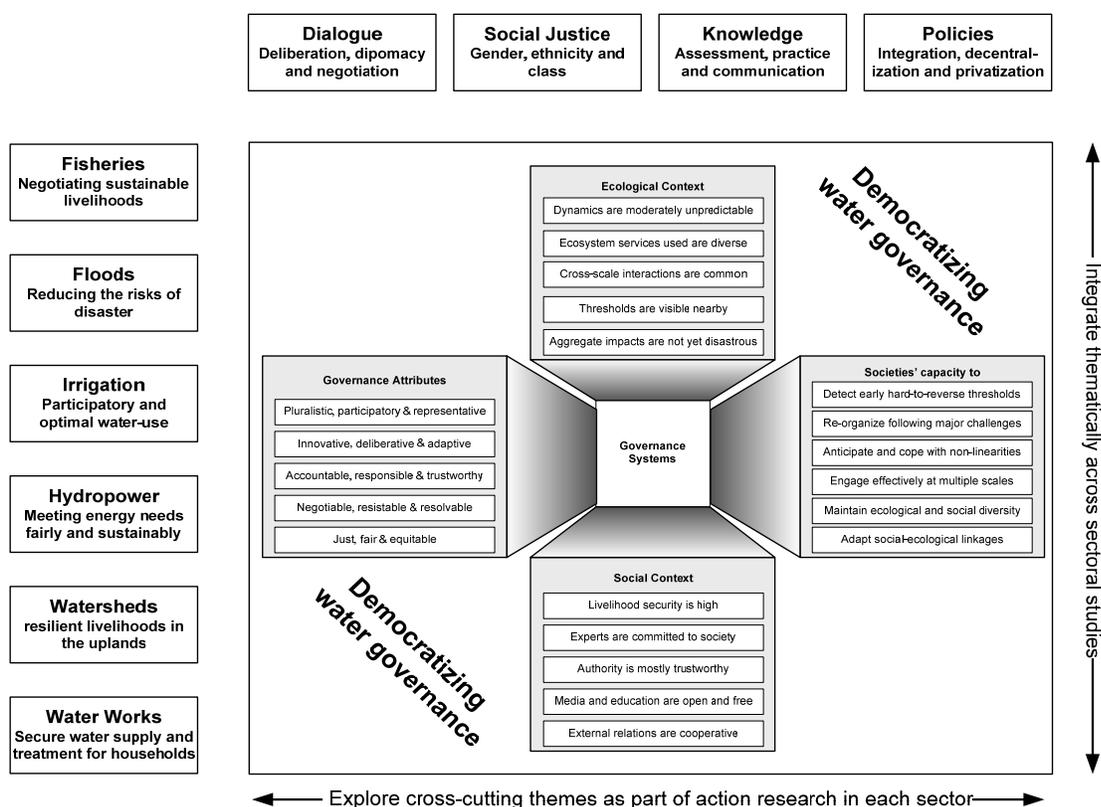


Figure 1. M-POWER framework—sectoral and cross-cutting themes.

The comparative studies and themes are all regional. Synthetic activities are guided by research leaders that build up multicountry and multiorganization teams. The 11 research leaders include academics, researchers, and international experts and help bring together the individual experiences of partner organizations. M-POWER network has been joined by 29 partner organizations working in the region; including eight academic institutions, 11 NGOs, seven international organizations, and 3 others; national policy institute, regional media and environmental consulting firm. Partner organizations are the main source of effort to M-POWER and working with M-POWER they enhance the impact of their organization in implementing their own agenda, plus add greater regional value and experience. Capacity building and sharing are important goals of the network, and are supported by a fellowship program. Thirty fellowship research projects have been provided to 35 researchers; including five Cambodian, five Chinese, 10 Thai, 10 Vietnamese, and the remainder from outside the Mekong region. The fellowship research focuses on various comparative studies areas presented in the research framework, and they often concentrate on more than one cross-cutting governance theme (Table 1). The distribution shows that comparative study areas such as water works and cross-cutting themes such as social justice are less integrated than others. The situation calls for more efforts in those areas in future.

Table 1. M-POWER fellowship research by comparative study areas and governance themes.

Comparative study	Governance themes				Total
	Dialogue	Social justice	Knowledge	Policies	
Fisheries	0.67	0.33	1.83	1.17	4.00
Floods	0.83	0.50	0.83	0.83	3.00
Irrigation	1.67	0.00	0.67	4.67	7.00
Hydropower	3.08	0.75	0.58	0.58	5.00
Watersheds	2.83	0.83	1.00	1.33	6.00
Waterworks	0.33	0.83	0.00	0.83	2.00
Multiple	0.50	0.33	1.83	0.33	3.00
Total	9.92	3.58	6.75	9.75	30.00

Note: The total column at far right of the table indicates the number of research activities under each comparative study area. The four columns under governance themes indicate relative weight assigned to each theme based on focus of each fellowship research.

The value-added of M-POWER derives from the extent to which it facilitates working together across organizations and countries. There have been several outstanding individual efforts as analyses, events, or other kinds of activities. For example, during last year, M-POWER coordinated a visit of Chinese delegates to Tonle Sap Lake. What was possible through a network would have been very hard to arrange via formal state channels. But there are still many significant untapped opportunities for members to work even more closely together on some of their activities, and we are exploring collaborative efforts already underway or proposed to see how they can be strengthened.

Creating space for dialogue and deliberation

Mekong countries represent diverse political settings. Some of them are under centralized political systems and in some the political decisions are mostly influenced by a military junta. The political ideology and their relative closeness hinder the researchers' ability to raise various governance-related issues. But, regionalizing an issue can provide secure spaces for individuals to raise concerns about trans-boundary impacts and fairness, which would otherwise be exceedingly difficult to do.

M-POWER has been involved in organizing dialogues at various levels. M-POWER, with other partners, organized 'Mekong Region Water Dialogue' which was a regional multistakeholder platform, and provided the opportunity for debate and learning that contribute in improving water governance in the Mekong region (IUCN, TEI, IWMI, M-POWER, 2007). This event was made possible by an informal but organized network which could avoid bureaucratic hassles associated with formal state authorities, and bring together different stakeholders who otherwise would be unlikely to ever sit at the same table.

M-POWER aims to ensure that significant policies and projects are examined at public forums. Considering this fact, M-POWER researchers are involved in the process of dialogue and policy advocacy of various large-scale infrastructure projects that have negative environmental and social consequences. For example, scholarly output of M-POWER researchers support informed multistakeholder dialogue on electricity and water resources planning at national and regional levels.

Working as a knowledge hub: policy inputs

Networks are also important for rapid mobilization of knowledge inputs for collective actions as well as the more reflective sharing of experiences and tactics. M-POWER has put organized effort to manage the role of knowledge and research on water governance-related issues, and most importantly transform them to policy and action. M-POWER is an epistemic community as it is a 'knowledge-based group of experts and specialists who share common beliefs about cause-and-effect relationships in the world and some political values concerning the ends to which policies should be addressed' (Haas, 1992).

The findings of a survey of M-POWER stakeholders (conducted by Dr. A. Contreras, leader for the 'Knowledge' Theme) showed that most of the network members strongly agree on the fact that M-POWER should work to influence policy, and simple correlation analysis showed these members also agree that research conducted by M-POWER should be directed at changing policy and practice. Those who agree M-POWER harnesses its knowledge resources toward activities that enable it to influence policy also agree that the way M-POWER is structured and managed enables them to link their work to the policy process. They also agree that the policy context in which they operate in the country where they work enables them to link their work to the policy process.

M-POWER has been instrumental in bringing researchers together and contributes to the knowledge-base that ultimately feeds the policy process. In the Mekong region floods and flood-related disasters are normally understood as a technical problem. M-POWER researchers across the region have dispelled that myth and suggested that floods and disaster management require attention to institutional and political issues (Lebel et al., 2007). Some scholarly outputs such as the information on linkages of land and water resources development on a river basin scale are helpful in making policy decisions regarding investments on water resources, mainly for irrigation (Molle and Floch, 2008). Sharing of knowledge based on research within the M-POWER network has been effective in informing local policy.

Sharing the outcomes of the research activities is a major component of M-POWER. Regular interaction with the stakeholders through dialogues, international forums, and conferences are tools used. The various communication products of the network and contemporary developments on water governance issues are shared with the wider audience using listserv. It is effective in maintaining a cohort of researchers, a social capital that can be mobilized when the need arises.

Some limitations: identity and coordination

It is often noted that coordinating the scientific community is like herding cats. M-POWER is no exception to this. M-POWER, through partner organizations, theme leaders, and fellowship, believes in collective engagement and effective collaboration in order to facilitate research, dialogue, and consultation process to help democratize water governance in the Mekong region. But the activities of stakeholders are going at different speeds.

We must note some important issues: the diversity in working environment and interest of stakeholders involved, and variation in compliance to the requirements of coordination node. The multiple actors involved in the network have their own interests and they operate at diverse political settings. As a network, working collectively while maintaining this diverse interest of the actors has been a challenge. The members of the network differ greatly in approaches they take (due to different backgrounds as discussed in the first subsection), the emphasis they place on analysis versus advocacy for particular positions or changes, and in the special skills and contributions they could, and want to, make. The diversity of network members sometimes has created difficulty in coordination.

CONCLUSION AND RECOMMENDATIONS

In recent years, various regional networks have been engaged in governance of environment and natural resources. At the transnational level, the network of like-minded organizations and scholars is important to achieve the desired outcome, in the form of collective action. The critical reflections showed that as a regional action research network, M-POWER has been successful in bringing together researchers and organizations with expertise and interest in water governance issues in the Mekong region. Regionalizing the context of such issues, this network has provided the safe space for the researchers to raise their concern on such transboundary and political aspects of water governance. The experiences show the success of the regional network especially in terms of putting the water governance issues collectively. However, efforts are needed to maintain the individual identity of the actors and effective management coordination. Regional networks are crucial to facilitate the collective action in water governance. But this is not the panacea for all.

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MUS upscaling and outscaling: from household to community level and national water law in Thailand

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Abstract

Multiple uses of water (MUS) have been traditionally practiced in Thailand for a long time, until the introduction of specific objectives of water use during the past 50 years. Single uses of water resources then became normalized according to the mandate of government sectors on water resource development. This was partly due to limited understanding and lack of information and knowledge about the specific purposes of the development projects of government agencies. Despite the severe reduction in the level of multiple uses in modern development programs, many leading villagers are still developing multiple-use practices at household and farm levels. They could achieve various objectives of integrated water resource management for a successful economy, improved livelihoods, and resource resilience. Successful developments often match previous local water resource management practices and actual water resource requirements, which follow the rhythm of natural water resource availability in different ecosystems.

Since the 1997 economic crisis, Thailand has reiterated former sustainable development objectives by emphasizing self-sufficiency for sustainable development. As a result, water resource management has been considered as a key basic parameter. As such, integration of local wisdom into integrated water resource management concepts became a vital ingredient from plot scales to watershed levels up to national policy and onto the national agenda. With local wisdom blending with government support, multiple uses of water resources has become a best practice for improving resources and livelihood of small farmers in most ecosystems with diverse water resource availability.

From the successful cases at the farm level, the MUS principles of multiple sources, multiple uses, and multiple benefits for water use efficiency have been adopted as national policies, and a key guideline of a draft 2007 national water law and its regulations. The main aim of the law is sustainable water resource management at household and watershed levels. The Thailand case could demonstrate that MUS has played a major role in the successful integrated development of household, community, and watershed levels through group and network efforts for sustainable resource development. The key lesson learned is timely integration of the right organizations and stakeholders for the highest potential success.

Media grab

MUS is necessary for people's livelihoods and the MUS practices should be integrated into government programs and national policies.

Introduction

Multiple uses of water resources (MUS) have been a conventional livelihood practice for people in rural of Thailand for more than 100 years (Ruaysoongnern, 2006a). Developments during the past 50 years have changed the way projects used and managed water resources, from multiple use objectives to single use designs. Therefore, when the CPWF-MUS project began in 2004, it was a good opportunity to reiterate the traditional practices lost during nine National Development Plans that emphasized adopting single uses over multiple uses.

Since the beginning of the project, numerous activities have progressed as a result of learning alliance approaches, knowledge management, policy intervention research, and integration of research results to budgeting systems and national legislation, especially national water law. Some activities were quite successful but some are still in the development phases (Penning de Vries and Ruaysoongnern, 2005). This paper demonstrates the processes and potential practices as lessons learned on how to integrate a research project into national policies and development programs, particularly for Thailand and the Mekong Basin.

Background of MUS in Thailand and the northeast

Before the age of national development plans, people in rural areas with water resource scarcity, particularly in the northeast (Mekong Basin), developed their own knowledge on multiple uses of existing water resources for their livelihood. The basic principles were utilization of water resources from multiple sources, with multiple uses for

each source according to quantity and quality, for multiple benefits to cover necessities of their life, and finally sharing benefits to multiple hierarchies within and across basins (Ruaysoongnern, 2006a). As a result, people could eventually have sufficient water for all their needs from drinking to domestic uses, from home garden to large-scale agricultural production, from households to community, and from community to environmental protection (Ruaysoongnern, 2006b). Environmental protection ensured basic resources and livelihood of local and regional people. Most developments are suitable and beneficial to their livelihood, but some could be beneficial only to the on-site users with potential hazards to other people living downstream. With previously low population pressure, however, the off-site damages were minimal.

At the beginning of the water resource development in floodplain regions in Thailand more than 100 years ago, water resource development was primarily for travel routes, with potential development of agriculture along the waterways, which were somehow multiple uses of water resources for domestic, community development, and productive uses.

When population pressures increased during the 1950s, national development plans were initiated. With the development plans, especially for the earlier ones, single uses of water resources were emphasized to solve specific problems with large reductions of multiple uses. This caused a number of problems for local people, and impacted water resources, the environment, and sustainable development. After environmental impact assessments were initiated, the damages were evident. Water resource development plans have been gradually altered to a combination of single uses and more recently multiple uses under recently integrated water resource management (Ruaysoongnern, 2006b).

Development programs and constraints

Single use development program

During development planning of water resources, most of the plans were single use because of the mandates of sectoral government offices (e.g. domestic, agriculture, groundwater, watersheds, pollution, industrial, power generation, and other uses). The narrow objectives and practices were also due to education and information systems of specialization of various offices. With the mandates and emphasis on specialization, development plans were virtually single approaches and resulted in single use development with usually separated single benefits (Ruaysoongnern, 2005). Most water resource developments were either productive uses or domestic uses. Only with further experience on the part of users, were other single uses added. Even for domestic uses, they could be mostly for washing and cleaning rather than cooking and drinking. Evidence of failure of public drinking water development is the booming bottled drinking water industry throughout Thailand, even in the rural areas. Therefore, development of MUS under the single use mindset, we need integration of development plans, stemming from action plans, budgeting, project management, monitoring, and maintenance of the resource systems. Integrated plans have been continually developed for more than 10 years but success is relatively low due to bottlenecks in the budgeting system, impractical development plans, nonparticipation, insufficient knowledge on multiple uses at the household level, and political issues (Penning de Vries et al., 2005). Those constraints require policy intervention research and knowledge development for integrated sustainable development at the household, community, region, and basin scales.

Multiple use practices

Many empowered local households and communities have maintained and sometimes developed multiple uses of water resources at the farm and household levels for their own livelihood, applying primarily an indigenous multiple use concept. The multiple uses include drinking, cooking, washing, home garden, livestock, home industries, fisheries, agriculture, paddy, habitat, and environment in diverse ecosystems (Ruaysoongnern, 2004a), with some integration of appropriate scientific knowledge. The successful practices for livelihood and economics have become models of integrated water resource management, and multiple use of water (Ruaysoongnern, 2005). The successful cases leading to self-sufficiency have been the platforms for knowledge development and understanding of how to operate integrated water resource management, especially for appropriate planning, budgeting, and timely action plans for normal and special situations, and more recently national water laws.

MUS project context and its development

Reinstate MUS into development programs

Since the beginning of the CPWF-MUS project, development plans have been analyzed through system approaches and analysis techniques by stakeholders of water resource uses. From the analysis of plans and practices on water resource development, it was determined that constraints of water resource management at all hierarchies from

plot to community watersheds had been due to single-use approaches without considering other co-existing uses. Even the irrigation systems, the main project targets, were only water collections and allocations for rice production without any water resource management. Target water users have rarely participated in planning and design of even the single use programs, nor in integrating multiple uses into existing single uses. Moreover, most of the development projects rarely emphasized the needs of people for multiple uses (Penning de Vries and Ruaysoongnern, 2005).

Farmers and local communities have nevertheless tried very hard to divert existing designs for rice crop production to fisheries, domestic, livestock, tree, and home industries. A major task of the CPWF-MUS project is reinstating multiple uses into practice, policy, and budget systems to ease development at the local level (Ruaysoongnern 2004b).

In fact, the project is focused on supporting development of learning alliances for multiple use approaches through knowledge sharing, action research for knowledge development, and policy intervention research. At a later stage, integration of the multiple uses has been applied to Thailand National Water Law through the hard work of learning alliances and beneficiary groups.

Currently multiple uses is in the process of integration into practices of many government offices and budgeting systems, and integration into national water law and its subsidiaries.

Integration of MUS into planning and practices

Earlier, there were separate attempts at water resource development and integrated water resource management, even for the same target areas. With continuous development of learning alliances within the CPWF-MUS project, most government agencies and NGOs have been invited to join and blend their beneficial concepts and efforts for multiple uses into plans of each agency. The common objectives of development plans for water uses has gradually developed into integrated single uses, and finally to practices of multiple uses of water resources for livelihood and self-sufficiency of farmers and local people (Penning de Vries and Ruaysoongnern, 2005).

One of the approaches used during learning alliance development is successful experience and knowledge sharing, exchange field visits, and counterpart development (Penning de Vries et al., 2005). All of the continuing approaches and development have developed into integrated, planned practices for multiple use water resource development at all levels.

Integration MUS into budgeting and legislation

During the research project period, there were occasions when researchers met with ministers and directors-general responsible for water resource management, including: the Minister of Agriculture and Cooperatives during the planning of 3 million multiple use ponds on 12 July 2004 at the Satuk farmer learning center; the Minister of Natural Resources and Environment during Megaproject development 9 November 2005 at Government House, Bangkok; the Prime Minister during water resource management for economic sufficiency on 15 May 2006 at Lamplaimas Farmer Learning Center; and the Deputy Prime Minister and Minister of Agriculture and Cooperatives at Kandong Farmer Learning Centers on 19 October 2007. In addition, many meetings were held with the DG of Land Development Department, the DG of Water Resources, and the DG of the Irrigation Department for MUS and other development plans. Responsible directors under these departments are also members of existing learning alliances. The learning alliances have greatly assisted in integrating MUS into planning, policy, budgeting, and finally into legislation of water laws.

Lessons learned

Learning alliances development

The success of project activities can be largely attributed to learning alliances at community, regional, and national levels. Although the approach sounds simple, the practices were extremely delicate, requiring continuous goodwill at all levels. In particular, major limitations were placed on existing conflict resolutions of different organizations. At such meetings, organizers had to be highly sensitive to the mandate, regulation, working culture, and beliefs of their counterparts. Thereafter, blending of the idea and concept was extremely important prior to actual cooperation and continuing friendships outside the office.

With delicate personal handling of learning alliances, the outcome of the project could be achieved even against 'impossible' odds.

Knowledge management

With learning alliance development, the techniques used to encourage cooperation included knowledge sharing, exchanging site visits, and sharing views and ideas. Finally when sound understanding was established, the sharing of plans and resources of different offices were readily accepted.

Development techniques for multiple uses, particularly approaches and practices, were usually lacking in original single use plans. Understanding existing knowledge was also important for sustainable development. Knowledge development was emphasized to central officials and field staff, rather than just supplying them with documentation.

Comparative economic returns of MUS over single uses

Economic analysis data (Ruaysoongnern, 2008) showed that poverty alleviation could be done more effectively through MUS than through single use or even combinations of single uses. Clear explanations were offered on overall lower costs of MUS practices and higher returns of MUS over single use or combinations of single uses. The reductionist's view of development programs, however, usually considers that single use designs might be simpler and easier to manage with lower project cost. This reductionist evaluation procedure is still an obstacle to MUS development.

Policy intervention research and policy development

Knowledge sharing and development of learning alliances have led to voluntary development of resource sharing and official agreement to solve the existing constraints. There were joint attempts to tackle bottleneck policies to which most of the learning alliance members agreed (Ruaysoongnern, 2007). With this approach, joint policy intervention research was developed to verify integrated water resource management for further development and modeling (Ruaysoongnern, 2008). The MUS models and sites finally became research and learning sites for learning alliances and for everybody involved. As a result, policy development was eventually facilitated and achieved (Ruaysoongnern and Penning de Vries, 2005).

Research and legislation procedures

It was quite fortunate that during the life of the project, there were government and community efforts to develop better water law for Thailand. With continuous publicity of the research work and project activities, project staff and well-known learning alliances were invited to public hearings and, the drafting of water laws and its regulations. Multiple use concepts of water and water resources have been fully integrated into legislation. The most significant part is the right of people to use water resources for their livelihood (multiple uses), and not just activity-oriented allocations as before. Another important point in the law is water resource ownership: the water belongs to the people, not the nation or government, which is the crucial starting point for integrated water resource management by local committees for multiple uses.

Conclusions and recommendations

From the project activities, multiple use concepts were reinstated into national practice and policy, using a platform of learning alliances and through knowledge sharing and development. The objectives of the project were achieved at all levels. The key techniques on learning alliance development and knowledge sharing are prime principles of research for development of poor communities. The concepts and approaches can be applied with a clear understanding of the delicate balance of the role and power of each side. With continuous development of social capital under the learning alliance approach, other research programs and development initiatives could be done using similar practices. The lessons learned can be transferred to other working systems with a potentially high chance of success.

Acknowledgments

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An evaluation of policy impacts in Thailand, South Africa, Zimbabwe and Ethiopia of the multiple use systems project

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Abstract

Governments of Colombia, South Africa, Zimbabwe, and Thailand have taken up recommendations of the Multiple Use Systems Project and have adapted a national policy towards planning and implementation of multiple water uses. The government of South Africa has drafted national guidelines for multiple water use services and is testing these in pilot-projects with local governments. In Zimbabwe there is a proposed law incorporating MUS.

This paper evaluates these claims. It describes the changes in policy that the MUS project has influenced and identifies which project strategies and mechanisms worked, and how context influenced what worked where. Other contributing factors are described. The paper compares the originally conjectured project impact pathways with those that actually led to change. The reasons why MUS was less successful in Ethiopia, contrary to initial expectations, are examined. The actual and potential benefits and costs of the policy change are estimated, and compared to the investment in the project. An attempt is made to estimate the potential benefits and costs of the policy change.

Collective approaches to fish production

Fisheries and livelihoods in dispute around Pak Mun Dam, Thailand

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Abstract

This paper reviews livelihood and fisheries-related disputes following construction of a large run-of-river dam (located just above the confluence of the Mekong River and its largest tributary, the Mun) in Thailand. What role has local and expert knowledge played in decision-making, in a setting of ecological uncertainty and conflict? I focus on validity of knowledge claims made to support particular mitigation strategies. The study relied on field visits during 2001-05, with six weeks of intensive work in 2004. Written discourse analysis was used to explore policy narratives and to assess argumentation strategies. Approximately 30 interviews were conducted with farmers and policymakers. Farmers (predominately growing rice on rainfed plots of <7 ha) fell into two sets: one felt the dam, in operation since 1994, had damaged fisheries livelihoods. This group participated in multiple rounds of collective action for compensation. The second, larger group accepted official claims about the dam's benefits. Socioeconomic differences between the two were slight. Two basic narratives for operations exist: (1) 'decommissioning restores migrating fisheries;' and (2) 'a four-month wet season opening allows migration and dry season storage.' Both solutions rely on inadequate knowledge: decommissioning may overestimate the importance of wild fisheries, in the context of increased off-farm labor. Seasonal-opening underestimates the difficulties farmers have accessing pumped river water and growing profitable crops. In the face of uncertain knowledge (e.g., about fisheries trends), both narratives invoke normative models, making the debate intensely political. Improving complex on- and off-farm livelihoods requires authentic deliberation and more holistic application of the sustainable livelihoods framework.

Media grab

Wild inland fisheries in the Mekong are difficult to quantify because they are diffuse, variable, and politicized. But they make meaningful contributions to livelihoods.

Introduction

Ever since its authorization in 1989, Pak Mun Dam has sparked controversy, linked on the one hand to resistance networks that have sought to defend, mitigate, and restore fisheries-dependent livelihoods, and opposed, on the other hand, by state-sponsored networks led by local authorities.

Regardless of their participation in dam-related disputes, villagers in the lower Mun River basin pursue similar livelihood strategies. They are smallholder farmers who grow one main crop of rice during the May–October monsoon. Holdings are typically 5-7 ha, but soils near the dam are often poor. By Thai standards many households are income poor. Almost all households supplement their income by off-farm labor, with significant rates of seasonal and long-term out-migration, especially among younger people (Ubon Ratchathani University [UBU], 2002).

This study's objectives were to: (1) document competing policy narratives used to justify alternative policies for the operation of Pak Mun Dam in Thailand; and (2) to assess their credibility, in a highly politicized context. The study contributes to a case study on water allocation decision-making in the Mekong Region being prepared as part of PN67 of the CGIAR Challenge Program on Water and Food.

Pak Mun Dam is located approximately 80 km downstream from the provincial centre of Ubon Ratchathani and 5.5 km upstream of the confluence of the Mun and the Mekong. Constructed by the Electricity Generating Authority of Thailand (EGAT) during 1990–94, the dam is 17 m high, 300 m wide, with eight hydraulic gates that can be fully opened to release water. The Mun's living aquatic resources are noted for their high biodiversity and contribution to subsistence and trade (Roberts, 1993; Srettachau, 2002; Burawoy, 1998; Roberts, 2001). When the gates of Pak Mun Dam were opened in 2001-02 for a year-long experiment, two studies counted more than 150 species of fish (Srettachau, 2002; UBU, 2002). Fishermen use a variety of gear, including hook and line, traps, nets, and beach-haul seines. Total catch has not been estimated for a number of reasons, including the large number of landing

sites, subsistence consumption, and—most importantly for sustaining important fish populations—lack of a long-term fisheries assessment program. A concrete fish ladder was installed in 1996 but its design does not allow significant upstream migration (Roberts, 2001). Instead, in a 2003 Cabinet decision, EGAT is requested to fully open the dam's gates during the annual wet season, nominally for 4 months beginning June (Foran 2006).

Because it is a run-of-river dam operated for power generation, Pak Mun cannot also be used to store significant amounts of water. Yet since the early 2000s—partly as a result of populist development policy—the state has expanded small pumped irrigation systems near and upstream from the dam. Critics view this initiative as a justification for not opening Pak Mun's gates beyond four months (Foran, 2006: Ch. 8), reserving the dam instead for power generation at least eight months of the year, including during Thailand's peak power demand hot season. The dam's installed capacity is 136 MW. Prior to the four-month seasonal opening, its actual energy output was approximately 300 million kWh per year. With the gates opened during June–September, energy output declines to approximately 150 million kWh.

Methods

The study was informed by discourse-oriented theories of politics. Politics can be explored using a conceptual framework consisting of actors' interests, prevalent discourses, and institutions (Hajer, 1995; Lichbach and Zuckerman, 1997; Foran, 2006). Interests and discourses drive politics, but in a manner shaped by institutions. Interests are objectives and preferences. Institutions are enduring ideas, formal and informal, about how to achieve desired social outcomes (Foran, 2006, p31). Discourse is 'written and spoken communication and the thinking that underlies it' (Johnson, 2000). An important component of discourse is ideas: broad worldviews, and more specific normative or causal beliefs.

The author used written discourse analysis to explore narratives and argumentation strategies. These were tracked historically and politically (i.e., in terms of possible influence on decision-making) from the dam's approval in 1989, to an influential decision in 2003 to open Pak Mun's gates four months a year. In particular, the author focused on assessing the knowledge claims in scientific narratives commissioned by the government to inform decision-making. The scientific studies were produced in the context of a remarkable decision to suspend hydropower production and fully open the gates of the dam (2001–02) to allow study of fisheries and livelihood impacts.

The study also relied on field visits in 2001–05, with six weeks of intensive work in 2004. Approximately 30 interviews related to livelihood issues were conducted with farmers and policymakers.

Results and discussion

Discourse analysis revealed two general policy narratives for the continued operations of Pak Mun Dam: (1) 'decommissioning restores migrating fisheries;' and (2) 'a four-month wet season opening allows migration and dry season storage.' The narratives were deployed by two broad clusters of actors: a mainstream cluster and a critical cluster. Local farmers belonged to both. Opponents felt the dam, in operation since 1994, had damaged fisheries livelihoods. This group participated in multiple rounds of civil disobedience for livelihoods compensation. The second, larger group accepted official claims about the dam's benefits. They were also 'free rider' beneficiaries of successful campaigns for enhanced compensation waged by dam opponents (Foran, 2006: Ch. 6-7).

Expert knowledge commissioned by the Thai government (under PM Thaksin Shinawatra) to inform its decision-making provided conflicting knowledge claims. A multidisciplinary study by Ubon Ratchathani University (UBU, 2002) reported that although households interviewed wanted irrigation water in the dry-season, new river-pumped irrigation systems would have a minimal positive impact. Soils were poor, pumping costs were high, and farmers lacked capital inputs needed to grow high-value dry-season crops.

Similarly, farmers near the dam told me in 2004 that the main benefit of pumped-water irrigation is to safeguard the wet season rice crop from punitive yield losses because of poor rains (cf. UBU, 2002: Ch. 3, p.32). A secondary benefit is the ability to control the timing of rice seedling production and transplanting, allowing farmers to more reliably commit to off-farm work.

The university study argued that for at least another 5 years, the dam's primary benefit—improving electric power reliability in the lower Northeast—could be substituted by increasing imports of electricity. Technical substitutes existed for the electricity, but no technical solution existed for improving the security of community-based livelihoods (UBU, 2002).

In late 2002, however, the government challenged the university's findings, by ordering the National Statistics Office (NSO) to survey occupations and attitudes of residents in the lower Mun basin toward dam management. NSO reported that among 3750 householders sampled from 150 villages, the least disruptive and most favored option was a 4-month dam opening. Only 4% of respondents stated that fishing was their primary 'occupation' (*achip*); less than 7% stated it was their secondary occupation (National Statistics Office, 2003).

Several weeks after the poll, NSO held a public meeting about its survey. Dam opponents argued that in the context of rural livelihoods, it would have been more accurate to ask villagers about their fishing activities, not if they regarded fishing as their 'occupation.' One villager asked: 'Why didn't you gather information using wording such as 'Pho Yai [grandfather], do you have children or grandchildren that fish?'—indicating that the response to this question would have been different than to questions based on 'achip.'

Concepts such as occupation, fisher, and farmer were contested by experts using different methods. NSO used an extensive, single-encounter method, whereas Ubon Ratchathani University deployed researchers for more intensive fieldwork. The NSO poll took place several months after the government had announced its support for a 4-month dam opening policy. More than half of the NSO officials were from Bangkok, and each surveyor collected approximately 30 samples per day. Encounters were brief, constrained by the large sample size (N=3750) and the government's request for results in several days. In such a context, interviewees may have given responses calculated to be conciliatory (Burawoy, 1998). Respondents could also have interpreted the poll as an implicit request from the Thaksin administration for a show of support for its handling of the case.

NSO asked for a yes/no response to the following: 'If there were to be an opening-closing of the Pak Mun Dam sluice gates in the following cases, would your household be troubled (*dueat ron*) or not?' If respondents answered yes, they were asked to state their reasons (NSO, 2003). The phrase *dueat ron* (troubled) is ambiguous, however. By contrast, UBU asked a series of questions about food security, including 'How has the construction and trial opening of Pak Mun Dam affected the convenience of obtaining food for your household?' The choices were: no change; improved; much improved; worsened; much worsened (UBU, 2002: Ch. 6, p.47). The UBU question occurred in the context of a much more extended questionnaire about incomes, assets, and livelihood strategies. The use of multiple thematically related questions would, other things being equal, reduce bias in survey design or administration. It may also have increased the odds of obtaining a reliable answer.

Upon scrutiny, the results of the NSO poll are uncertain and ambiguous (Foran, 2006, ch. 8). The poll's political effect was clear, however. It gave voice to what the government claimed was a hitherto silent majority of local farmers. These farmers, according to the poll, wanted the dam closed 8 months a year. In early 2003, the government justified its 4-month operating rule based on the preferences of this majority.

Conclusions and recommendations

In the lower reaches of the Mekong's largest tributary, the degree to which local people derive benefit from living aquatic resources, especially wild fisheries, has been a topic of multiple rounds of dispute. Although marginalized in state-sponsored livelihood surveys, and difficult to quantify because diffuse, variable, and politicized, living aquatic resources make meaningful contributions to livelihoods (Srettachau, 2002; UBU, 2002; Foran, 2006, Ch. 8). This is especially true for land-poor farmers.

In the context of increased off-farm labor, calls to suspend power production at Pak Mun may overestimate the importance of wild fisheries. A policy of a 4-month seasonal opening, however, underestimates the difficulties farmers have accessing pumped river water and growing profitable crops. In the face of uncertain knowledge (e.g., about fisheries trends), both policy narratives invoke normative models, making the debate intensely political. Improving complex on- and off-farm livelihoods requires authentic deliberation and more holistic application of sustainable livelihood approaches.

The case offers sobering lessons about the politics of knowledge. Concepts such as occupation, fisher, and farmer were contested by laypeople and by experts using different methodologies. Nuances of smallholder livelihood strategies were ignored by contending experts, who needed simple conclusions on key issues such as the importance of wild-capture fisheries to local livelihoods. With authority highly concentrated in the state's executive branch, knowledge production was manipulated.

I conclude by recommending that livelihood research focus on the following questions:

- Will viable populations of key migratory species (Roberts, 2001a, b; Jutagate et al., 2003) persist in the lower Mun if they cannot complete their downstream migration?
- Is fishing effort on key species sustainable? If not, what are the most appropriate stock conservation measures, given their trans-boundary nature and possibly high levels of fishing effort throughout the river basin? Will government sponsored artificial breeding and release programs make any difference?
- Is fingerling stocking an efficient and effective means of sustaining fisheries?
- Will new irrigation canals make any significant impact on intensification or reduce vulnerability among recipient farmers?
- What interventions—e.g., occupational health and safety interventions, wages, and benefits packages—will most benefit the well-being of household members who work away from the lower Mun?

In order to begin addressing these topics in the near-term, debate over livelihoods need to be partly recontextualized. Attention to the above issues may reframe the polarized debate over the management of Pak Mun Dam. Basic concerns include understanding the coping strategies of most vulnerable households in the context of the 4-month opening, and evaluating the state's new intensification programs.

Acknowledgments

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Managing resilience in West African small-scale fisheries

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Abstract

The central hypothesis of this research is that the concept of resilience, revisited from a socioecological and adaptive management perspective, can reduce the vulnerability of fishing communities and lead to improved resource management and water productivity. In order to test this hypothesis, the project described in this paper seeks to operationalize the concept of 'resilience management.' A range of participatory assessment and adaptive management tools are used to develop and evaluate management interventions to reduce vulnerability to external processes and promote durable decision-making. The methodology of this approach is implemented in two pilot fishery systems in the Niger River Basin and presented together with the first results obtained by the project.

Media grab

Faced with uncertainty and variability, small-scale fisheries in developing countries need a new management approach. Resilience provides a promising alternative that now needs to be operationalized.

Introduction

In many developing countries, small-scale inland fisheries are important to the livelihoods of the poor, contributing both income (through capture and postharvest activities) and food security (Béné et al., 2006). This is particularly true for river fisheries, and especially so in Africa, which has important inland and de facto unregulated open access fisheries, on which millions of poor households depend. These inland fisheries are characterized by complex multi-species, multi-gear exploitation systems, and large numbers of fishers operating completely within the informal sector. This makes small-scale inland fisheries extremely difficult to assess and manage, thus contributing to livelihood uncertainty and vulnerability.

Even more importantly in the context of water management, small-scale fisheries are significantly affected by processes outside their control. In particular, water allocation policy and investments (e.g. dams and irrigation schemes) are dominant factors driving many inland fishery dynamics. Additionally, the unpredictable institutional and policy environment typical of many countries in sub-Saharan Africa is a source of great uncertainty and potential threat. Further, the uncertainty induced by climate changes will in the future increase the unpredictability of fishery systems and competition for water, thereby impacting severely on the capacity of the local populations to rely on those resources to sustain their livelihoods.

Faced with such constraints and multiple uncertainties, conventional management has, by and large, failed to provide a basis for sustainable development of aquatic resources. The project 'Managing resilience in West African small-scale fisheries' has been designed to initiate and guide major changes in the way small-scale fisheries in sub-Saharan Africa are assessed and managed. The project, which has a strong 'action research' orientation, aims to strengthen the resilience of fishing communities through the field-testing and application of an innovative framework for participatory diagnosis and adaptive management. Where effectively adopted, this new resilience management approach is expected to reduce the vulnerability of these fishing communities to external threats and changes, thus enhancing their capacity to contribute more actively to the process of economic development and poverty alleviation. Two pilot sites have been chosen in the Niger River Basin to try this new approach, one in Mali in the Inner Delta of Niger and one in Nigeria on the shore of Lake Kainji.

The concept of resilience

For the prospects of fisheries to improve, established theory, approaches, definitions of sustainability, and indicators of management performance have to be reconsidered (Andrew et al., 2007). The last decade or so has seen fisheries research and management broaden considerably in the search for better ways of addressing fisheries problems. New approaches, concepts, and methods, have been proposed such as the precautionary principle (FAO, 1995), ecosystem approach (FAO, 2003), sustainable livelihoods framework (Allison and Ellis, 2001), participatory methods and co-management (Pomeroy and Riveira-Guieb, 2006). More broadly, recent developments in socioecological theory have provided new concepts and approaches to move these issues forward (e.g. Folke et al.,

2002). In particular, a consensus has now emerged across disciplines (ecology, social sciences), that emphasizes the necessity to build management around the concepts of resilience and adaptive management (Carpenter et al., 2001; Walker et al., 2002).

In a broad sense, analysis of 'resilience' is about the capacity of systems to adapt to shocks, recognizing that disturbance and change are integral components of complex systems. More formally, resilience analysis proposes to focus on mechanisms and processes that help systems absorb perturbations and shocks, and cope with uncertainty and risks. Defined in such a way, the concept of resilience thus appears particularly useful for the management of small-scale fisheries. While the resilience concept is appealing, however, particularly in the face of the failure of current management approaches, the danger is that it remains largely academic and theoretical, and not of great help in effectively improving the way natural resources are managed on the ground. The challenge, therefore, lies in a pragmatic approach to operationalizing the concept of resilience and making its implementation on the ground practical and meaningful. We propose a framework aimed at this objective. We illustrate it in the specific context of small-scale fisheries in the Niger River Basin.

A framework to manage resilience

In practical terms, the goal of resilience management is to ensure that the socioecological system under consideration will remain within a set of ecological and socially desirable configurations (Carpenter et al., 2001). One needs therefore to identify indicators and thresholds that define these desired configurations. This is the role of the first component of the framework: the participatory diagnosis.

More formally, the objective of this participatory diagnosis is to identify key threats and resilience indicators specific to the system (in the present case a fishery). This participatory diagnostic can be implemented using various techniques. In our case, we use a 360° integrated assessment map -see also Garcia et al. (in press). The idea of this integrated assessment tool is to 'scan' in a systematic and comprehensive manner the system in order to gain a better appreciation of the true nature of drivers and processes that affect its dynamics. Four domains are considered: (a) natural system, (b) livelihood and people, (c) institutions and governance, and (d) external drivers (Fig.1).

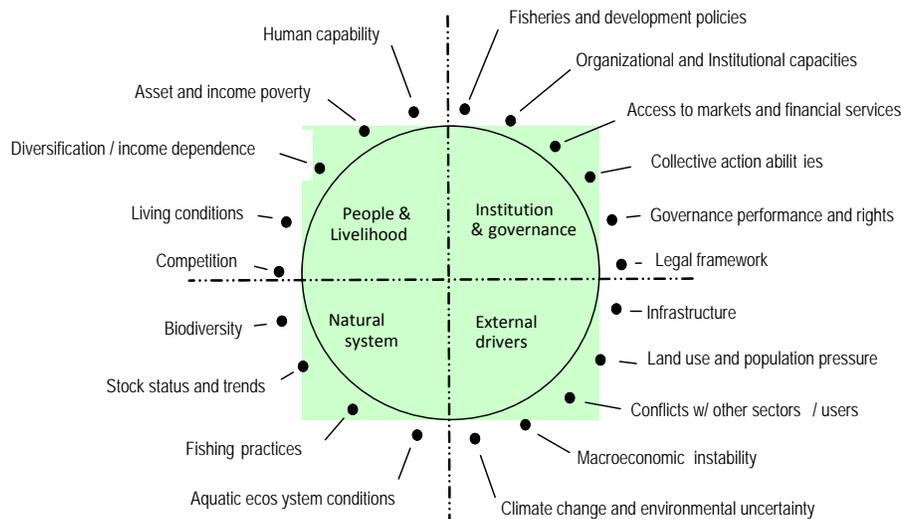


Figure1. The 360° integrated assessment map.

In each of those four domains, resilience indicators are identified, and the current conditions of the system assessed against those indicators, using a combination of quantitative variables and thresholds. One example is used here to illustrate the process. In the case of the indicator 'Asset and Income poverty' in the domain 'People and Livelihood', stakeholders (say, the fishing households) will be asked to assess their situation in terms of income by identifying two thresholds; one distinguishing what those households consider as a 'desirable' situation from an 'undesirable' one. Above, say, US\$4 per household per day, the fisherfolk consider that their situation is satisfactory ('desirable'), while below that same US\$4 threshold the situation is considered as unsatisfactory ('undesirable'). Finally, under a lower threshold of US\$2 per day the households regard the situation as a 'crisis.' Over time (season, life), the households income varies, passing above or below the thresholds (Fig.2). The objective of resilience management is to ensure that household income remains in the 'desirable' zone.

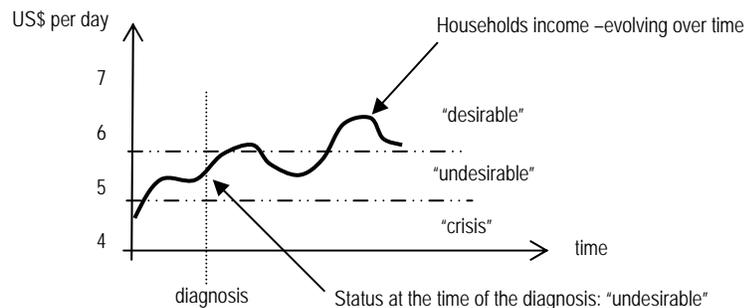


Figure 2. Assessing the conditions of the system against thresholds.

Applying this approach to each of the indicators considered critical by the stakeholders, a dashboard can be constructed, which reflects, for each indicator, the perception of the stakeholders about the conditions of the system.

Different stakeholders can contribute to the evaluation of different indicators (or even domains) of the system. One may, for instance, request a panel of experts to assess the situation of the system for the 'external drivers' domain, while the local community may be asked to express their views about the 'people & livelihood' or the 'natural system' domains. An abridged example of a dashboard is given below in Table 1, which was produced by key-stakeholders assessing the situation of the artisanal fisheries of Lake Kainji in Nigeria.

Table 1. Example of dashboard –with one indicator per domain extracted from a full dashboard completed for Lake Kainji fisheries (Nigeria).

DOMAIN	INDICATOR	JUSTIFICATION	VARIABLE	THRESHOLD	STATUS
Natural System	Fish Biodiversity	Maintaining a high and stable biodiversity is crucial to fisheries and fisheries dependent communities. The sustainability of the fisheries is dependent on maintaining the ecological integrity of the natural resources.	Number of species available	- Desirable: > 130 species in the system - Crisis: < 90 species	> 120 species (stable)
People and livelihoods	Health centers	Health facilities (e.g. hospitals, clinics, dispensaries, pharmacy) are vital to human capital and the sustainability of livelihoods. Health has implications for household and community productivity, poverty reduction and food security.	Distance to health facilities	- Desirable: < 5 km to health centers - Crisis: > 10 km to health centers	> 10 km to health care centers (crisis)
Institutions and governance	Accountability of traditional institutions	Accountability and responsiveness of traditional institution is vital to providing a basis for measuring the confidence and cohesiveness of rural fishing communities.	Approval rating amongst community members	- Desirable: > 70% approval (accountable) - Crisis: < 50% approval (low accountability)	> 80% (getting better)
External drivers	Infrastructure (roads)	Access road is important for easy movement of fish and other agricultural products to market	Percentage of feeder roads in motorable condition during the rainy season	- Desirable: > 70% in motorable condition - Crisis: < 30%	< 10% (crisis)

The completion of the dashboard allows the identification of site-specific indicators for which the system is considered in crisis—in the present case the access to health services and the conditions of infrastructures—and for which immediate actions are requested. For those indicators, management actions will be identified and implemented by the stakeholders (with the support of the project) with the objective of bringing back the variables to levels considered as 'acceptable.' At the time of writing this article, the fishing communities of the two sites selected by the project in Mali and Nigeria are yet to identify the specific management actions they wish to pursue. Once those are identified, a continuous cycle of adaptive learning will be established. The project will help

stakeholders to progressively enhance their ability to diagnose and respond to the various changes or shocks that affect the fishery. The improved managerial capacities that will result from this process will lead to better informed and more appropriate decision-making processes in the fishery. This adaptive process is expected to lead in the long-term to a more resilient management system and the reduction of the overall vulnerability of the households who depend on the fishery viability for their livelihoods.

Discussion

Because the dashboard allows presentation of indicators of any nature, it provides a powerful way to integrate the combinations of economic, environmental, and social dynamics which characterize the realm of fisheries management. In this sense, it is an effective tool for multi-criteria assessment. The main merit of using the dashboard, however, is in its capacity to initiate and then strengthen the resilience management process. First it helps all those involved in the process realizing that there is no one unique management target. This aspect is critical in the sense that it clearly distinguishes this approach from the perception that the large majority of practitioners and researchers still have about fisheries management: under the resilience approach, management is not about looking for the unique, or 'fair' solution, it is about negotiating a set of acceptable configurations, and agreeing on interventions, incentives, or constraints to stakeholder behaviors to ensure that the system stays within these negotiated and accepted configurations.

By so doing the dashboard also helps stakeholders to realize that the management process is bound to rely on trade-offs between ecological, social, and economic indicators of management performance. A vivid example of these trade-offs could be a situation where catching 'too many' fish is a short-term objective that might be 'acceptable.' Indeed when small-scale fisheries are set within the reality of societies with great poverty, insecure food supplies, and/or variable fisheries resources, such levels of harvest may be necessary and unavoidable for a while as long as the overall system is not irreversibly affected.

If run through a participatory process that involves a large range of stakeholders, the dashboard assessment exercise can easily create the preliminary conditions that facilitate the adoption, comprehension, and acceptance of the concept of resilience management amongst stakeholder groups that are not necessarily familiar with this rather abstract concept. The simplicity of the criteria ('undesirable' versus 'desirable' configurations) captures in a straightforward and clear manner the configurations of the system and management objectives. The dashboard can facilitate communication and knowledge exchanges between the different groups of stakeholders, thus making the negotiation process easier, and sets the stage for rules and patterns of social interactions between stakeholders during the following adaptive learning process. In particular it can facilitate the identification of mechanisms and options that allow the fishery to move away from undesirable states. The identified resilience indicators will then be used during the implementation of the adaptive management phase to monitor the 'health' and evolution of the system under a resilience management approach.

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Enhancements and institutional arrangements for scaling-up fish productivity of tropical reservoirs in Indo-Gangetic Basin

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Abstract

In India, reservoirs are recognized as sleeping giants for fisheries development, with their large expanse (3.15 million ha) and vast untapped production potential. The project CP34 (of the CGIAR Challenge Program on Water and Food) is aimed at improving fisheries productivity and management in tropical reservoirs. In the Indo-Gangetic Basin, two reservoirs, Dahod (460 ha) and Pahuj (518 ha), were undertaken for fisheries development. Major interventions included: (1) enhancement through stocking of fish seed; and (2) improvement of the institutional arrangements for fish catching and marketing. Based on limnological parameters and biological productivity of the reservoirs, the fish seed stocking rate was estimated at 400 fingerling/ha. The experiments on *in situ* fish seed raising in enclosures (cages) recorded growth of common carp from 20 to 98 mm and grass carp from 19 to 83 mm in 105 days. The survival rate was over 50%. The fish seed thus raised was directly stocked in the reservoirs. The fishers were provided with cycles fitted with ice-boxes for transportation of fresh fish to nearby markets fetch better prices. Both the interventions yielded very encouraging results in one year of the project. The impact of the interventions led to increased fish landings by over 60%. The share of commercially important fishes in the catch also increased significantly. The fishing intensity increased both in terms of average number of monthly fishing days (16 to 19) and number of fishers fishing per day (8.6 to 14). The project is targeted for a three-fold increase in fish productivity of reservoirs. These case studies are helpful to formulate strategies for reservoir fisheries development in the Indo-Gangetic Basin.

Introduction

In India, with its large number of river valley projects, a chain of impoundments has been created during the post independence period, with the primary objective of storing river water for irrigation, power generation, and public uses. The Indo-Gangetic Basin has 1.16 million ha reservoir area (37% of total Indian reservoirs). The maximum reservoir area is in the state of Madhya Pradesh followed by Uttar Pradesh and Rajasthan. The exploitation level of these waters is much below potential because of traditional methods of fishing and nonadoption of methods for improving production (Sugunan, 1995). Fish yield enhancement in these reservoirs is possible with low capital investment and practically negligible environmental degradation through culture-based fisheries interventions. Enhancement options include stocking species of commercial value, and habitat enhancements. Such enhancements will directly benefit poor traditional fisher communities, especially in the surroundings of the reservoir.

With this background, project CP34 was implemented with the goal of improving fisheries productivity and management based on the assessment of socioinstitutional settings, limnological characteristics, and fish stocks. The interventions were made through enhancing tools (fish seed stocking and improving the habitat) and institutional arrangements (leasing policy and marketing). This paper briefly discusses the results of these interventions and the suggestions for overall reservoir fisheries development.

Methods

After the desk review and survey of Indian IGB reservoirs, Dahod (460 ha) in Madhya Pradesh and Pahuj (518 ha) in Uttar Pradesh were chosen by the project for fisheries development. The selected reservoirs are representative of small reservoirs of IGB. Physical, chemical, and biological analyses were conducted along with fish and fisheries, socioinstitutional environment, and potential markets for reservoir fish production. The physicochemical characteristics of reservoir water and sediment were analyzed by the methods of APHA, AWWA, WPCF (1992). The quality and quantitative estimation of food-chain was done by following standard methodology. The potential production of each water body was estimated on the basis of biophysical data and information generated on primary and secondary production.

Results and discussion

Physical features

Dahod is an irrigation impoundment near Dahod village in Goharganj Tehsil of district Raisen in Madhya Pradesh. The impoundment was constructed in 1958 and has a surface area of 460 ha, with maximum depth of 9.2 m and mean at 3.4 m. Pahuj reservoir is near Jhansi in Uttar Pradesh. It was constructed in 1909 with an area of 518 ha,

maximum depth at 10 m and mean depth at 3.5 m. The volume of Dahod and Pahuj reservoirs was estimated at 27.75 and 18.25 million m³.

Limnological profile

Observations on limno-chemistry of water in Dahod reservoir revealed that water was moderately alkaline with water pH values of 7.3-8.6, alkalinity, 34-86 ppm, and hardness, 32-84 ppm. The concentrations of dissolved nutrients were in the range: nitrate-N: trace-280 ppb, phosphate-P: trace-220 ppb, and silicate-Si: 2.5-9.2 ppm.

In Dahod 30 species of fish, 44 species of plankton, 31 species of macrobenthos, and 10 species of macrophytes were recorded. Macrophytes were dominant in the littoral zone. Phytoplankton dominated over zooplankton in all seasons, and among benthos, gastropods dominated followed by dipterans.

In Pahuj reservoir, the limno-chemical profile of water revealed moderately alkaline water with pH values ranging between 7.4 and 8.7, total alkalinity was 80-220 ppm, and hardness 82-178 ppm. Dissolved nutrient concentration was nitrate-N: trace-210 ppb, phosphate-P: trace-180 ppb and silicate-Si, 2.9-6.2 ppm.

In Pahuj reservoir 25 species of fish, 54 species of plankton, 12 species of macrobenthos, and 24 species of macrophytes were recorded. The zonation of macrophytes and distribution of benthos was closely related. A higher density of molluscs was recorded in the littoral zone. Phytoplankton were dominant at all six sampling sites of Pahuj recording blooms at times.

Estimation of fish production potential

The fish production potential on the basis of biophysical parameters was estimated at 290 kg/ha/year for Dahod and 300 kg/ha/year for Pahuj, reservoir, but the actual yield was only 40 and 78 kg/ha, respectively. The project targeted a fish yield of 125 kg/ha/year for both reservoirs.

Enhancement strategies

To achieve the targeted fish yield, strategies on habitat, stock, and species enhancements were formulated in consultation with all stakeholders.

Habitat enhancement

Both reservoirs were infested with weeds, which impacted negatively on the fish yield. In Dahod reservoir, stocking of *C. idella* (grass carp) was suggested to reduce the weed infestation. The fishing activities were suspended in Pahuj reservoir during the preproject period (2005-06 and 2006-07) as the reservoir could not be leased out due to drastic reduction in water level and inflow of domestic sewage and deterioration of the aquatic environment of the reservoir. The reservoir was weed-choked and contained a significant proportion of minnows. To provide a congenial environment for the commercially important fish species, planned fishing of minnows and weed clearance were implemented for habitat improvement. These interventions resulted in bulk harvest of minnows and considerable clearance of macrophytes. This resulted in development of carp fishery and shift in fish catch in favor of commercially important fishes.

Stock enhancement

As mentioned above, potential productivity of the reservoirs was estimated at 290 and 300 kg/ha/year for Dahod and Pahuj, respectively. The existing fish yield was much lower than the potential, which demanded stock enhancement in both reservoirs. Based on the gap between the actual and targeted fish yield, the stocking rate was estimated at 435 and 386 advanced fingerlings/ha for Dahod and Pahuj reservoir, respectively. The stocking protocol implemented involved direct seeding of fingerlings and fry raised in cages up to advanced fingerling stage, followed by stocking. In Dahod reservoir, out of 0.17 million fingerlings stocked, 60% fingerlings were directly stocked and 40% were raised in the cages. For Pahuj reservoir, out of 0.2 million fingerlings, 70% fingerlings were directly stocked and the remainder raised in cages.

Species enhancement

Another way of improving the productivity is through increasing the share of commercially important fish species in the total catch through species enhancements. The share of major carps in total fish production was 36 and 7% in Dahod and Pahuj reservoirs during the preproject period. These fish species fetch very good prices. An increase in their share would enhance the fishers' income. Therefore, another intervention was through species enhancement. The species composition of stocked fingerlings was 45% *C. idella*, 10% *C. carpio* (common carp), and 45% Indian major carps in Dahod, while the composition of stocked fingerlings was 25, 10, and 65% of the same species in Pahuj reservoir.

Raising of fingerlings in cages

Availability of appropriate fish seed in time and space is the main constraint in reservoir fishery development. To overcome this problem, fingerlings were raised from fry (18 mm average length) in situ in enclosures at both the reservoirs. The results are highlighted below:

Cage experiment in Dahod

In the first phase, one battery of eight cages was installed in the reservoir with each cage 5 m x 3 m x 3 m. The cages were stocked with 90,000 (*C. idella*-54,000, *C. carpio*-36,000) fish fry (20-22 mm size). After a rearing period of 105 days 45,240 fingerlings (survival-50%) were released into the reservoir. The stocking size and weight of *C. idella* was 70-96 mm and 5.0-11.0 g, respectively, while for *C. carpio*, it was 85-112 mm and 19-26 g, respectively.

In the second phase, two batteries of eight cages each were installed. In three cages 36,000 Indian Major Carp fry of 30-34 mm size (*L. rohita*: *C. catla*: *C. mrigala* = 5: 2: 3) were released. After a rearing period of 150 days, 23,322 fingerlings (survival-64.7%) were recovered and stocked in the reservoir. The stocking size and weight for different species was: *C. catla*: 90-150 mm and 19-32 g, *L. rohita*: 88-160 mm and 15-28 g and *C. mrigala* 82-130 mm and 12-23 g. In the remaining 13 cages 140,000 fry of *C. idella* (40%) and *C. carpio* (60%) were raised to fingerlings. After a rearing period of 160 days, 107,693 fingerlings (survival-77%) were released into the reservoir. The stocking size of *C. idella* was 98 mm in length and 3-10 g in weight as compared to *C. carpio* 72-110 mm in length and 10-21 g in weight.

Cage experiment at Pahuj

In Pahuj reservoir one battery of eight cages (each cage size 5 m x 3 m x 3 m) was installed and 100,000 fry (*C. idella* 74% and *C. carpio* 26%) were released. The length of fry at release was 16-28 mm. After a growing period of 145 days 62,400 (survival-62.4%) fingerlings were released into the reservoir. The stocking size for *C. idella* was 65-96 mm in length and 4-12 g in weight. For *C. carpio* stocking size in length was 74-115 mm and in weight was 12-22 g.

Institutional arrangements

The policy documents and Fisheries Acts of State Department of Fisheries (DoF) of both States were procured to have details of institutional issues related to fishing regimes and leasing systems.

Both the reservoirs are under the ownership of the irrigation department. For fisheries purpose, the reservoirs are controlled by respective DoF. At Dahod reservoir, DoF was responsible for fisheries management including fish seed stocking, and monitoring of fish catch. Besides fisheries, the reservoirs were used for irrigation to agriculture, domestic potable water supply, flood control, and day to day domestic uses for the littoral population.

Dahod

The fishing rights of Dahod reservoir are with the three cooperative societies. The fishers of these societies are fishing in the reservoir on royalty basis @ Rs. 15/ kg for major carps and Rs. 8/ kg for minor carps. The fishers pay the royalty to DoF and dispose the catch either by themselves or to a local dealer or wholesaler. The disposal pattern depends upon its quantum. Small quantity is either pooled by the fishers or disposed off locally, and in case of a larger quantity, it is disposed of at wholesale market at Bhopal.

Pahuj

Pahuj reservoir witnessed different fishing rights since its adoption for fisheries. The fishermen cooperative had the fishing rights with a royalty system during 1961-81, followed by fixed quota during 1982-92 and free quota during 1994-2005. After 2005, the fishing was suspended for 2 years as the fishing rights of reservoir could not be auctioned because minimum lease amount fixed by DoF was very high. During 2007 the reservoir was leased out to the contractor for a period of 3 years at INR 0.8 million/year with 10% annual increase. Across different systems, the highest yield was under free quota 75 kg/ha and the minimum in fixed quota 33 kg/ha. The lease of the reservoir has been transferred to a contractor since 2007-08. He was a member of the earlier lessee fisher cooperative society. The contractor and his associates are responsible for fisheries management, monitoring, and fish seed stocking in the reservoir. The contractor engages the fisher parties/ local fishers for fishing in the reservoir. The fisher/fishing party hands over the fish catch to the contractor. The remuneration for fishers depends on the negotiations between the fishers and the lessee. Similar to Dahod, disposal of catch at Pahuj reservoir depends upon its quantum. The contractor collects the catch from fishers/fishing party and disposes of it either for auction at the wholesale market for local consumption or to terminal markets (Kolkata, Delhi, Amritsar, Lucknow, Gorakhpur) in case of higher catch.

The irrigation was the priority activity with fishing as the secondary. The constraints of multiple use were primarily due to escape of fish from the sluice gates during release of water for irrigation and maintenance of minimum water level for fish. The latter was generally not common as water at the dead storage level of the reservoir is sufficient for requirements of fish. Regarding escapement of fish, the loss was estimated at 5-15%. To minimize this loss, the irrigation department would inform the dates and time of opening of gates, so that fishers can take care of this loss at a barrage downstream. Furthermore, demonstration of improved fish productivity and increase in revenue from fisheries would highlight fishing as one of the major activities, and emphasize the holistic approach for reservoir water use favoring or promoting fisheries. These efforts may be supplemented with measures for improving the efficiency of postharvest operations including marketing.

Impact of the interventions

The impact of interventions made was assessed in terms of increase in fish production and fishing intensity (number of fishers and fishing days). The information on fish landings and fishing efforts was gathered from landing sites and records of respective DoF of Madhya Pradesh and Uttar Pradesh. To assess the impact these parameters were compared for pre- and post-project period.

Dahod

It is the second year of the fisheries enhancements under the project and the impact is thus only available for one year of interventions. The interventions have increased the fish production of the reservoir from 20 to 22 t (Table 1).

The maximum increase was for major carps (51%), while the catch for other categories of fish had declined. The composition of fish catch of the reservoir was changed in favor of stocked fishes, the major carps. It indicated a positive impact of fisheries enhancements on the reservoir productivity. The outcomes of interventions will be more pronounced with time, as impact of regular stocking, species, and habitat enhancements will be visible through better fish harvests in future. The result promises immense scope for fisheries enhancement and other institutional interventions for scaling-up and scaling-out. Recognizing the impact of the project, state DoF put forward a massive plan for implementation of these interventions in most of the reservoirs of the state.

Table 1. Impact of interventions on fish catch of Dahod reservoir.

Fish category	Fish catch(in t)		% increase	Fish catch (in %)	
	Pre	Post		Pre	Post
Major carps	7.36	11.14	51.47	36.31	50.52
Catfishes	5.98	4.98	-16.80	29.52	22.56
Miscellaneous	7.02	5.93	-15.65	34.66	26.86
Total	20.26	22.06	8.86	100.00	100.00

The fishing effort per month of one of the lessee fisher societies was compared for pre- and post-project implementation period (Table 2). An increase in fishing effort in terms of average number of fishing days/month and number of fishers/day was noted. The average fishing effort reached over 263 fishing days/month, up from 138 indicating that fishing effort was nearly doubled after implementation of the project.

Table 2. Impact of intervention on fishing effort at Dahod reservoir.

Period	Fishing days/month	No. of fishers/day	Effort/month
Pre	16.00	8.65	138.40
Post	18.50	14.23	263.26
% change	15.63	64.51	90.21

One of the major problems in fish disposal is access to the reservoir and maintaining quality of fish before its disposal. To solve these problems market and transportation support was provided to the Fisherman Cooperative Societies in the form of six bicycles fitted with iceboxes. The market survey and opinions of fishers and market intermediaries revealed good impact of the intervention. The fishers were also encouraged to operate collectively to reduce cost of transportation, storage, and marketing and better bargaining for price negotiations with the local dealers. The fishers are now able to transport their catch promptly and in good condition, which increases the remuneration of their catch. The provision was also made under the project for one boat for prompt assembling and monitoring of catch. These interventions are expected to result in better remuneration and income of fish catch for the fishers in the coming years. It was suggested that the fishers establish a separate shop at the local or primary wholesale fish market with a freezer for the storage and maintenance of better quality fish. It is expected that this will help fishers to fetch better prices for their produce.

Pahuj

Impact of interventions on the fish production and composition were analyzed and an evident positive impact was noticed for both the production and composition of fish catch. As mentioned earlier, fishing was suspended in the reservoir for 2 years prior to its adoption under the project. Habitat enhancement in terms of harvesting of minnows resulted in 300 t of fish, which were dried and sold at a very good price. After the clearance of weeds and minnows, the reservoir became favorable for commercial fisheries. The fish catch for only 3 months during project implementation period was more than fish production for whole the year during preproject period. The total production increased from 26 to about 42 t (Table 3).

Table 3. Impact of interventions on fish catch of Pahuj reservoir.

Fish category	Fish catch (t)		% increase	Fish catch (in %)	
	Pre	Post*		Pre	Post*
Major carp	6.62	8.97	35.50	25.40	21.50
Minor carp	4.97	3.24	-34.81	19.07	7.76
Catfish	2.49	13.32	434.94	9.55	31.92
Weed fish	11.98	16.2	35.23	45.97	38.82
Total production	26.06	41.73	60.13	100.00	100.00

*Catch only for March-June.

This indicated an increment of over 60% in catch. The maximum percentage increase was for catfishes followed by major carps and weed fishes. The fisheries favored catfishes due to easy availability of food, but they were difficult to harvest during pre-project period. Clearance of weeds and minnows during the project period made their fishing easy and led to a four-fold increase in their catch. The increment in catch of major carps was over 35%. Considering the wide gap between existing and potential fish production in the reservoir, regular stocking of carps is expected to improve their production and contribution in total catch significantly. This statement may be supported by the first year results of the project. The results also indicated that stocking and species enhancements had changed the catch composition in favor of stocked fishes, the desired outcome.

The reservoir is located near Jhansi city and has good fish demand. Considering this demand for fish, it was suggested to have a separate shop of the contractor/fishers at the primary wholesale fish market at Jhansi with a deep freezer for the storage and maintenance of better quality fish to fetch higher prices. The fishers have given consent to implement this intervention. Further, involvement of reservoir fishers and their family members for direct disposal of fish catch in retail market as vendor to the consumers was also suggested. Potential local markets were identified for direct sale of fish. The fishers received better prices and returns after following this intervention.

Institutional interventions for scaling up and scaling out

The results of the project regarding fisheries enhancements, change in institutional arrangements and postharvest operations were regularly discussed with senior officials from fisheries development agencies: Ministry of Agriculture, Government of India, State Department of Fisheries, National Fisheries Development Board, Fishermen organizations. The agencies are convinced about the positive impact of project outputs and agreeing for their scaling-up and -out. They are willing to implement the project outputs in a phased manner with stakeholders' participation. The State of Madhya Pradesh has already initiated to implement the project outputs in 50 reservoirs under the supervision of our institute (CIFRI, Barrackpore) to improve fish productivity.

Conclusions

Most of the Indo-Gangetic Basin reservoirs have a wide gap between the actual and potential fish production and productivity. The major reasons for this gap are traditional fisheries management practices and the institutional environment. The project documented two reservoir fisheries management success stories. Fisheries enhancement results in increased fish productivity. Regarding institutional environment, two major constraints of multiple use with priority for irrigation, were escape of fish during release of water for irrigation, and maintenance of minimum water level for fish. Improved fish productivity in the reservoirs established fisheries as one of the major activities. It has put more emphasis on a holistic approach for reservoir water use favoring or promoting fisheries. These efforts are supplemented by providing the institutional and physical support for efficient fish marketing practices. Scaling-up of these fisheries management norms through their refinement at different sites and conditions and their scaling-out with stakeholders (DoF and fishers) participation would enhance reservoir fish productivity of Indian small reservoirs, and uplift the socioeconomic status of poor fisher communities operating in these reservoirs.

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Community-based fish culture in seasonal floodplains and irrigation systems

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Abstract

The Challenge Program on Water and Food project 'Community-based Fish Culture in Seasonal Floodplains' is a 5-year interdisciplinary action research project with an overall aim of enhancing fish production in seasonal floodplains to improve and sustain rural livelihoods. The research is being carried out in seasonally flooded areas where rice is cultivated on individual household plots during the dry season. During the flood season, the same land is inundated, creating an open access waterbody, subject to multiple uses including the capture of wild fish. The project has sought to develop technologies and institutional arrangements to support collective fish culture in the flood season appropriate to a variety of environmental and sociocultural settings represented by Bangladesh, Cambodia, Vietnam, China, and Mali. In the fourth year of implementation, the development of collective approaches to fish culture with local stakeholders has met with varying degrees of success. Negotiating access, the development of community-based management institutions, and benefit-sharing arrangements within a system where rights are dynamic, overlapping, and heterogeneous has created particular challenges for the development of the project. The variable success of the community-based fish culture activities in the project countries has led to a deeper consideration of context and its contribution to the success or failure of collective action under differing socioecological conditions.

Media grab

WorldFish initiative supports learning and adaptation to encourage rural households to innovate and develop locally appropriate technology for fish culture in seasonal floodplains.

Introduction

Seasonal flooding in many parts of Asia and Africa creates a dramatic shift in livelihoods and resource production for many households in floodplain areas (IIRR, IDRC, FAO, NACA, and ICLARM, 2001). During the dry season, agricultural production dominates, with cropping of rice and other commodities for sale and domestic consumption. Boundaries between private and commonly owned land are clear, and households focus on production from their individual homesteads or by providing labor to other households. In the flood season, land boundaries in deep-flooding areas become indistinct, and many areas revert to common ownership. Water resources become subject to multiple uses by multiple users. Fish production in these areas is based on the capture of wild fish. The community-based fish culture project is based on the premise that production from these water bodies could be enhanced by stocking locally important fish species, providing local communities with an additional source of income and an increased supply of affordable fish for sale or consumption (Dey and Prein 2003; WorldFish 2002; IIRR, 2000; Sinhababu et al., 1984). The added investment, however, required by resource users to sustain this intervention has important implications for access arrangements to waterbodies as well as their potential productivity. This concern is echoed by Haylor et al. (1997) who note that if the owners of rice fields suitable for fish production fence off their fields (converting access from open to private), this could affect access to fish by the poorest. Intervention therefore requires the participation and support of multiple resource users. With stakeholder support, the project is testing a range of models for collective approaches to aquaculture in the five project countries.

Methods

The project is being implemented in selected sites in five countries: Bangladesh, Vietnam, Cambodia, China, and Mali. Sites were selected based on hydrological conditions (height, extent, and duration of flooding), existing infrastructure (dikes, irrigation canals), and willingness of local communities to participate in the project, and support from local authorities. Although the exact nature of participation varies between countries, membership of a fish culture group, convened to undertake fish culture activities and to share the benefits of fish production, is open to all members of the community who wish to join. A management committee is elected from within the group to provide leadership and to oversee the coordination of fish culture activities. The creation of fish culture groups is supported by field staff from within the national partner institutions, who visit the groups regularly to provide guidance to farmers and, occasionally, to assist in conflict resolution.

Fish stocking has been carried out at each of the project sites under the guidance of national partners with expertise in local aquaculture systems. Locally preferred species have been stocked in polyculture systems, with stocking densities and proportions varying from year to year as the culture systems have evolved. Enclosure designs have similarly been locally adapted and modified.

Results

Implementation of the project has led to a range of outcomes, both anticipated and unanticipated. Collective approaches to aquaculture have met with variable success in each of the project countries, with the project delivering different levels of benefits both within and between countries. Negotiating access, management institutions and benefit sharing arrangements within a system where rights are dynamic, overlapping, and heterogeneous has created particular challenges for the development of the project.

In Bangladesh, successes have been substantial at some project sites, whereas disputes, conflicts, and ultimately discontinuance have arisen at others. Building on previous community-based fisheries management experience in the country, community-based fish culture has been introduced in floodplains subject to a complex array of administrative arrangements. The project is currently being implemented in government *khas* lands, or land reserved for distribution to the landless, and in areas with public and private ownership with no leasing arrangements. In each system, enclosures have been created within floodplain depressions. Fish culture is managed by a Floodplain Management Committee made up of representatives from all communities surrounding the floodplain, with participation of landowners and landless. As described by Haque et al. (2008), however, the complexities of access and ownership to land, water, and fishing rights have created serious challenges to the project. Despite these challenges, the community fishers' society at Beel Mail, Rajshahi District, with the support of local authorities, has secured an extension to their current leasing arrangement allowing them to continue fish culture until 2013. Fish culture is now financed by savings from successful fish culture during previous years.

Fish culture activities in southern Vietnam have been introduced on a collective basis in flooded rice fields of the Mekong Delta. In contrast to Bangladesh, the flooded land is entirely under private ownership, with members of the fish culture group drawn from households whose land is situated within the flooded area. Where annual flood height is low enough to permit the creation of enclosures around individual household plots, there has been a general preference toward fish culture on an individual basis, or a third rice crop, and insufficient incentive for farmers to work together collaboratively to raise fish. Consequently, there have been high levels of discontinuance of community-based fish culture in these areas, although approaches to collective fish culture are now evolving amongst groups of households who favor fish culture in a small number of enclosed rice fields. In the provinces of the Mekong Delta that border Cambodia, flood waters are deep, permitting only two rice crops each year. In these areas, the cost of creating individual enclosures, using fences of sufficient height to contain stocked fish, is prohibitive, making collective fish culture a more viable option. Benefit-sharing arrangements, management, and leadership of fish culture in community groups and fish marketing present significant challenges to the success of the approach.

In Cambodia, establishing community groups to successfully manage fish culture within flooded areas has proved problematic. Fish culture activities have been introduced in open access reservoirs and flooded rice fields. Initially, households were keen to participate in the project. Farmers have since demonstrated a preference for fish culture on an individual basis, introducing the technology instead on their own homesteads and private plots. As in Vietnam, in some areas there has been a move toward collective fish culture amongst smaller fish culture groups of 10-12 households who practice fish culture in 3-4 enclosed rice fields. Members of these fish culture groups are currently improving the rice field environment for fish culture by creating ditches along the rice field perimeter to act as refuges when waters are shallow. Fish culture activities have only continued in Takeo province, a fish-deficit area. The approach has met with less success in Prey Veng province. Although the reasons for this failure are not yet clear, it is possible that incentives to participate may be lower due to the presence of support from numerous international organizations and NGOs. During the next phase of project development, community-based management of dry-season fish refuges will be introduced.

Farmers in China have adopted a different approach to collective fish culture than their counterparts in other project countries. The project is being implemented in two provinces, Yunnan and Jiangsu. In Jiangsu province, fish culture has been introduced into irrigation canals. In Yunnan, fish have been stocked in flooded rice nurseries that are also used for the production of lotus. In both cases, management of fish culture has been entrusted to an individual who acts as a caretaker, feeding and guarding the stocked fish. In return, they receive a larger proportion of the benefit from production, with the remainder shared amongst project participants and local community funds.

Fish culture is a new activity in Mali, creating a new set of challenges in addition to those faced in the Asian countries. Fish will be stocked into mares or floodplain depressions, which are generally managed by one community. Caution is needed to ensure that the introduction of fish culture does not undermine traditional access to the water, subject to multiple uses by a variety of resource users, or that the change in value of both the water resource and fish production transforms the management and allocation of rights to water and fishing. A detailed analysis of access rights and institutions forms the basis of the research in this area.

The variable success of the community-based fish culture activities in the project countries has led to a deeper consideration of context and its contribution to the success or failure of collective action under differing socioecological conditions, recognizing that the results of stocking are often unexpected (e.g. Lorenzen and Garaway, 1998; Garaway, 2006; Garaway et al., 2006). Socio-political history, in particular, is likely to have had a strong influence on project success. For example, the suggestion that private property, although no longer recognized as privately owned during the flood season, should revert to collective management for the purposes of fish culture has important implications in countries such as Cambodia and Vietnam, where recent history makes collectivization socially sensitive. At the local level, an additional range of factors can be said to influence the sustainability of community-based institutions, including social context and motivation for collective action, group

leadership, local markets, ecological context, and the role of the implementation process itself. Recognizing the broad influence of context on project success, a framework was developed to guide the research during the final phase of the project (Figure 1). The framework provides a basis for the comprehensive analysis of the many factors that make up the complex socioecological context in which the project sites are embedded. Adopting a political ecology perspective, the framework addresses issues of historical, political, socioeconomic and cultural context, placing them firmly within an understanding of the socioecological linkages occurring at the landscape level. The application of the research framework in each of the project countries will help to generate a deeper understanding of the factors that have led to the success and discontinuance of collective fish culture, and to assess the potential role of collective fish culture as a multiple use, floodplain system.

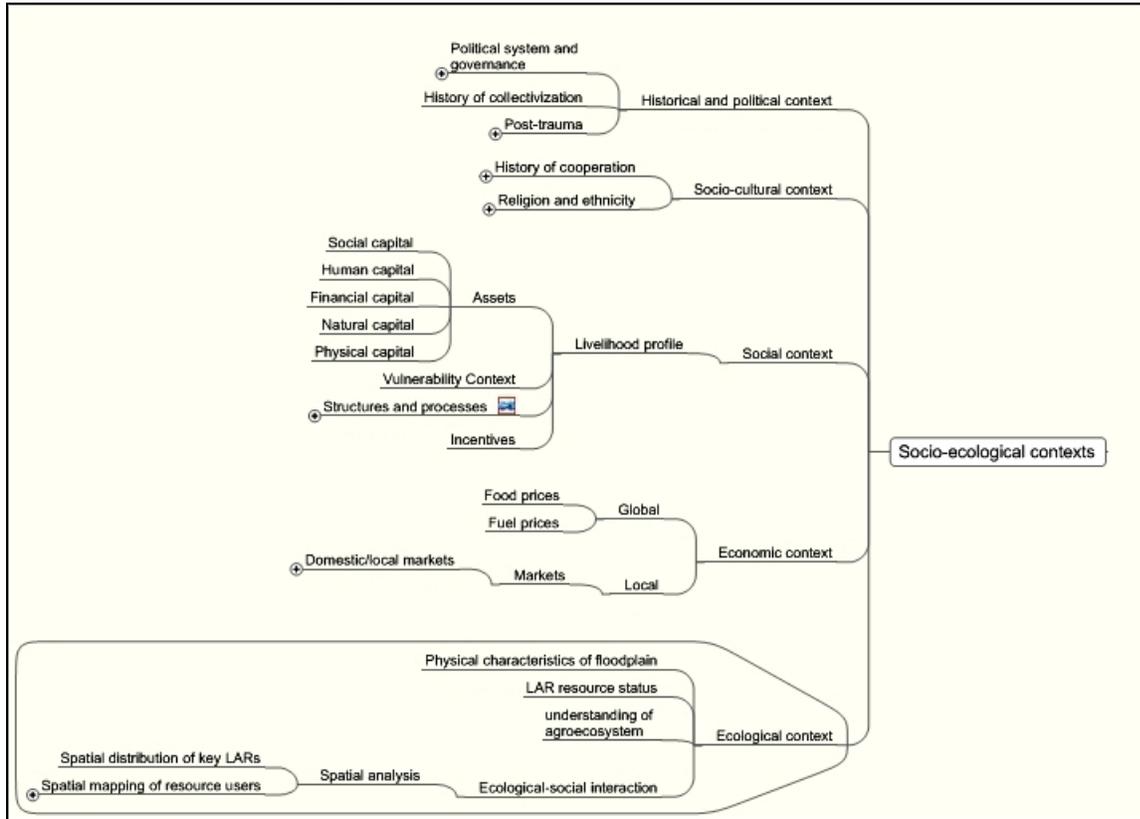


Figure 1. Framework for understanding socioecological factors supporting or constraining collective approaches to aquaculture, and the potential contribution of collective aquaculture to the multiple use of floodplain resources.

Discussion

The introduction of collective approaches to fish culture in a group of countries that are culturally, politically, and geographically diverse has created a number of challenges to the implementation of project activities (addressing sensitivities to collective action, negotiating benefit sharing with a range of stakeholders, ensuring equitable access to resources amongst multiple users, promoting participatory decision-making in the identification and implementation of technical and institutional options for fish culture). It has also provided an important opportunity for developing a greater understanding of a range of issues of increasing significance to the allocation and management of natural resources.

Water, and the aquatic resources it supports, is often subject to multiple use and overlapping access and use rights (Bene, 2003; Benda-Beckmann et al., 1996; Meinzen-Dick and Knox, 1991). Seasonal floodplains are a particularly dynamic example of these changes in rights, at the interface of both land and water resource use. This creates a particular set of social and ecological challenges for resource management. Within the context of the community-based fish culture, the dynamic nature of property rights is a significant factor. Dry season private property is submerged during the flood season, creating open access water bodies available for use by multiple resource users. In addition to this complex set of rights to both water and land are the rights associated with the capture of wild fish. Despite the private ownership of the flooded land, the capture of wild fish is generally not restricted, and landowners accept open access conditions on otherwise private land. Numerous overlapping rights, coupled with issues of enclosure and fisheries enhancements, introduce additional layers of interest to the management of land, water, and fish resources. However, integrating aquaculture into existing water systems can change this dynamic (e.g. Lorenzen and Garaway, 1998; Garaway, 2006).

Conclusions and recommendations

It is clear from experiences to date that the socioecological context plays a major role in the success or failure of collective action. The historical and social context into which any intervention is introduced is likely to influence the success and outcomes of collective action. The Community-Based Fish Culture project aims to contribute to the growing body of knowledge on collective action in multiple-use systems where property rights are dynamic. At this stage, the Community-Based Fish Culture project has introduced collective approaches to fish culture in five socially, politically, and geographically diverse countries where it has the potential to increase the production of living aquatic resources from floodplains. Despite the processes of adaptation and evolution of collective fish culture systems to fit local needs, the approach has had variable success within and between countries, suggesting that the conditions under which collective fish culture is appropriate must be better understood. The conditions that support and constrain collective approaches to fish culture in different socioecological contexts will be explored using a detailed framework of analysis during the final phases of the project.

Introducing community-based or co-management approaches to resource management must respond to local complexities, and acknowledge that the associated incentives to adopt collective approaches may not always be sufficient to support sustainable community-based institutions. The complexity of rights and access encountered in the floodplain context add an extra dimension to current knowledge and experience regarding collective action. It is, therefore, essential to understand the local context, and to evaluate the potential impacts of intervention on existing access and ownership dynamics prior to the introduction of any new technology.

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Institutional issues on management of seasonal floodplains under community-based aquaculture to benefit the poor in Bangladesh

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Abstract

Bangladesh is endowed with large numbers of common pool aquatic resources. Sound institutional arrangements are important for sustainable management and uses of those resources. Our analysis of formal and informal institutions governing community-based fish culture in seasonal floodplains was carried out in three floodplains of the Indo-Gangetic River Basin, located in different regions of Bangladesh. The present study was carried out in 2006-07 to understand the complex institutional relations that govern ownership, access, and control of the floodplains brought under community-based fish culture with a goal to increase fish production, income, and overall livelihood gains of the poor. This study makes use of participatory approaches and involved diverse stakeholders from formal and informal institutions. The important institutions identified were: Department of Fisheries (DoF), Department of Land (DoL), and Local Fisheries Society. Important stakeholders included were lease holders of public water bodies in the floodplains, private landowners, seasonal and professional fishers, and poor people living in communities adjacent to floodplains. The outcomes of the study revealed important similarities as well as differences in institutional arrangements between the floodplains under study. This constitutes a vital part of the institutional analysis of the project and is of importance to develop institutional options for effective management of community-based fish culture in seasonal floodplains in Bangladesh.

Media grab

This paper identifies effective mechanisms and institutional arrangements for involvement of different stakeholders in community-based fish culture in seasonal floodplains.

Introduction

Seasonal floodplains are water bodies that retain water for 5-6 months during which they are suitable to grow fish and other aquatic animals. During dry months they are largely used for rice production. There are 3.0 million ha of floodplains in Bangladesh. A large proportion of these are suitable for fish culture (Dey and Prein, 2004; WorldFish Center, 2007). The floodplains differ largely in physical features, size, ownership and location. Previously, irrespective of ownership regimes, most of the floodplains were used as common pool resources for harvest of fish and other aquatic animals and plants during the monsoon. In recent years the demand for floodplain fish production has increased largely due to decreasing trends in capture fish production from the floodplains. It was also realized that floodplains offer a high potential for increased production through fish culture during monsoon. Attempts to bring the floodplains under fish culture to increase production and include the poor in sharing the benefits are surrounded with complexities, however. Institutional issues are amongst the most important challenges for achieving success.

Ownership regimes of the floodplains in Bangladesh are diverse and complex with some floodplains being completely under public ownership, some public but surrounded by private lands, and some under completely private ownership. Floodplains with public ownership are normally leased out by the DoL in auction, with a priority to get leased by registered fishers' society. In most cases it is the moneyed and politically influential people who paid lease money and took control over the floodplains to use it for fish culture. There are initiatives to bring privately owned floodplains under fish culture by contract between the owners and individual entrepreneurs. Initiatives to bring public and privately owned floodplains under community-based systems with multiple beneficiaries are less common, however.

The present study improves our understanding of the complex institutional relations governing community-based fish culture in seasonal floodplains. The purpose of the study is to identify appropriate institutional options for the sustainable use of floodplains and maximize their benefit to large numbers of people, including the poor in Bangladesh.

Methods

Three floodplains of Brahmaputra, Padma, and Teesta river basins located in different areas of Bangladesh were selected for the studies by the researchers in collaboration with DoF. The floodplain 'Beel Mail' at Mohanpur in Rajshahi is located in the Padma River Basin. The floodplain 'Angrar Beel' in Pirgonj, Rangpur, is located at Teesta River Basin, and 'Kalmina Beel' in Fulbaria, Mymensingh, located at the Brahmaputra River Basin of Bangladesh.

All three floodplains selected for the studies were large under two types of ownership categories: 'public and private' and 'private.' The floodplain Beel Mail (40 ha) is under public ownership with public water bodies (15.2 ha) surrounded by privately owned land (24.8 ha). The two other floodplains, Angrar Beel (31 ha) and Kalmina Beel (33 ha), were under private ownership. In selecting floodplains, the feasibility of putting fencing in some of the outlets with minimum investment to prevent the escape of stocked fish was an important criterion. The presence of solidarity among the people in the communities surrounding the floodplains, and their interest in implementing the project, was taken into account (Dey et al., 2005).

The communities surrounding the floodplains were visited and the lists of beneficiaries with basic information were collected. The specific details of different types of beneficiaries were collected through further visits and by arranging focus group discussion (FGD) with them. For each floodplain a floodplain management committee (FMC) was formed from the representatives of different types of beneficiaries in a participatory way. With support from DoF and the research team the FMC developed an annual work plan, budget, and implementation of activities of community-based fish culture in the floodplains. They played a role in the resolution of conflicts and took part in the distribution of income among the beneficiaries of the project. In addition a project implementation committee (PIC) was formed at the local level with representation from DoF, other related government departments, the representative of the research team, and the leaders of the FMC (the president and the secretary). The PIC was formed to encourage establishment of comanagement strategies in the use of floodplains for fish culture for its effectiveness and greater sustainability. Several authors emphasize the importance of comanagement of common resources (Ostrom, 1990; Pinkerton, 2003). In the use of community resource for the benefits of diverse groups of stakeholders, it is important to establish norms and rules through establishing comanagement strategies. As an action research process, initiatives were taken to empower the poor fishers by different measures (advocacy, awareness workshop, and exchange visit). During the studies, specific details on involvement of institutions (formal and informal) and their roles were recorded.

Results and discussion

Ownership of floodplains and beneficiaries

Floodplains completely under private ownership (Angrar Beel and Kalmina Beel) were similar in size, with similar numbers of beneficiaries and similar proportions of different types of beneficiaries (landless, fishers, and landowners) with similar numbers of communities surrounding the floodplains. For the floodplain with public ownership and surrounded by private lands (Beel Mail), the public land was leased out. For this floodplain it was the fishers' group that constituted the majority (55%) among the beneficiaries. The area of the floodplain was larger than that in Angrar Beel and Kalmina Beel, but the total number of beneficiaries was lower (Table 1). The higher proportion of fishers among the beneficiaries in Beel Mail was related to the fact that they were the leaseholders of the floodplain. In floodplains under public lease normally the lessees took control over the floodplains (including the private lands) during monsoon. Landowners involved as beneficiaries, in this case, were politically influential and solvent people. They earned income from the floodplain through returns on their financial investment in the scheme (they paid the lease value, management cost, and security), rather than as landowners (DoF, personal communication). In privately owned floodplains brought under community-based fish culture, landowners were the major stakeholders. The inclusion of landless and fishers, however, who get benefits from the system, was also given importance.

Table 1. Numbers of different beneficiaries in floodplains brought under community-based fish culture.

Floodplain	Area (ha)	Number of communities	Number of beneficiaries (%)			
			Landless	Fishers	Landowner	Total
Angrar Beel	31	5	38 (22)	23 (13)	110 (65)	171
Kalmina Beel	33	5	52 (29)	25 (14)	97 (57)	174
Beel Mail	40	5	22 (18)	68 (55)	34 (27)	124
Total	104	11	112 (24)	116(25)	241 (51)	469

Dey et al. (2005) carried out pilot studies on community-based fish culture in privately owned small (1.3 to 18.3 ha) seasonal floodplains in Bangladesh, with an average of 38 beneficiaries. Overall, they demonstrated success in fish production and income earning. But flooding and escapes of fish, social conflicts within the community, and conflicts resulting from inclusion of people from outside the community caused poor performance and discontinuation of the activities. Social harmony among the group members is important in the success of community-based fish culture in the floodplains.

Institutions and their roles

Formal and informal institutions played their role in bringing the floodplains under community-based fish culture. Institutional linkages between DoF, WorldFish Center and Bangladesh Agricultural Research Council (BARC) played a key role in ensuring success. DoF is a government institution with establishments at different levels. Through its linkages with other institutions and collaboration with the research team, DoF played an active and strong role in

resolving many of the acute social problems, and ensured technical management support (Rahman et al. in these proceedings). DoF played a major role in the selection of floodplains, beneficiaries, and formation of FMC and PIC. It also took necessary measures to protect fish from uncontrolled harvest and to ensure benefits to the poor (fishers, landless). DoF played an active role in ensuring a longer-term (5 years) lease from the Department of Lands (DoL) for the floodplain 'Beel Mail.' This significantly empowered the fishers, as they are no longer facing loss of their lease in open auction. Formal institutions also provided necessary monitoring and support. Fish production increased significantly compared to previous years despite some variation, and all the beneficiaries were able to increase earnings. Nevertheless it became evident that for large floodplains with different types of beneficiaries and stakeholders, there were large complexities in ownership, access, illegal pressure, as well as technological aspects. DoF played a decisive role in ensuring successful implementation of the project under such complex circumstances. The institutional linkages of DoF with other institutions are shown in Figure 1.

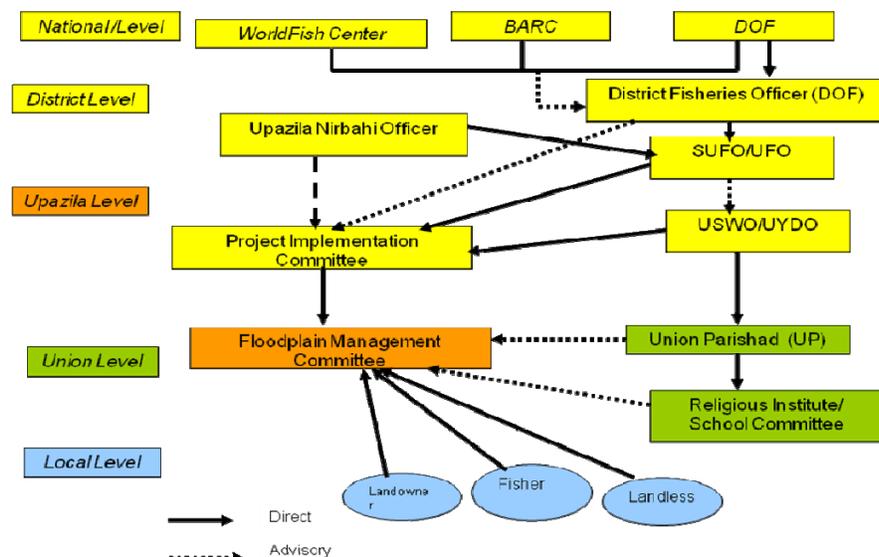


Figure 1. Institutional relationships between different stakeholders (Upazila Nirbahi Officer—the main Administrative Officer of the Upazila (sub-district); SUFO- Senior Upazila Fisheries Officer, UFO- Upazila Fisheries Officer, USWO- Upazila Social Welfare Officer; UYDO- Upazila Youth Development Officer).

For small floodplains with fewer beneficiaries, the promotion of community-based fish culture by NGOs was implemented successfully in collaboration with other institutions (Dey et al., 2005). In all floodplains the involvement of school committees and mosque committees helped to encourage people to participate in community-based systems and utilize the unused potential of floodplains by bringing them under fish culture. In Bangladesh the role of such institutions is often important in carrying out community-based activities, as people normally respect and value the opinions of the leaders of these institutions. Similarly, people provide support to those institutions through income earned from community-based activities (e.g. donation of some of their income to the mosque committee). This suggests that school and mosque committees play a critically important role in organizing and educating people and the establishment of communal action as well as benefit-sharing mechanisms.

Conflict and conflict resolution

In Bangladesh conflicts of various types are common due to the complexity of inland fisheries, including those in floodplains. The competition for control over these resources and their benefits is often strong (Thompson et al., 1999). Access to communal resources can result in various types of conflicts, normally due to problems with ownership (e.g. public lease vs. private landownership, private landowners illegally occupying public lands), and social and political reasons (e.g. local conflicts due to power relations). In Beel Mail floodplain, conflict arose when outsiders tried to harvest fish from beneficiaries of the floodplains. Dialogue with people in the surrounding communities by arranging meetings to clarify the objectives of the project was helpful in resolving the problem. In some instances this also required the assistance of other formal institutions (the Upazila Nirbahi Officer, the Chairman of Union Parishad, the police department) to resolve the conflicts. In Kalmina Beel floodplain no significant conflict was observed. The active role of FMC with support from DoF and the research team was helpful in avoiding conflict.

In Angrar Beel floodplain, however, conflicts arose between the president of the FMC and the other members. This was largely related to the dominant attitude of the president. DoF, together with the research team, took strong initiatives to resolve the conflict by forming a new FMC with involvement of all the beneficiaries of the floodplains, and by imposing strict rules and regulations.

Benefits from fish culture and arrangements for sharing of benefits

The share of net profit from fish production from the floodplains, agreed at the start of project activities, varied according to types of beneficiaries, and across floodplains. Benefit sharing was decided and agreed upon by the beneficiaries and finally by the FMC (Table 2). For the Beel Mail floodplain, the fishers received around 15% of net profits and the landowners received almost 50% of net benefits, as they paid the lease money for the floodplain. The fishers in the floodplain, however, received considerable benefits by taking control of fish harvest from the floodplain. They received 50% of the price of the harvest of nonstocked fish and 10-15% of the stocked fish. Furthermore, access of landless and seasonal fishers from communities surrounding the floodplain using local gear was allowed throughout the season. In the Kalmina Beel floodplain all stakeholders (fishers, landowners, and landless seasonal fishers) deposited around 30% of their net profit in a revolving fund. As in Beel Mail, the landless seasonal fishers were allowed to harvest fish for their subsistence throughout the season. The professional fishers group got their income through commercial harvest of fish. In Angrar Beel floodplain, the landless seasonal fishers had open access to harvest the nonstocked fish during monsoon. Because of the lower than expected profit from the harvest of stocked fish, it was not possible for them to deposit into the revolving fund.

Table 2. Plan on arrangement of sharing of benefits of floodplains under community-based fish culture.

Source of benefit to distribute	Distribution of net profits by floodplain (%)		
	Beel Mail	Kalmina Beel	Angrar Beel
Fishers	30	5	10
Landowner	45	50	45
Landless	5	5	5
Deposit to use as revolving fund	20	40	40

Conclusions and recommendations

In seasonal floodplains under community-based fish culture, better outcomes and sharing of benefits is vital for sustenance of the community-based systems (Dey et al., 2005). It is technologically feasible to bring large floodplains under public and private ownership successfully under community-based fish culture. Involvement of DoF as implementing institution is important. Large numbers of people, including landless, poor seasonal fishers, professional fishers, and landowners, benefited from the success in implementation of activities in all the floodplains. The outcomes demonstrated a significant increase of benefits to different stakeholders through sharing of benefits derived from their involvement.

Despite the conflicts that arose, an environment with a win-win situation was created for large numbers of people, with active participation of DoF in implementing and strategic roles. The outcomes of the present study in large public and privately owned floodplains, together with similar studies carried out on privately owned seasonal floodplains, demonstrate that community-based fish culture in seasonal floodplains can be successful if supported by effective institutional arrangements.

Acknowledgments

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Fisheries productivity and its contribution to overall agricultural production in the Lower Mekong River Basin

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Abstract

We examined the spatial and temporal trends in capture fisheries and aquaculture production and value in the Lower Mekong River Basin. We compared fishery contribution with crop and livestock sector contributions, and discuss the level of likely future demand and the prospects for the fisheries of the Basin meeting the demand. The overall production of fish is 2.5-3 million t. Production is dominated by capture fisheries in Cambodia, Laos, and Thailand, and by aquaculture in the delta in Vietnam. Production from capture fisheries increased relatively little from about 1995 to 2005 in all four Lower Mekong countries. The greatest estimate of value was about US\$3 billion, mainly from the capture fisheries. Aquaculture in Vietnam is rapidly increasing in value, to match the increase in production, and in 2005 was worth over US\$1 billion. The contribution of the fisheries sector to overall agricultural production is significant in Laos and Thailand, and large and growing in Cambodia and Vietnam. The Lower Mekong fisheries face threats to production from changed water availability, quality, and barriers to fish migration and overfishing. If the increased demand is to be met, these threats must be managed such that developments do not reduce the production of fisheries, especially capture fisheries.

Media grab

Is the production of fisheries enough to meet the growing demand in the Lower Mekong?

Introduction

The Mekong River has one of the most diverse and abundant fisheries in the world. The fisheries are a major factor in the well-being and livelihoods of the 60 million people who live in the Lower Mekong Basin. Some 40 million people or two-thirds of the Basin's population are involved in Mekong fisheries, at least part-time or seasonally. Not only do they derive their livelihood from the fishery, they also depend on fish and other aquatic animals for food security. Fish and other aquatic animals are the most important sources of animal protein, and thus a major support to food security, in particular of the rural population in the Lower Mekong Basin (van Zalinge et al., 2003).

There are many studies of fisheries of the Mekong, however, precise estimates of the total fisheries production are lacking (Rab et al., 2005). There are no studies on fisheries productivity for the whole Lower Mekong Basin below the country level, none that compare the contribution of this sector to overall agricultural production, and few that give trends (none for the whole of the Lower Basin). Most of the studies provide aggregated country level information for a season or a year. We analyzed the fisheries productivity of the Basin both spatially and temporally. We compare its contribution to the overall agricultural production to those of the crop and livestock sectors, and discuss the level of likely future demand and the prospects for the fisheries of the Basin meeting the demand.

Methods

We defined the fisheries productivity in terms of production and gross value of production per capita. Gross value of production (GVP) can be defined as:

$$\text{GVP (US\$)} = \text{Production of fisheries (tonne)} \times \text{Landing price of fisheries (US\$/tonne)} \quad (1)$$

The fisheries comprise inland capture fisheries and aquaculture. We have estimated GVP of both capture river fisheries and aquaculture.

Estimates of fisheries production in the countries of the Lower Mekong Basin are found in statistical databases and in various reports and papers. The former give production statistics and often economic information. In the case of Cambodia and Vietnam, they also give a provincial breakdown of the data. The papers and reports, particularly the more recent ones, tend to use different methods of estimation, and give different and often much higher values of production. They generally have fewer temporal and spatial trend data (usually a single production figure for a whole country for one year), and often give production with less attention to economic data. Therefore, aiming to combine the better estimates of the recent literature with the trend and other information from the statistics, we present data from both sources. It must be emphasized, however, that the statistics are regarded as low and unreliable estimates of fish production.

The literature sources of data are mainly the papers and reports available on the MRC website (www.mrcmekong.org) and the CD 'Fisheries Information in the Lower Mekong Basin Version 1' published by the

MRC. Statistical sources of data are the FAOSTAT database faostat.fao.org and the official statistical website of the respective riparian countries. Mainuddin et al. (2008a) estimated detailed province-wise crop and livestock productivity for the Lower Mekong Basin. We used the results from that report to compare here with the fisheries productivity. We have estimated productivity by province where data were available, however, we present only the country-level results. The details of the data sources, the method of analysis, and the provincial productivity can be found in Mainuddin et al. (2008b).

Results and discussion

Production per capita and GVP per capita of fisheries (both inland capture fisheries and aquaculture) based on the statistical data are given in Table 1. Aquaculture data were not available for Laos and Thailand, therefore, Table 1 shows only the inland capture fisheries for these two countries. Production and GVP per capita for Thailand is also for the whole country, though only about one-third of the country is in the Basin. Per capita production for Laos and Thailand remained the same due to the increase in population, although the total production gradually increased over the years. Total production for Laos increased from 19,500 t in 1993 to 29,800 t in 2004. For Thailand, production increased from 175,140 t to 201,700 t during 1993 to 2004. The GVP per capita gradually decreased for Laos, mainly because the US dollar increased in value against the local currency. The GVP per capita for Thailand remained static around US\$3 per capita.

Recent consumption-based estimates for Laos yield much higher values of around 42 kg/person/year, which in turn give much higher estimates of total fish production of around 183,000 t/year (Hortle and Bush, 2003; van Zalinge et al., 2003). The gross value of production implied by the higher estimate is perhaps in the order of US\$200 million per year. van Zalinge et al. (2003) reported that among the four riparian countries, Thailand has the highest capture fisheries production, estimated at 932,300 t, based on per capita consumption of 52.7 kg. Mahasarakarm (2007) reported that annual consumption of fish and fish products in the Mekong Basin of Thailand amounts to 30-35 kg/capita, equating to an estimated total consumption of inland fish of 795,000 t. At a conservative first sale price of about US\$1/kg, the freshwater fisheries (capture fisheries and aquaculture) of the Mekong in Thailand are worth about US\$700 million per year (Mahasarakarm, 2007).

Production and GVP per capita for Cambodia appears, according to the statistics, to have increased over the years, with a particularly marked increase in 2002-04 (Table 1 and Figure 1). This is mostly because of revised estimates of capture fisheries post 1998, including small-scale fishing (Figure 1). Aquaculture production also increased gradually from 7336 t in 1993 to 20,050 t in 2004. The fisheries production, however, is dominated (over 90% of the total) by inland capture fisheries (Fig. 1). Aquaculture production is much lower than the capture fish production in Cambodia with average production of 1-2 kg/capita. Other estimates of fisheries production range from similar to, to higher than, the official statistics in recent years. The highest of these is published by van Zalinge et al. (2003) based on consumption survey, which estimates the total production as 719,000 t (shown by the single point in Figure 1) (65 kg/capita) with total GVP of US\$680 million (US\$61/capita).

Table 1. Production and GVP of fisheries per capita based on statistical data.

Year	Laos		Thailand		Cambodia		Vietnam	
	Production (kg / capita)	GVP (US\$ / capita)	Production (kg / capita)	GVP (US\$ / capita)	Production (kg / capita)	GVP (US\$ / capita)	Production (kg / capita)	GVP (US\$ / capita)
1993	4.3	9.4	3.1	4.6	7.9	10.9		
1994	5.2	11.2	3.4	3.0	7.4	10.2		
1995	5.9	12.8	3.2	5.3	8.2	11.2	22.5	20.6
1996	5.0	10.8	3.5	5.9	7.1	9.7	24.3	21.7
1997	3.9	8.4	3.4	4.7	8.1	9.9	23.5	23.2
1998	4.0	5.5	3.4	3.6	8.3	10.2	22.9	22.5
1999	5.9	8.2	3.4	3.8	7.8	7.3	24.1	21.9
2000	5.6	7.8	3.3	3.4	8.9	8.4	29.1	29.3
2001	5.8	7.2	3.3	3.1	12.5	11.5	32.1	40.5
2002	6.1	7.2	3.2	3.1	28.0	25.0	35.7	42.4
2003	5.2	6.2	3.2	3.1	24.5	21.8	39.2	48.5
2004	5.1	6.8	3.2	3.2	19.2	19.9	44.5	56.6

Among the four riparian countries, Vietnam has the highest per capita production and GVP (Table 1). Per capita production has increased two-fold during 1995 to 2004, despite the increase in population. In Vietnam, aquaculture is well developed and unlike Cambodia the production is significantly higher than capture inland fisheries production. Aquaculture production was 71% of the total in 1995; in 2004 it was 91%. Inland fisheries production remained static over the years (Fig. 2). Both capture fisheries production and aquaculture dominate in the Mekong Delta. The Central Highlands produce only around 1% of the total fisheries production.

Other estimates of fisheries productivity diverge from official statistics to a degree similar to that shown in Laos, Thailand, and Cambodia. van Zalinge et al. (2003) reported capture fishery production of about 845,000 t in 2000

based on consumption surveys. Aquaculture production was put at 171,600 t, and the total fish production of just over 1 million t was equivalent to the consumption of 60 kg/person/year. The total fish production according to this estimate, which excludes marine fish, is just short of the total production including marine fish in the official statistics, as shown in Fig. 2.

Being located along the coastline, the Mekong Delta of Vietnam has an additional source of fisheries, that is, marine fisheries. The Mekong Delta is one of the major sources of marine fisheries in Vietnam. In the analysis of fisheries productivity described above, however, we did not consider the capture marine fisheries. To show the importance of the marine fisheries in the Mekong Delta part of Vietnam, it was included in Figure 2. In 1995 it was the most important part of the fishery, but by 2005 marine production had been superseded by that of the rapidly growing aquaculture sector.

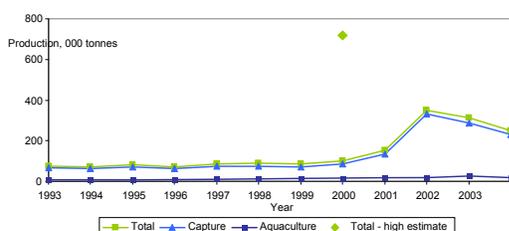


Figure 1. Production of fish in Cambodia, according to official statistics, with the high estimate from van Zalinge et al. (2003).

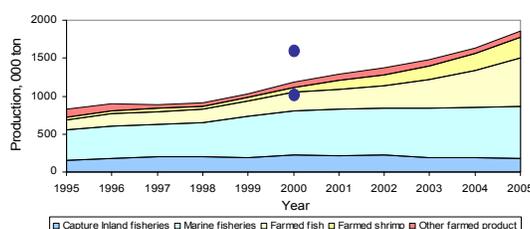


Figure 2. Production from different fisheries sectors in Vietnam. The Lower dark blue point is the total production estimate, excluding marine fisheries, of van Zalinge et al. (2003), while the upper dark blue point is the van Zalinge et al. (2003) estimate added to the official marine production value.

The comparison of GDP for different sectors is shown in Figure 3. The value of fisheries in the Lower Mekong is at least as important as that of livestock even if the Lower catch-based estimates are used. The consumption-based estimates lead to estimates of the value of fisheries considerably greater than that of livestock. The overall production is dominated by the crop production in Laos, Thailand, and Cambodia, however. In Vietnam, due to rapid increases in aquaculture production, the contribution of crop sector to overall production is decreasing though the total production remains almost static.

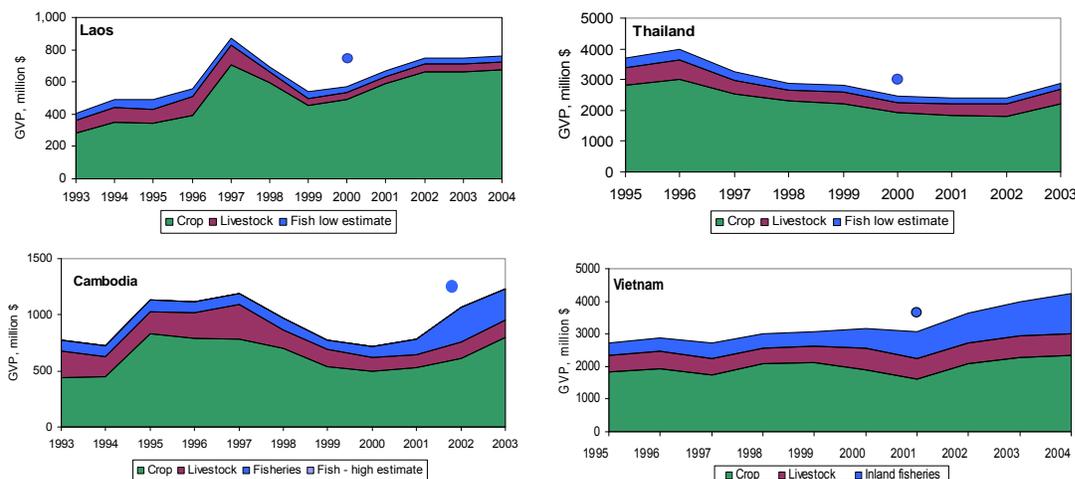


Figure 3. Agriculture and fisheries gross value of production in the Lower Mekong Basin. The blue point shows the high estimate of van Zalinge et al. (2003).

Threats and Opportunities in Fisheries Production

The population of the Lower Mekong Basin is likely to rise from the present 60 million or so to perhaps 80 million or more by 2020, and more than 100 million by 2050. Delgado et al. (2007) suggested that fish consumption in Southeast Asia to 2020 will grow at 1.4-1.7% per year, partly because of rising population and partly because of improving diets with increasing development. Sokhem and Sunada (2006) suggested that an increase of 0.4-1.6

million t will be required by 2050, based on a production of 3.1 million t in 2003. These increases are roughly proportional to the expected increase in population, and therefore appear not to be associated with an increase of fish in the diet. A growth rate of 1.4% per year, as suggested by Delgado et al. (2007), from the 3.1 million t base figure, would lead to an increase of 0.8 and 2.9 million t to 2020 and 2050, respectively, and a growth rate of 1.7% per year would lead to increases of 1.0 and 3.7 million t.

There is some evidence of overfishing in the Mekong: combined with the apparent low growth of capture fisheries (albeit based on unreliable statistics), it appears reasonable to suggest that capture fisheries are unlikely to meet this demand. At the same time, there are concerns about several threats to the capture fisheries of the Lower Mekong Basin as a result of dam construction, increased diversions, and increased sediment load due to deforestation (Sverdrup-Jensen, 2002). Although growth appears unlikely, capture fisheries are the greatest source of fish in the Mekong, and efforts to maintain the production and minimize impacts from these threats, are clearly crucial.

There has been considerable growth in aquaculture in the Lower Mekong Basin, particularly in the Mekong Delta in Vietnam. This, however, appears to be largely for the export market. It is reasonable to suppose that further growth is likely. Rice-fish farming systems also offer prospects for improved production and livelihoods, but they must be managed with considerable care as integrated systems so that rice farming and pesticide use do not affect the fish production (Frei and Becker, 2005). External impacts such as river pollution from aquaculture must also be managed. Whether these systems can meet future demand is unclear.

Conclusions

Fisheries production is a major source of animal protein in the Mekong, mostly from capture fisheries. Production and production trends are difficult to estimate; however, it appears that capture fisheries production is not increasing greatly, whereas aquaculture production in the delta is increasing rapidly. The contribution of fisheries to overall agricultural production is, perhaps, greater than the contribution of livestock, but crop production dominates overall production. Fisheries production is threatened by changed flows due to upstream development and climate change, but the extent of the threats cannot be quantified with current information. It would appear that the greatest prospects for growth are from aquaculture and perhaps also rice-fish production systems. There will be trade-offs between fisheries production and upstream development, including the development of irrigated agriculture, but the extent of the trade-off has not been quantified.

Acknowledgment

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Technical issues on management of seasonal floodplains under community-based fish culture in Bangladesh

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Abstract

The Indo-Gangetic Basin of Bangladesh has large numbers of seasonal floodplains that offer great potential for promotion of fish culture to benefit the poor. Since 2006 studies carried out under the WorldFish Center managed Community-Based Fish Culture project, in collaboration with the Department of Fisheries (DoF) and Bangladesh Agricultural Research Council (BARC), looked at the technical aspects of management of seasonal floodplains in Bangladesh. Three floodplains located at three different regions of the country, were selected for fish culture. The floodplains hold water for 6-7 months and cover an area of 30-40 ha during monsoon. Suitable technical aspects for the purpose of holding water and fish by management of inlets and outlets of the floodplains were studied. In addition to existing structures, these inlets and outlets were largely managed by setting locally available low-cost bamboo fencing. The mesh size of bamboo fencing allowed the entrance of nonstocked small indigenous fish in the floodplains from outside sources. Fish fingerling stocking strategies varied, depending on availability, size, and the performance of fish species stocked in the floodplains. The technical measures resulted in production of 441 kg/ha (291 kg stocked and 150 kg nonstocked) fish, generating a net income of Bangladeshi Taka (BDT) 15,000/ha (US\$220/ha) and 50 person-days/ha employment for poor fishers. The poor people in surrounding areas of the floodplains using local gear harvested at least 10% of the nonstocked fish for sale and for household consumption.

Media grab

Fish culture in seasonal floodplains in Bangladesh benefits the rural poor.

Introduction

Bangladesh has rich freshwater resources, and a huge potential for fisheries development. There are 4.58 million ha of inland waters, 62% of which are floodplains (FRSS, 2007). During monsoon almost half of country is inundated, and these areas are reported as floodplains. In years during which the water in the floodplains lasts for several months, a large proportion of the land is unavailable for crop production (Ahmed, 2005; DoF, 2005). If properly managed, these water resources can play a pivotal role in boosting fish production, generating income, and creating employment opportunities. Culture of fish in the seasonal floodplains can be an important tool for strengthening the rural economy of the country (Rahman et al., 1999; Dey and Prein, 2006). Floodplains were the major sources of natural fish production in the past, but present fish yields are declining. Typical capture fish yield usually ranges from 150 to 350 kg/ha (WorldFish, 2007). Recent studies indicate that there are good prospects for enhancement of fish production in the floodplains through improved management. There are opportunities to use floodplains for fish culture by providing enclosures in parts of this floodwater, and stocking fingerlings in addition to the nonstocked fish. Fish culture in seasonal floodplains, by stocking of fingerlings and application of feeds and fertilizers on a regular basis, has been established in the central part of Bangladesh. In Daudkandi, Comilla district, increases in fish production and income earnings have been achieved. These activities, however, were not community-based and were largely implemented by a company that sold shares to the beneficiaries.

Our study is based upon earlier research carried out under community-based fish culture in seasonal floodplains in a limited scale in Bangladesh and Vietnam, which showed increased production and income earnings (Dey et al., 2005). The studies showed that although there were positive outcomes, benefits but it may vary from country to country and between locations within the same country. Further studies have been carried out on technical issues to develop appropriate technical options for the promotion of fish culture in seasonal floodplains to benefit primarily the poor.

Methods

Selection of study areas, beneficiaries, and institutions

This study was conducted in three seasonal floodplains located in the northwest and northern part of Bangladesh in three large river basins: Padma, Teesta, and Brahmaputra (Table 1). The floodplains varied in size, ownership arrangements, and physical setup. Other variables included the number of users/beneficiaries and differences in existing institutional setup (Table 2). The floodplains were selected for implementation of fish culture under a CGIAR-supported Challenge Program on Water and Food collaborative action research project of the Bangladesh Agricultural Research Council (BARC), Department of Fisheries (DoF), and the WorldFish Center.

The beneficiaries consisted of landowners, fishers, and landless people but their proportions differ across the floodplains. In the 'Beel Mail' floodplain fishers dominated as beneficiaries. They are legal leaseholders of the government Khas lands. In the two other floodplains of 'Kalmina Beel' and 'Angrar Beel' private landowners dominated as beneficiaries. An important outcome is that community-based fish culture in seasonal floodplains also benefits stakeholders without land ownership.

Table 1. Descriptions of the floodplains of different river basins located in different areas of Bangladesh.

Floodplains	Area (ha)	Ownership	River basin	Project intervention (year)
Beel Mail, Mohanpur, Rajshahi	40 (public 15.2 ha, private 24.8 ha)	Public and private	Padma	2006, 2007
Kalmina Beel, Fulbaria, Mymensingh	33	Private	Brahamaputra	2007
Angrar Beel, Pirganj, Rangpur	31	Private	Teesta	2007

Table 2. Number of beneficiaries selected in three floodplains under the study (figure in parentheses are percentages).

Floodplain/ownership	Area (ha)	Number of villages	Number of beneficiaries			
			Landless	Fishers	Landowner	Total
Beel Mail	40	5	22 (18)	68 (55)	34 (27)	124
Kalmina Beel	33	1	52 (29)	25 (14)	97 (57)	174
Angrar Beel	31	5	38 (22)	23 (13)	110 (65)	171
Total	104	11	112 (24)	116 (25)	241 (51)	469

The beneficiaries of the floodplains were actively involved in planning, implementation, stocking of fingerling, monitoring, fish harvesting, marketing, and profit-sharing activities. The institutions involved in implementation of activities of floodplain aquaculture were: the local fishers society, the floodplain management committee (FMC), and the project implementation committee (PIC). The Department of Fisheries at the local and central level, Bangladesh Agricultural Research Council, and the WorldFish Center provided necessary support.

Technological interventions

Technological interventions included: (1) Management of the water inlets and outlets and the embankments of the floodplains by constructing bamboo fences at inlets and outlets and raising of the dykes. This varied largely by floodplain; (2) Maintenance of water levels and area coverage appropriate for fish culture in the floodplains, affecting the outcomes; (3) Manipulation of species combinations, ratios, and stocking densities of fish fingerlings. These also differed between floodplains and were based on local level information sharing and empirical knowledge about the performance of various fish species; and (4) Harvesting of stocked and nonstocked fish from the floodplains for sale and for household consumption.

Records of fingerling stocked were taken on a sample basis. The individual length of fish species stocked was measured and the average weight was recorded by taking a bulk sample of 1 kg, divided by the total number of fingerlings in the sample. The same was done at harvest. The harvesting of fish was started after 4 months of stocking and continued up to 6 months after stocking. In some cases fish were harvested over a 2-3-month period as decided by the beneficiaries. At harvesting time, length (cm) and weight (g) of each fish were recorded. Numbers per species in the harvest were counted. Production and sale records were maintained.

Results and discussion

Management of waters by fencing

The three floodplains brought under community-based fish culture differed largely with respect to their physical features. This resulted in differences in management of the water structures. Bamboo fencing was used in all the floodplains as measures to confine the fish while allowing the water to pass and maintain appropriate levels. In Beel Mail and Angrar Beel more investment was required to protect fencing or dykes compared to Kalmina Beel, where minimal use of bamboo fencing was required. An important advantage of the bamboo fencing used was that it allowed the small indigenous species of fish to enter into the floodplains, while preventing the stocked fingerlings from escaping. The investment is lower compared to building a solid structure, and the fencing can be used for two seasons with minimal repair. The cost of fencing ranges from 7-15% of total investment costs for floodplain aquaculture.

Fingerling stocking strategies

In 2007 community-based fish culture was started in the three floodplains. Fingerlings of different species of fish, largely from local sources, were stocked in all three floodplains during June-July. The stocking density was: 41 kg/ha, 31 kg/ha, and 42 kg/ha for Beel Mail, Kalmina Beel, and Angrar Beel floodplain, respectively (Table 3).

Table 3. Different species of fingerlings stocked in the floodplains under the project intervention in 2007

	Area (ha)	Fingerlings stocked (kg)						Total
		Silver carp	Catla	Bighead	Rohu	Mrigal	Common carp	
Beel Mail	40	100	82	1099	50	50	251	1632
Kalmina Beel	33	212	267	-	20	30	497	1026
Angrar Beel	31	430	133	235	188	-	316	1302
Total	104	742	482	1334	258	80	1064	3960

The fingerlings stocked in 2007 were large (mean of total length $14\pm 2 - 22\pm 2$ cm for Beel Mail; $16\pm 1.5 - 18\pm 1.5$ cm for Kalmina Beel; and $16\pm 1.5 - 18\pm 1.8$ cm for Angrar Beel). In Kalmina Beel and Angrar Beel, fingerlings were stocked for the first time in 2007 under project intervention. In Beel Mail floodplain, however, the fingerling stocking was started in 2005 by the initiative of the beneficiaries. In 2006 Beel Mail was stocked as part of the project intervention (Table 4).

Table 4. Description of fish fingerlings stocking in Beel Mail floodplain in the first year of intervention in 2006 (US\$ = 69.8 BDT).

Species	Mean length (cm)	Mean weight (g)	Total weight (kg)	Total number	Rate (BDT/kg)	Total cost (BDT)
Catla	16	64	556	8688	110	61160
Bighead	15	38	1557	40973	70	108990
Ruhu	12	46	509	11065	100	50900
Mrigal	12	42	308	7333	90	27720
Common carp	12	35	553	15800	100	55300
Total			3483	83859		304070

Fish harvests and production

The comparative analysis of the fish production of the three floodplains brought under fish culture in 2007 showed significant variations in terms of production of fish (for stocked and nonstocked fish). Beel Mail floodplains showed the highest level of production of 625 kg/ha (total production 24,989 kg); for Kalmina Beel and Angrar Beel the corresponding production levels were 196 kg/ha (total 6469 kg), and 215 kg/ha (total 6663 kg), respectively. Compared to the year before project intervention, fish production in Beel Mail (282 kg/ha), Kalmina (46 kg/ha), and Angrar Beel (43 kg/ha) increased significantly (Table 5).

Table 5. Production of stocked and nonstocked fish from the floodplains under the studies in 2007 (the figures in parentheses are the yield in kg per ha).

Floodplain	Area (ha)	Total stocked fish (kg)	Nonstocked fish (kg)	Total (kg)
Beel Mail	40	13174 (329)	11815 (295)	24989 (625)
Kalmina Beel	33	4943 (150)	1526 (46)	6469 (196)
Angrar Beel	31	5345 (172)	1318 (43)	6663 (215)
Total	104	23462 (226)	14659 (141)	38121 (367)

In Beel Mail the production of fish in 2006 and 2007 was similar: in 2006, 25,429 kg (stocked 18,446 and nonstocked 6983 kg), and in 2007 24,989 kg (stocked 13,174 kg and nonstocked 11,815, kg). The production of stocked fish was significantly lower in 2007, and the production of nonstocked fish was significantly higher. This variation was largely related to the lower amount of fingerlings stocked in 2007 compared to the previous year. In 2007 the floodplains flooded twice. This may have resulted in the loss of some of the stocked fish, while facilitating the entrance and production of nonstocked fish. The results showed that flooding did not hamper production and income-earning from the floodplains brought under community-based systems. Measures were also taken not to harvest fish by using large net gear for a certain period of time during the flooding.

This encourages the nonstocked fish to enter the floodplains from the nearby water bodies. The presence of a connecting channel between Beel Mail floodplains and the nearby river, where sanctuaries are established, also facilitates the entrance of nonstocked fish into the floodplains during the period of flooding. The production of fish in Beel Mail after intervention of the project (2006 and 2007) was significantly higher than the year before the project intervention, even though the Beel was brought under fish culture under the community's own initiative. The production of fish in Beel Mail in 2005 was 11,285 kg (stocked 4273 kg and nonstocked 7012 kg). The outcomes showed that the implementation of the technical strategies is helpful in increasing fish production in the floodplains under the community-based approach. In floodplain aquaculture the exotic species of fish showed the highest contribution in total fish production. Of the exotic fish species stocked the contribution of bighead carp (32%) was the highest, followed by common carp (27%), and silver carp (17%). Among the native fish species catla showed a modest contribution (18%) and the contribution of the other two native species, rohu (4%) and

mrigal (2%), was the lowest. The fixed costs (bana fencing, boat, dyke repairing, pump) of aquaculture in the floodplains varied from BDT1212 to BDT3584/ha. The variable cost (lease money, fingerling, guarding) for the floodplains varied from BDT3675 to BDT999/ha.

The gross income from production from the floodplains was BDT10,742 to BDT28,543/ha with a net income of BDT5226 to BDT16,314/ha. The benefit cost ratio (BCR) for Beel Mail was 2.65, Kalmina Beel 2.78, and Angraer Beel 1.71. Fish culture in all the seasonal floodplains is profitable under the present set of management arrangements. The mean fish production as achieved from the floodplains under the project is higher than the national average of 254 kg/ha from the floodplains (FRSS, 2007). This is largely due to the implications of community-based management practices including technical interventions of fish culture in the floodplains.

Among the various factors that influence the wetland ecosystem are depth, coverage of catchment, area or river basin, precipitation, and duration of connection to the river. Macrophyte plant material as well as paddy straw residue settles at the bottom of the Beel upon decay and decomposition, resulting in a huge amount of organic detritus that forms a substrate for heterotrophic bacteria and fungi. Under such circumstances detritivorous fish flourish and contribute to the fishery yield. Detritivorous fishes like bighead carp and common carp are well recognized as fast-growing species (Jhingran, 1983). Silver carp benefits from primary production resulting from inorganic and organic nutrient enrichment from bioturbation and browsing activities of the detritivorous fishes. The results of the present investigation indicate that among the species stocked, bighead carp, common carp, silver carp, and catla had higher growth rates than other species. The higher growth rate and production of these species are likely due to adequate availability of natural feeds available in the floodplains.

Conclusions and recommendations

Technical interventions for fish culture in seasonal floodplains lead to significant improvement in the production of stocked and nonstocked fish. The productivity of stocked fish and nonstocked fish is affected by flooding. The connection of floodplains to rivers and other perennial sources of water results in a significant increase in the production of nonstocked fish at the time of flooding. The stocking of the exotic species (bighead, common carp, and silver carp) showed better performance in production compared to the native species (catla, rohu, and mrigal), without hampering the production of the nonstocked fish. The use of bamboo fencing is effective in creating enclosures for culture. Mesh in the bamboo fencing allows water to pass through and provides entry of nonstocked small fish into the floodplains.

Acknowledgments

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Tools for understanding collective action around water management

Agent-based modeling and simulation of integrated rice-shrimp farming in Bac Lieu Province, Mekong Delta, Vietnam

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Abstract

Shrimp aquaculture is economically profitable to coastal people in the Mekong Delta, Vietnam. Nevertheless, conflicts are arising between shrimp and rice farmers from environmental and socioeconomic impacts of shrimp aquaculture. For example, shrimp farming encroaches upon land previously devoted to rice cultivation. This study aims at integrating and sharing knowledge about the rice-shrimp farming system in Bac Lieu Province. Companion modeling (ComMod) was used to involve stakeholders in the construction of a simulation model and discuss its outputs. The first stage of the modeling process consisted of a role-playing game (RPG) in which farmers from two villages in the province recreated their farming decisions. The process revealed diverse water and land-use strategies. In the second stage, agent-based modeling (ABM) used a subset of individual farming decisions to parameterize a generic model of integrated rice-shrimp farming. The initial ABM scenario spatially generated production areas and water salinity patterns similar to the ones used during the RPG sessions. This similarity is expected to convince farmers of the accuracy and value the ABM analysis, and help create continued interest when requested to 'validate' it by providing user feedback on its features and rules. Additional scenarios based on different sluice operators decisions, risk, and economic conditions were collectively simulated and assessed.

Media grab

Farmers and scientists can use ABM to understand better the complexity of rice and shrimp production systems, and accelerate the collective improvements in their design and management.

Introduction

Asian and Pacific region shrimp aquaculture contributes about 87.4% of cultured penaeid shrimp to the global market (FAO, 2004). During the past decade, coastal zones of several Asian countries have experienced significant conversions from rice to shrimp farms, including the Mekong Delta in Vietnam. As a consequence, traditional rice-farming area in this delta decreased from 757,300 ha in 1995 to 363,400 ha in 2006, whereas shrimp farming area increased from 289,400 ha to 699,200 ha in the same period (GSO, 2006).

Bac Lieu Province has experienced similar land conversion pressures. Rice and shrimp are concurrently produced as main sources of local people's income generation (Hoanh et al., 2003). The degree of integration between rice and shrimp farming relies on farmer decisions based on interactions among biophysical and socioeconomic factors. These interactions are often complex and difficult to understand.

The research objectives are: (1) to understand better the land-use decisions based on interactions among water quality, risk perception, and market price factors; (2) to provide a research process for analyzing decision-making in land-use that can be used for modeling and policy analysis. A participatory modeling approach (ComMod) (Bousquet and Trebil, 2005) is applied. In the ComMod approach, all key stakeholders who are directly or indirectly using common resources are involved in the research process through participating in the RPG. Participants contribute to the collective design of the model and discuss scenarios for exploring the use of common resources and associated environmental and economic impacts. ABM helps to analyze the interactions among numerous biophysical and socioeconomic factors that affect land-use decisions. Moreover, the research process helps support all stakeholders to share experiences in land-use decisions and strengthen the adaptive management capacity of local communities.

Model description

A conceptual model was collectively built based on available knowledge learnt from previous studies on land-use changes in Bac Lieu Province, and a series of RPGs conducted in 2006 and 2007 (Dung et al., 2007). The ABM was developed using the Common-pool Resource and Multi-Agent System (CORMAS) platform (Le Page et al., 2000) as presented in the following sections.

Spatial-temporal setting

The model is to involve households that are representative of farmers in the province. These include 5 households in upstream and 8 households in downstream villages. Household size varies from 4 to 7 members, and the farm plots range from 1-4 ha. Diversed patterns of rice-shrimp integrated and rice-shrimp integrated combined with fish and crab, are main farming systems in the study site. These elements are created as spatial settings in the model.

Spatial setting is made up of aggregated cells that represent different types of land-uses as rice-shrimp plots, farm composing of plots, and canal at the two villages (Figure 1). Cell is the smallest unit that equals 0.5 ha. A number of cells are aggregated into a plot. A farm comprises of one to eight cells and covers from 0.5 to 4 ha of land. The weekly time step is applied in this study, and the simulation period can be run from 1 to 5 years. Each year is from 1 January to 31 December.

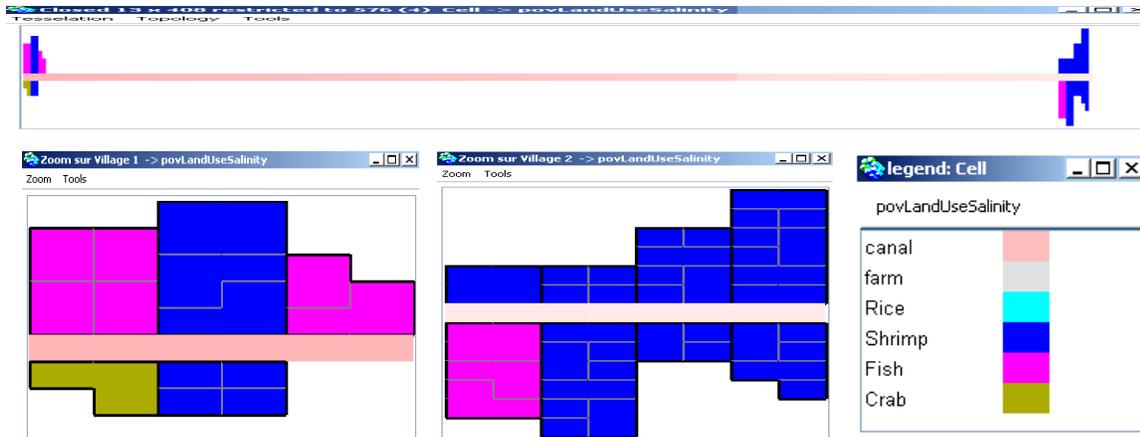


Figure 1. Spatial setting represents different land-use types at two villages, downstream (left), and upstream (right) in the study area.

Overview of model structure

Three components of the model, the water, production, and social modules, and their relationships are presented in a class diagram using unified modeling language (UML) (Wuyts, 2004/2005) (Figure 2). The water module is the core component of the model since it links the farm activities that are managed by the household in the social module with the plot that is occupied by the crop in the production module.

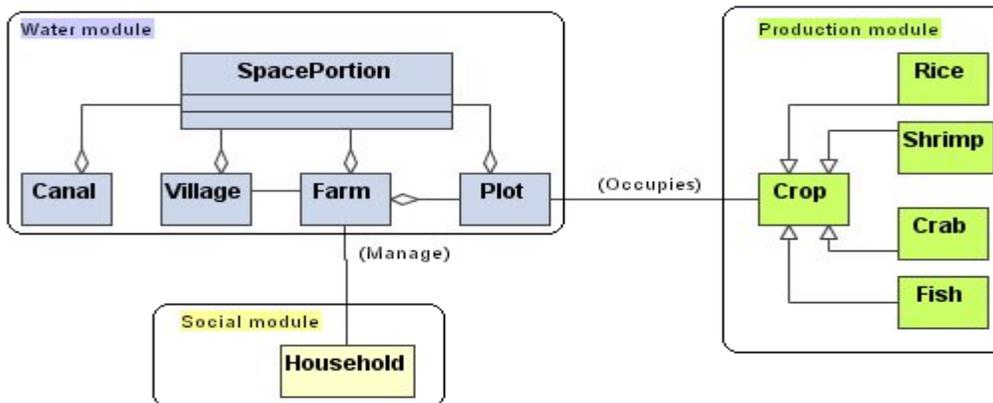


Figure 2. Class diagram of model's structure in UML.

Water module

Water is a key factor to provide salinity seasonally for rice and other aquatic species to be grown in the farms. It is built into a separate module in which a super class entitled SpacePortion aggregates four classes of canal, village, farm, and plot. The functions of these classes are:

- Canal: carry water for rice crop and other aquatic species' requirements. An important attribute of the canal is the state (opened or closed) of sluice connected to the canal that controls the salinity in the farm.
- Village: contain the farm and the canal, two main spatial entities of the model.
- Plot: where rice and other aquatic species are cultivated.
- Farm: aggregated by plots, the farm can be considered as a core class where the crops in the production module are produced and the household in the social module can implement its management strategy.

Production module

The production module is composed of four classes: shrimp, rice, fish, and crab. These are the products for income generation. Their key attributes and operation method are briefly described as follows:

- Shrimp: the highest value product. Its main attributes are shrimp stock, risk of shrimp disease, harvesting time, harvesting method (partial or full harvest). Shrimp attributes are affected by water quality regarding timing and degree of salinity.
- Rice: the second product in terms of importance in the study area. Its main attributes are growing duration and yield response to degree of salinization of the soil where saline water has been kept in the dry season for shrimp culture.
- Fish: can be combined into shrimp or rice crops as an additional income source. Its main attributes are fish stock and weight of individuals to be harvested. It can be stocked with a wide range of salinity levels, either in dry or rainy seasons.
- Crab: crab can be combined into shrimp crop in brackish or fresh water. Crab is more preferred for raising in the downstream village of Phong Thanh. Similar to fish, its main attributes are crab stock and weight of individuals to be harvested.

Social module

The module is composed of one single class of household, an active agent that would have a number of attributes and do several operation methods. Its main attributes are village code, farm size, income, and cost for production. Other attributes to present inputs of labor and fertilizer in rice and shrimp production can be temporarily ignored due to its minor contributions in decision-making regarding salinity change in the model. Three key operation methods of the farm are to initiate household income status, to produce crops, and to harvest products.

Sequence of activities

At present the model simply includes only one active agent (the household) that can make decisions on crop production, but more active agents as sluice operator, middleperson to buy products will be added. The sequence of activities performed in the model are as follows:

- Setting salinity of water in the canal: monthly salinity is dependent on the sluice operation. In the model there are three patterns of salinity variations corresponding to three sluice operation schedules selected by the sluice operator and villagers living in the two villages (Figure 3).

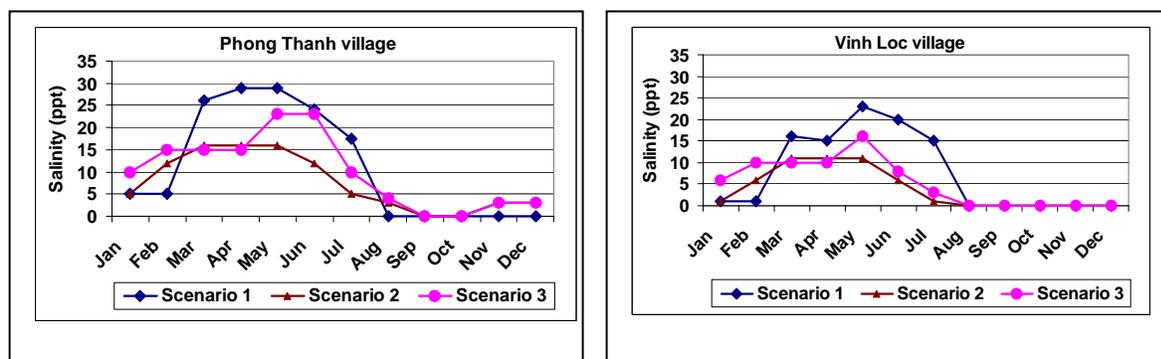


Figure 3. Saline water schemes by scenarios of three different sluice operators.

Producing crops: four major products and their timing are presented in the followings:

- Shrimp is the first crop started at the beginning of the year. Whenever salinity is higher than 5 ppt, usually in November in the previous year, shrimp seed can be stocked. Since intensive shrimp farming with high inputs is not sustainable, hence not encouraged, extensive or improved extensive shrimp farming with maximum density of 4 seeds/m² is practiced.
- Crab is the second crop started in a year, but only at Phong Thanh village near the sluice, because salinity of at least 5 ppt from 4-6 months is needed for crab growth.
- Fish is the third crop to be considered in a year. Fish can be grown in low salinity or in fresh water conditions, which is available mostly from June to December in both Phong Thanh and Vinh Loc villages.

- Rice crop is started after September when salinity is lower than 4 ppt. Rice is produced in the entire upstream village (Vinh Loc), whereas it is seldom practiced in the downstream village (Phong Thanh).

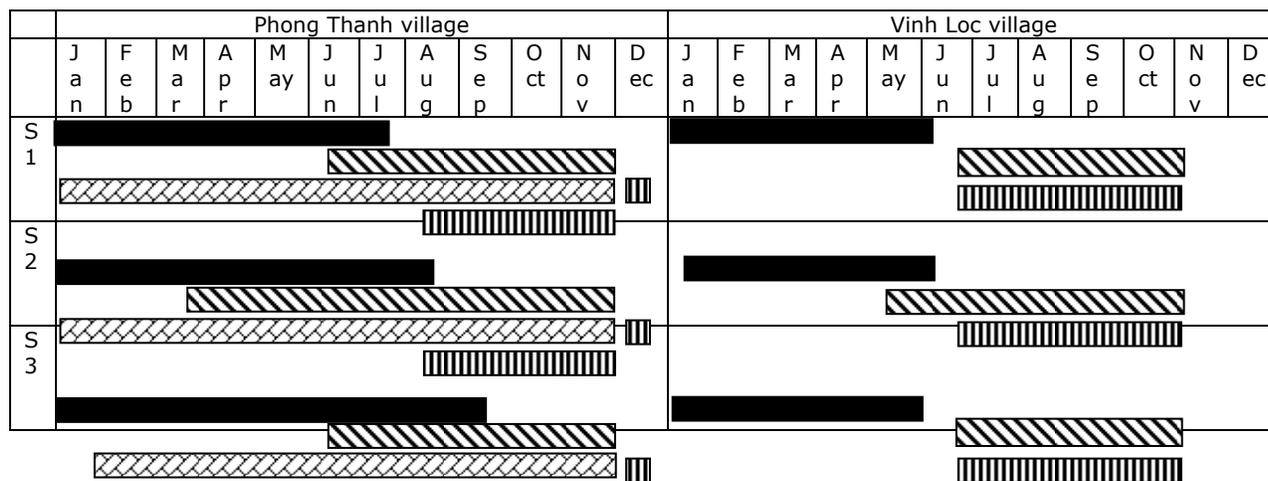


Figure 4. Farming calendar in two villages under different scenarios.

Module	Attributes	Unit	Value	Unit	Source
Spatial	Salinity		0 - 29	ppt	CPWF PN#10
	Area	Farm size of a household	0.5 - 4	ha	Gallop et al., 2003
Production	Stock amount	Shrimp density	10,000 - 40,000	Seeds /ha	Interview with farmers (2006)
		Crab density	200 - 1,000	Seeds /ha	
	Risk	Shrimp dead due to disease	30 - 80	%	Key Informant Interview (2006)
		Survival rate	Rate of shrimp survived	65 - 72	
		Rate of crab survived	50 - 80	%	
	Weight	Weight of harvested shrimp	0.022 - 0.067	Kg	Interview with farmers (2007)
		Weight of harvested crab	0.3 - 0.5	Kg	
	Yield	Rice yield/ha	3,000 - 5,500	Kg	
Fish yield/ha		500 - 1,000	Kg		
Price	Market price of shrimp	50,000 - 120,000	VND/kg	http://www.vneconomy.vn (26/09/2006)	
	Market price of rice	2,250 - 3,500	VND/kg	http://www.vneconomy.vn (17/11/2006)	
	Market price of fish	4,000 - 6,000	VND/kg	Interview with farmers (2007)	
	Market price of crab	120,000 - 200,000	VND/kg	Interview with farmers (2007)	

Note: US\$1 is approximately equivalent to 16,000 VN (2008).

Harvesting crops:

- Shrimp can be harvested after 14 weeks from stocking date. Shrimp survival rate ranges from 65 to 72% of initial population at harvesting time. There is a risk of 30 to 80% of shrimp dying due to disease. There are two harvesting methods: (1) full harvesting (all shrimp are harvested at one time), and (2) partial harvesting (only big shrimp are harvested). The full harvesting is applied by 20% of households. Shrimp is a most valuable product in the study area with the price ranging from 50,000 to 120,000 VND/kg.
- Crab can be harvested after 4-6 months from stocking date. Survival rate of crab is high, from 50 to 80% of initial population. Depending on harvesting time, farmers can sell crab at a price of 200,000 VND/kg.
- Fish crop can last from 18 to 22 weeks. Risk due to disease is minor. Fish yield can be varied from 500 to 1,000 kg/ha, but price is not high, from 4,000 to 6,000 VND/kg. So, fish is a popular crop to provide additional income to other crops.
- Rice in Phong Thanh is harvested in December, 3.5 months after sowing. However, in Vinh Loc rice can be harvested later, up to January. Market price of rice is relatively stable, from 3,000 to 5,500 VND/kg, depending on variety and quality.

The model has been collectively built based on available knowledge collected from secondary data, group meetings with local stakeholders, and RPGs with farmers. At each time step land-use change in each farm is displayed in the spatial interface (Figure 1). These changes are consistent with results of land-use patterns under the two scenarios of early and late salinity intake into the system selected by players at the RPGs in 2006 and 2007. At present more technical parameters such as production cost, price of product return, and risk of shrimp disease, and new operation methods attributed to the new active agents (sluice operator, middleperson or intermediary) are included in the model. These will be tested for analyzing more complex land-use decisions under various scenarios, such as variation in prices of products and of inputs for production.

Conclusions

This ABM prototype can display the spatial settings and present the impacts on production due to changes in water salinity, similar to what farmers were practicing during the RPG sessions. Various scenarios based on different sluice operations, risk perception, and economic conditions could be collectively simulated and assessed by stakeholders. More active agents will be added to reflect the complexity in land-use decisions in selecting production systems at two extremes of the canal with different salinity conditions.

ACKNOWLEDGMENTS

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Agent-based modeling of the interaction between water and labor availability in the rainfed rice ecosystem of northeast Thailand

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Abstract

An Agent-Based Model (ABM) was co-constructed with local rice farmers to represent the human-environment interactions between land/water use and labor management. A rainfed area located South of Ubon Ratchathani Province in lower northeast Thailand was the study site. This ABM evolved along a Companion Modeling (ComMod) process to integrate the research team's scientific point of view with the local farmers' desired development outcomes. The model consists of four interacting components: climate, hydrology, household, and rice. The 'household' module is a rule-based agent that makes daily decisions on the different stages of rice production depending on water and labor availability. Four main rice decision-making processes are modeled: (1) nursery establishment, (2) transplanting, (3) harvesting, and (4) postharvest decisions including labor migration. The toposequence of lower to upper paddies and types of land-use (water bodies, human settlement, paddy fields) are defined in the spatial settings. The paper describes the structure of key decision-making algorithms implemented in this ABM. The participatory use of this model to facilitate the discovery and assessment of different water and labor availability scenarios is also explained. The impact of different scenarios on farming practices and labor management is also analyzed and discussed.

Media grab

An agent-based model was co-constructed with rice farmers to integrate indigenous and academic knowledge into a shared representation of the interaction between water and labor availability in northeast Thailand.

Introduction

The northeast region of Thailand is known as the poorest in the country. Most of its inhabitants are resource-poor workers in the agricultural sector (NSO, 2007). Rice is extensively grown in rainfed lowland areas but productivity is low because of erratic rainfall distribution and coarse-textured infertile soils. To escape from poverty, many 20-35-year-old-northeast farmers out-migrate to urban areas searching for more profitable employment in the industrial and service sectors. Northeast Thailand has the largest percentage of out-migration—more than a third of all interregional migration originated from this region (Santiphop, 2000). Therefore, labor migration is a key adaptive strategy adopted by poor farmers to cope with severe agro-ecological constraints. An improved understanding of the interaction between land and water use and labor migration is urgently needed as the construction of major new water infrastructures in this region is under study.

Toward this goal, in this study researchers and farmers worked together in a ComMod process to co-design and construct an ABM (Bousquet and Trébuil, 2005) based on a shared representation of the rice ecosystem and farmers' decision-making processes. ABM is a tool for the analysis of a complex system, in which the human decision-making process is an integral part (Gilbert, 2008). This co-designed ABM is used with local farmers to simulate and explore the outcomes of land, water, and labor use scenarios.

The study site is located in Det Udom district, the largest district of Ubon Ratchathani Province covering around 1400 km² with moderate population density of 119 persons/km. Twenty-two farmers from Ban Mak Mai village in this district participated in the modeling process. The village is a typical rainfed lowland rice-producing area of lower northeast Thailand, with a comparably high average annual rainfall of 1600 mm, but unpredictable distribution. Farming households are diverse with different living conditions ranging from very small at an average of 3.2 ha to large farm holders averaging 6.4 ha (Naivinit et al., 2007). This social differentiation among rice farmers needs to be represented in the model. This paper describes the Ban Mak Mai (BMM) model (BMM after the name of the village where we conducted this study), its spatial, temporal, social settings, and three key interacting modules, as well as the sequence of farm and non-farm activities operating in the model within a crop year. Later, the results of the model validation and the identification of scenarios with local farmers are discussed.

Methods

The BMM model is spatial-explicit, composed of three interacting modules situated and operated in a defined spatial interface representing rice farming under rainfed conditions. The BMM model is also a discrete event-driven model with heterogeneous agents differently reacting to the consequence of interactions between modules.

Spatial and temporal settings

The BMM model spatial configuration has field, farm, and community levels representing three land-use types: paddy fields, water bodies such as farm ponds and streams, and human settlements including houses, villages, and roads (Figure 1). The smallest spatial unit, or cell, is equal to 0.04 ha (1 ngan in Thai area unit). Elevation ranges from 97 to 133 m to represent upper and lower paddies. The sandy Korat soil series typically found in this area

(Aumsamut and Boonsomphonphan, 1999) is applied to each cell. A paddy field is an aggregation of cells, and a farm is an aggregation of paddy fields. To represent the heterogeneity of farm size and water availability, two small farms (3.3 ha) and two large farms (6.5 ha) with different farm pond sizes were created. A simulated crop year starts at the end of the dry season on April 1. A daily time step is used to model farmers' rice production management decisions. The BMM model is designed to run up to 10-year-long simulations.

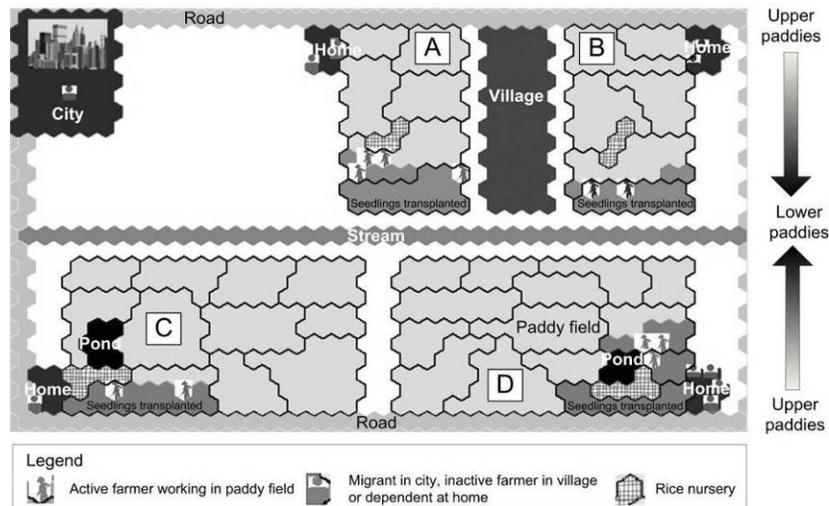


Figure 1. Spatial configuration of the BMM model representing two small farms (A and B) and two large farms (C and D) during rice transplanting.

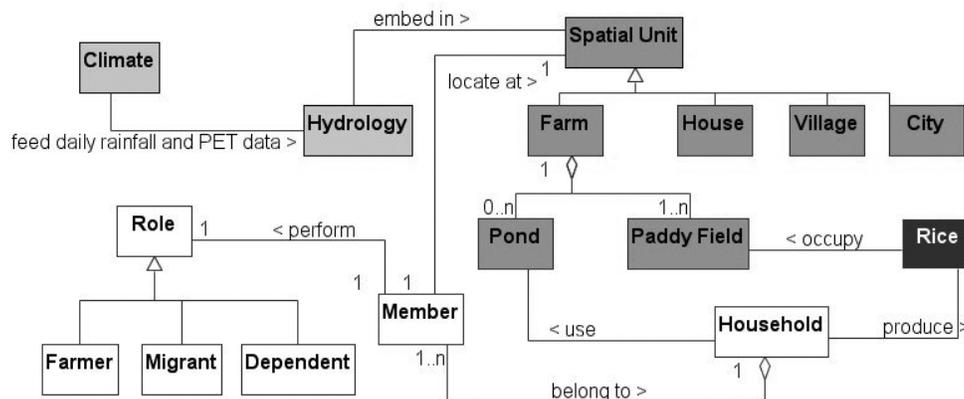


Figure 2. The BMM conceptual model in a UML class diagram representing key entities and their relationships.

Overview of the model structure

The BMM model structure consists of three key interacting hydroclimatic (hydrology and climate), rice and household modules (Figure 2).

Hydroclimatic module

This module is embedded in the spatial units to calculate water availability. Four virtual hydrological tanks for ponding, root zone, subsoil, and water storage are superimposed vertically depending on land-use type. For instance, a paddy field is composed of a ponding tank on the top, a root zone tank in the middle and a subsoil tank at the bottom, while a single water storage tank corresponds to a pond. Data on daily rainfall and potential evapotranspiration from the regional meteorological center located in Ubon Ratchathani Province are used and 10 years of different actual climatic years are used in simulation runs. The hydrological processes depending on daily rainfall patterns previously developed to simulate the availability of water in paddy fields and ponds were integrated in the BMM model (Lacombe and Naivinit, 2005).

Rice module

This module provides information to the household regarding the rice growth stage at any given time. Information from this module prompts the household to make corresponding actions relevant to the current rice growth stage. The climatic conditions (wet or dry spells), however, also determine whether such actions are possible or not.

Household module

This module integrates three social levels: individual member, household, and village. It has six interacting entities: household, member, role, farmer, migrant, and dependent (Figure 2). A household is a group of members whose roles can change over time, depending on the activity at a given moment. The member is in charge of migration decisions, thus the location of a member determines his/her role. For instance, in a city the member is in a migrant; in a paddy field he/she is a farmer. Two types of farmers are identified. One is an active farmer working in paddy fields, while the other is an inactive farmer in the village waiting for employment (Figure 1). To integrate diverse farming households into the BMM model, households were created with different size, assets, and number of workers. Small farming households A and B have six members, but household A has three laborers and three dependents while household B has four laborers and two dependents. Meanwhile, large farming households C and D have two laborers and one dependent, and three laborers and four dependents, respectively (Figure 1).

Sequence of key activities throughout a crop year

The household performs a sequence of farming activities driven by interactions between changing climatic conditions and rice-growing stages, except for the migration decision which is individually controlled by a member. The key successive activities are as follows: nursery establishment, transplanting, harvesting, postharvest phase, and labor migration.

Nursery establishment

Water availability provided by the hydroclimatic module triggers this activity. This depends on the farm pond's water volume or the rainfall threshold to establish nurseries (Table 1). Water is pumped from a pond by a farmer agent during this period if there are 12 successive days without daily rainfall higher than 20 mm in order to alleviate water stress (Table 1). Rice seedlings belonging to farmer agent without possession of ponds or with inadequate water in ponds can be damaged by a long water-stress period. The rice module is responsible for the growth of rice seedlings, which are ready for transplanting once the seedlings are 30 days old.

Transplanting

All households wait for a daily rainfall higher than the threshold to start transplanting (Table 1). Once transplanting starts, all members with seasonal migrant role return home to help household workers. When a household cannot complete transplanting on their own in the specified period, additional laborers are hired. Water in farm ponds is not used for this activity.

Table 1. Default values, units and sources of key parameters for each module of the BMM model.

Module	Parameter	Default value	Unit	Source	
	Water quantity need to supply a 0.04 ha nursery	40	m ³	RPG 2	
	Percent of minimum water level needed to be kept in pond to the depth of pond	10	%	RPG 1	
	Maximum age for villagers to migrate	45	year old	PS2	
	Average annual household net income	20,000	baht	NSO, 2007	
	Average farm input cost excluding labor cost	3,750	baht/ha	OAE, 2005	
	Amount of paddy needed for self consumption	350	kg/person/year	Farm survey, 2004	
	Price of high quality paddy	18	baht/kg	Thai Rice Mills Association, 2008	
	Price of fair quality paddy	12	baht/kg		
	Price of poor quality paddy	9	baht/kg		
	Wage offer during transplanting period	120	baht/person/day	PS2	
	Wage offer during harvesting period	150	baht/person/day		
	Hydroclimatic	Rainfall threshold to establish nurseries	30	mm/day	RPG 2
		Rainfall threshold to start transplanting	20	mm/day	
		Rainfall threshold to harvest	10	mm/day	
	Rice	Rainfall threshold for seedlings related to water stress	20	mm/day	PS1
Period duration for seedlings related to water stress		12	days		
Maximum paddy yield		2,250	kg/ha	RPG 1	
Minimum paddy yield		938	kg/ha		
Duration needed for rice seedlings to be mature		30	day	PS1	
Duration needed to complete transplanting after rice seedlings are 30 days old		21	day		
Limited date to establish nurseries		115 (3 rd week of July)	day		
Limited date for transplanting activity		168 (2 nd week of September)	day		
Limited days for harvesting high quality paddy		10	day		
Date to harvest early maturing rice		224 (10 th November)	day	Bureau of Rice Research and Development, 1999	
Date to harvest late maturing rice	235 (21 st November)	day			

Notes: RPG1: Role-Playing Game Session on 9-10 July 2005
RPG2: Role-Playing Game Session on 10-11 October 2006

PS1: Participatory Simulation on 5-6 February 2008
PS2: Participatory Simulation on 19-20 March 2008

Harvesting

Two harvesting dates are used for early- and late-maturing rice varieties (Table 1). Households start to harvest rice on the harvesting date defined in the Rice module in relation to 'rainfall threshold to harvest' in the Hydroclimatic module. The availability of enough laborers is critical because a fast harvest yields a higher quality paddy to be sold at a higher market price (Table 1). This algorithm states that all farms get high quality paddy before December 1, or fair quality paddy until December 9. After December 10, additional laborers are no longer needed to secure a high quality product.

Postharvest phase and labor migration

Once rice production activities are completed, households compute their net incomes. Sources of income are rice sales, wages, and remittances. Expenses are farm inputs, cost of hired labor, and other household expenses. Afterwards, the demographic characteristics of member entities, which are important to determine potential migrants and migration patterns, are updated. The criteria to become a potential migrant are based on the combination of two factors—the member's demographic characteristics; and the social and economic status of its

household (De Jong, 1997). Meanwhile, two kinds of migration are taken into account. A seasonal migrant always returns home to help in rice production, while the more-permanent migrant is removed from the list of family laborers. At the end of the activity, members can decide to move to the city or stay in the village over the dry season.

Results and discussion

The BMM model was used with farmers in two steps. Scenarios to simulate were first identified with them before their participation in the assessment of their simulations. During a participatory workshop through a simulation of baseline scenario defined as mentioned in spatial and temporal setting and household characteristics, scenarios regarding water and labor availability were collectively identified. Unlimited water availability, for instance an access to irrigation canal, and an increasing number of cheap foreign laborers during rice-growing season from Lao PDR and Cambodia were specifically addressed by participating farmers.

In a first scenario based on no water constraint, the synchronization of rice farming activities (all farms are able to start producing rice at the same time) induced problems for larger farms due to lack of hired labor for transplanting. Furthermore, there was a higher risk of rice production failure as well as higher farm input costs as agents started nursery establishment sooner to take advantage of the available water. One virtual farm could not complete transplanting when the heavy rains came late, and by then some rice seedlings were too old to be used. In a second scenario characterized by the presence of abundant cheaper hired laborers, the simulation showed high income differentials across farm types. Smallholdings A and B lost some income from wages received from households C and D. In contrast, without labor constraint, large farming households C and D earned higher incomes from selling high quality paddy because of faster harvest despite high labor costs.

Conclusions

Based on the results of monitoring and evaluation activities carried out with participating farmers, the BMM model sufficiently represents the interactions between water and labor availability of their community. As a consequence of the collaborative modeling process, researchers and local farmers gained better understanding of this interaction through the simulation analysis of changes in farming practices, and migration behavior. The BMM model is gradually developed based on this common understanding. As an integrated knowledge tool, the BMM model is now being used in a series of participatory simulation workshops. This model will be used further in the field to assess more scenarios regarding water and labor availability, and to stimulate collective knowledge-sharing and learning among local farmers.

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Agent-based modeling to facilitate resilient water management in Southeast and South Asia

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Abstract

Water is used and managed by stakeholders at different levels for diverse objectives, therefore understanding decision-making and supporting coordination is crucial in achieving resilient water management. Companion Modeling (ComMod) is an interactive process facilitated by evolutionary models for knowledge generation and exchange, and for supporting collective decision-making. Role-playing games and computerized agent-based simulations for focused group debates are complementary tools combined in a ComMod cycle and used at the field workshops. Agent-based modeling is used to understand how different processes in direct competition are coordinated, and to mediate the collective search for acceptable solutions to conflicting parties facilitated through exchanges. This paper compares the process of agent-based modeling applied in eight case studies with diverse natural and socioeconomic conditions and different resource management problems in Bhutan, Thailand, and Vietnam, to show the creative thinking in developing and applying flexible ComMod modeling tools and provide lessons for their use in other situations.

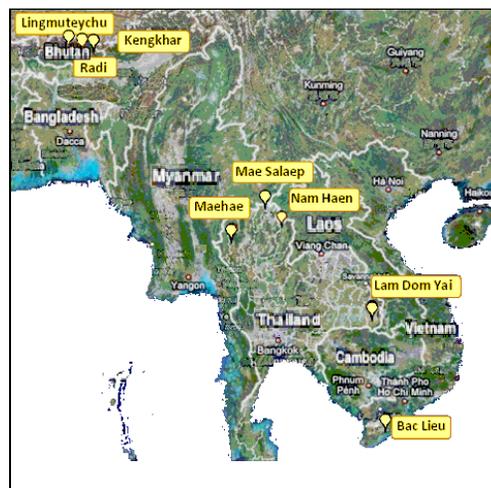
Media grab

Even under diverse conflicting water management situations with very different biophysical and socioeconomic conditions, agent-based modeling can be flexibly applied for generating and exchanging knowledge and to facilitate collective decision-making.

Introduction

Water is a resource used for diverse purposes such as agricultural production, fisheries and aquaculture, transport, tourism, and drinking. It is widely recognized that inadequate coordination among stakeholders leads to inefficient water use, economic and environmental damage, negative externalities, and social conflicts. ComMod is an interactive process facilitated by evolutionary models to support dialogue, shared learning, and collective decision-making in resilient water management (Bousquet et al., 2006). Key complementary analytical tools combined in a ComMod cycle and used during field workshops are conceptual models, role-playing games (RPG), and computerized agent-based models (ABM) with focused group debates. The modeling approach is applied for two objectives: (1) to integrate knowledge for understanding how different processes in direct competition are implemented by different stakeholders; and (2) to provide tools for mediating the collective search for acceptable solutions to conflicting parties facilitated through exchanges. Eight case studies (Figure 1 and Table 1) are being implemented under the PN25 project of the CPWF, which deals with conflicts regarding water sharing and social tensions over water use in Bhutan and northern Thailand (Gurung et al., 2006; Barnaud et al., 2006, 2007; Dumrongrojwathana et al., 2007), conflict between agricultural intensification and labor migration in northeast Thailand (Naivinit et al., 2007), and conflict between rice and shrimp producers in the Mekong Delta, Vietnam (Dung et al., 2007). This paper compares the agent-based modeling processes developed in these case studies to illustrate how they are flexibly applied in diverse ecological and sociocultural conditions for different land and water management problems.

Figure 1. Location of the



Methods

ComMod is an approach to improve coordination processes at the watershed level among an increasing number of diverse stakeholders using common water resources (Bousquet et al., 2006). It uses various tools in a participatory way to generate a common vision of optimal resource use among stakeholders, and to identify and examine new resource-sharing scenarios. Two key tools used in ComMod are Role Playing Games (RPGs) and Agent-Based Model (ABM). RPG and ABM are usually coupled in agent-based participatory simulations, but they can also be applied separately (Barreteau, 2003).

Table 1. Characteristics of the eight study sites.

Site	Location	Catchment/ Basin	Area (km ²)	Population density (persons/km ²)	Main land use types	Main research objectives*
1. Lingmunteychu	Punakha, Bhutan	Punatshang Chu, Bhrmaputra	34	24	Irrigated wetland	Improve irrigation water sharing for rice cultivation
2. Radi	Trashigang, Bhutan	Gamri Chu, Bhrmaputra	54	111	Rice, yak & cattle herders	Develop strategies to address grazing land conflict
3. Kengkhar	Mongar, Bhutan	Kurichu, Bhrmaputra	156	12	Dryland farming	Promote sharing water from spring ponds
4. Mae Salaep	Chiang Rai, Thailand	Mae Chan, Chao Phraya	3	83	Maize, lychee, green tea	Promote sharing irrigation water
5. Nam Haen	Nan, Thailand	Nam Yao, Nan, Chao Phraya	106	7	Maize, orchards & forestry	Facilitate communication among villagers and Nanthaburi National Park
6. Maehae	Chiang Mai, Thailand	Ping, Chao Phraya	32	94	Rice, vegetable, orchards	Stimulate collective learning for land and water allocation
7. Ban Mak Mai	Ubon Ratchathani, Thailand	Lam Dom Yai, Mun, Mekong	1,680	119	Rainfed lowland rice	Understand interactions between land-water use and labor migration
8. Bac Lieu	Bac Lieu, Vietnam	Mekong Delta	2,600	269	Rice, shrimp, fish, crab	Analyze farmers' decision-making in rice & shrimp production

*More details and results from some case studies are presented in other papers at this conference.

In a RPG, participants are assumed to represent 'fictional characters' and collaboratively create the stories close to their actual situation on the farm. Participants determine their actions based on their characterization, and these actions succeed or fail according to a formal system of rules and guidelines. Under this PN25 project, RPG is used as a social learning tool for researchers and players to exchange information for better knowledge on the ecological system and human behavior, and also to facilitate discussions, dialogues, and negotiation in water resource management.

In an ABM, a system is modeled as a collection of computerized autonomous decision-making entities called agents. Each agent individually assesses its situation and makes decisions on the basis of a set of rules, for example, producing certain crops or selling certain products based on expected incomes. An important characteristic of ABM is the potential asynchrony of the interactions among agents and between agents and their common environment having its own ecological dynamics. For example, in the Bac Lieu case, rice farmers and shrimp growers are interacting in a coastal area affected by tide and different weather conditions in each year. With the help of a computer, interactions between agents can be repeated to explore the dynamics of the system.

Although RPG is a useful tool that allows multiple stakeholders to interactively examine the complexity of the systems that they are part of, in operation it is costly and time consuming, cumbersome setting up, slow in simulating new scenarios, and difficult to analyze its results. To overcome these constraints, a hybrid ABM-RPG can run interactive simulations in which some of the decisions are taken by real participants, while others are taken by artificial agents (Barnaud et al., 2007). This combination enables the stakeholders to easier understand what the ABM will simulate.

Discussions

The following discussions are based on the agent-based modeling processes in eight case studies summarized and compared in Table 2. In all cases, there is production of knowledge through the interaction among researchers and local stakeholders. But in the last two cases, gaining a better understanding of complex environments and decision-making process (K) for researchers or for local stakeholders through training activities is the main objective, while in the first six cases it is a methodological requirement to support collective decision-making processes (C) in complex situations.

RPG (G) were used in all eight cases. In the Radi and more recent Kengkhar cases, however, neither ABM (A) nor hybrid model (H) were applied yet. In Radi, the process is temporarily stopped after the RPG because of the legal and institutional complications in dealing with conflicts in using grazing land between rice growers and herders living in two parts of the watershed. In Kengkhar, where coordination for sharing water is needed, the process is

just starting, and an ABM will be developed. ABM (A) and/or hybrid model (H) were applied in six cases to explore scenarios in participatory simulation sessions. In the Mae Salaep case a hybrid model (H) was used after the RPG (G) to explore the effects of new water allocation rules on lychee and tea farms. When using the hybrid model, each player was a farmer interacting with a computer artefact that made all decisions in land use except one about water allocation decided by the player. In the Nam Haen case a hybrid model (H) was developed to communicate the outputs of the gaming sessions to more villagers and the national park officers. In this case, some players were autonomous computer agents while the others were farmers, except at the final workshop the model was run with only computer agents (corresponding to the 'A' of this case in Table 2) in several scenarios identified and discussed by participants who had played the RPG before.

Table 2. Agent-based modeling tools applied in the eight case studies.

Site	Main objective	Tools	Spatial dimension	Temporal dimension	Decision-making entities	Interactions	Model components	No. of sessions
1. Lingmuteychu	C	G A	Fi, Fa, Vi, Ca	G: Annual, 3 years A: Annual, 10 years	Farmers, Village administrators	E C	Water flow Rice production Information exchange	G: 3 + 1 training A: 8
2. Radi	C	G	Fa, Vi, Ca	G: Annual, 5 years	Farmers	E C	Livestock Land degradation	G: 1+ several with small groups
3. Kengkhar	C	G	Fa, Vi	G: Annual, 6 years	Farmers	E I C	Water tank Household water use	G: 1
4. Mae Salaep	C	G H	Fi, Fa, Vi, Ca	G, H: Annual, 5 years	Farmers Village representative Religious leader	E I C	Crop, farm, slope Irrigation channels Small reservoirs	G: 2 H: 1 + several with small groups
5. Nam Haen	C	G H A	Fi, Fa, Vi	G, H: Annual, 2-5 years	Farmers Village leader National Park Royal Forest Depart.	E	Crop Non timber forest products	G: 2 H: 2 G+ A: 1 + teaching tool
6. Maehae	C	G A	Fi, Fa, Vi, Ca	G: Seasonal, 4 years A: Monthly, 9 years	Farmers Foresters Community Network	E I C	Forest Crop Water	G: 4 A: not yet.
7. Ban Mak Mai	K	G A	Fi, Fa, Vi	G: Daily, 1-2 years A: Daily, 10 years	Farmers Village	E I C	Hydroclimatic module Household module Rice module	G: 3 A: 3
8. Bac Lieu	K	G A	Fi, Fa, Vi, Ca	G: Monthly, 2 years A: Weekly, 5 years	Farmers Water manager Middleman Seed provider	E C	Rice, shrimp Water salinity Household budgeting	G: 4 A: 2 (planned)

Notes for columns:

- Objectives: K = knowledge generation and exchange, C = collective decision (communication, negotiation).
- Tools: G = Role playing games, A = Agent-based model, H = Hybrid (combined G and A).
- Spatial dimension: Fi = Field, Fa = Farm, Vi = Village, Ca = Catchment.
- Temporal dimension: time step (annual, seasonal, monthly, weekly, daily) and time horizon (no. years).
- Interactions: E = via environmental factors, I = peer to peer interaction, C: collective within group.
- Number of sessions that were organized with local stakeholders or for other purposes (training, teaching).

In the spatial dimension, the farm (Fa) and village (Vi) levels were considered as important in all eight cases. The lower and higher levels, field (Fi) and catchment (Ca), were included in six and five cases, respectively. So, under this PN25 project, the applications of agent-based modeling are focusing on water use conflicts among farmers at the village level, but when needed they also include lower or higher levels.

In the temporal dimension, five cases applied the time step of one year, but the time step in the three other cases were shorter, from daily in the Ban Mak Mai case to reflect the detailed crop calendar, to monthly/weekly in the Bac Lieu case to simulate the salinity variation, and to seasonal/monthly in Mae Hae to describe the forest management. In most of the cases, the same time step was applied in both RPG and ABM or Hybrid, except in the Maehae and Bac Lieu cases where time step in the ABM is shorter. As simulation scenarios are run much faster with ABM, longer time horizons than that of the RPG were used in most of the cases. This advantage allows the model user to analyze the long-term impacts that could not be found during the RPG. However, when it was combined into the hybrid model, the time horizon was only equal to that of the RPG, as in the Mae Salaep and Nam Haen cases.

The farmer is the main decision-making entity that existed in all cases. The other ones are diverse and vary by case. A representation of the community management is included in four cases, whereas religious leader, national park, government officers and local administrators, foresters, and water managers found in different cases show the diversity of stakeholders concerned and to be involved in the search for resilient water management.

The collective interactions (C) within agent groups in six cases show that a collaborative management of water resources has been stimulated at these sites. Also in six cases (not the same with C), the interactions were through environmental factors (E), for example, water flow from upstream to downstream villages as in Lingmuteychu, Kengkhar and Maehae cases, or soil erosion at Radi and Mae Salaep sites, or canal water salinity in Bac Lieu. Peer

to peer interactions (I), i.e. discussion between two individual agents without participation of the group, were also recorded in four case studies.

Different model components were identified and developed in different cases. These components were based on the nature of conflicts, the related resources and products, and the agents involved and varied in a wide range from physical entities as water and climate, production systems as crop or livestock, to management as irrigation or economic as household finance. Similarly to the decision-making entities, these components were not fixed during modeling, but could be modified or added as needed. A relevant example for this dynamic in modeling is the Mae Salaep case with two ComMod cycles (Barnaud et al., 2007). In the first cycle, the researchers' model MAE SALAEP 1 was developed by integration of scientific and indigenous knowledge on farming systems and soil erosion to focus on land use and land degradation. The model was then translated into an initial RPG that could be described as a simplified and noncomputerized version so that farmers could validate it. With knowledge on farmers' land-use strategies acquired during the MAE SALAEP 1 gaming sessions, a simpler MAE SALAEP 2.1 ABM with rules and features similar to the RPG was developed. The second cycle was to set up a collective learning process on the socioeconomic conditions for adoption of perennial crops by different farm types. A new model version, the MAE SALAEP 2.2, was developed based on the previous version to represent the interactions between investment in perennial crops, formal and informal credit, and off-farm activities; to explore the interactions between decision-making processes at household level and the resultant collective dynamics at community level; and to support the exploration of scenarios with all stakeholders. Similar dynamic processes have been also applied in other case studies.

The number of RPG or ABM or hybrid sessions with the participation of stakeholders also varied by case study. In general, organizing RPG or hybrid sessions took a lot of time and effort compared to participatory ABM ones. Therefore the maximum number of RPG sessions was only four (in Maehae and Bac Lieu), but the maximum of ABM sessions was eight (at Lingmuteychu site). The agent-based modeling tools used in Lingmuteychu, Mae Salaep, and Nam Haen have also been used for training purposes at several universities in Bhutan, Thailand, France, and Japan. Ban Mak Mai case is a special one with many sessions organized for a group of 10-15 participants or small groups of 3-4 participants to emphasize the co-designing and testing characteristics of the ABMs. In this case, the co-designer farmers are already involved in the presentation of 'their' ABM to master students at the regional university.

Conclusion

With two objectives, knowledge generation and exchange, and collective decision-making, these eight case studies showed that the agent-based modeling approach could be applied for diverse conflicting problems in water management under different biophysical and socioeconomic conditions. Although only two key tools, RPG and ABM, were used either separately or integrated into hybrid gaming ABM models, creative thinking and flexibility was required in tailoring them to specific needs and using them in each different case.

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Monitoring use increases cooperation among water users in the Mekong Delta of Cambodia and Vietnam

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Abstract

We used field experiments as a method to study underlying strategic actions Cambodian and Vietnamese natural resource users take in regard to the appropriation of common-pool resources. A common-pool resource (CPR) game was implemented in the two countries, investigating the importance of monitoring natural resources on the users' strategies. We found that users' cooperation rises significantly when monitoring is introduced into the game, representing an external agency that monitors and sanctions offenders. Other field experiments and qualitative research, however, showed that other key factors also significantly influence the likelihood of collective action and that cooperation in the field was dependent on many more factors. This paper presents findings about monitoring and the cooperation levels of players in eight villages in Cambodia and Vietnam. We compare results between the countries, draw conclusions from the experimental outcomes, and make suggestions for further research.

Media grab

Water users in the Mekong Delta of Cambodia and Vietnam face severe challenges in regard to the collective management and sustainable use of water resources.

Introduction

A functioning and resilient natural resource base plays a significant role in the livelihoods of people in Cambodia and Vietnam, as people living in the Lower Mekong Delta rely heavily on agriculture and fishing. Sustainable resource management in Cambodia and Vietnam faces severe challenges, however. Significant parts of the natural resource base are confronted with open access situations. Thus, these resources are rapidly degrading, threatening income streams of local users, and affecting the region's ecosystem. Water and land resources are mainly shared by different neighboring communities with a tendency of overuse because limiting appropriation rights of existing users is difficult to enforce. In both countries, decentralization efforts are under way to empower communities and improve the management of resources. This is done although the underlying patterns of resource users' interaction, and the effects of external intervention, have not yet been fully understood in the policy arena.

In order to understand better users' strategies and interaction in natural resource management settings, game theory analyses and described actions of individuals in a situation where the outcome for each individual is not only dependent on his or her own decisions but also the decisions of other players. We present the field context and explain the assumptions about the players' behavior, and the experimental design of the game is described.

Research activities were implemented in six Cambodian and two Vietnamese villages. The target provinces in Cambodia were Kampong Thom, Kampong Cham, Prey Veng, and Takeo. In Vietnam, both villages are in Can Tho province. Problems of resource degradation and overexploitation are well known in the research sites. Thirty-eight percent of the participants reported that natural resources in their village are in poor condition.

Coordination problems are found in most public good and common-pool resource settings worldwide. They are often complex and interrelated (Ostrom et al., 1994; Steins and Edwards, 1999). Within this study, we use game theory to focus on specific aspects of the complex situation. In this paper, we present the effects of punishment on appropriation of common-pool resources. Many analysts would describe the situation of resource management in the research villages as a common-pool resource dilemma, as individuals are jointly appropriating from their limited natural resource base without being able to prevent free-riding. Hardin (1968), with his highly controversial hypotheses, states that self-interested individual behavior will lead to the 'tragedy of the commons' and that local users are not able to manage their natural resources sustainably. According to this and other theories, it is assumed that there is no solution to prevent the dilemma, and that individual rationality leads to an outcome that is not rational for the group. This corresponds to the assumptions of standard game theory. Here it is stated that players are self-interested and that the individual will always favor the private account over the public account.

This does not explain, however, cooperative behavior observed in many experiments, and yet there is no consensus on what is really happening in common-pool resource games (Schlager et al., 1994). Many scholars found, contradicting noncooperative game theory, that various communities are able to adopt strategies that prevent the dilemma and enable sustainable natural resources management (Ostrom et al., 1994; Keser and Gardner, 1999). Ostrom (1990) developed eight design principles that are relevant to natural resource users to

prevent the dilemma. Communication as well as monitoring and sanction systems are, according to Ostrom (1990), essential measures to reduce resource exploitation. Experiments undertaken by other scholars find that monitoring and sanctioning decreases free-riding substantially, and that these measures lead to socially more profitable outcomes, even when punishment is costly for players (Ostrom et al., 1994; Fehr and Gächter, 2000; Mascllet et al., 2003).

In this study we used framed field experiments instead of lab experiments. Our aim was to adapt the decision situation in the experiment to decision situations the Cambodian and Vietnamese participants already know from their real life experience. According to the results presented by experimentalists and game theorists, we formulate the following hypotheses for the results from the two games:

- Extractions will neither be at Nash equilibrium nor at social optimum. A substantial amount will be left on the public account. Over time, extractions will increase.
- Monitoring and sanctioning will significantly decrease free-riding, and thus increase group outcomes.

Methods

The extraction game was played with 128 players (16 participants per village divided into four games). Players were chosen by village representatives and from all wealth groups. Each game consisted of 20 rounds, where appropriations as group totals only were announced after every round. After ten rounds, monitoring was introduced, whereby the subjects were unaware of any rule change before they were introduced. They were informed, however, that the game would last about 2 hours.

Participants were aware of the identity of the other group members, and they knew each other as players were all selected within the village. In both games, however, decisions were made in private, individually, and were kept confidential even after the game ended, although in reality decisions of villagers were often known by other villagers. To keep decisions confidential, however, reduces individual behavior to the economic decision alone, which we wanted to test. Each experiment lasted 1-2 hours.

Experiment instructions were presented orally in Khmer or in Vietnamese. The facilitators in Cambodia and Vietnam remained the same for all sessions. Players knew the number of people attending the session, as well as the incentives from investing the token in the private account or in the group account. The instructions included examples of possible actions and outcomes.

The games were framed according to the local situation. This was to assure that (a) confusion about subjects and intentions within participants was minimized, and that (b) illiterate participants had equal opportunities to participate. Additionally, all games were arranged in a manner that reading and writing was not necessary for participation.

We used a common-pool resource game ('Extraction Game' hereafter) (Ruffle and Sosis, 2002), whereby people extracted fish from a common pond. Each round the pond was endowed with 40 units of fish and players decided to extract units of fish to the private account or leave it to the public account. Tokens extracted into the private account were immediately private gains, whereby fish units left in the common pond also yielded a return to each group member. Regardless of extraction levels of individual players each fish unit left was rewarded by the amount of 0.5 token. If the group total extraction was more than 40 units of fish, no player received any reward.

Accordingly, the individual payoff function in the Extraction Game is:

$$g(x_i) = \frac{2(40 - \sum_{j \neq i}^{n-1} x_j - x_i)}{n} + x_i, \text{ if } \sum_{i=1}^n x_i < 40$$

$$g(x_i) = 0, \text{ if } \sum_{i=1}^n x_i > 40$$

In this experimental setting, free-riding is the dominant strategy. Because the private rewards of extracting from the public good is higher than the private rewards from the public good, individual (Nash) incentives to extract dominate. At the social optimum, however, all players would be better off if none of the players extracts any unit. This rule was introduced as villagers were involved in an aquaculture project, whereby benefits to the whole group were maximized when no fish was extracted until the common harvest. Fish were then fully grown and yielded more benefits. The common harvest is then displayed through the equal distribution of all fish to the group members at the end of the round.

After ten rounds, a monitoring system was introduced. Players were told that the new rule is to extract zero units, because this is the best strategy for the group as a whole in order to reach highest benefits at the common harvest. After each decision and the announcement of the group total, a dice was thrown and with the probability of one to six an external monitoring of all players occurred. Every player who extracted more than zero units from the common pond received a fine of four times the units he or she extracted. These units were then subtracted from the players' total payoffs. Sanctioned players also did not receive shares from the common pond in the respective round. One unit extracted thus was punished by four units, two units by eight units of fish and so on. After 20 rounds, the end of the game was announced and players received money for each token they gained during the game, whereby one unit of fish was equal to 100 Riel or 1.000 Vietnamese Dong.

Results

We compared results from Cambodia and Vietnam and investigated how the introduced monitoring changed the strategic behavior of the participants. We tested each hypothesis introduced with our data. Payoffs in each round were calculated according to the daily income of a rural family. A game lasted around 2 hours with an additional 30 minutes interview after. For each player it was possible to earn 20 times a daily income, when social optimum would have been played all the time. In each round, players decided about a fourth of their daily income.

For the Extraction Game, total payoff of all participants was US\$1374, whereby the Cambodians earned US\$6.70 on average, and the Vietnamese US\$22.80 on average.

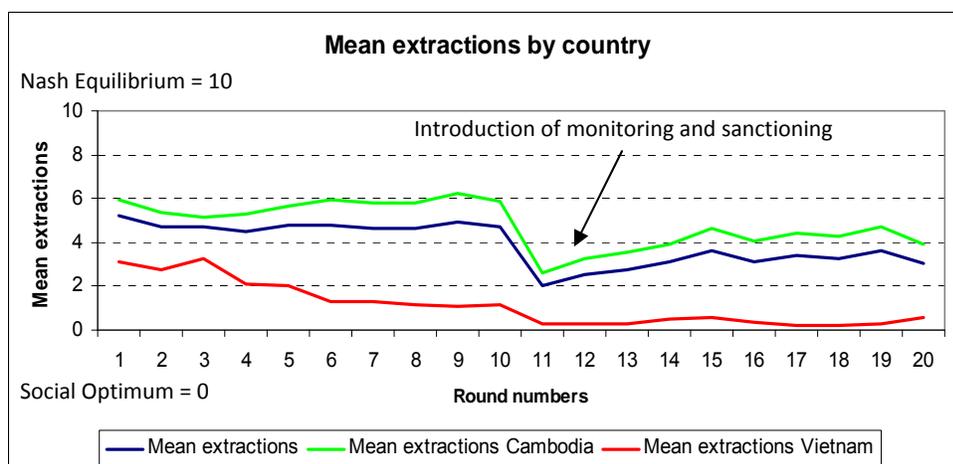


Figure 6. Mean extractions by country.

The mean extraction of all players for both countries and separately for Cambodia and Vietnam is shown in Figure 1. The mean extractions are between the Nash equilibrium (10 tokens) and the social optimum (0 tokens) and are 3.9 tokens. The standard deviations are 4.47 (both countries), 4.56 (Cambodia), and 2.75 (Vietnam).

The cases when social optimum, Nash equilibrium and over-extraction occurred within the groups is summarized in Table 1. In 10% of all rounds ($n=640$ rounds) a social optimum was reached. On the other side, the Nash equilibrium resulted in only 2.7% of all rounds. Overextraction (more than 40 tokens played as group) occurred nine times in all games, and thus represents only 1.4% of the total rounds.

Table 2. Totals and percent of rounds social optimum, Nash and overextraction played in Ext. game.

	Social optimum		Nash equilibrium		Overextraction	
	Total	%	Total	%	Total	%
Cambodia	9	1.9	17	3.5	8	1.7
Vietnam	55	34.4	0	0	1	0.6
Total	64	10	17	2.7	9	1.4

In Figure 2 the frequencies of tokens played are shown. Individuals extracted more often at the social optimum level than at the Nash equilibrium. Only five players (out of 128 players), however, never extracted any tokens from the common good, and thus played continuously at the social optimum. However, free-riding occurred, and on 179 occasions (in 2560 decisions) people extracted even more than 10 tokens.

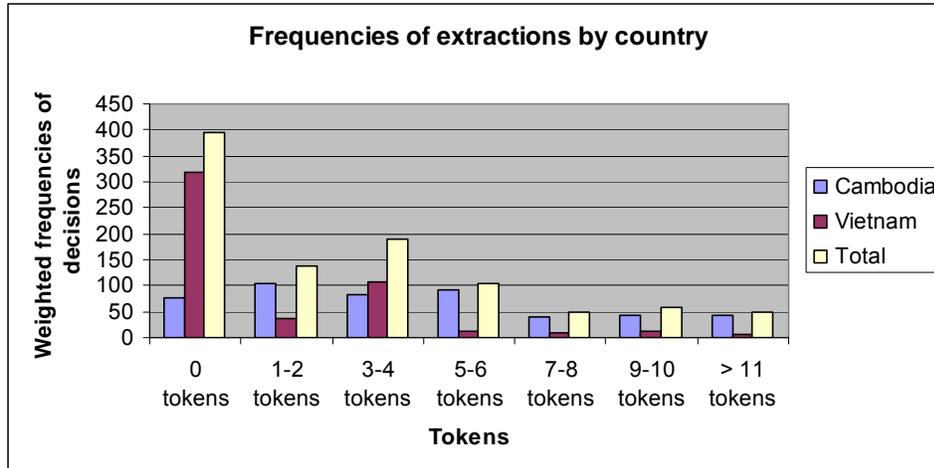


Figure 7. Frequencies of extractions by country.

We find significant differences between the extraction levels in all rounds when comparing Cambodia and Vietnam (Kruskal-Wallis test 0.0001). The Vietnamese participants play much closer to the social optimum (1.15 tokens on average) and extracted 3.67 tokens less on average than the Cambodian players (4.82 tokens on average). Also, the frequency of zero tokens played is much higher in Vietnam than in Cambodia.

In Figure 3, the change in extractions between round 10 and 11 already shows how much monitoring affects people’s extractions level. The means of tokens extracted before monitoring has been introduced are 4.76 for both countries, 5.7 tokens for Cambodia and 1.94 tokens for Vietnam. The respective means after monitoring was implemented are as follows: 3.05 tokens (both countries), 3.94 tokens (Cambodia), and 0.37 tokens (Vietnam). In Vietnam, the mean contributions after introduction of monitoring move very close to the social optimum. Also, the Wilcoxon signed ranks test comes to the conclusion that the effect of monitoring to extractions is significant. The differences in the distribution, the shift of the mean, and the reduction of the variance are shown in Figure 3.

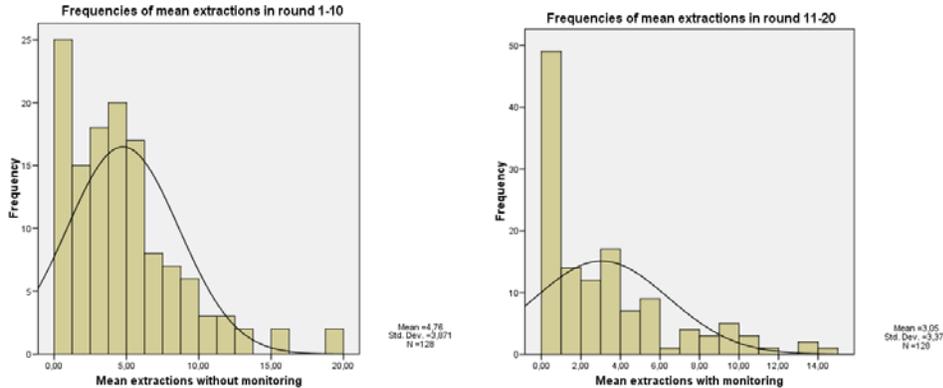


Figure 8. Frequencies of mean extractions in round 1-10 compared to round 11-20.

The assumptions made in the beginning were tested against our results. Extractions are neither at Nash nor at social optimum. We could not find, however, that extractions increased over time as suggested by other studies. The introduced monitoring had significant effect on cooperation and significantly decreased extractions. Vietnamese players played more cooperative from the very beginning of the Extraction Game, but especially after the introduction of monitoring measures with penalties.

Discussion and conclusions

Being a local user of natural resources in Cambodia and Vietnam, ones’ own decision always influences fellow villagers. In return, the decisions of others always influence one’s own livelihood. Cooperation in natural resource management is thus essential, especially within the local village context, where livelihoods are almost exclusively assured from the daily use of natural resources.

The findings of our research show results that are in line with earlier research on common-pool resources and public goods. Our hypotheses were all supported by the analysis, except for the surprising fact that free-riding did

not increase over time. This leads to the assumption that our groups were learning how to reach a higher group and thus a higher individual outcome, and improved their cooperation over time.

The results concerning the impact of introduced monitoring measures into the game are noteworthy. Players reacted sensitively to the threat of being punished. In both countries, reactions might be related to the recent history of (civil) war, as most people are still traumatized and fear punishment.

On the other hand, monitoring and sanctioning are rather random and insufficiently enforced, and people are not really used to getting punished for offending behavior in regard to natural resources. This is more evident in Cambodia as current natural resource management government structures in Cambodia often are not able to address negative natural resource management practices.

Further research in the region concerning the users' behavior is necessary in regard to different monitoring regulations, also including whether people would be willing to contribute money to monitoring activities. It would also be appealing to investigate what institution people would prefer, if they could choose. As appropriations as well as voluntary contributions usually include larger numbers of individuals, further research in the Lower Mekong area could also take into account how group size influences people's willingness to cooperate.

The Cambodian as well as the Vietnamese government aims at decentralizing natural resource management to lower jurisdictional levels to provide more effective and sustainable governance. New institutional arrangements, such as community-based forestry or fisheries, are now being promoted by the governments with the aim to give decision power and fiscal means to the local communities that live with and from the natural resources. To ensure that these measures contribute to a better and more sustainable resource management, it is required to understand people's behavior toward natural resources. It is necessary to understand the challenges natural resource users face in regard to the management to adjust policies and give essential support from higher jurisdictions when needed. With this research we hoped to improve our understanding of people's strategies, to more effectively evaluate planned and implemented policies in the region. We found that cooperation in the communities is definitely present, and that community-based management is promising. It became obvious, however, that different institutional measures or rules can increase cooperation levels. This should be taken into consideration when planning decentralization measures in order to support communities in their rather difficult task of sustainable resource management.

Acknowledgments

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Enhancing stakeholder participation in regulation studies of the equatorial lakes

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Abstract

Over the past decade, the application of systems analysis techniques and decision support systems to support the operation of existing and planned dams in the Nile Equatorial Lakes Basin have been recognized as important steps in the quantification of the costs and benefits of different operating options. There has been very limited progress, however, toward implementation of the regulation regimes proposed by such DSS. This is partly because: (1) there is no basin-wide framework to support consideration and adoption of new regulation strategies; and (2) social and environmental concerns have not been considered. This paper presents the findings of a consultative exercise designed to agree upon broad management objectives for regulating the Equatorial Lakes within a participatory problem-structuring framework. Representatives of different stakeholder groups were able to rank decision criteria and agree on priority concerns. The process was facilitated through the use of an objectives hierarchy methodology, commonly referred to as value trees. The findings provide a sound foundation on which to base further development of a decision support system for this basin.

Media grab

Large dams remain highly controversial. Involvement of all stakeholders is a prerequisite for better decisions related to their operation.

Introduction

The operation of dams and large reservoir systems is often complicated by a multiplicity of conflicting project uses and purposes that ultimately affect different groups of people or interests. Resolving the dam operation problem is compounded by system managers who do not easily perceive the trade-offs and often resort to assigning priority to objectives that realize the greatest monetary benefit. For example, between 2000 and 2005, in the Upper Nile Equatorial Lakes Basin (Figure 1), hydropower plants at the outlet of Lake Victoria increased power generation, by releasing greater volumes of water through their turbines than is consistent with the Agreed Curve (i.e., an internationally agreed release regime, based on the relationship between outflow and Lake Victoria level that existed prior to construction of the Owen Falls Dam. Over the same period Lake Victoria levels dropped close to unprecedented lows. The role of hydropower production in this decline is not clear and has been much debated (EAC, 2006). Nevertheless it is clear that low lake levels had an adverse impact on landing sites, navigation facilities, and shoreline industries and settlements, leading to a range of mostly negative socioeconomic and ecosystem impacts. Several recent studies have utilized DSS to assess the impact of different regulation rules on hydropower production (e.g. Mott MacDonald, 1998; Georgakakos, 2004; Wardlaw et al., 2005). To date, however, no progress has been made in implementing any of the identified plans. It is probable that failure to consider environmental impacts and the lack of a framework to support consideration and adoption of new regulation strategies has impeded progress. In this paper, the findings of a consultative exercise designed to clarify different stakeholder opinions, and agree upon broad management objectives, are presented.

Methods

A two-day stakeholder meeting was organized and held in Entebbe in Uganda in July 2007. The meeting attracted participation from representatives of a wide range of stakeholders from the three riparian countries of Lake Victoria (Table 1). The aim of the meeting was to achieve a common understanding of stakeholders' interests and desired goals. A number of presentations were made to facilitate discussion around different stakeholder positions. Key amongst these was a presentation made by ESKOM (the operator of the dams), which illustrated the challenges facing the company in resolving water-sharing issues within a framework of cascading hydropower plants along the Victoria Nile. Presentations were also made on the legal aspects of public participation in the planning and management of large dams. Extracts of relevant literature were presented to the participants to facilitate their examination of problems similar to the one under consideration (e.g. Hämäläinen et al., 1999; Soncini-Sessa et al., 2002; Castelletti et al., 2004; Marttunen and Suomalainen, 2006). These illustrated stakeholder participation methodologies, processes, and techniques in DSS frameworks.

During break-out sessions, stakeholders formed two broad groups influenced by similar concerns (e.g. 'Fisheries and Environment' vs 'Economics') and were accordingly asked to articulate their preferences and identify criteria to be used in the evaluation of a proposed regulation policy. Eliciting preferences was not straightforward as many of the participants were not aware of, or sure about, their preferences amongst several management objectives. Consequently they were not able to state them exactly. Hence, they were asked to initially define a wide range of

Results

Each of the stakeholders articulated their own priorities. Representatives from NAPE sought to define management objectives that take into account issues related to cultural, spiritual, and ethical values. They were, however, urged to be prepared to make some concessions due to the difficulty of incorporating such non-tangible considerations within a DSS framework. Representatives from ESKOM argued that the underlying seasonality in annual Lake Victoria Levels implies that alternatives to the Agreed Curve should take into account the fact that more water is available between April and September each year. ESKOM also indicated that additional challenges in dam operation would arise once downstream power plants along the Victoria Nile were completed and expressed concern that, over the long term, large-scale withdrawal of water from Lake Victoria by upstream riparian countries would impact negatively on hydropower production. FIRRI focused on the need to maintain both upstream water levels as well as downstream flows to maintain important fisheries production in wetland areas. LAKIMO emphasized the importance of Lake Kyoga for the maintenance of many rural livelihoods and the need for timely inflows from the Victoria Nile to safeguard these livelihoods. Representatives from Kenya and Tanzania highlighted the importance of Lake Victoria for many of their citizens and the problems of excessive drawdown on the water supply to several large towns. An agreed value tree for regulation of Lake Victoria is shown in Figure 2, where the decision criteria were divided into four main objectives: i.e. economic, social, ecological, and institutional.

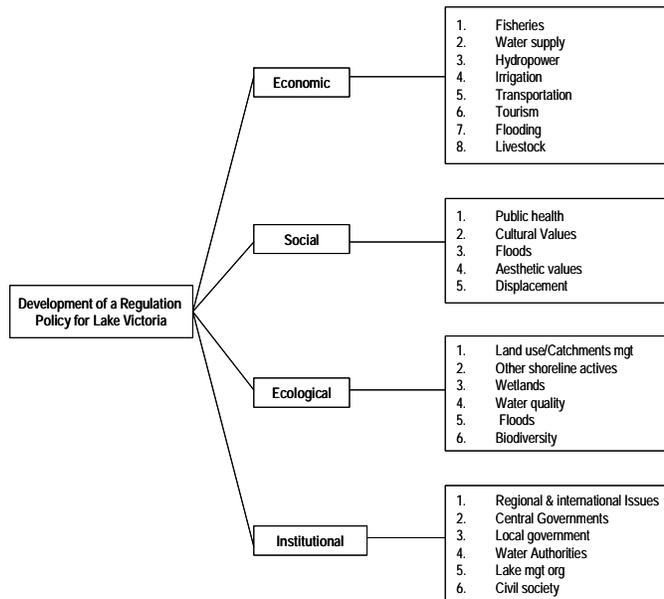


Figure 2. Value tree developed to highlight key issues to be considered in the regulation of outflows from Lake Victoria.

Institutional management objectives in this context are taken to be constraints imposed on regulation strategies. The priorities were validated in the plenary session by a method of public vote ranking. The results are a prioritized cardinal list of stakeholder objectives/preferences rather than an exhaustive ordinal list of regulation alternatives. Additional work will be required to support the generation, comparison, and choice of alternatives. The final choice usually occurs at the end of the decision-making process but, as demonstrated in this meeting, the process can be assisted with the early use of Multi-Criteria Decision Making (MCDM) tools that improve communication between stakeholders and facilitate the gathering of values seen to be important. The magnitudes of potential trade-offs will be derived after application of a multiobjective optimization algorithm and the use of multicriterion decision analysis techniques. This is beyond the scope of this paper, but is the subject of future work. Trade-off analysis that may be considered could include:

- Demonstrating ways of meeting hydropower demand targets while sustaining the necessary volume, levels, and timing of water flows to support important freshwater ecosystems.
- Striking a balance between upstream use of water for irrigation and downstream hydropower production.
- Minimizing damage to shoreline settlements, disruption to navigation, and water abstraction facilities by limiting the range of water level variation but also ensuring that legal commitments are not violated.

Discussion

The workshop underscored the diversity of concerns and the wide range of stakeholders with interests in how the waters of the Equatorial Lakes Basin are regulated. It proved to be a useful forum for discussion of concerns and, facilitated by the use of value trees, enabled the development of a broad consensus on the range of priority issues related to the operation of dams. Ideally dam-operating regimes need to be tailored to ensure that, as far as possible, all these objectives are met. It is clear, however, that pragmatically some trade-offs will be required. A strength of modern DSS is being able to predict the implications of different operating regimes for a range of objectives. The workshop did not succeed in developing quantitative objectives and with hindsight, it is recognized that this was too ambitious an objective for such a short meeting. Nevertheless, the consensus on priority issues provides a useful basis for determining the focus for DSS development currently underway.

Conclusions and recommendations

The workshop highlighted the fact that decision-making related to dams is not simply an intellectual exercise related to optimizing benefits, but is in fact highly emotive. In such complex situations, where the potential for conflict is high, the decision-making process is as important as the final outcome. It is difficult to compare the findings of this study with others as it only covers the initial stage of problem structuring. Similar lessons learnt at this stage, however, and noted in many other studies, are that the methodology needs to be kept simple to be understandable to nontechnical stakeholders. Although the impacts of the workshop itself are difficult to evaluate it certainly promoted better mutual understanding of different stakeholder concerns. It also contributed to transparency in decision-making and fulfilled the objective of providing a firm foundation for further development of a DSS for dam operation in the basin.

Acknowledgments

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Vertical asymmetries and collective action in watershed management

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Abstract

Watersheds have the characteristic of connecting people vertically by water flows, making relationships among users of water more complex. The location of the people along the watershed defines their roles in the provision and appropriation of water. Verticality in watersheds thus imposes a challenge to collective action. This paper presents the results of field experiments conducted in four watersheds in Colombia and Kenya. We recruited 639 watershed inhabitants from upstream, midstream, and downstream locations in these basins, and conducted field experiments to study the role that location and verticality plays in affecting cooperative decisions on provision and appropriation. Two field experiments were conducted: the '*Irrigation Game*,' a new experimental design that includes the provision and appropriation nature of the resource, and the '*Water Trust Game*,' an adaptation of the Trust Game where we explicitly announce the actual location upstream or downstream of the two players. The results show that reciprocity and trust are very important motivations for upstream-downstream cooperation, and that the role of upstream players has important implications in water provision decisions. Results from both experiments suggest that the lack of trust from downstream players toward upstream players restricts the possibilities of cooperation among the watershed users.

Media grab

Group communication can be better than regulation for increasing collective action around water management; upstream residents have a key role to play in initiating catchment-level processes.

Introduction

Watersheds connect people vertically by water flows, creating complex relationships among users of the resource. The social and biophysical interdependency among users of the watershed generates challenges to water and watershed management. The location of the people along the watershed defines their role in the provision and appropriation of water, so verticality in watersheds imposes a challenge to collective action.

Watersheds are characterized by an important biophysical and socioeconomic heterogeneity that generates a variety of actors. These actors face different economic and environmental challenges, such as access to the resources, especially in terms of its quantity and quality. 'Watersheds may include grazing land, agricultural land, residential areas, forests, wetlands, common waterways, and water-storage structures, each of which may be used by a variety of resource users. Lateral flows of water, soil, and nutrients between source and destination areas may link those resource users to other stakeholders, some of whom live outside the watershed. Effective watershed management requires coordination in the way that various stakeholders use and invest in the resources' (Knox et al., 2001).

The connection among actors in a watershed involves coordination and cooperation in the management of natural resources to improve their collective actions. Trust and reciprocity are important in a relationship that involves externalities and coordination failures, and these factors are enhanced by the awareness of dependence among participants (Ostrom, 1998; Ostrom and Gardner, 1993).

We conducted experimental designs in the field with the participation of residents of four watersheds in two countries: Colombia and Kenya. Through these experiments we expected to observe the factors that can enhance trust and collective action in a context of dependence among people in different locations along a watershed.

We recruited 639 watershed inhabitants from upstream, midstream, and downstream locations of Coello River and Fuquene Lake watersheds in Colombia and Awach and Kapchorean rivers in Kenya. The *Irrigation Game* was conducted with a sample of 355, participants and the *Water Trust Game* with a sample of 284 participants. The gender composition of the sample was of 48% for the irrigation game and 51% for the water trust game. The sample distribution across basins, games, and treatments is shown in Table 1. Not all cells were sampled due to budget and time restrictions. We guaranteed, however, that both games were conducted in both countries, and within each country we obtained data for all treatments of the irrigation game.

Table 1. Distribution of the participants across watersheds, games and treatments.

Basins	Participants in Irrigation Game (1 session = 5 players, 20 rounds)					Participants in Water Trust Game (1 Session = 2 players, 1 round)	Total Basin
	Base Line	Communication	High Fine	Low Fine	Total Irrigation Game		
Awach (Kenya)	20	20	20	--	60	124	184
Kapchorean (Kenya)	20	20	--	20	60	--	60
Coello (Colombia)	20	30	20	30	100	--	100
Fuquene (Colombia)	35	35	35	30	135	160	295
Total	95	105	75	80	355	284	639

The field experiment approach was used to achieve a better understanding of the effect of participants' location on water systems and the factors that influence provision decisions in this context. Two field experiments were conducted: the '*Irrigation Game*,' a new experimental design (Cardenas et.al., 2008a) that includes the provision and appropriation nature of the resource, and the '*Water Trust Game*,' an adapted version of the Trust Game, framed around water that presents the dependence among players related to water and compensation (reverse) flows. In all games the participants received monetary incentives based on the tokens earned during the games. The average payment received by players ranged between 1 and 1.5 days of work paid at the minimum wage rate.

Methods

Irrigation game

This game introduces the asymmetries in the water provision and access to the resource among players. In this game five players make two decisions in each round, one of contributing to a public project to produce water for the group, and another of extracting water for individual gains from irrigation. In the first part of the game, players make decisions on how many tokens to invest in a public fund to maintain water canals, from an initial endowment of ten tokens in each round. The amount of available water for the group is increasing as the group contributions increase. Noncontributed tokens are kept in a private account. These tokens are paid at the same monetary rate as the water units to be extracted in the second stage of each round. The second decision of the players is the individual water extraction from the total water produced. This decision is taken according to the location of the players along the water canal, which is defined randomly for the entire sequence of rounds, and is represented by a letter: A for the player in the first position and E for the player in the last position. The water is allocated, therefore, according to the location in the following manner. Player A first receives all the water produced by the group project, and decides how much water to extract. The remaining water is then shown to player located in B who then decides how much to extract and how much to leave to the remaining players downstream, and so on for players C, D, and E. This sequence is conducted for 10 rounds.

After the first ten rounds of baseline treatment, rules changed for some groups and this change is announced aloud to the players. Some groups were permitted to communicate, others face external regulation treatments, and other groups continued playing with the baseline conditions.

In the face-to-face communication treatment, players were allowed to communicate with the other players in the group before returning to their places to make their own private decisions. Likewise in the baseline, they know the aggregate decision but not the individual decisions after each decision round. In the external regulation or penalty treatments players were told that there would be a chance of being monitored each round. The experimenter rolled a dice in front of the participants each round and if the number obtained was 6, all the participants would be inspected. Thus, with a probability of 1/6 of being inspected, the monitor would verify if the player had extracted more than the allowed water amount, namely, 20% of the produced water by the group in the provision stage, and if so, they would pay a fine. In the high penalty treatment, the fine was the extra water in excess extracted plus six units from the earnings; in the low penalty treatment the fine was just the extra amount taken.

Water trust game

Based on the standard trust game (Berg et al., 1995), we adapted the basic incentives structure as a *water trust game (WTG)* framed around water production and distribution between two people located in different positions of a watershed. At the beginning of the game both players are endowed with 8 tokens. Player 1 (the proposer) can send any fraction from 0 to 8 tokens of her initial endowment to player 2 (the responder). As in the canonical version of the trust or investment game, the amount sent by player 1 is tripled before it reaches player 2 who then decides how to split the tripled amount plus her initial endowment between herself and player 1. This increase in the amount being sent reflects how a decision in favor of watershed conservation would increase the possibilities of a greater social outcome to be distributed along the watershed members. In our framing we explicitly framed the decision of player 1, if upstream, as the quantity of clean water sent to player 2 downstream, and player 2's

decision as an economic compensation for the water provided by player 1. If the game started with a downstream player, also such decision was framed as an economic compensation for the water provided by player 1.

We implemented the trust game using the strategy method, that is, player 2 was asked the complete strategy of responses to each possible offer by player 1. Therefore player 2 had to respond, without knowing yet the amount offered by player 1, how many tokens she would return to player 1 for each possible offer by player 1 (0, 2, 4, 6, 8 units). During each session we also asked each of the players the amount they expected from the other player. A typical experimental session lasted between 2 and 3 hours, including the time of explaining the rules and practice rounds to make sure every participant had understood the incentives and rules of the game.

Results and discussion

Irrigation game

The Social Optimum or Maximum Social Efficiency is a contribution of 100 units of water that means an individual contribution of 45-50 tokens. Nash Equilibrium is zero-contribution obtaining a suboptimal result of 50% of the maximum social efficiency possible. The overall results replicated the patterns of previous public goods or CPR games where predictions of noncooperative game theory were not a common result and communication improved cooperation.

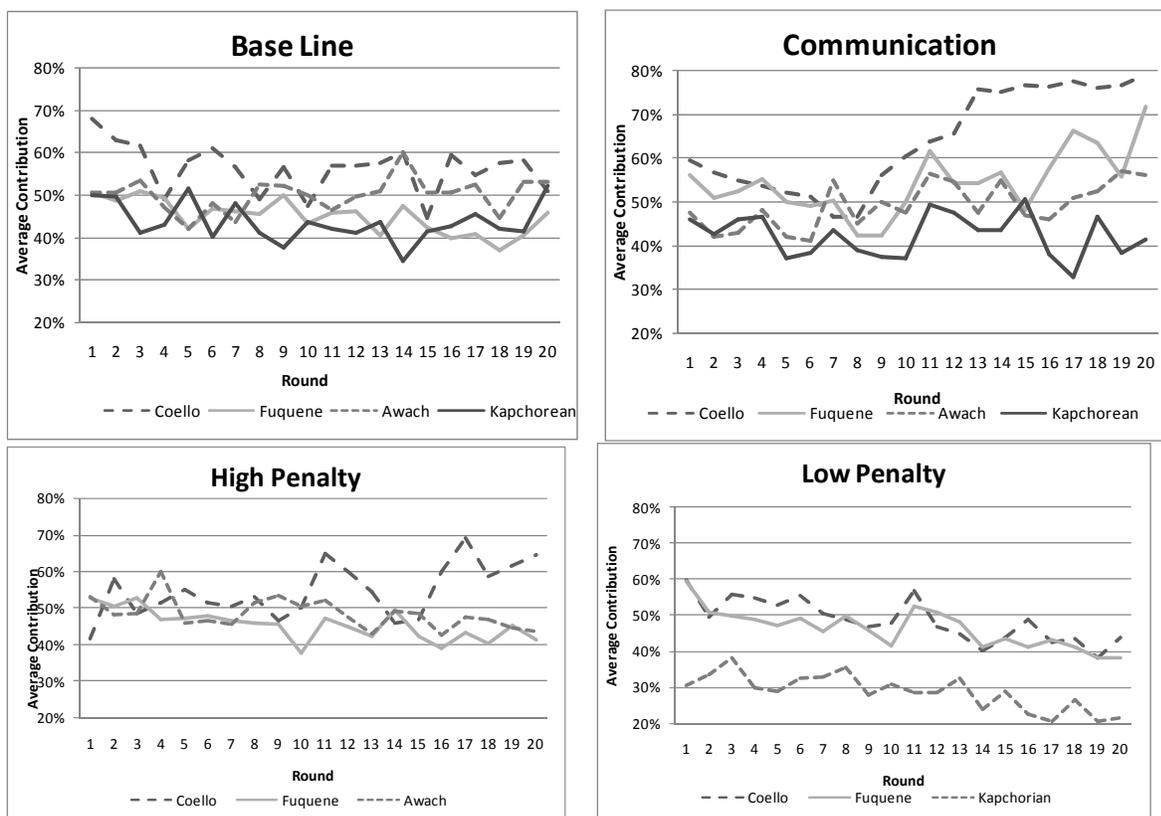


Figure 1. *Irrigation Game* contribution by treatment (Baseline, Communication, High Penalty, and Low Penalty).

The four panels in Figure 1 show the average contributions in the first stage of the game as a percentage of the endowment in each round. The contribution was on average 4.82 tokens, i.e. 48.2% of players' endowment, for the 10 initial rounds. For the second stage of the game (rounds 11-20), the groups that continued playing under the baseline condition continued a similar pattern (47.1% of their endowment), whereas the groups that could communicate reached a contribution of 5.9 tokens on average. The penalty treatment groups obtained an average contribution of 4.83 for high penalty and 3.96 for the low penalty groups.

The variance of the contributions behavior was rather constant and similar across the four treatments or across the watersheds. The standard deviation of the contributions ranged between 2.5 and 3 units and remained constant over rounds. We did observe a slightly higher variance for the communication data ($sd=2.05$ units for rounds 11 to 20 compared to 2.83, 2.64 and 2.88 for the baseline, high and low penalty treatments, respectively). This higher variance in the communication treatments is expected as the dynamic of a group conversation induces a significant number of players to contribute their entire endowment while other players remain in the low contributions,

namely the free-riding strategy, creating a more dispersed distribution if compared to the normal distribution observed in the base line data.

A look at average and variance of the contributions, however, may hide an important piece of information for our analysis of cooperation in watersheds. These are averages of five players who are located asymmetrically along the watershed, with contributions being greater for the head-ender (player A), intermediate for players B and C in the mid-stream location, and low for the last two players downstream. This is shown in Figure 2 in the left section where we report data for the first 10 rounds of all sessions, before they learned under which institution they would play in the subsequent rounds. The remaining sections of Figure 2 show the average contributions by players under the different treatments and for each location.

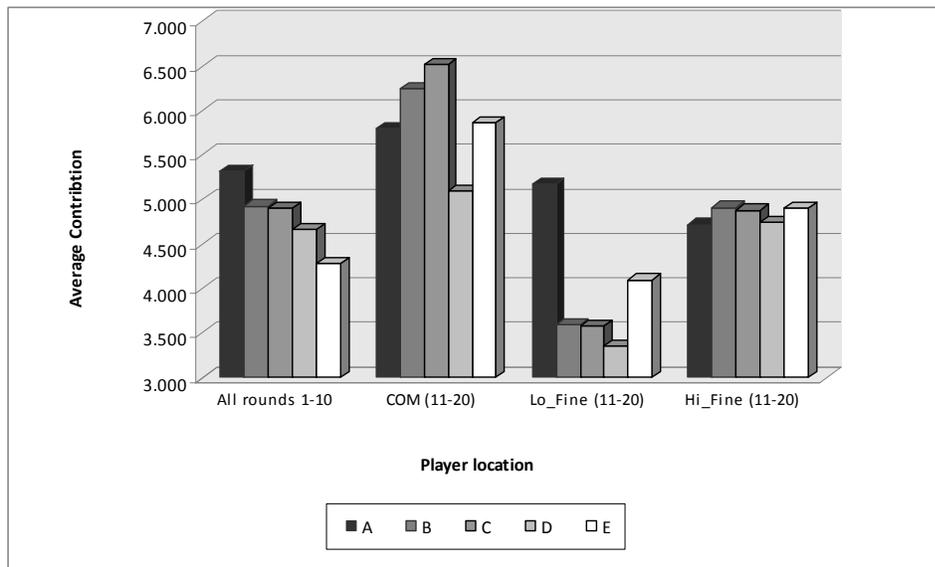


Figure 2. Irrigation Game contribution by player location (rounds 1-10 all groups and treatments).

Remember that these locations are assigned randomly at the start of each session and remain constant throughout the game. The results of the first 10 rounds (see left portion of Figure 1) suggest that in a baseline situation, as one individual is assigned a unit further down in the irrigation system, her willingness to contribute to the public fund that provides water for all players is lower, showing an erosion of the possibilities of building collective action along the watershed. We do not include here details about the particular behavior over time and across treatments for each of the types of players along the irrigation system. We can see, however, see from Figure 2 that communication increases substantially the contributions of all players, and particularly of downstream players. Notice also the poor performance of the fines, low and high, if compared to the baseline or the self-governance solution, and how the higher fine if anything helped produce a fairer contribution across locations. We will discuss implications of these findings later.

Water trust game

Regardless of the location, the Nash prediction in the trust game is for player 1 to send zero and player 2 to return zero tokens. Under nonbinding contracts there are no obligations nor warranties of positive returns on any amount offered by player 1. On the other extreme, the maximum social efficiency is achieved when the first mover sends all her endowment producing 32 units to be distributed among both players depending on the decision by player 2. What we observed, and as several other studies using the Trust Game have found, is that player 1 offers positive amounts and player 2 returned positive amounts, proportional to that player 1 offers. The interesting variation of our design is whether location of the player, Upstream (U) or Downstream (D) had an effect in offers and amounts returned.

The results of average amount offered, in units, by player 1 to player 2 by treatment are shown in Figure 3⁵. Across the two watersheds in Colombia (Fuquene) and Kenya (Awach), players 1 sent on average 3.34 units out of their 8 unit endowments (41.8%) to player 2. However, the four treatments do show differences worth discussing. We observe that the DU treatment (downstream participants being player 1 and upstream participants as players 2) shows lower (and statistically significant) offers. On average, the offers sent by players 1 located in upstream

⁵ UU=player 1 and player 2 are both located upstream; UD=player 1 is upstream and player 2 downstream; DD=player 1 and player 2 are both located downstream; DU=player 1 is downstream and player 2 upstream.

positions were higher than when players 1 were located downstream. In all treatments both players were informed of the actual location of the other player in the watershed.

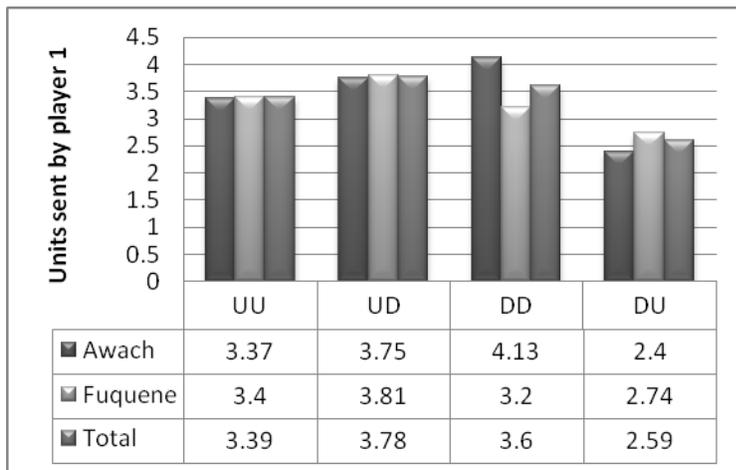


Figure 3. Average amount of units sent by player 1 to player 2.

The more striking difference appears when players 1 are located downstream and must send their offers to players 2 located upstream. This phenomenon is observed in the Kenya and Colombia samples.

Turn our attention to players 2 behavior, Figure 4 shows the average amounts, in tokens, returned by player 2 as a response to each of possible options that player 1 could offer to player 2 in our design. We are able to capture this information because we use the strategy method in the trust game, that is, we ask players 2 to elicit their responses to all possible offers by player 1, before they realized the actual offer. The results show that more trust is responded reciprocally, consistent with much of the literature using the trust game. For a survey of field and lab experiments using the canonical version of trust game see Cardenas and Carpenter, 2008c⁶. It is worth noting that players 1 received on average positive returns on their investment, that is, the average unit sent to player 2 generated a >1 return, although the returns were much higher for lower contributions, including getting on average 2.08 units for a zero offer.

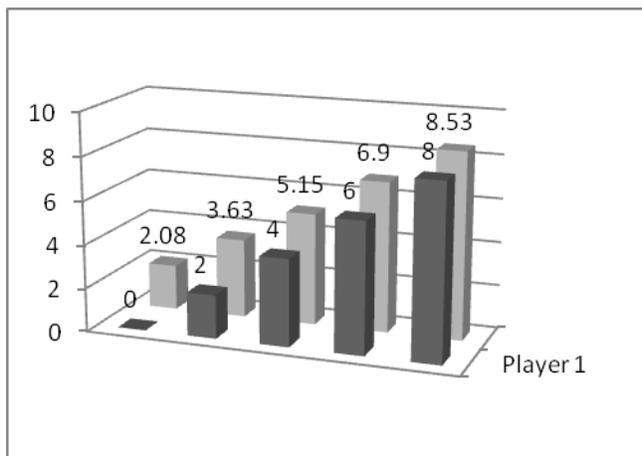


Figure 4. Amount sent by player 1 and returned by player 2.

These two phenomena, that downstream players seem to be less trusting, and that individuals in general include reciprocity in their strategic behavior, could explain in part why we observed in the irrigation game such lower contributions by players downstream; players D and E suffer more explicitly the negative effects of water over

⁶ The variation of the two observed decision variables, offers by players 1 and responses by players 2, showed a standard deviation of 2.04 units for offers by players 1. With respect to responses by players 2 we need to calculate the standard deviation for each possible response with standard deviation values of 2.17, 2.81, 3.52, 4.50 and 6.05 units for 0, 2, 4, 6 and 8 offers by player 1, respectively.

extraction by players upstream and therefore are more sensitive to such unidirectional externalities. Experience with such externalities can drive a reduction of trust among downstream inhabitants toward the rest of watershed users, and it is well reflected with the experimental and actual location of the players in both games.

Contextual analysis

There are several types of variables at the individual, experimental session, and regional level, that can also help explain the variation of the behavioral variables by our participants in the two games, beyond the experimental design and treatments. Due to lack of space, we cannot report here a regression analysis to explain the contributions by players in the provision stage of the irrigation game, and the offers levels by players 1 in the water trust game. The data confirm our hypothesis of a downstream erosion of cooperation in the vertical collective action problem because of decreased trust by the downstream players in the game. The econometric analysis is discussed in detail in Cardenas et al. (2008b), where we explored the individual contributions in the irrigation game as a function of the experimental conditions, including the round, the location in the irrigation system, and the institutional treatment (baseline, communication, high fines, and low fines). We then continue with the individual characteristics given the richness of the demographics we were able to sample in the field. We included several context controls such as dummy variables for the watersheds and also for the particular five players context. We chose, therefore, to run a robust standard errors fixed effects model where the fixed effects were captured by each of the particular 71 sessions conducted in the four watersheds. We test several formulations of the estimator, including a pooled data model, a semi-pooled model with dummies for the watersheds, and an unpooled model where we estimate one separate regression for each of the watersheds. We also tested different institutional changes in round 11 for these sessions and compared them to the baseline treatment where players continued after round 11 under the same rules and incentives. Confirming our basic results reported here, we find that that the location in the irrigation system (A,B,C,D,E) does play a significant role in the level of contributions; in the unpooled model for each of the watersheds, we found that only for the case of Awach such effect is not significant under the baseline treatment, although it is statistically significant for the communication treatment⁷. Also, we observe the powerful effect of the communication treatment in increasing contributions for all estimated models. The introduction of high and low fines, however, seems to have a poorer effect on the contributions; if anything, some of the estimated models show a positive effect of the high fine, and for the case of low fines all coefficients are negative and not significant (Cardenas, 2004, 2005) for similar results comparing these type of regulations with face-to-face communication treatments in common-pool resource experiments conducted in the field.

We also found that the contributions by the other people in the group in the previous round helped explain contributions with a negative effect: the higher the contribution by the other four players the smaller the contribution by the average player in the next round. This contradicts the reciprocity effect but the size of the coefficient is rather small. It could be, as a reviewer wisely suggested, that players would perceive that the group was making a sufficiently high effort, and therefore they could save some of the tokens for their own income, but also that when contributions were substantially low, they felt that an extra effort should be made to increase the group contributions. This effect changes substantially, however, if we study separately the institutional context of the regulation in the second stage, that is, this coefficient varies with the treatment. We found that lower levels of contributions for the two Kenyan watersheds and the effect of the 'other contributions lagged' turns out to be positive and significant for the Colombian basins, and negative for the Kenyan ones. We had already shown the much stronger effect of communication for the Colombian cases.

With respect to demographic characteristics of the participants, we found that more educated, older people, living in larger households seem to contribute more to the provision stage of the game. Other factors do not seem to present a robust effect across the different subsample models estimated.

The analysis of the role of the different regulatory treatments shows that the asymmetry in the coefficients for the player location is decreased for the case of the communication treatment. One of the major effects we observed of the self-governed solutions generated in the face-to-face communication within the groups is that players began to contribute in a more homogeneous manner as well as distributing better the water along the sequence. The watershed effects remain robust, with the Colombian watersheds showing higher levels of contributions for all treatments and with the Coello watershed showing a substantially higher level of contributions in all treatments.

As for the case of the water trust game, we conducted an equivalent regression analysis. In this case we have 142 observations (pairs) for 284 participants in this game, and sampled from different locations in two of the watersheds (Fuquene of Colombia and Kapchorean of Kenya). We conducted all possible permutations of pairs for upstream and downstream locations of the players with the purpose of studying if there is, in fact, an effect of the actual location of the people in the watershed on the level of trust, a key element of collective action.

We estimate the amount offered by player 1 to player 2 as a function of the same kind of explanatory variables used in the previous analysis. Model (1) considers the pooled data set, whereas model (2) includes a dummy for

⁷ We do not think it is a country effect or an experimenter effect, because the Kapchorean watershed did show statistically significant effects for the location of the players in the game, and the experimenters were the same in both Kenyan locations.

the Fuquene watershed that turned out to be significant (also consistent with the higher levels of contributions in the irrigation game for the Colombian samples). Models (3) and (4) consider the separate samples for each of the watersheds.

Some robust results are worth mentioning. Reciprocal behavior drives trust by players 1. Those expecting more are sending greater amounts to players 2. This is consistent across the estimated models. Older and more educated people and females have a slight but not significant tendency to offer less. The more time the player has lived in the community the higher the offers with a significant effect, however.

Let us now turn to the verticality effect. We had already in our descriptive analysis of offers (Figure 3) that the actual location of the player in the watershed might be playing a role. We do find that Player 2's location is significant and negative for all estimated models, meaning that when the offers come from downstream players and player 2 is upstream, such offers decrease. Downstream players trust upstream players less, and that has a significant effect on trust and social efficiency since each token not sent represents three fewer tokens not generated for the social efficiency of the pair of players.

Conclusions

The challenge of vertical collective action emerges from the asymmetry in the location of players along the irrigation system. Head-enders or upstream players have better opportunities to capture the benefits of a public project that maintains or produces water because they have an earlier access to the resource. On the other hand, their actions cause direct externalities to those downstream. Therefore, tail-enders or downstream players notice two effects on their well-being: those upstream have better chances to benefit from the resource, and their appropriation actions affect them directly. Further, the appropriation by those downstream has no direct effect on players upstream and therefore the possibility of signaling through reciprocal responses is less available for downstream players. In our irrigation game this mechanism seems to operate through the contribution stage. Players downstream are willing to contribute less than upstream players to the public project; it seems that the effect is, if anything, of negative reciprocity that triggers even more the vicious cycle of reciprocity, trust, and reputation described by Ostrom (1998).

These effects can create a similar negative effect to that of heterogeneity in collective action, in this case because of location. The distance created by these asymmetries (i.e. better resource availability and unidirectional externalities) from those upstream seems to reduce the level of trust and cooperativeness of downstream players.

It seems that one major challenge to solve the vertical challenge is to address the asymmetries in a manner that players perceive a more fair allocation of the resource, and of the effort contributed to provide the resource. Remember, irrigation and water systems require solving both the provision and the appropriation problems, and proportionality between contributions and appropriation is part of the challenge. 'When rules are based on a clear principle of proportionality and all participants recognized that the rules enable them to reach better outcomes than feasible in the 'state of nature' game, and all are prepared to punish rule breakers, more productive equilibria are reached and sustained over time' (Ostrom and Gardner, 1993).

The challenge is to bring downstream players to the group-oriented outcome of the game by creating better allocations of effort and resource extraction along the watershed. This is what the face-to-face communication treatment achieved in our results. It balanced the effort between upstream and downstream contributions and therefore increased substantially the water produced by the irrigation system, providing better chances for the downstream players (D and E) to obtain water in each round. 'Asymmetries among participants facing common-pool resource provision and appropriation problems can present substantial barriers to overcoming the disincentives of the 'state of nature' game between head-end and tail-end farmers. However, these asymmetries are frequently overcome in settings where farmers are made aware of their mutual dependencies; after all, head-enders and tail-enders may need the resources provided by tail-enders when it comes to maintaining the system over time' (Ostrom and Gardner, 1993).

The lack of trust among the two ends of the watershed, and in particular of players downstream who suffer the most effects of the decisions and better location by those upstream, imposes a major challenge here. Further research is needed to explore the impacts of simply informing better about the expectations and intentions of both players upstream and downstream, and how different government and nongovernment actors can play in decreasing this lack of trust that we observed both because of the experimental location or the actual locations of

our hundreds of participants in Colombia and Kenya. Acknowledging these asymmetries, and addressing them to increase trust among head- and tail-enders could provide better foundations for the implementation of self-governed solutions for watershed management.

On the methodological side, combining these experimental methods with other tools in the field can offer reflection spaces for communities as well as deeper understanding of the dynamics of behavior and rules. In fact the design of the irrigation game reported in this paper emerged from a National Science Foundation-funded project where collaborators from these different approaches have been applying lab and field experiments as well as role games (See <http://www.public.asu.edu/~majansse/dor/nsfhsd.htm> for details.)

Acknowledgments

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Interactive models to catalyze collective water management: a companion modeling approach in northern Thailand

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Abstract

How can simple interactive models catalyze collective learning and action about local water management? This paper aims at providing an answer to this question by drawing on a Companion Modeling (ComMod) experiment on irrigation water sharing in a highland community of northern Thailand. In a ComMod process, simulation models integrating different stakeholders' points of view on the problem at stake are developed and used as communication platforms to facilitate the collective exploration and assessment of various possible future scenarios. In this case study, the ComMod process combined a preliminary diagnostic-analysis of the heterogeneous sociopolitical context, a role playing game (RPG), and an associated simple agent based model (ABM). An ABM was used to run simulations to stimulate a plenary debate and, later on, to facilitate discussions within small homogeneous groups of farmers. The various effects of the process on the participants in term of learning, communication, behavior change, and new practices were evaluated through a series of individual interviews. This ComMod process stimulated individual and collective learning and coordination among multiple stakeholders exploring pathways to solve their common irrigation water use problem. We show that in participatory modeling, simple models can be useful to mediate water use conflicts and accommodate multiple interests among stakeholders. To do so the participatory aspects of the modeling and simulation process must be carefully managed. In particular, much attention needs to be paid to the initial sociopolitical context and its power inequities to ensure the genuine involvement of all concerned stakeholders, including the usually voiceless and resource-poor ones.

Introduction

In the highlands of northern Thailand as in several upper watersheds around the world, water management issues are more and more complex and uncertain, involving an increasing number of stakeholders and combining more and more interacting agroecological and socioeconomic dynamics (Johnson et al., 2001). To tackle such a complexity, researchers have built a wide range of models aimed at better understanding these issues and/or facilitating decision-making processes in these complex systems (Costanza and Ruth, 1998). Box and Draper (1987) wrote that 'all models are wrong, but some are useful.' Building upon this idea, we wondered how can we produce useful models. More precisely, we wondered how simple models can catalyze collective learning and action about local water management.

This paper aims at providing an answer to this question by drawing on a companion modeling (ComMod) experiment on irrigation water-sharing in a highland community of northern Thailand. In a ComMod process (which is participatory by its very nature), simulation models integrating different stakeholders' points of view on the problem at hand are developed and used as communication platforms to facilitate the collective exploration and assessment of various possible future scenarios (Bousquet et al., 1999). In the ComMod process presented in this paper, we adopted a critical perspective, i.e. much attention was paid to the initial sociopolitical context and its power inequities to ensure the genuine involvement of all concerned stakeholders, including the usually voiceless and resource-poor ones.

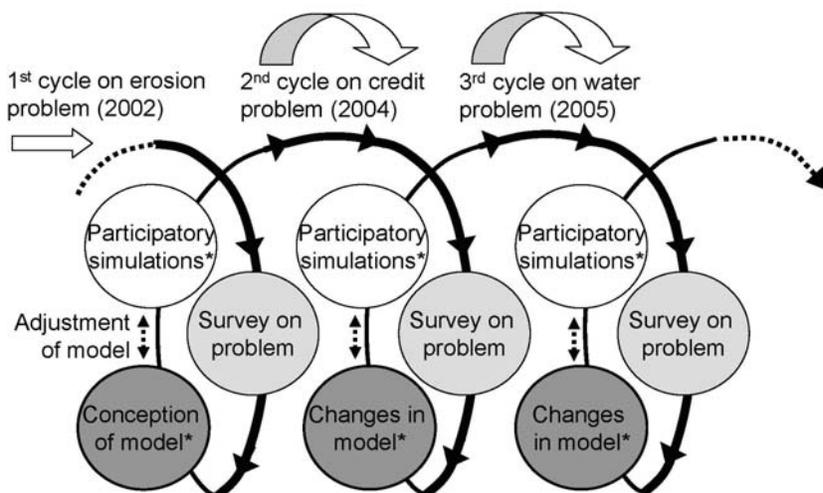
After a presentation of the context, methods and tools of the ComMod process conducted in the Akha community of Mae Salaep, this paper analyzes the main effects of this process in terms of collective learning and action about local water management. To conclude, we present the main lessons drawn from this experiment.

A ComMod approach

ComMod is a continuous and iterative modeling process alternating field and laboratory activities in a cyclical way, its main successive phases being as follows: (1) Characterization of the problem; (2) Modeling, i.e. converting knowledge into a formal tool to be used as a simulator; and (3) Simulations to explore various scenarios (Bousquet et al., 2005). Two kinds of simulation tools were used: ABM and RPG. According to Duke (1974), RPG is an excellent mode of communication to convey complexity, as it allows multiple stakeholders to interactively examine the complex systems of which they are part. Players can test alternative scenarios, but quickly this becomes costly and time-consuming, and the number of participants remains limited. To alleviate these constraints, it is possible to build a simple computerized ABM, very similar to the RPG in its features and rules, but far more time-efficient to

simulate scenarios and allowing a higher number of participants. Moreover, the RPG allows the players to understand the ABM model, to validate and criticize it, and later on to easily follow ABM simulations.

Discussions about a specific problem in a ComMod cycle might raise new questions, which can then be examined in a following one. This is what happened in the ComMod process conducted in the village of Mae Salaep (Figure 1).



* 1 model, 2 forms : Role-Playing Game & Agent-Based Model

Figure 1. Successive ComMod cycles conducted in Mae Salaep, Chiang Rai Province, 2002-2007.

Context of Mae Salaep catchment

In this village located in a highland catchment of Chiang Rai Province, small-scale poor farmers are being rapidly integrated into the market economy. Over the past 20 years, their former agrarian system based on swiddening was replaced by permanent cash crop-based agriculture. In the meanwhile, these changes led to an extensive socioeconomic differentiation among farming households, characterized by different availability of productive resources, and different socioeconomic and land-use strategies. Type A farmers are smallholders growing mainly maize for cash, while type B farmers hold self-sufficient medium-sized farms and grow upland rice for self consumption in addition to maize. Some of these type A and B farmers have small nonirrigated plantations of lychee or Assam tea. Type C farmers have relatively large and diversified farms, grow paddy rice and maize, and have extensive irrigated plantations of lychee or Oolong tea. In this context, after an initial ComMod cycle focusing on the interactions between soil erosion and crop diversification (Trébuil et al., 2002), the participants asked to focus the second cycle on the credit constraints to the adoption of nonerosive perennial crops such as tea and lychee (Barnaud et al., 2007, 2008). In a subsequent third cycle, which is presented in this article, the villagers requested a focus on water management at the catchment scale because these perennial crops require irrigation and their expansion in the catchment creates conflicts over water in the community. Presently, only a minority of relatively well-off farms have access to water to irrigate their plantations because of the first-come-first-served rule stipulating that once a farmer has set up irrigation pipes to draw water from a creek, other villagers cannot get water from its upstream section. Villagers also requested the participation to this ComMod cycle of the *Tambon* (sub-district) Administrative Organization (TAO) which is funding local projects such as the construction of small-scale water infrastructures.

The initial sociopolitical context related to this water management problem involved several types of stakeholders with their own interests and perceptions of the issue at stake. A matrix illustrating the relative influence and importance of these stakeholders is given in Figure 2.

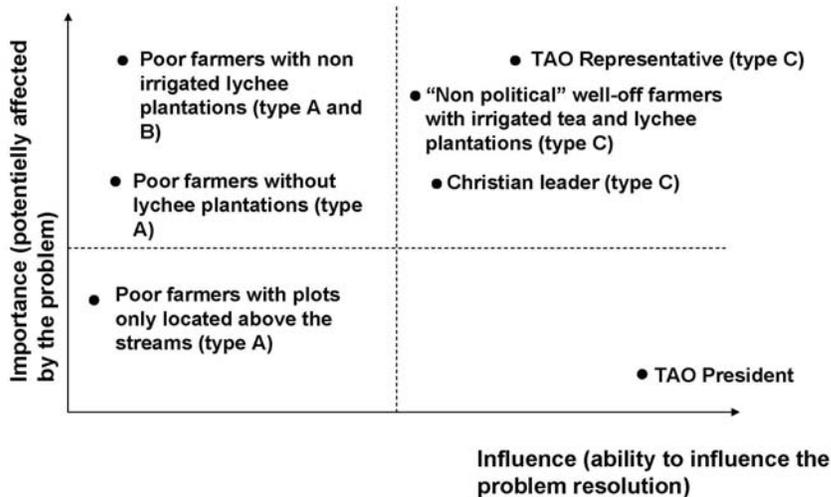


Figure 2. Matrix showing the relative influence and importance of the main stakeholders regarding the water management issue in Mae Salaep, northern Thailand.

Type C farmers are well-off, belonging to influential clans of first settlers. Fifteen years ago, they started to irrigate their orchards and claimed that the first-come-first-served rule was an ancestral custom to regulate access to water. Using their high economic status and their traditional authority to exert power, they reinforced this rule when more villagers sought access to water. As a result, most of type A and B farmers do not have access to irrigation water. Some of them do not feel concerned by this issue since their plots are located above the streams and could not benefit from gravity irrigation anyway. But some others start to complain about the 'lack of water' in the catchment, especially the farmers with small lychee plantations who could increase their production if they had access to irrigation water during the dry season. Most of them, however, do not question the first-come-first-served rule, since they are usually in a relation of dependence (or patronage) with the powerful type C clans from whom they borrow money when needed or work as daily hired laborers on their farms. Two opposing leaders played a key role in this ComMod cycle about water. The first one is one of the two elected villagers sitting on the TAO council. He recently concluded a deal with an external investor who bought a very large piece of land in the village catchment to plant Oolong tea in the future. As such a plantation would require a lot of irrigation water, he had a strong personal interest in participating in this ComMod process. Another key stakeholder of the process is the religious leader of the village Christian community (60% of the village population). He is a respected person in the village, not only as a religious leader but also as a leading innovator and a knowledgeable person on agricultural matters, actively supporting poor households facing difficulties (by providing technical advice, through free distribution of tea seedlings, for example). He was the first one who suggested to the research team to use the ComMod tools to discuss water management issues in the community.

Methods

This ComMod cycle started with field interviews about the water problem in the community and its related sociopolitical context. The RPG and the associated ABM used in the previous cycle were modified to address the irrigation water-sharing issue and used in a three-day participatory workshop. On the first day, gaming sessions were organized with 12 villagers-players (Box 1 and Figure 3.b). After a first session played with rules corresponding to the current water-use situation, a collective debriefing was organized for the participants to discuss the problems encountered in this gaming session and their possible solutions. A second gaming session allowed them to test these potential solutions by modifying the initial rules of the game. On the second day, individual interviews were conducted to understand better the players' behaviors during the game and the plenary discussions, to validate the model of the game, and to assess its learning effects. On the third day, participatory ABM simulations were conducted to support plenary discussions about possible future scenarios (Figure 3.a). An original feature of this semi-autonomous or hybrid ABM was the possibility to run very interactive simulations in which some of the decisions were taken by the villagers, while others were taken by artificial agents. At each time step, the simulation stopped when it was time to allocate water among the farmers, and the 12 participants in the game (corresponding to 12 'Farmer' agents in the model) had to decide together how they would allocate the water among them. Three weeks later, new simulations were conducted within smaller and more homogeneous groups of farmers to accompany the evolution of discussions about water allocation in the village. To assess the short-term and mid-term effects of the ComMod process, individual interviews were conducted 3 weeks, 3 months, and 10 months after the workshop.

The 12 participating villagers play the role of farming households managing their farm. They are given various amounts of land resources, family labor and financial means according to the actual farming conditions of the three main socio-economic types of farming households in the village (types A, B and C for poor, medium and well-off farms respectively). Their plots are located on a 3D gaming board representing a small catchment with two creeks running into a river. Each year, the players successively:

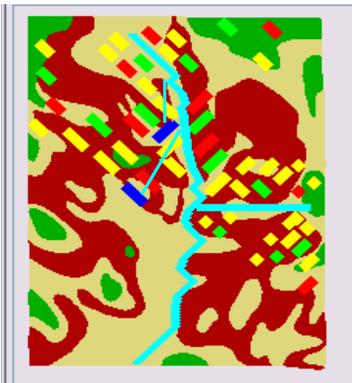
- Go to the "credit desk" to ask for credit if needed,
- Decide whether or not to send some family members to work off-farm in town,
- Assign a given crop to each of their fields (taking the labour and financial constraints into account),
- Decide whether or not to invest in water pipes for irrigation,
- Go to the "market desk" to sell their farm products and to pay for their expenses,
- Go to the credit desk to reimburse their credit if needed.

The situation at the beginning of the game is similar to the situation of the village 20 years ago: the players have neither perennial crops nor pipes for irrigating them yet.

The representation of the water system is highly simplified. Farmers can set up pipes in creeks for gravity irrigation. Depending on rainfall, that varies randomly each year, one creek can provide

Box 1. Main principles of the RPG focusing on water management in Mae Salaep.

3.a. Model's spatial interface



3.b. Gaming board



Figure 3. Similarities between the gaming board and the spatial interface of the agent-based model used in the ComMod cycle focusing on water management at Mae Salaep, northern Thailand.

Results

Increased awareness of the problem to be solved collectively

During the first gaming session, the players acted in the game as in reality: the well-off farmers urged to install their pipes first, and did not allow others to get water from the upstream sections later on. This highlighted the current conflict due to the first-come-first-served rule and increased the participants' awareness of the problem, its urgency, and the need to solve it collectively. As a village leader said during an interview: 'no need to say anything, the game showed to everyone that we need to change the water allocation rules.'

During interviews before the gaming sessions, well-off farmers who had access to water always said: 'there is no water problem in the village, no conflict, everything is all right.' They had obviously a good BATNA (Best Alternative To Non Agreement), and more interest in maintaining the status quo than being part of a process raising the water problem. If the ComMod process had started with a more classical meeting in which communication skills prevail, the water-sharing problem might not have been put on the agenda of the discussions. The game facilitated a different form of communication that allowed the less powerful villagers to raise this problem and to create a collective awareness of its existence.

Exchanges of perceptions among stakeholders about the problem

The ComMod process also stimulated exchanges of perceptions among the participants about their common water problem. Ten out of the 11 participants interviewed after the gaming sessions said that the game allowed them to understand better the other villagers' situations, problems, and/or perceptions. Players without access to water could see that 'many villagers faced the same problem,' while well-off farmers with water access realized that the first-come-first-served rule would create more and more social tensions under the current expansion of irrigated

plantations. Such a result might be surprising at first sight, since these villagers belong to a small community in which they all know each other, but as a participant said: 'in everyday life, every one goes to his fields; we do not have such opportunities to discuss together.'

Problem reframing and integrative negotiation of possible solutions

Once the problem was identified, the ComMod activities facilitated a collective process of problem reframing and integrative (or win-win) negotiation. First, the TAO representative suggested building a single reservoir for the village. This idea was rejected by the other players who feared that this would benefit only a minority of households. Later on the religious leader suggested building small weirs on each creek, and sharing water among small groups of households. This idea was accepted by the majority by vote. It is interesting to notice that this leader did not openly put into question the first-come-first-served rule because he knew that the well-off clans would not accept it. He suggested instead a more integrative solution which was acceptable to them: he said the problem was the lack of water, therefore new water storage infrastructure was needed to increase the volume of water available at the village level. Then, when such infrastructures would be built, farmers would have to discuss again the water allocation rules. As several players stated, 'new infrastructures are the only way to change the rules.' This was a typical integrative negotiation process in which stakeholders looked for solutions to 'increase the size of the cake' instead of fighting about the way to 'divide the cake.'

Collective evaluation of solutions through interactive simulations

The small weirs solution was collectively tested in the second gaming session. It stimulated discussions among players regarding the way to share water among beneficiaries of the weirs facilitated by the hybrid ABM. During the first set of participatory simulations in plenary session, the member of the sub-district administration (a well-off farmer) imposed sharing water proportionally to the farmers' plantation size. But three weeks later, the participants had continued to discuss this point, and during the simulations, within each small group, they collectively decided to simulate the sharing of equal volumes of water among them, adding that there should be a possibility to lend, temporarily, water rights to other farmers in case the volume of water available exceeded ones needs. This illustrates the importance of discussions occurring between field workshops and the necessity to monitor them and take them into account.

Discussion

Empowerment of the resource-poor stakeholders: a levelled playing field

Aware of the fact that power inequities express themselves in a participatory process, and of the subsequent risk of increasing social inequities, much attention was paid to the initial sociopolitical context to ensure the genuine involvement of all concerned stakeholders, including the usually voiceless ones. This ComMod process successfully empowered them in the negotiation arena and allowed them to voice and assert their interests. This was achieved through a process of both personal and collective empowerment. The ComMod activities improved the participants' self-confidence and supported the development of their capacity to understand the situation and imagine new solutions: "I am so proud. I did not know that I would be able to play the game, to think by myself about solutions," said a female participant. As for collective empowerment, 7 out of the 11 interviewed participants claimed that the game made them realize that they were collectively 'stronger' or 'more intelligent' (in their own words) than individually. This ComMod process also triggered a process of collective empowerment through the creation of alliances allowing the reinforcement of a counter power as the less powerful stakeholders realized that they could join a charismatic leader (the Christian leader) to make their voice louder. "If I think alone, I do not have good ideas. But if we think all together, we can all benefit from the good ideas of people like the Christian leader," said a woman.

Negotiation with higher level institutions: the main limit of the process

Ten months after the last workshop, the villagers had prepared a document to request funding from their TAO to build new water infrastructure. Unfortunately, the president of this administration rejected their proposition, in spite of her previous discourses about the importance of villager's participation in local politics and management of renewable resources. This was the main limit faced by this ComMod process and one of the key future challenges.

Conclusion

How can simple models catalyze collective learning and action about local water management? This paper demonstrates that a model's usefulness relies much more on the modeling process than on the model itself. Moreover, although water management issues are complex, when the model aims at facilitating collective learning and communication, there is no need for exhaustive models computing a large amount of data. Very simple models can be very useful. Their simplicity is even an advantage, as it facilitates the understanding and appropriation of this model by local stakeholders. Such simple models also have the advantage to be highly adaptive, and can be easily modified to accompany evolving local stakeholders' representations and preoccupations. The modeling process itself, however, should not be 'quick and simple,' but carefully participatory to ensure the genuine involvement of the concerned stakeholders.

To sum up, what we call a carefully participatory process or a critical companion modelling process includes:

- An initial analysis of the sociopolitical context to identify constraints to an equitable outcome of the process and to mitigate them by adapting the tools and methods used;
- The careful selection of participants to ensure that all participants are able to defend their interests and, eventually, to empower some of them through increased self-confidence and creation of alliances;
- The use of tools that are accessible to all kinds of stakeholders, whatever their level of formal education;
- The use of tools and methods highlighting the diversity of interests so that all interests are taken into account during the debates, even the usually voiceless ones;
- The use of tools and methods favoring integrative or win-win negotiation processes that are acceptable to influential and more marginal stakeholders;
- Alternating plenary discussions, small group debates, and individual interviews, to ensure that all stakeholders feel free to express themselves (sometimes not in the presence of the most powerful stakeholders);
- Not to stop at the first apparent consensus as it often reflects the most powerful stakeholders' opinion;
- A continuous and iterative process to favor and accompany discussions behind the scene, where most of negotiation processes finally take place; and
- The need for a specific monitoring and evaluation system to know what happens between two gaming and simulation field workshops.

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