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Soil Fertility and Climatic Constraints in Dryland Agriculture

Proceedings of ACIAR/SACCAR Workshop
held at Harare, Zimbabwe,
30 August–1 September 1993

Editors: E.T. Craswell and J. Simpson

Australian Centre for International Agricultural Research
Canberra 1994

Contents

Foreword

Agriculture in Eastern and Southern Africa has to cope with unpredictable seasons, gradual loss of soil fertility, soil degradation, increasing pressures by human and livestock populations, and the restricted resources (cash, labour, and drought) of many farm households. Combined these produce stagnation or decline in productivity and reduce capacity to invest in improved management. The relative importance of these factors will vary between districts, depending on exact soil types, rainfall expectations, social/political issues etc, but the general syndrome is consistent and widespread, and indeed is shared by many farmers in dryland areas of Australia. Definitive and comprehensive research providing clear and appropriate recommendations for better and sustainable management of the available resources is still urgently needed.

This volume records the proceedings of a workshop held to consider the problems of dryland agriculture. The workshop was organised jointly by ACIAR and the Southern African Centre for Cooperation in Agricultural Research and Training (SACCAR) with three main objectives in mind:

(a) to survey the commonality of problems facing small-scale farmers within the semi-arid zones of the SADC region, and recent research on those problems, including its possible development into techniques that are adoptable by farmers;

(b) to present and discuss the findings of the recently completed ACIAR/KARI project in eastern Kenya (1984–93) which defined some new scientific approaches to analysing the feasibility of different management options for small-scale farmers in semi-arid areas;

(c) to examine the opportunities for increased research collaboration between the SADC countries, Australia and the International Centres.

The sixteen papers recorded in these proceedings were presented before an audience of some 40 participants and several local observers in the first two days of the meeting. Agricultural researchers residing in Zimbabwe plus the Australian group made up the bulk of the audience. Other SADC countries (Malawi, Tanzania) and Kenya were well represented. The meeting was opened by the Australian High Commissioner in Harare, His Excellency Mr J Thwaites. Researchers from International Agricultural Research Centres (CIMMYT, IBSRAM, ICRAF, ICRISAT, IFDC, IFPRI and ILCA), and from the African Centre for Fertilizer Development and the World Bank, Harare, also took part. Their participation was especially appreciated.

Particularly valuable was the discussion on the third day which was spent in working groups and in plenary sessions to formulate recommendations on future research in semi-arid areas of southern Africa. Opportunities for research collaboration at national, regional and international levels were explored and the outcome is summarised at the end of this proceedings.

ACIAR acknowledges with sincere appreciation the cooperation and help of several groups. The enthusiasm and support of Dr M L Kyomo, Director of SACCAR, was essential. In Harare, an informal committee comprising the Director of Research, Mr R J Fenner, the acting Head of Agronomy, Mrs D. Hikwa (both of the Department of Research & Specialist Services) and Dr S R Waddington of CIMMYT, guided the early organisation of regional contributions. Staff from the Australian High Commission in Harare helped with preparations for the meeting. Local knowledge and enthusiastic help with all the detailed arrangements by Ms Judith Ward was especially valuable. Finally I want to thank Ms Maureen Kenning of ACIAR Communications Program who helped prepare the proceedings for publication.

G H L Rothschild
Director
ACIAR

Overview of the Current Situation and Previous Impact of Adaptive Agricultural Research in Southern Africa

Stephen R. Waddington*

Abstract

This paper appraises the contribution made by a decade of Farming Systems Adaptive Research (FSAR) to the improvement of productivity in smallholder cropping systems of southern Africa, with emphasis on the management of soil fertility and climatic risk in maize.

FSAR programs in southern Africa have been successful in diagnosing production constraints in maize crops and in developing relevant new research opportunities to overcome those constraints. There are also many examples where FSAR has successfully modified technology to feature reduced inputs at levels suitable for smallholders, adjusted management to fit smallholder circumstances and operational constraints, or introduced methods that enable farmers to move toward known ideal practices, but few have led to significant adoption of adapted technology by smallholder farmers.

Technical reasons for this modest impact from FSAR include over-reliance on 'fine tuning' of existing technology (often appropriate technologies from commodity or disciplinary research did not exist for semi-arid areas), and shortcomings in the conduct of FSAR, such as excessive emphasis on site-specific on-farm trials of conventional design coupled with standard analysis and interpretation of results.

The closer integration into FSAR of (a) plant improvement (to develop genotypes more efficient in their use of water and mineral nutrients), (b) crop modelling (to help focus on suitable technology combinations and assess climatic risk), and (c) geographic information systems (to target technology to specific agroecological areas or groups of farmers), along with the incorporation of a longer-term natural resource management perspective, will lead to a more robust research approach that better addresses the technology needs of smallholders.

Background

Characteristics of smallholder farms and maize-based cropping systems

The vast majority of farm households in southern Africa use their own resources, especially family labour, to produce crops (and often livestock) on 0.5–10 ha of land held under traditional tenure arrangements. Since most smallholder farmers do not own the land they farm, they lack collateral for commercial loans to purchase inputs and generally rely on assistance through government schemes. In large parts of the region, particularly southern Zambia, Botswana and much of Zimbabwe, animal (mainly oxen) traction is used to prepare the land and help weeding, while in Malawi, northern and eastern Zambia, and northern Mozambique human labour using hand-held hoes is the predominant power source.

Generally, maize exceeds 60% of the total smallholder crop area in sub-humid zones and is also an important cereal in many semi-arid areas. It is grown predominantly in loose rotations with such crops as groundnuts and sunflowers, and is often sparsely intercropped with beans, groundnuts, cowpeas or pumpkins. For semi-commercial crops such as maize, seed for planting and fertiliser are the main purchased inputs. Table 1 summarises the main characteristics of smallholder maize-based cropping systems in southern Africa.

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Table 1. Summary characteristics of main Smallholder Maize Production Systems in southern Africa*.

System characteristic	Ox cultivators		Hand-hoe cultivators
	Sub-humid	Semi-arid	
Maize croppings			
Total maize area (000 ha)	1250	1100	1700
Percentage of total area	31	27	42
Maize area per farm (ha)	2 (1–10)	1 (0–4)	0.75 (0.25–2.5)
Average yields t/ha	1.5–2.5	0.25–0.75	0.75–1.25
Physical environment			
Annual rainfall (mm)	700–1200	300–700	700–2000
Elevation m a.s.l.	1000–1800	100–1200	400–1600
Major soil textures	sandy loam sandy (>70%) some loam and clay loam	sandy loam loam (>90%) some clay	mixed but mainly loam, clay loam and sandy loam
Farming systems locations			
Main geographical locations	central and north Zimbabwe central and southern Prov. Zambia Lesotho and Swaziland	southern Zimbabwe southern Mozambique Botswana	Malawi eastern Prov. Zambia northwest Mozambique
Other crops in addition to maize (% arable land occupied)	groundnuts (20) finger millet (10) sunflower (5) cotton (5), beans	sorghum (10–60) groundnuts (10) Millets (10–30)	groundnuts (20) finger millet (10) cassava (5–10) several grain legumes intercrop with maize
Intercropping			
Percentage of area	5 (but most as sparse pumpkin and cowpea intercrops)	2	20–80
Main species	pumpkin and cowpea	cowpea	groundnut, beans cassava chickpea, pigeonpea
Cattle	Important	Very important	Not important
Percentage farm output sold for cash	50 +	<25	15
Main maize practices			
Main varieties	hybrids 80%+ (e.g. R215,MM603) 'local' maize	hybrids approx. 70% (e.g. R201, MM504) 'local' maize	'local' maize 80%+ composite (5%) hybrids (10%+)
Fertiliser use			
Percentage area fertilised	80	20	20
Average application (kg/ha^{1})	80–120N, 10–20P	20–50N, 5–10P	20N, 5P
Weed control	Mechanical/hand-hoe (some delays, especially on later plantings)	Mechanical/hand-hoe (delays for on-row weeds)	Hand-hoe (large delay for part of crop)

*Botswana, Lesotho, Malawi, Mozambique, Swaziland, Zambia, Zimbabwe

Achievements of FSAR in Southern Africa

Since the late 1970s and throughout the 1980s a Farming Systems Adaptive Research (FSAR) approach has been widely used by national agricultural research systems (NARS) in southern Africa to develop and adapt agricultural technology suited to the needs of smallholder farmers. FSAR has tended to be commodity- and location-specific, and to focus on incremental change in production practices and inputs to ease their adoption by farmers. The emphasis was on solving short-term production problems. This was done through informal diagnostic surveys that identified and characterised on-farm production constraints, on-farm experiments that modified and tested technology under farmer circumstances, and the use of criteria for technological acceptability besides biological performance, such as timing of food availability, cooking and storage quality, breaking labour or draught power constraints, cropping system compatibility and risk (e.g. Collinson 1987; Low and Waddington 1991; Tripp 1992).

FSAR has had two core roles in the region:

- to diagnose, identify and quantify production problems (and their related research opportunities) in key farm crop enterprises, and
- to adapt or test technologies (inputs, equipment or techniques) to address identified production problems and better suit the needs of smallholder farmers (Collinson 1987; Low and Waddington 1991; Waddington and Heisey 1991).

The following paragraphs summarise CIMMYT's perception on the achievements of FSAR in southern Africa, concentrating on the two core roles given above, with examples related to the management of soil fertility and climatic risk for maize. This summary draws heavily on the comprehensive reviews of Low and Waddington (1990, 1991), Low et al. (1991), and proceedings of a regional network workshop on impacts of on-farm research in eastern and southern Africa (Heisey and Waddington 1993).

Identification of production problems

Observers agree that FSAR programs in southern Africa have been successful in diagnosing production constraints in maize and other crop enterprises and in developing relevant new research opportunities to overcome those constraints. Table 2 illustrates several examples related to soil fertility and risk management.

Table 2. Examples of production constraints for maize related to soil fertility or climatic risk identified through adaptive research on smallholder farms in southern Africa.

Production problem and location	Research opportunity
Current long-cycle hybrids perform poorly in areas with a short rainy season or under late plantings, where late weeding is done or little fertiliser used.	Develop earlier maturing hybrids and open pollinated varieties (commodity research). Test widely with farmers under their conditions and assessment criteria
Late planting is common and it greatly reduces yields. All current recommendations assume early planting.	Develop maize adapted to late plantings (earlier maturity, tolerance to low soil fertility and to weeds) (commodity research) and test on-farm. Bring forward timing of topdress fertiliser.
Draught power shortage is common in ox-plough systems, leading to late planting.	Adapt zero and reduced ox tillage systems on-farm.
Basal and topdress fertiliser are often applied late. Little is known about fertiliser rates for open pollinated maize, planted late on sandy soils.	Modify timings and rates of fertiliser to fit smallholder capability and for OPVs in semi-arid areas and late plantings.
Late and inadequate weeding is common in smallholder maize.	Look at chemical and mechanical weed control to reduce labour and draught power needed for weeding.

Adaptation and testing of technologies

When the development, adaptation and testing of improved technologies for adoption by smallholder farmers, mainly through participatory adaptive on-farm trials and demonstrations, are examined the current outcome is more mixed. There are many examples of FSAR successfully reducing inputs to levels suitable for smallholders, adjusting management to fit smallholder circumstances and operational constraints and introducing methods that enable farmers to move toward known ideal practices (Low and Waddington 1991). Table 3 illustrates examples related to soil fertility and reduced climatic risk for maize.

In addition, FSAR has had some success in orientating commodity or disciplinary research to develop technology appropriate for smallholders. For maize, most of the clearer examples involve orientation of plant breeding efforts that include encouragement to develop semi-flint hybrids in Malawi and offer earlier-maturing 'open pollinated varieties' (OPVs) and hybrids in Zambia. Indeed the greatest long-term impact of FSAR in this region may not come through its directly placing more appropriate technology in the hands of smallholders, but by bringing together different agricultural research and extension approaches and technical and socioeconomic staff to focus on their needs.

Compromised impact of FSAR

Despite these successes, it is widely appreciated that there has not been widespread adoption by farmers of technology outputs from FSAR. In a study of 53 FSAR initiatives from Swaziland, Zambia and Zimbabwe undertaken in 1991 (Low and Waddington 1991; Low et al. 1991), only 15 initiatives had led to any adoption by farmers, of which just three technologies, all involving new varieties, were widely adopted. Recent evidence suggests FSAR has had some further, but modest, impact on farmer practices in this region (e.g. Chikura et al. 1993, Zimbabwe, and Warland et al. 1993, Swaziland).

Analysis suggests a variety of reasons why FSAR impact on farmer adoption and productivity has been moderate and slow. These range from simple over-expectations by donors and others of what FSAR could do, through technical shortcomings within FSAR concerning over-reliance on 'fine tuning' of existing technology, with on-farm trials that were often inadequately designed, implemented, analysed and interpreted, to those of a more socioeconomic and institutional nature. Included are overemphasis on separate FSAR units divorced from the rest of agricultural research, insufficient awareness of intra-household decision-making and gender issues in farming, ineffective links with extension services, and failure of FSAR to address deficiencies in input

Table 3. Examples and impacts of technologies to address soil fertility or climate risk for smallholder maize production from on-farm adaptive research derived in southern Africa.

Example of Technology	Reasons for outcome
Outcome: Led to wide adoption of technology by farmers	
Shorter season open pollinated varieties and hybrids with semi-flint grain widely tested on-farm in Malawi and Zambia	— provide food during hunger period — suited to on-farm storage and processing — good performance with little fertiliser
Outcome: Demonstrated advantage over current practice but little adoption	
Zero tillage with herbicide in Zambia On-row tillage with herbicide in Zimbabwe Herbicide weed control on Swaziland Combined weed and fertiliser management in Zambia, Malawi and Zimbabwe	Many and varied reasons for non-adoption include: — little support by extension — implement unavailable — high cash cost to start using — training needed
Outcome: Confirmed superiority of farmer practice over standard recommendation	
Application of basal fertiliser at planting in Zimbabwe	— yield gains were minor compared to farmer practice of applying 1–2 weeks after planting — farmers reluctant to apply until seedlings emerge — labour shortage at planting time — slows down planting process
Outcome: technology shown to be ineffective on-farm	
Tied ridges to stabilise yield on granitic sandy soils in NR 3 and 4 in Zimbabwe	— little yield increase obtained in dry years but yield decreased in wet years due to waterlogging and low soil fertility in furrows

supply and marketing and to respond by targeting agricultural policy makers with appropriate information (e.g. Low and Waddington 1991; Low et al. 1991; Tripp 1992; Waddington 1993).

Technical shortcomings in FSAR

There is no doubt that technical shortcomings within FSAR have constrained its impact. For example, in the analysis of 53 FSAR initiatives from Swaziland, Zambia and Zimbabwe, Low, Waddington and Shumba (1991) found that about 50% of the failures of initiatives before adoption by farmers were due to implementation deficiencies in FSAR, mostly related to on-farm trials.

Technical shortcomings within FSAR include:

- superficial characterisation of production problems and causes and difficulties in identifying the bounds of target groups because of reliance on single-visit informal surveys of farmers in small geographical areas;
- lack of systematic planning procedures which, until recently, meant that the rationale for research thrusts was often questionable;
- over-reliance on complex (multi-factor) on-farm experiments with conventional designs from on-station research, leading to difficulties implementing trials and analysis and interpretation of the results;
- difficulties in extrapolating research results from location-specific on-farm trials to a wider farming community, meaning uncertainties of the value of research results outside the immediate research zone; and
- deployment of inexperienced staff and high staff turnover of staff (e.g. Waddington and Low 1988; Low and Waddington 1991; Shumba 1991; Waddington 1993).

For FSAR in more marginal, semi-arid environments, some inadequacies are more common and have more serious implications. There is large micro-variation within sites (leading to high coefficients of variations in on-farm trials) coupled with large variation in rainfall and soil types over sites (which requires testing at many sites and over several years), and often operational problems in working a long way from home base (Chiduza and Nyamudeza 1990). In some semi-arid areas many on-farm experiments conducted over almost a decade have led to little that can be recommended to farmers (Jeranyama 1992, for Chivi, Zimbabwe).

It should be no great surprise that these inadequacies exist. As an holistic approach to research, FSAR was developed by social scientists, and in early years drew on agronomic techniques then available. Only over the last few years have agronomists, biometricians and other technical scientists begun to develop or modify techniques specifically for FSAR. Examples of recent improvements in FSAR methods include multi-visit agronomic monitoring of crops in farmers' fields (Byerlee et al. 1991), and new experimental designs that better cope with micro-variation (Mead 1990).

These technical shortcomings can be reduced by the wider use of procedures that already exist within FSAR, such as systematic planning procedures for on-farm experiments, use of simpler on-farm trials that can be analysed statistically across many sites and seasons, newer experimental designs that account for variability, thorough agronomic and biological interpretation of results (including explanation of within-site treatment interaction in trials), economic analysis and assessments of risk, and closer farmer participation in the research process (Waddington 1993).

Combining additional research approaches and tools with FSAR

It seems impossible for the techniques described to bridge the gap between the current reality of FSAR and the technology needs of smallholder farmers in southern Africa. What then are the alternatives?

First, it seems unlikely that there are serious alternative research frameworks or approaches that can do better than FSAR in providing smallholder farmers with beneficial technology that they want to use. With FSAR now well established in NARS, a more constructive approach is to look at which additional research approaches and tools can be combined with FSAR to reduce the limitations of current FSAR procedures.

Role of crop improvement

For semi-arid areas, in particular, experience is that for most agronomic inputs and practices (such as ridging systems, fertiliser) that imply certain recurrent costs but uncertain benefits, risk-averse smallholder farmers are reluctant to adopt them. On the other hand, improved seed is usually a cheap input (although the large development costs may have been absorbed at national level) and readily adoptable.

Plant breeding for genotypes more efficient in their use of limited chemical resources such as water and mineral nutrients will continue to reduce the risk associated with cropping in marginal areas and open new opportunities for agronomic research. As an example, CIMMYT at its headquarters in Mexico and in this region is developing maize with improved tolerance to water deficits and with higher N fertiliser-use efficiency (Short and Edmeades 1991).

Crop growth models and geographic information systems

Computer-based crop growth models and what have become known as geographic information systems (GIS) (e.g. Nix 1987) have great potential for increasing the efficiency of adaptive agricultural research in Africa. Among other things they help predict the effects of crop inputs and management under variable rainfall and soil fertility regimes (reducing the need for empirical on-farm trials), and can delineate target agroecological areas or groups of farmers for which a particular technology is appropriate (e.g. Dent and Thornton 1988; Keating et al. 1992).

Yet, while biological simulation models and GIS have many benefits for adaptive research, such models have, as yet, several major limitations. Firstly, there is a lack of confidence in outputs from crop models in marginal areas of southern Africa because their performance has yet to be tested for such areas and because sufficient minimum input data may not be available from such areas (Chiduza and Nyamudeza, 1990). Secondly, current models are insensitive to many sources of variation and complexity in smallholder cropping systems, such as crop–livestock interactions, rotations, weed competition and intercropping (Dent and Thornton 1988; Thornton et al. 1990). Thirdly, while adequate GIS databases are probably available for rainfall and temperature, those on soils, soil fertility, and cropping systems are not complete and too general, while those on biotic constraints such as weed pressure have yet to be compiled.

Even when versions of models with these sensitivities become available and when sufficient input data are amassed, the application of crop growth models and GIS should not be viewed as a new panacea. Evidence is already available to show that when applied to smallholder farming in Africa, the thoughtful use of crop models may not lead to major modification in farmer practice. The excellent work with the CERESMaize model in semi-arid Kenya at Katumani (Keating et al. 1991; Keating et al. 1992) and the associated work on response farming (Stewart 1991) led to greater understanding by researchers of interactions between maize plant density, moisture and N fertiliser, and to the demonstration of clear benefits from application of amounts of N fertiliser conditional on rainfall events early in the cropping season (Wafula et al. 1992). Yet while researchers became more confident about promoting N fertiliser on maize in semi-arid eastern Kenya, such benefits were not easy for farmers to appreciate, and few farmers have so far adopted the practice. There is a major challenge for adaptive research and extension, (Wafula et al. 1992; Muhammad and Parton 1992).

While there is a long way to go in perfecting models for traditional African smallholder farmers, now is the time to integrate them into the mainstream of agricultural research for smallholders in this region. This workshop has provided such an opportunity.

A 'sustainability' perspective

The incorporation of a natural resource management or sustainability perspective into agricultural research presents new challenges and opportunities for FSAR. The last five years or so have seen intense researcher and donor interest in the maintenance of biophysical resources such as soil water, mineral nutrient cycling and organic matter in smallholder farming systems and the often complex or composite technologies that may help, such as multiple cropping, agroforestry and integrated pest management.

Pure sustainability research has some characteristics not especially compatible with FSAR. Among these Posner and Gilbert (1991) identified long research lead times, scientific complexity, lack of proven technologies and incompatibility with the production objectives of farmers. But a shared concern for the future (and some donor pressure) has led to FSAR taking on some of the sustainability perspective. For example, the most successful FSAR program in southern Africa, Adaptive Research Planning Team in Zambia, has for several years had long-term on-farm experiments that tackle soil fertility restoration or improvement (ARPT 1991). An integration of the sustainability perspective should be the way ahead, rather than separate 'sustainability researchers'. FSAR can provide sustainability researchers with expertise in working on smallholder farms, where most of the sustainability problems exist, through experience in running on-farm trials. FSAR knowledge of farmer adoption behaviour also is vital in tailoring technology that combines long-term resource conservation with near-term productivity increases, to encourage adoption.

Conclusion

The following papers cover in detail some of these additional research approaches and tools, especially modelling. They examine how, given their current state of development, such tools help research that targets soil fertility and climatic constraints in smallholder dryland agricultural systems in southern Africa. The challenge is to decide what these approaches can offer southern Africa, and how they can be integrated with more established research approaches better to address the long-term technology needs of smallholders.

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Maize Water Use as Affected by Nitrogen Fertilisation

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Abstract

The effects of nitrogen fertiliser on yield, water use and water use efficiency of maize were investigated at two sites in Zimbabwe during the 1992–93 season (Makoholi and HRC, Marondera). Crops in 1991–92 at the same sites had failed due to drought.

At both sites grain yield responses to N were large (increases up to 2 t/ha) but total water use at each site was not significantly changed. Thus water use efficiency improved from 1.6 to 4.9 and from 2.4 to 5.4 kg/ha/mm at the respective sites.

The implications of these findings in terms of understanding nitrogen and water interactions, and for modelling crop growth in semi-arid environments, are discussed.

DRYLAND farming systems revolve around the principle that water is the main limiting factor, and to increase or maintain an adequate level of yield, one must maximise the water use efficiency (WUE) for crop production. While research work by the Department of Research and Specialist Services (DR&SS) in the semi-arid communal areas of Zimbabwe has covered a wide range of topics over the years, the results of most agronomic treatments can be interpreted in terms of their influence on the water and nitrogen balance. Plant populations, planting date, fertilisers, rotations, intercropping and soil surface management have all been studied in this context. A common problem that links most of the research work has been the difficulty of interpreting research results that vary greatly in response to seasonal variations in rainfall amount and distribution.

Under dryland conditions, crops are subjected to unpredictable periods of high moisture stress between rains. If in these periods of limited moisture fertilisers can increase the nett assimilation rate or growth without exhausting water at a faster rate, then total yield and WUE can be increased. If fertilisers accelerate the rates of both growth and water use (WU), the yield and WUE will depend on the total supply of water and the status of the crop when the moisture supply becomes exhausted. Thus accelerated WU through fertilisation can be disastrous for grain crops if the moisture supply is exhausted and the rains do not come before the grains are filled.

Past reviews demonstrate that water requirements of crops grown on poor soil may be reduced by half to two-thirds by the addition of fertilisers (Viets 1962). Some workers conclude that each plant must attain a certain mass before grain production can begin, that the critical mass is somewhat greater for plants grown in infertile soil, and that WUE is less for crops grown on infertile soil, resulting in a much greater water requirement to begin grain production under such conditions. The favourable effects of fertilisers, when nutrients are deficient, on the mass and distribution of roots have been reported and are generally well known. In general, fertilisation promotes top growth faster than root growth, leading to an increased top to root ratio. Some studies suggest that the improved WUE by fertilised crops was accomplished without noticeable increase in total water consumption. However, there are only a few reports on the concurrent effects of N fertiliser on total water extraction and on vertical and horizontal changes in the extraction patterns. Changes in depth of rooting or ramification of roots in the soil would be of particular importance under conditions of limited moisture supply where full exploitation of soil moisture would be of greatest significance.

In the current study, soil moisture measurements were undertaken beginning in the 1991–92 season on field plots of maize. The basic objective of the

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experiment was to determine the amount and pattern of water use of the maize variety R201 fertilised with varying rates of nitrogen under rainfed conditions on sandy soils.

Experimental Procedures

During the 1991–92 season one experiment was established at Makoholi Experiment Station (see Table 1). Two planting dates and six rates (0, 30, 60, 90, 120 and 150 kg/ha) of nitrogen fertilisation treatments were planned. The first planting was done on 17 December 1991, but emergence and plant establishment was so poor that the crop had to be replanted on 22 January 1992. The planned second planting was done one week later. Nitrogen was applied in the form of ammonium nitrate. A basal dressing of 30 kg N/ha was applied to all plots except for the controls. Due to the dry weather conditions no N topdressing was applied. The crop was sprayed with Thiodan to control blotch web.

Table 1. Site characteristics.

Site	Natural region	Soil type	Mean annual rainfall (mm)
Makoholi	IV	5G	614
HRC	11a	7G.2	885

Soil Types: (see Thompson and Purves 1978)

5G: kaolinitic order (fersiallitic group), moderately shallow, greyish brown, coarse grained sands throughout the profile formed on granitic rocks.

7G.2: kaolinitic order (orthoferrallitic group), moderately deep reddish brown, coarse grained sandy loams over yellowish red clay.

In the 1992–93 season two experiments were established, one at Makoholi and the other at the Horticultural Research Centre (HRC), Marondera (see Table 1). The three rates of nitrogen fertilisation were 0, 30 and 60 kg/ha. Soil moisture determinations were done every two weeks at Makoholi, using gravimetric sampling for the top 0–15 cm soil layers and using a neutron probe (CPN 503DR Hydroprobe) for the deeper soil layers down to a depth of 90 cm. At HRC, soil moisture determinations to a depth of 45 cm were done gravimetrically. For all experiments there were three replications.

Water consumption by the crop was computed from the sum of water in the profile at the beginning of the season plus seasonal rainfall less profile moisture at harvest. Evaporation loss during the growing season accounts for part of this total consumption value. A correction was made allowing for around 10% runoff of the rainfall, to make moisture consumption values more realistic. Although strictly empirical and no doubt an over- or under-estimate in many cases, the error in this correction is presumed to be identical for all treatment levels.

Results and Discussion

Cumulative water use, grain yields and water use efficiency

During the 1991–92 season there were no measurable responses to fertiliser application as the crop was severely affected by the drought. The first planted crop received a total of only 82.9 mm rainfall and the second 35.9 mm. The second planting went into fairly moist soil compared to the first planting but below 15 cm depth there was negligible plant-available moisture. The crop did not reach physiological maturity due to the prolonged drought. Later inspections revealed that plant roots did not penetrate beyond 20 cm.

By contrast the 1992–93 season was fairly wet. The crops at Makoholi and HRC received 628.5 mm and 663 mm rainfall respectively. Levels of production were high at the experimental sites in response to N fertilisation, which greatly improved water-use efficiency by the maize crop at both sites (see Table 2).

Table 2. Influence of N fertilisation on total water use, grain yield and water use efficiency at Makoholi and HRC.

	Site					
	Makoholi			HRC		
Nitrogen level kg n/ha	0	30	60	0	30	60
Total water use (mm)	627.4	613.2	635.0	601.4	597.8	590.0
Grain yield t/ha	1.06	2.15	3.19	1.46	2.90	3.16
WUE kg/ha/mm	1.63	3.38	4.85	2.43	4.85	5.36

Cumulative water use and rainfall at Makoholi and at HRC during the 1992–93 season are shown in Figures 1(a) and 1(b). Rainfall kept ahead of water use throughout the growth of the crop at Makoholi. Total water use from planting to maturity for the three N treatments is shown in Table 2. The crop receiving 30 kg N/ha used rather less water than the zero N crop (P=0.05) but produced a greater grain yield. Water use differences between the three fertiliser rates increased as the season progressed. At the highest rate of 60 kg N/ha, increasing amounts of water were used to reach each growth stage, because N had increased total plant growth and developed a more effective root system. For this treatment total water use was not significantly affected but grain yield increased to 2.13 t/ha. The water use efficiency values were therefore greatly improved by N fertilisation. Stored soil water supplied 61.7, 47.8 and 69.3 mm of water to the maize grown on the three respective N treatments.

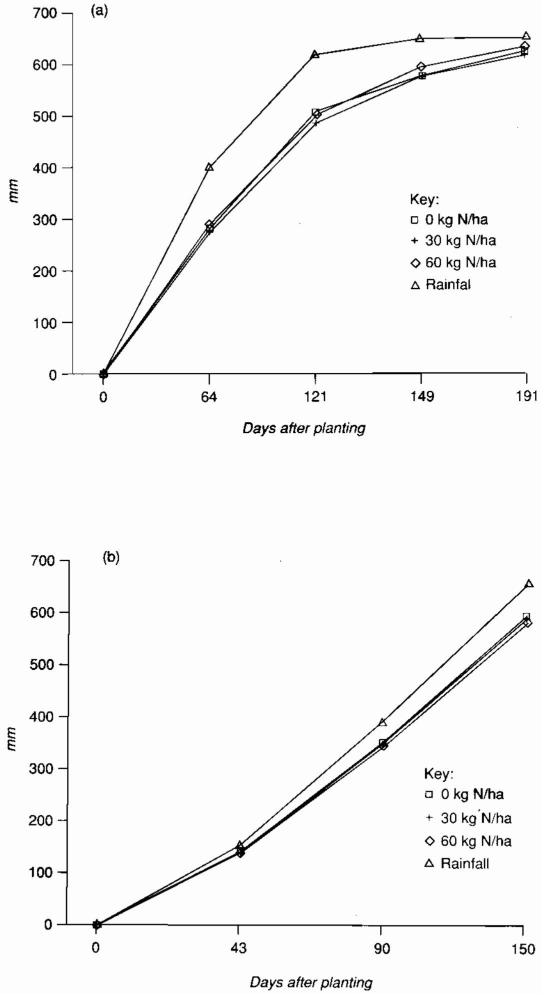

Figure 1. Cumulative water use and rainfall (a) Makoholi, 1992–93, (b) HRC 1992–93.

At HRC, N fertilisation more than doubled the grain yields and WUE values when compared to the control crop. The improved WUE with fertilisation was accomplished without any noticeable increase in total crop water use. Compared to Makoholi, the crop at HRC used, on average, less water but produced similar yields at the high N treatment. The higher total water use values at Makoholi are probably related to the higher evaporative demand (mainly due to higher temperatures and lower humidities) at this site compared to HRC. Soil moisture was progressively depleted by all crops to a depth of 90 cm.

Conclusions

The use of moderate amounts of nitrogen fertiliser in 1992–93 more than doubled the water-use efficiency compared to the control crop at both sites, increases being almost in proportion to yield response to fertiliser. In other semi-arid regions of the world, a balanced nutrient supply has been found to enable the crops to make more efficient use of the available moisture (Arnon 1975; Olson et al. 1964; Russell 1973). It has been demonstrated that a nutrient deficient plant, even though it is not growing, or is growing slowly, is using water at about the same rate as a nutritionally balanced plant, yet will produce a considerably lower yield (Brown 1971). Work reviewed by Bolton (1981) indicates that different levels of soil moisture at seeding require different levels of applied nitrogen in order to balance the moisture and nitrogen supplies for maximum water use efficiency.

Crop yields from rainfed cropping systems in most of the communal areas in the semi-arid zones of Zimbabwe are low and variable mainly due to the low and erratic rainfall and the inherently poor soil fertility of the dominant granitic sands.

There is great interest at the moment in eastern and southern Africa in the use of crop models for assessing the potential of different management strategies (including N fertiliser use) for sustainable crop production (Keating et. al.1991). Basic research on the interactions of N use and crop water use can provide a fundamental input for model development and validation. Work on calibrating and validating the CERES-Maize model (Version 2.1) for the local maize varieties SR52 and R201 is currently underway in the Department (DR&SS). Given the high variability of rainfall in the semi-arid areas of Zimbabwe and the large impact of moisture supply on N-use efficiencies, simulation models that describe the effects of weather on N supply and demand can offer an invaluable tool for assessing N-fertiliser management strategies for these areas.

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The Potentials and Limitations of Agroforestry for Improving Livestock Production and Soil Fertility in Southern Africa

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Abstract

Drawing upon a wealth of research information available for the southern African subcontinent, the potential and limitations of agroforestry for improving animal production and soil fertility are discussed. Agroforestry is reputed to incorporate essential components of sustainability and self-sufficiency into some agricultural systems. Evidence is given that agroforestry, by providing shade in pastoral systems, thereby reduces heat stress in livestock and increases animal performance and overall productivity. A wide range of agroforestry trees provide forage with high crude protein and low fibre contents, making them a source of home-grown and cheaply available supplements for poor quality roughage feedstuffs such as cereal crop residues. Evidence is presented that browsing on such trees improves feed intake, animal performance and overall utilisation efficiency of poor quality roughage. However, in some leguminous trees, the presence of tanniferous compounds could cause depression of dry matter and nitrogen digestion in the rumen.

Due to the inherent low soil fertility of major areas of the southern African subcontinent, and to the rapidly increasing population pressures, systems of agricultural production that combine the use of leguminous shrubs and trees to recycle nutrients of importance are discussed. Evidence is given that several agroforestry technologies, e.g. improved fallows, relay cropping, hedgerow intercropping and tree biomass transfer, can improve soil fertility and sustain crop yields.

A SYSTEMS approach to agricultural production in southern Africa involves an integration of crop and livestock production. Logically, this includes pasture and forage production on the lands which are marginal for cropping, and crop production on higher potential land. Agroforestry is an activity that can enhance the production of both the crop and livestock subsystems. It can incorporate essential components of sustainability and self-sufficiency into the whole agricultural system (Hazra and Rekib 1991). This can be achieved by providing multiple products such as fuelwood and charcoal, timber for construction, food, medicines, tanstuffs, dyes, shade and shelter, by prevention of soil erosion and increase in soil fertility and by provision of forage for livestock (Sardinha and Sousa 1988). This review will attempt to highlight the potential and limitations of agroforestry in improving soil fertility and livestock production in the southern African subcontinent. To do this effectively, the experiences of the research thrust of the southern Africa Agroforestry Network will be drawn upon, together with available information from elsewhere in the subhumid and semi-arid tropics.

Livestock Production in the Southern African Region

Southern Africa has broadly two types of livestock production. The first involves extensive use of land, i.e. low human and livestock density (de Leeuw and Rey 1993). This type of system is common in the pastoral and agropastoral areas of the arid and semi-arid zones where rainfall patterns preclude reliable cropping and limit the support capacity of land for both people and livestock.

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The other system of livestock production, also extensive, exists in the higher potential areas along with mixed farming systems where overall land use is intensified, increasing population pressure. In this system the livestock subsector is used to increase the overall output of land through exploitation of the synergism between cropping and livestock subsectors through soil nutrient enhancement from livestock and improved soil tillage through animal traction (de Leeuw and Rey 1993). However, while overall land use becomes more intensified, livestock management and feeding strategies remain extensive. Livestock continue to rely on natural pastures, plus crop residues for dry season feed; external feed inputs are applied strategically to increase productivity at certain times (Dzowela 1993). For instance, to improve the work output of traction (draught) oxen, supplementary feed is provided when demands for tillage and transport are high i.e. early in the crop growing season and during or after crop harvests (de Leeuw and Rey 1993).

Benefits of trees for livestock

Shade

In traditional livestock production systems, animals crowd the shade of trees during hot sunny weather and some trees in pastoral systems are browsed (Cameron et al. 1991). It is reported from work in the Australian tropics that high temperatures can induce conception failure, abortion in pregnant ewes and reduced lamb birth weight (Roberts 1984).

Young calves, and pregnant and lactating cows are more susceptible to heat stress than other cattle, but all classes of animals grazing for a greater part of the day made greater weight gains in paddocks with shade than in those without (Daly 1984). Shade significantly increased milk yield of dairy cows from 17.2 to 19.2 kg/cow/day in the Australian tropics (Davidson et al. 1988).

Leguminous trees for browse

Historically, the use of leguminous trees on the southern African sub-continent has been confined to the lopping of native species for drought feeding of livestock. Many species have value in this role; *Piliostigma thonningii, Combretum* spp., *Brachystegia* spp. and a wide range of *Acacia spp.* are known in these roles among herders (Sibanda and Ndlovu 1992). Other species are shown in Table 1. No comprehensive chemical data is available for the major tree legumes used as fodder. A majority probably have high nutritive values, as suggested by data on only a few of them (Table 2). These are among the 200 main browse species listed by Le Houerou (1987) and Lamprey et al. (1980).

Table 1. Nitrogen-fixing tree and shrub legumes used for forage (by family, genera and species).

Mimosoideae	No. species	Papilionoideae	No. species	Caesalpinoideae	No. species
Acacia	12	*Cajanus*	1	*Parkinsonia*	1
Paraserianthes	1	*Chamaecytisus*	1	*Calliandra*	1
Desmodium	1	*Desmanthus*	1	*Erythrina*	2
Leucaena	5	*Gliricidia*	1	*Sesbania*	4
Pithecellobium	1	*Medicago*	1		
Pterocarpus	2	*Pangamia*	1		
Prosopis	4	*Robinia*	1		

Source: Brewbaker (1986)

Table 2. Drymatter (g/kg) and chemical composition (g/kg DM) of lcoal browse (leaves and tender stem) at Matopos, Zimbabwe.

	Local Browse Species			
Parameters	Acacia karroo	Acacia nilotica	Securinega virosa	Ziziphus mucronata
Drymatter	568	513	382	484
Nitrogen	19	25	34	26
Crude protein	118	154	211	162
Crude fibre	142	120	125	121
Ether extract	24	41	35	23
N-free extract	672	637	535	624
Ash	44	47	94	70
NDF	337	314	305	336
ADF	235	225	208	216

NDF = Neutral detergent fibre ADF = Acid detergent fibre

Source: Adapted from Dube and Ncube (1993)

Among the exotic species, *Leucaena leucocephala* and others such as *Albizia* spp., *Calliandra calothyrsus, Gliricidia sepium, Cajanus cajan* and *Sesbania sesban* are increasingly proposed as suitable feed alternatives to herbaceous legumes, because the latter are unable to persist under heavy grazing (Blair et al. 1990). Use of leguminous trees and shrubs is particularly appropriate where feed is carried to tethered animals, a common practice in the humid tropics.

As most of the leguminous trees and shrubs used in agroforestry have high crude protein values (18–30%) and low fibre contents (9–30%) (Dzowela et al. 1993), they are a good source of feed to supplement poor quality roughage, such as cereal crop residues; they improve feed intake, animal performance and the overall utilisation efficiency of poor quality feedstuffs (Table 3).

However, limitations, exist in the use of the leguminous trees and shrubs fodder. The major constraint, in spite of their high nutritive value (Table 4), is the presence of such secondary compounds as condensed tannins and hydrolysable polyphenolics in

Table 3. Daily dry matter intake (DMI), dry matter digestibility (DMD), organic matter digestibility (OMD) and acid detergent fibre digestibility (ADFD) of rations of maize husk supplemented with urea, *Leucaena* and/or *Calliandra*, and daily weight gain by goats.

Parameters	Feedstuffs				
	Husk + urea	Husk + Leucaena	Husk + Calliandra	Husk + Leucaena + Calliandra	SE
Intake (g/d)					
Maize husk	249a	149b	147b	149b	0.9
Leucaena	—	182	—	—	—
Calliandra	—	—	168	—	—
Leucaena + *Calliandra*	—	—	—	168	—
Total DMI	249	331a	315b	317b	1.2
Digestibility (%)					
DMD	47c	63a	59b	60b	1.2
OMD	54c	65a	61b	62b	0.7
ADFD	43	52	52	55	0.7
Average daily gain (g)	4.8d	28.5a	19.0c	22.6b	0.1
Daily DMI ($\text{g/kg}^{0.75}$)	25	33	32	32	—
FE (kg DM/kg weight gain)	52.1d	11.6a	16.8c	14.2b	—

Where: SE = Standard error, FE = Feed efficiency;
Means followed by the same letter within the same row are not significantly different ($P<0.05$)

Source: Adapted from Phiri et al. (1992)

Table 4. Favourable characteristics in major multipurpose tree species with potential for fodder at Domboshawa, Zimbabwe.

Multipurpose Tree Species	CP (g/kg DM)		ADF (g/kg DM)		Ash (g/kg DM)	
	6 weeks	12 weeks	6 weeks	12 weeks	6 weeks	12 weeks
Acacia angustissima (syn. *boliviana)*	304	279	165	194	52	63
Calliandra calothyrsus	218	213	191	165	67	64
Cajanus cajan	247	214	250	260	63	53
Flemingia macrophylla (syn. *congesta)*	183	194	254	301	61	52
Gliricidia sepium	219	215	141	169	89	95
Sesbania sesban	218	252	98	99	96	93
Sesbania macrantha	252	244	156	136	ND	85

Where CP = Crude protein, ADF = Acid digestive fibre, ND = was not determined.

Source: Dzowela et al. (1993)

some trees. For instance, Dzowela et al. (1993) reported that of the seven major multipurpose tree species currently showing potential for addressing quality fodder shortages during dry seasons in Zimbabwe, three had appreciable levels of condensed tannins and hydrolysable polyphenolics when leaf materials were sampled 6 and 12 weeks after cutting in May 1992. These are *Calliandra calothyrsus* (12.3 g/kg DM), *Acacia angustissima* (10.3 g/kg DM), and *Flemingia macrophylla* syn. *congesta* (3.1 g/kg DM), but *Sesbania macrantha* had negligible amounts (Table 5). These compounds caused a depression in dry matter and nitrogen degradation in the rumen. Correlation of polyphenolic compounds content with the degradation coefficients of both dry matter and N in the rumen was negative (correlation coefficient. –0.49). This was found to be significant ($P<0.01$) at both 0 and 48 hours of incubation.

Too much emphasis is put on the cursory analyses of crude protein and fibre as indicators of fodder value, especially in tropical browse legumes. The presence of secondary plant compounds will interfere with the concept that high crude protein and low fibre indicate high nutritional value. Some of these compounds could affect palatability and acceptance by livestock. However, since the utilisation mechanisms by which the nitrogen supplements derived from leguminous trees and shrubs benefit livestock are not fully documented, there is need to understand better the fate of both low and high quality fodders in the rumen. They could supply and help to satisfy the microbial needs for protein synthesis on the one hand, or they may provide by-pass nitrogen to the small intestine where absorption occurs. This has important implications as most livestock are raised on poor quality roughage during dry seasons in southern Africa: use of the leguminous tree and shrub fodders as supplements and not as sole diets cannot be over-emphasised.

Soil Fertility Situation in Southern Africa

The southern African region devoted to reliable agricultural crop production is covered by dystrophic miombo savanna woodland, dominated by two tree genera *Brachystegia* and *Julbernardia.* These trees and associates form a 15–20 m high light single-storey but closed canopy over a forest floor dominated by *Hyparrhenia* spp. (Mathews et al. 1992). The area covers an altitudinal range of 600 to 1500 m above sea level and a rainfall range of 600 to 1200 mm annually falling unimodally between October and April. At lower elevations and where rainfall is less than 650 mm the tree stratum is dominated by *Mopane colophospermum, Acacia* spp., *Combretum* spp. and *Terminalia* spp. This is referred to as the eutrophic miombo. Here agricultural activities are restricted to drought resistant crops and extensive livestock production, on account of unreliable rains.

Generally, soils are acidic and low in inherent fertility due to the poor nature of parent material or, in the case of high rainfall areas (in excess of 1000 mm), due to leaching. Traditional agriculture had therefore evolved forms of shifting cultivation characterised by short cropping periods and long fallows known locally as *Chitemene* and *Fundikila* in

Table 5. Unfavourable characteristics of major multipurpose tree species with potential for fodder at Domoshawa, Zimbabwe.

Multipurpose Tree Species	Condensed tannins		Lectin activity*	
	6 weeks	12 weeks	6 weeks	12 weeks
	(g/kgDM)		(g/kgDM)	
A. angustissima (syn. *boliviana*)	9.3	11.2	16	16
C. calothyrsus	8.4	27.4	32	128
C. cajan	0	0.3	0	0
F. macrophylla (syn. *congesta*)	0.8	6.0	8	32
G. sepium	0	0	0	0
S. sesban	0	0	0	0
S. macrantha	0	0	8	8

* An indication of presence of hydrosyable polyphenolics

Source: Dzowela et. al. (1993)

Zambia, northern Malawi and the Shaba province of Zaire (Mathews et al. 1992; Stromgaard 1989) or forms of 'slash and burn' cultivation. However, pressure on land resulting from an increasing human population has resulted in longer cropping and shorter fallow periods (Kwapata 1984). Because soils are not given time to regain their fertility, there is a general decline in crop yields, which has made the traditional methods of restoring fertility either inappropriate or unsustainable.

Diagnostic and design surveys conducted in the region by the International Centre for Research in Agroforestry (ICRAF) showed potential for agroforestry interventions which are likely to restore fertility more quickly (Huxley et al. 1986).

Some Agroforestry Interventions

Improved rotational systems involving tree–crop fallows

Nutrient pumping is cited as one of the potential benefits of trees in agroforestry systems; trees have deep root systems which absorb nutrients from the subsoil and deposit them in or on the surface soil via above and below ground biomass production, decomposition of prunings of leaves and branches, or indirectly through the deposition from manure of browsing livestock (Nair 1984; Young 1989). This assumes that the translocation of nutrients to superficial soil horizons by trees can increase the amount of nutrients available to shallow-rooted vegetation and crops and improve overall productivity of the agricultural system.

Small-scale farmers who, until the present economic depression, relied on subsidised inorganic fertilisers to produce maize, could make use of agroforestry technology via improved fallow systems (Kwesiga and Coe 1993). *Sesbania sesban*-based improved fallows of 23 years duration have shown potential in overcoming low soil fertility and increasing crop yield with reduced or no inorganic fertiliser input. For instance, in subhumid Zambia where maize yield was about 1.5 t/ha without N fertiliser, Kwesiga and Coe (1993) reported that after one, two and three years fallow with *S. sesban* the yield was increased to 3.5, 4.4 and 5.3 t/ha respectively without N fertiliser (Fig. 1). The responses in yield with increasing N fertiliser levels were reduced progressively after zero to three year fallows, indicating that the effects of fallowing were largely to improve soil N supply.

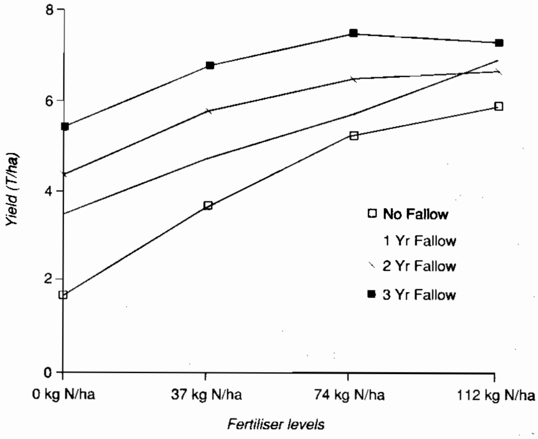

Figure 1. Responses of maize grain yields to fertiliser after different periods of *Sesbania* at Chipata, Zambia.

Improvements in soil fertility are sometimes hard to demonstrate due to the complex nature of the processes involved. However, limited data are available from the subcontinent. Table 6 shows some soil

Table 6. Comparison of soil chemical properties of the 0–5 cm depth of a sandy loam soil taken before planting a maize crop after one, two and three-year *S. sesban* fallow and previously fertilised and non-fertilised maize plots at Chalimbana, Zambia.

				Exchangeable cations				
Fallow period and fertiliser treatments	Organic Matter (%)	Total N (%)	P (ppm)	K	Na	Ca	Mg	CEC
				(---------meq/100 g soil---------)				
No fallow, no fertiliser	1.48	0.06	5.9	1.82	0.21	1.97	2.57	6.44
No fallow, fertiliser	1.74	0.08	14.2	1.79	0.08	3.33	2.36	7.56
One-year fallow	1.78	0.07	7.4	2.99	0.17	2.42	2.65	7.24
Two-year fallow	1.64	0.08	4.9	1.84	0.26	2.67	2.58	7.30
Three-year fallow	1.89	0.07	5.6	1.99	0.20	3.18	2.65	8.10
LSD (P<0.05)	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	15	9	18	8	14	21	23	7

Source: Adapted from Kamara and Chikasa (1992) chemical properties on plots after one, two and three-year *S. sesban* fallows compared with continuous maize plots with or without 200 kg/ha diammonium phosphate fertiliser (18–46–0 compound). Trends towards increasing contents of Ca, CEC and to some extent organic matter occurred after one year to three-year fallows even though the increases were not statistically significant.

In the densely populated areas of Southern Malawi, where farmers cannot afford fallows, relay cropping of maize with fast-growing multipurpose tree and shrub species such as *S. sesban* has produced good results. The relay cropping technology is a variant of improved fallows. Common multipurpose trees include *Cajanus cajan* and *Sesbania sesban*, producing substantial maize yield gains (Maghembe, pers. comm.).

Other candidate species for short duration fallows may include species widely adapted to the subhumid zone of Southern Africa. These are *Cajanus cajan, Flemingia macrophylla, Gliricidia sepium, Tephrosia vogellii* and *Acacia angustissima.*

Hedgerow intercropping (alley cropping)

This technology refers to the planting of crops in the spaces between hedgerows of trees or woody shrubs (Rosecrance et al. 1992). Trees are pruned to minimise resource competition and maximise nutrient availability to the crop. For nutrient recycling, the prunings are applied to the soil as green manure or incorporated as surface mulch (Kang et al. 1981). In humid environments, a wide range of crops can be planted in the alleys. Between these, the fast-growing leguminous trees or shrubs provide prunings, stakes and nitrogen fixed from the atmosphere (Yamoah 1988).

However, research results from the subhumid plateaux of southern Africa are showing that excessive competition for nutrients and moisture between the tree or shrub species and associated crops occurs in hedgerow intercropping systems. Also, climatic factors impose limitation, reducing leaf production of trees and shrubs. Thus it is only in fertile soils of high rainfall areas that the potential of hedgerow-alley intercropping to improve crop yields has been demonstrated (Kang et al. 1981; Akeyampong et al. 1992). Even in these areas the benefits are obtained only at the cost of a high labour demand.

Biomass transfer

Two forms of biomass transfer showing potential for soil fertility improvement and hence better more sustainable crop yields exist in Zambia and Zimbabwe.

In Zambia, multipurpose trees are grown in pure or mixed stands outside the farm area allocated for crop and livestock production. Tree leaf biomass is cut and carried from these stands to cropped land. Alternatively, it is cut and carried as fodder supplements for livestock feeding on a basic diet of poor quality roughage during dry seasons.

In Zimbabwe, farmers have recognised the positive effects of woodland litter when applied to crops and mixed with animal manure (Wilson 1989). There is a general belief among smallholder farmers that in years of good rainfall, litter from *Brachystegia/Julbernadia* savanna woodland increases crop harvests. Farmers will apply woodland litter, usually to supplement kraal manure, to land cropped with a wide range of intercrop mixtures including maize (Nyathi and Campbell 1993).

With the existing research background, it should be possible to identify what role agroforestry technologies might have in improving livestock and crop production in the southern African region. The planting of trees should, apart from increasing crop and livestock production, provide other products and services as well. The woody biomass remaining after using foliage and branches for fodder or manure provides fuelwood, stakes and poles, thereby reducing the need for further deforestation of remaining forest lands.

Conclusions

The potential and limitations for agroforestry have been reviewed with respect to animal and crop production in southern Africa, drawing upon results from current research. A wide range of leguminous tree and shrub species commonly recommended for agroforestry have potential use as fodder. When grown on-farm, they provide highly nutritious, high-protein and low-fibre supplements to poor quality roughage. Evidence exists that the readily degradable materials have high potential as fodder. Only tanniferous materials could be constrained in their utilisation by the presence of secondary compounds.

Several trees and shrubs have high potential for improving soil fertility and sustaining crop production. When integrated into farming systems for improved fallows, relay cropping, hedgerow intercropping or biomass transfers, they could become a useful and profitable way of complementing expensive inorganic fertiliser use by resource-poor farmers in the Southern African sub-continent.

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Computer Simulation Models as Management Tools for Sustainable use of Natural Resources in Highland–Lowland Systems

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Abstract

Wise use and management of natural resources depends on a proper understanding of the interaction of the various components of the system and availability of accurate and adequate information upon which to base management decisions. This paper highlights the efforts of Laikipia Research Project in developing management tools that can be used to (a) assess the effects of present land use and management changes on soil and water resources and on primary production; (b) identify the potential for conservation and improved management techniques; and (c) assist in planning for sustainable use of water, soil and vegetation resources.

NATURAL resources, particularly soil, water and vegetation resources, constitute some of the most important preconditions of man's existence and are important raw materials for his economic activities. Consequently, wise use and management of these resources is a prerequisite to sustainable production. Unfortunately, literature is replete with examples of widespread resource degradation, particularly in arid and semi-arid areas. Factors which contribute to resource degradation include:

- complexity of the production systems;
- high temporal and spatial variability in availability and quality of natural resources;
- scarcity of resources required for development, particularly capital and labour;
- competition for scarce resources among different users and associated conflicts;
- high production risk and, in some cases, low return on investment;
- social and cultural constraints to adoption of appropriate production technologies;
- lack of a proper understanding of the impacts of various resource allocation and management strategies on socioeconomic status and environmental stability; and
- inappropriate policies.

This paper outlines some research approaches and achievements of the Laikipia Research Program (LRP), a joint venture of the University of Nairobi and University of Berne in developing analytical tools for sustainable use and management of natural resources in a highland–lowland system.

Description of the Highland–Lowland System

Natural environment

The study area consists of the Upper Ewaso Nyiro river basin located to the west and north of Mt Kenya. This area is divided into four regions, namely: Mt Kenya humid slopes, Mt Kenya lower slopes (transitional zone), semi-arid plateau (volcanic soil) and semi-arid lowlands and hills (basement soils) (Fig. 1). The study area has a dramatic variation in environmental characteristics, as shown in Table 1.

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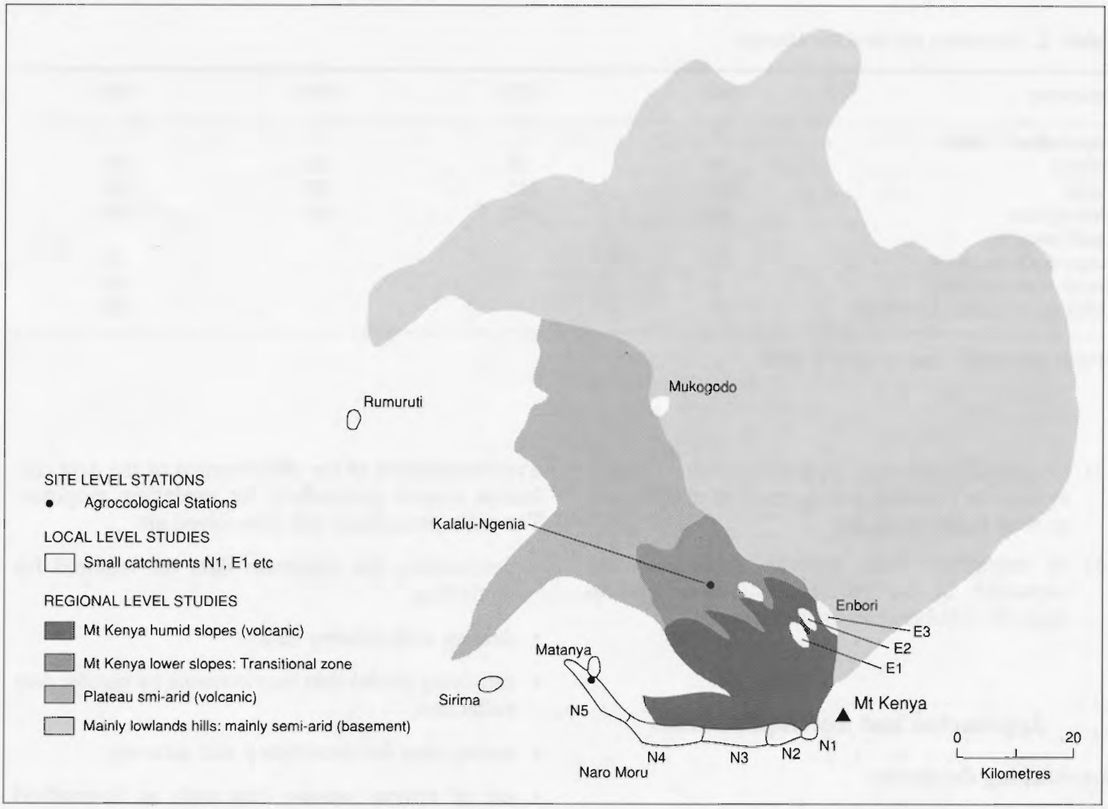

Figure 1. Water and soil resources management study area.

Table 1. Environmental characteristics.

Environmental variable	Range of characteristics
Climate	Afro-alpine, humid, semi-arid and arid
Altitude	5200–1000 m.above sea level
Annual rainfall	1500–500 mm
Soils	Vertisols, Andosols, Luvisols, Lixisols, Phaeozems
Vegetation	Montane forest to acacia bushland

Socioeconomic environment

Population pressure in the study area began building up after 1963, when former European farmers and ranchers started selling their farms and ranches to African land-buying companies. Kohler (1987) reported that the population of Laikipia district has been growing at an annual rate of 7.3% due to immigration and natural increases. Population and land use changes in the district are presented in Table 2.

Objectives of Laikipia research project

Laikipia Research Project (LRP) was established in 1984 as an applied research project aimed at providing answers to questions raised by rural development projects. The overall goal of the ecology sector of the project was to carry out applied research to promote sustainable utilisation of natural resources, with emphasis on soil, water and vegetation. The scope has been expanded and the main objectives of the current program are:

(1) to develop management tools (computer programs) that can be used to evaluate:
  - the interaction of highland-lowland production systems;
  - the effects of land use and management changes on soil, water and vegetation resources; and
  - the effect of land-use and water-use patterns on economic performance, environmental quality and human welfare;

Table 2. Population and land use changes.

Parameter	1960	1970	1980	1990
Population* ('000)				
Human	20	25	120	250
Cattle	250	125	180	250
Sheep/goats	20	100	200	480
Land use (%)				
Large-scale ranching	80			55
Small-scale ranching	0			25
Other (pastoralism, forestry)	20			20

*Partly estimated. Source: Taiti S. 1992

(2) to apply management tools as a decision support system for resource management at district and/or river basin level; and

(3) to strengthen field research and modelling capacities of the partner institutions and to improve collaboration among them.

Approaches and Accomplishments

Establishing databanks

Effective management of natural resource systems requires a clear definition of goals and objectives and an adequate and accurate database with information on:

- the physical system in terms of natural characteristics, available resources and development potential;
- resource use, allocation rules and associated demands;
- organisational structures, policies, legal and socioeconomic aspects; and
- interractions and interrelationships of physical and socioeconomic factors and their impacts on resource conservation, productivity and environmental quality.

The importance of good data in resource management was realised at the inception of the project and an extensive data collection network established. The main data sets collected on a regular basis include climatological, hydrological, soil, land use and vegetation, socioeconomic and experimental data.

Although an assessment of the quality and quantity of data required had been done at the start of the project, recent changes in approach have necessitated a re-examination of the effectiveness of the data collection system, particularly for modelling purposes. The main procedures still unresolved are:

- determining the minimum data set required for modelling;
- dealing with missing data;
- satisfying model data requirements by regular data collection;
- testing data for consistency and accuracy;
- use of remote sensing data such as Normalised Digital Vegetation Index (NDVI), LANDSAT and METEOSAT data in modelling;
- managing data to make it readily accessible to different computer modules and to reduce computer storage space and processing time; and
- using GIS in natural resources systems modelling.

Model development and validation

Although the use of computers is spreading rapidly in developing countries, few models have been developed for African Mountain Systems and no modelling approach exists to assist the integrated planning of water, soil and vegetation resources, and the identification of productive and attractive conservation and management practices. This is due mainly to (1) the lack of adequate training and involvement of African scientists in model development, (2) the lack of adaptation of the models to the conditions in developing countries, (3) the lack of long-term data records to calibrate, verify and validate the model components, and (4) inadequate long-term support for model development and application in developing countries.

In developing countries, computer modelling will gain importance and will be needed in natural resource management because it can be of great help, to:

- improve the understanding of the processes, and as an instrument to generate and test hypotheses;
- integrate different disciplines (climatology, hydrology, soil science, agronomy, crop/vegetation physiology, economics and sociology) and to bring researchers working in different areas together;
- identify information gaps and to minimise the need for experimental baseline data;
- extrapolate from experimental data and elucidate effects of climatic variability obtained over both short and long periods in the lowland–highland region;
- assess current and future risk areas of environmental degradation, and set up development strategies;
- identify optimum resource management and allocation options, to maximise primary production and minimise environmental degradation; and
- investigate in a prospective way the consequences of land-use change and the potential of resource conservation and management techniques.

Mt Kenya study region provides an unique opportunity to develop the model because of the following factors:

- the wide variety of ecological zones, land-use types and dynamics within a short distance, and respective problems of sustainable use of natural resources in this area, are typical of many African highland-lowland systems;
- the Laikipia Research Program (LRP) has developed an extensive database (including GIS) and currently maintains a field station network relevant to the proposed modelling project;
- the proposed project fits into the core of the Mt Kenya Ecological Program (MKEP), which is supported by a wide range of organisations, and will commence in 1994; and
- a model validation exercise has been proceeding since 1992, the first modelling experience gained with the CERES model in collaboration with ACIAR and CSIRO in Kenya (Keating et al. 1992). Figures 2 and 3 show the validation of a CERES-Maize model for Kalalu and Matanya Stations.

The main areas of single process model development are studies of:

- weather generator effects,
- soil and water balance,
- land-use and settlement dynamics,
- vegetation and soil cover dynamics,
- erosion and sediment transport,
- streamflow, and
- water demand and allocation.

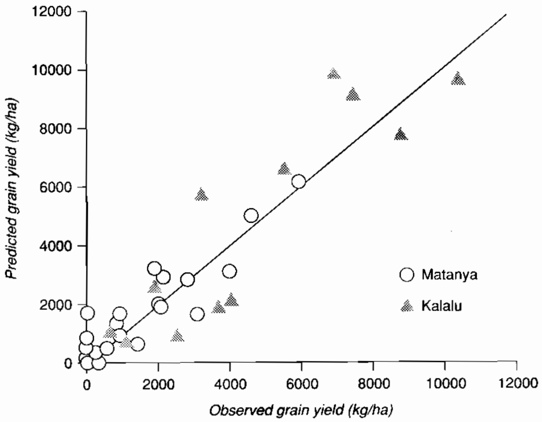

Figure 2. Observed and predicted grain yield of Matanya and Kalulu. Source: Ikonya et al. (1993).

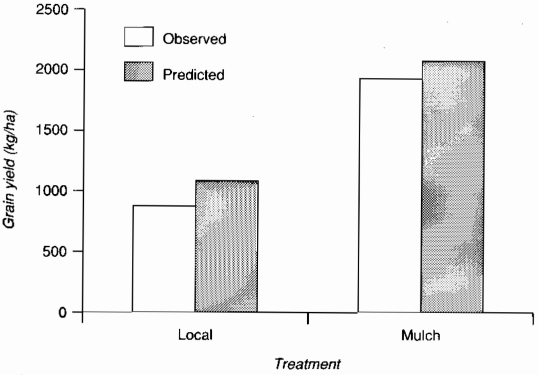

Figure 3. Mean effect of mulching on maize grain yield in Matanya (1986–91 data). Source: Ikonya et al. (1993).

To avoid 're-inventing the wheel', LRP researchers will use existing single process models or components. Model development will involve the following steps:

- understand the process to be modelled,

- identify existing models and their simplifying assumptions,
- undertake sensitivity analysis of model parameters and input data,
- collect field data (where none exists) relevant for modelling the process,
- validate model with existing data sets,
- evaluate each model,
- select the model with the closest fit,
- modify the model to incorporate local conditions, and
- calibrate and revalidate the model.

Modelling will be applied to three scales (see Fig. 4).

Site scale (farm or paddock scale)

This scale level covers small areas (plots) with uniform land use and natural characteristics 1–5 hectares. The basic idea is to calibrate and develop individual simulation modules and to link them to a central data-base or data exchange. The individual modules such as water balance (including runoff, deep percolation, crop water use, soil and ground water changes), erosion and crop growth and yields must be able to simulate different resource management practices. Simulation will be performed in time steps of one day or less. Data sets for calibrating the various model modules are already available, the results of more than five years of Kenyan-Swiss cooperative field research.

Small catchment scale

Runoff and sediment transport will be modelled on an event base while the water balance will be computed daily. The model on this level needs to be developed, whereby established models will be adapted and combined with routines for data management and exchange. The link between the models on the site and the small catchment level will be of special interest. The GIS component is important in order to link the different scales. Model calibration will be based on data from eight small catchments ranging in size from 1 to 5 km^2 in forested, agricultural and range areas in the highland and lowland zones.

River basin scale

Modelling of runoff and sediment transport will be done on a sub-basin scale (one hundred to several thousand km^2) based on data collected from 15 sub-basins using 30 runoff stations as a reference within the Upper Ewaso Nyiro Basin. The modelling will be based on the principles developed on the small catchment scale and the simplification or generalisation of the processes occurring there.

Model Applications and Relevance to Development

After the models are validated, they will be used by researchers, as tools in communication, learning and management.

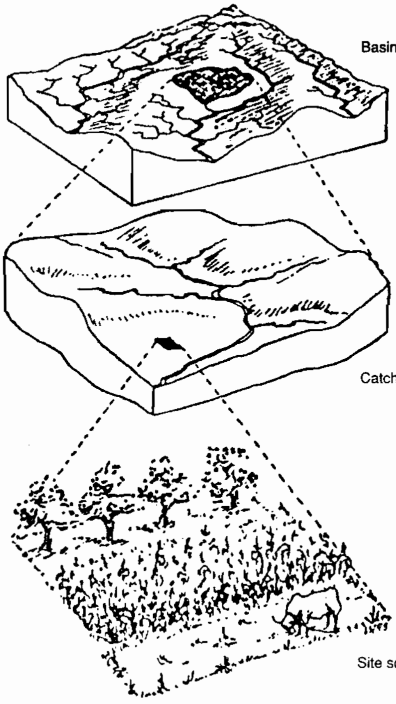

Figure 4. The three scales of modelling.

Research tool

The models, particularly single process models, will be used to improve our understanding of the processes, and will also allow the use of information obtained at several locations over a short period to record changes in natural resources over larger areas, longer periods of time, and in relationship to various scenarios.

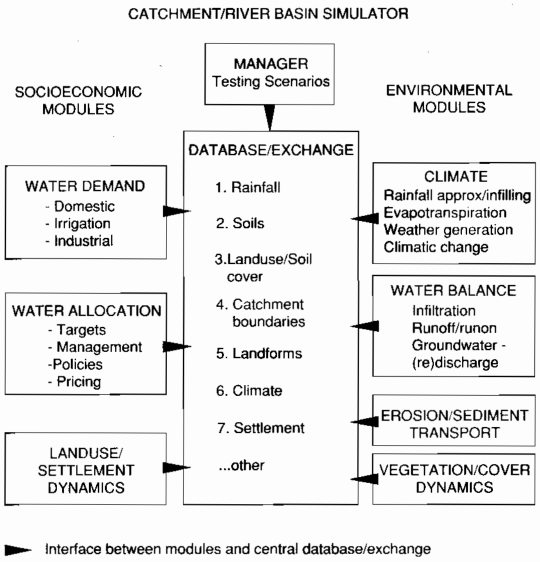

Figure 5. System modelling approach.

Learning and communication tools

The development and application of the models will catalyse the communication and collaboration among the different scientists involved and enhance the integrated understanding of processes in highland–lowland systems among scientists, administrators and implementors.

Management tool

The models will be used to assess different scenarios and provide answers to management questions such as:

- the impact of changes in land use and management on productivity and sustainability of water, soil and vegetation resources;
- allocation of water resources among highland and lowland users;
- minimum farm size for smallholder farms in semi-arid areas and the impacts of subdivision;
- impacts of climatic change on water and sediment yield and on primary production;
- economic and environmental consequences of different scenarios; and
- the policies most appropriate for good management.

Conclusions

The necessary foundation for effective modelling has been laid in the form of established relevant databases, building human resources with a capacity for modelling, acquiring existing models, and soliciting for collaborators in our modelling exercises, the major partners being LRP, ACIAR–CSIRO–DPI, the University of Berne Group for Development and Environment, and the Rockefeller Foundation.

Additional funds are still needed to enable Australian modellers to take a more active role in providing backstop assistance in further model development and/or adoption. We would also like to improve collaboration with eastern and southern African scientists to enable us to adapt and apply models to a wider scope.

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Strategies for Soil-water Management for Dryland Crop Production in Semi-arid Tanzania

N. Hatibu*, H.F. Mahoo*, E.M. Senkondo*, T.E. Simalenga*, B. Kayombo* and D.A.N. Ussiri*

Abstract

The vagaries of weather, especially rainfall, are considered by most farmers to be the most important limitation to agricultural production in the semi-arid areas of Tanzania. Therefore, above all else, the capture and efficient utilisation of rainfall is considered to be the most important management option. This paper explains the research work started in 1991–92 season in the semi-arid areas of Tanzania to identify management interventions for improving soil water availability and use by crops in dryland farming.

One of the first activities of the research was to conduct Rapid Rural Appraisal (RRA) at two locations within the semi-arid zone of Tanzania. These were Dodoma District in semi-arid central Tanzania, and Mwanga District in the north-east. Four villages from each location were included in the appraisals.

The results of the RRA and first season experiments indicate that farmers in semi-arid Tanzania will benefit from eliminating run-out (runoff losses), encouraging run-on, and from cultural practices (e.g. appropriate plant population, early planting, adequate fertiliser application) which optimise the efficiency of soil-water utilisation by crops. The experimental results show that in central semi-arid Tanzania, improved infiltration is the most effective way to increase yields. It was not possible to analyse the response to improved infiltration and nitrogen supply combinations as all treatments were supplied with adequate nitrogen. However, the experiments have been modified after finding from RRA that many farmers do not apply nitrogen fertiliser. Starting next season non-N control treatments will be included in order to test the importance of improved nitrogen supply.

Background

Overview

Tanzania has a land area of 886 000 km^2 with complex variation in climate, soils and topography. Approximately 5% of the total land area is under cultivation, of which 1 % is occupied by permanent crops. Several methods have been used to classify Tanzania into agro-ecological zones. The classification gives six major zones according to soil type, altitude, mean annual rainfall and duration of the growing season (LRDC, 1987). The zones are (1) coast, (2) arid lands, (3) semi-arid lands, (4) plateaux, (5) southern and western highlands, and (6) northern highlands and isolated granitic mountains.

Agricultural potential is limited over large areas of the country by a combination of low soil fertility, low and erratic rainfall, and tsetse infestation. Only 22% of the land receives 570 mm or more of rainfall in nine years out of 10. Truly fertile soils are confined to the volcanic soils of the northern highlands and the alluvial soils in large river basins. In general, land with a combination of adequate soil fertility, adequate rainfall and free of tsetse infestation is limited to less than 10% of the total area of Tanzania.

The 1988 census showed that the population of mainland Tanzania was 22.5 million people, 90% of whom live in 8500 rural villages. The most densely populated areas include the northern and southern highlands. Agricultural production is predominantly

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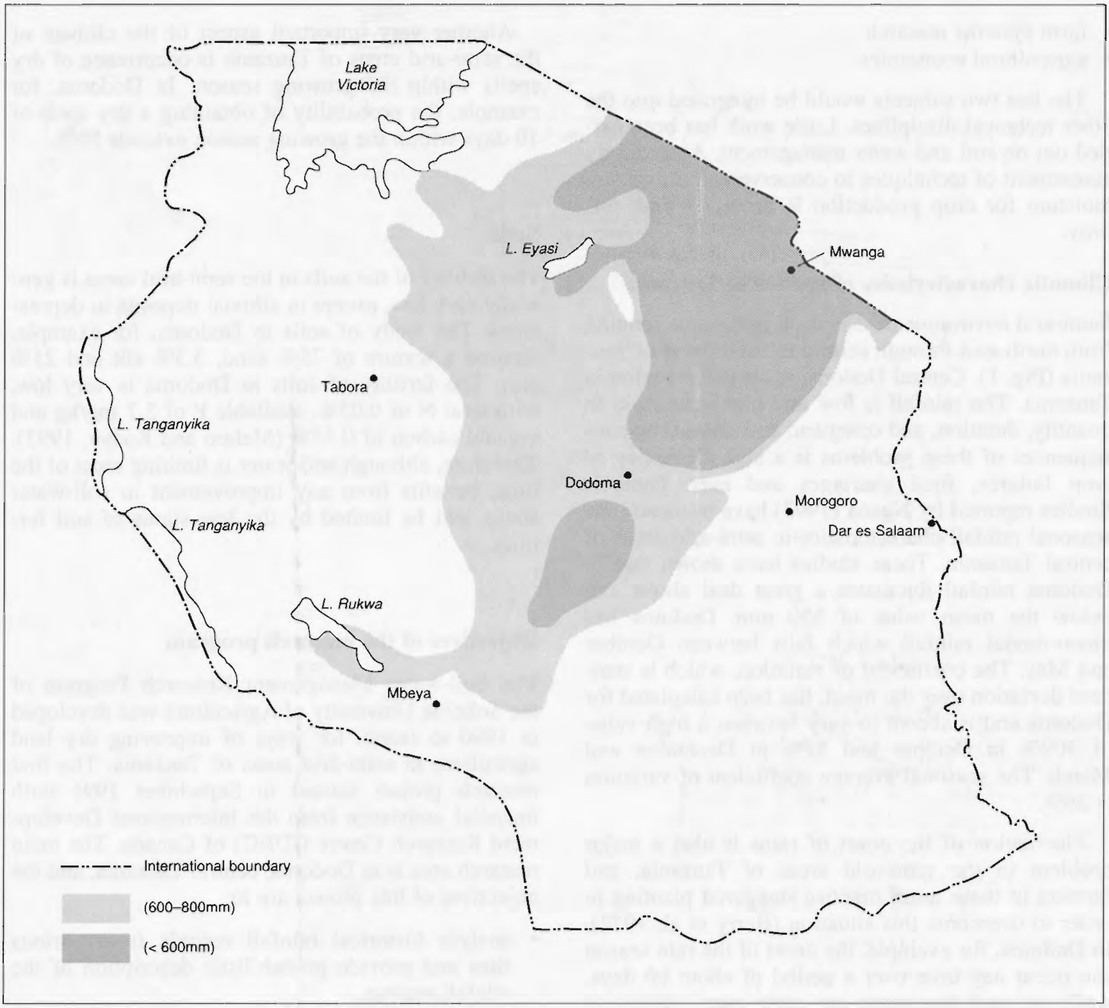

Figure 1. Extent of semi-arid areas in Tanzania.

subsistence and is undertaken by some 2.25 million farm families each operating on average two ha of cropping land with limited tenure rights. In some areas, particularly those with perennial crops, land use rights are inheritable.

Agriculture is Tanzania's key economic sector accounting for half the country's GNP, 80% of recorded export earnings and 90% of rural employment. While agriculture grew rapidly in the 1960s it stagnated in the 1970s and early 1980s, leading to an inability to meet the country's long-term development objectives, namely food security, sustainable food self-sufficiency and increased foreign exchange earnings.

The National Agriculture and Livestock Research Master Plan (1991), states that research should be seen as one important step in the general rehabilitation of the economy of Tanzania as foreseen in the economic recovery program. The master plan identifies the following areas of agricultural research as having top priority:

- coffee
- tea
- rice
- animal health and livestock diseases
- ruminant milk and meat production
- soil and water management
- agro-forestry

- farm systems research
- agricultural economics.

The last two subjects would be integrated into the other technical disciplines. Little work has been carried out on soil and water management. Accordingly assessment of techniques to conserve and utilise soil moisture for crop production is accorded high priority.

Climatic characteristics of semi-arid Tanzania

Semi-arid environments dominate in the area running from north-east through central to south-west of Tanzania (Fig. 1). Central Dodoma is the driest region in Tanzania. The rainfall is low and highly variable in quantity, duration, and onset and end dates. The consequences of these problems is a high frequency of crop failures, food shortages and even famines. Studies reported by Ngana (1993) have evaluated the seasonal rainfall characteristics in semi-arid areas of central Tanzania. These studies have shown that in Dodoma rainfall fluctuates a great deal above and below the mean value of 550 mm. Dodoma has mono-modal rainfall which falls between October and May. The coefficient of variation, which is standard deviation over the mean, has been calculated for Dodoma and is shown to vary between a high value of 309% in October and 57% in December and March. The seasonal average coefficient of variation is 26%.

Fluctuation of the onset of rains is also a major problem in the semi-arid areas of Tanzania, and farmers in these areas practise staggered planting in order to overcome this situation (Berry et al. 1972). In Dodoma, for example, the onset of the rain season can occur any time over a period of about 60 days, while the end may occur any time over a period of 30 days (Fig. 2).

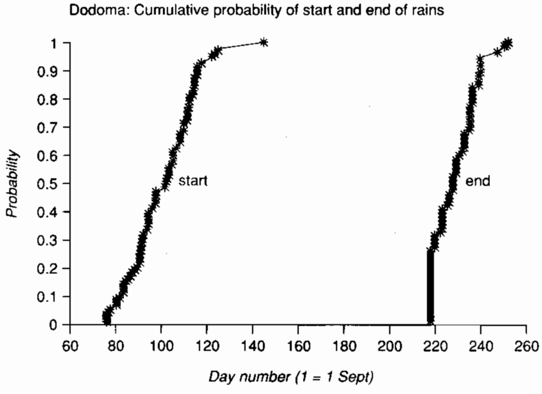

Figure 2. Probability of timing of rains in Dodoma.

Another very important aspect of the climate of the semi-arid areas of Tanzania is occurrence of dry spells within the growing season. In Dodoma, for example, the probability of obtaining a dry spell of 10 days within the growing season exceeds 50%.

Soils

The fertility of the soils in the semi-arid areas is generally very low, except in alluvial deposits in depressions. The study of soils in Dodoma, for example, showed a texture of 75% sand, 3.3% silt and 21% clay. The fertility of soils in Dodoma is very low, with total N of 0.05%, available P of 5.7 mg/kg and organic carbon of 0.53% (Mahoo and Kaaya, 1993). Therefore, although soil-water is limiting most of the time, benefits from any improvement in soil-water status will be limited by the low status of soil fertility.

Objectives of the research program

The Soil-water Management Research Program of the Sokoine University of Agriculture was developed in 1990 to search for ways of improving dry land agriculture in semi-arid areas of Tanzania. The first research project started in September 1991 with financial assistance from the International Development Research Centre (IDRC) of Canada. The main research area is in Dodoma, central Tanzania, and the objectives of this project are to:

- analyse historical rainfall records from various sites and provide probabilistic description of the rainfall regime;
- characterise the soils of the research sites within the study area;
- investigate means of improving infiltration of water into the soil profile, reducing runoff and improving the efficiency of utilisation of soil moisture by crops;
- determine the effects of rainfall and other weather parameters, slope, soil characteristics, soil fertility and fertilisers, crop genotype and agronomic practices on runoff, soil moisture balance, soil moisture uptake by crops, and crop development;
- assess water harvesting techniques for increasing soil water supply in the cropped area; and
- conduct socioeconomic studies aimed at generating information that will direct research activities to the most important constraints.

In August 1992 a second project received funds from ODA-UK through the Natural Resources Institute (NRI) to investigate in detail the technology of rain-water harvesting (RWH) and to develop, in collaboration with the University of Newcastle-upon-Tyne, a computer model for designing rainwater harvesting systems for crop production in semi-arid areas of Tanzania.

The specific objectives of the RWH trials are:

- to appraise and describe farming systems and indigenous soil-water management and conservation in the semi-arid areas of Tanzania;
- to review past research work in rainwater harvesting with particular attention to Tanzania;
- to assess the technical, economic and social potential for rain-water harvesting, in semi-arid areas of Tanzania, and
- to develop and validate a structured model of the processes involved in rain-water harvesting (in collaboration with University of Newcastle-upon-Tyne).

Farming systems and socioeconomic setting

Farming systems

The main farming systems found in semi-arid Tanzania are:

- agro-pastoralism, where farmers are mainly cattle-keepers but practise arable cropping as a way to keep tsetse fly at bay; slash and burn cropping is practised in these areas, leading to environmental degradation; and
- Livestock–sorghum–millet, which is the most common system in central Tanzania. Livestock are kept as security and selling animals is mainly to buy food in bad years. However, the animals provide milk for direct consumption and are a source of manure for the homestead fields. In the semi-arid areas of the north-east, maize is more dominant than sorghum and millet is not grown at all. However, in many aspects the system is the same.

Results of rapid rural appraisal

One of the first activities of the research program was to conduct Rapid Rural Appraisals of the target villages in Dodoma District in central Tanzania and Mwanga District in the north-east (Fig. 1) (Hatibu et al. 1992,1993). Four villages from each district were studied. The objectives of the RRA were:

- to identify crop production constraints and opportunities related to soil-water management;
- to assess the existing soil-water management practices; and
- to assess farmers' views on different methods of soil-water management.

Dodoma district

Crop production is organised on three district categories of fields which are:

- garden plots within the yard surrounding the homestead, intensively cultivated with vegetables;
- homestead fields, where manure application and intercropping are practised, planted with sorghum, millet, sesame, groundnuts, bambara nuts and pigeon peas; and
- bush (distant) fields of at least 1 ha per household located in the valley bottoms, where sorghum, millet or maize are grown.

Pre-planting land preparation comprises weed or stover removal by a hand-hoe (*kuberega*). No deep digging or ploughing is involved. The weed or stover is left to dry on the surface and then collected for burning. This leaves the soil surface bare and hard which leads to high runoff loss of water from the first rains.

Dry sowing of millet, sorghum, sesame and castor is common practice. Villagers say that this is intended to take advantage of the very first rains and also to allow uniform germination and maturity over a wide area, which helps to reduce the intensity of bird damage.

Soil is dug and turned during the first weeding operation, which is conducted after a good amount of rain has fallen and the soil is moist enough.

There is very little use of inputs such as improved seed, fertiliser and chemicals. Seed is normally retained from the previous harvest. However, a good number of farmers reported that they are using the recommended plant spacing, especially for sorghum. There is no application of inorganic fertilisers in the project area. This is because, soil-water being limiting, the few farmers who tried applying fertiliser in the past did not observe any significant difference. Only manure is applied and only to the fields near the home-steads. The manure is normally trampled by animals and mixed with sand in the boma. This is spread on the fields and mixed into the soil during the weeding operation. Labour shortage and limited transportation facilities and the main limitations to manure usage. Further to this, there are high nutrient losses from the manure during long periods in bomas and trampling by animals into fine powder.

When asked to rank the most important constraints to crop production in their area farmers in semi-arid central Tanzania listed:

- low and erratic distribution of rainfall (see Fig. 2).
- shortage of draught or manual power, as farmers have noted that deep tillage prior to sowing and rains reduced runoff, increased infiltration and increased yields;
- low soil fertility and poor yield responses to fertiliser application;
- crop pests and vermin (e.g. birds); and
- poor marketing arrangements for cash crops such as groundnuts, sunflower and castor.

In central Tanzania soil-water management is built into most of the cultural practices. Soil-water is managed in a variety of ways, listed in order of importance:

- mixed cropping and staggered sowings to help reduce the impact of dry spells on crop yields;
- weed control, a major role in the reduction of water lost through evapotranspiration; and
- crop selection and allocation to the appropriate area as a vital soil-water management tool.

Mwanga district

Continuous cropping is practised in many parts of the area. Mixed cropping is used widely, and includes such combinations as maize–beans, maize–groundnuts, maize–peas, and sorghum–sunflower.

Pre-plant land preparation involves deep digging using a hand-hoe or ploughing using a tractor. All the planting activities are by hand. Many farmers use improved seeds, and the most common types of maize seed used include Cargil, Tuxpeno, Staha, Kito and TMV 1 . Use of both manure and inorganic fertilisers is hampered by lack of capital or lack of transport to haul the manure to the fields. Most farmers start weeding 4–6 weeks after germination and this is done manually using hand-hoes.

Livestock is integrated into the cropping system in the semi-arid areas. The majority of farmers have a herd of about five cattle per household, though a small minority may own up to 400 cattle per household.

Most farmers cultivate between 0.1 and 4.0 ha of land per household. Crop yields give a very clear indication of the importance of water. A farmer who practises good management can obtain up to three times higher yields in a bad year than one who does not use good water management.

When asked to rank the most important constraints to crop production in their area farmers listed:

- insufficient and uneven distribution of rainfall, especially when dry spells occur towards the end of the season;
- potential for high crop damage by vermin (including larger wild animals);
- shortage of capital and relatively high costs of inputs;
- high potential evapotranspiration; and
- high runoff and erosion risk.

Different methods such as ridge cultivation, stream flow diversion, contouring, and broad bed or furrowing are used by farmers to manage and conserve soil and water. Farmers identified high labour demand and high risk of damage by livestock as the major constraints to the adoption of soil-water conservation methods which involve soil and or stone structures.

Description of the Experimental Program

The field work is undertaken at three sites: Morogoro (M), on the University farm, Kisangara (K) in Mwanga District, north-east semi-arid area, and Hombolo (H) in Dodoma District, central semi-arid area.

Morogoro

The site has two experiments.

- Cropping under RWH experiment. This includes six blocks of six within-block randomised treatments. The treatments involve different catchment area to cropped field ratios (CA:CF) (0:1; 2:1; 4:1). These are combined with two tillage methods. The cropped area is planted with maize and is treated as flat cultivation or staggered ridging. The catchment area is cleared of weeds and compacted. Slopes across the blocks are categorised into 2–4% and 6–8%.
- Run-off yield experiment. This assesses the effect of catchment slope, catchment length, and surface cover on runoff yield. The plots are arranged with a within-block randomisation. Including the catchment slope differences, a total of 16 treatments is replicated twice.

Hombolo

The experimental work at Hombolo also consists of two experiments.

- Tillage and fertiliser application experiment. This involves seven tillage treatments combined with four fertiliser treatments on a completed randomised block design with three replications. The tillage treatments are zero tillage, flat (hand-hoe) cultivation, flat (hand-hoe) cultivation plus mulch, strip catchment (hand-hoe) tillage, tied ridging with hand-hoe, flat tractor cultivation, and flat tractor cultivation with mulch. The fertiliser treatments include farmyard manure (FYM) at 10t/ha and triple superphosphate (TSP) applied at 100 kg/ha. Nitrogen fertiliser at 40 kg N/ha is used on all treatments. The test crop used is sorghum (sorghum *bicolor* cv, Tegemeo) planted on 5 x 20 m plots, row spacing of 0.75 m and within-row spacing of 0.30 m, giving a plant population of 89 000 plants/ha, thinned at three leaves to 45 000 plants ha.

- Cropping under RWH Experiment. This consists of three replicates (blocks) of ten treatments (0:1, 2:1 and 4:1) CA:CF ratio. There are two differences from the Morogoro trial. Here the cropped field is split and planted one half with maize and the other with sorghum. Also the harvested runoff is applied to the cropped field either with or without storage. On the plots with storage, the runoff is directed into a storage tank, the overflow from which is lost to the crop. These tanks hold 1.25 and 2.5 m^3 on the 2:1 and 4:1 plots, respectively. When the soil moisture in the cropped field drops below a certain level, the water in the tank is used to irrigate the crop until it runs out.

Kisangara

This site contains five different experiments.

- Cropping under RWH without storage experiment. this is similar to that of the Morogoro site. However, from next season, fertiliser treatments will be superimposed at Kisangara.

- Cropping under RWH with storage reservoir. This is similar to that of Hombolo, but with a large storage reservoir.

- Runoff yield experiment: which is similar to that described for Morogoro.

- Runoff yield of large catchments. Runoff from large catchments will be measured using water-level recorders in flumes.

- Soil and water conservation experiment. This consists of six blocks of five within-block randomised treatments. These are zero tillage, flat cultivation, contour ridging, stone bunds, and vetiver grass on Iduri tree barriers.

Preliminary Results

Only results from the 1991–92 season in Hombolo have been fully analysed. The other sites were opened during the 1992–93 season and harvesting has not been completed yet. From the Hombolo results several issues have emerged which can be summarised as follows.

Tillage and fertiliser experiment

The results are shown in Table 1. A high grain yield was recorded for strip catchment tillage (SCT), with 1/2 FYM and 1/2 TSP application, but similar yields were obtained from tied ridging fertiliser combinations. The increased grain yields under SCT and tied ridging can be attributed to high water infiltration and to harvesting of rainwater along the interrow space (Willcocks 1984). Although infiltration rate itself is not increased appreciably, tied ridges facilitate rainfall infiltration into the soil by retaining a major proportion of the rainfall received on-site. Consequently, most crops planted on tied ridges have deeper and more extensive root systems, and greater vegetative growth and yield by comparison with flat cultivation.

Cropping with RWH experiment

The results show that crops grown under a CA:CF area ratio of 4:1 with storage gave the highest yields of both maize (3.26 t/ha) and sorghum (3.22 t/ha), followed by the CA:CF area ratio of 2:1 with storage which yielded 2.4 t/ha and 2.67 t/ha respectively. Therefore there was a significant increase in yield as a result of reservoir storage. The most important comparison was between treatments with CA:CF area ratio of 0:1, that is, no water input from outside catchment. Cropped areas protected against loss of water by run-out yielded 1.8 t/ha sorghum while unprotected fields yielded 1.22 t/ha. This shows that the yield losses due to water lost through run-out from cropped fields are significant in semi-arid areas of Tanzania.

Table 1. Effect of tillage and fertiliser treatments on grain yield of sorghum at Hombolo, Dodoma.

Tillage	Treatments Fertiliser		Yield (kg/ha)	
Zero tillage	A:	Control (no fertiliser	1952	abc
	B:	Farmyard manure (FYM)	1962	abcd
	C:	Triple superphosphate (TSP)	1954	abc
	D:	FYM ($^1/_2$) plus TSP ($^1/_2$)	1869	abcd
Flat cultivation	E:	Control	1289	efgd
	F:	FYM	2252	ab
	G:	TSP	2044	abc
	H:	FYM ($^1/_2$) plus TSP ($^1/_2$)	1995	abc
Flat cultivation and mulch	I:	Control	1829	abcde
	J:	FYM	1981	abc
	K:	TSP	1569	defg
	L:	FYM ($^1/_2$) plus TSP ($^1/_2$)	1863	abcd
Tied ridging	M:	Control	2142	ab
	N:	FYM	2137	ab
	O:	TSP	2037	ab
	P:	FYM ($^1/_2$) plus TSP ($^1/_2$)	2155	ab
Strip catchment tillage	Q:	Control	1267	fg
	R:	FYM	2152	ab
	S:	TSP	2037	abc
	T:	FYM ($^1/_2$) plus TSP ($^1/_2$)	2386	a

Letters a–g denote significance at the 5% level using Duncan's new multiple range
Means with the same letter are not significantly different

Conclusion

This paper describes a research program just started in Tanzania to search for ways of improving soil moisture for dryland agriculture in semi-arid areas.

Surveys of farmers have shown that farmers rank shortage of soil moisture as the most important limitation to crop production in these areas. This has been proved by the significant yield increases observed in cropped fields when extra water is supplied through RWH. However, improving soil moisture without paying attention to soil fertility will lead to low water-use efficiency by crops.

There is potential for collaboration with other SADC countries.

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Modelling of Maize Growth and Development in Malawi

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Abstract

A series of field trials was conducted during the 1989–90 to 1991–92 crop-growing seasons at three experimental sites, Chitedze, Mwimba and Chitala. The overall goal was to increase the efficiency of the transfer of technology in both the design of appropriate packages for smallholder farmers and in the extension of results through the integration of an existing biological simulation crop model for selected major maize-growing areas in Malawi.

A comparison of measured and simulated results has shown that the CERES-Maize model was successful in predicting maize grain yields with a reasonable degree of accuracy over the range of soils and climatic conditions which prevailed during the study period. This has been well illustrated by a close match between predicted and measured grain yields, and the fact that when simulated grain yields were regressed on measured yields the intercept was not significantly different from zero nor was the slope of the line significantly different from 1.

Location and Environmental Characteristics

Malawi is a small landlocked country located in southeastern Africa between latitudes 9° to 18°S and longitudes 33° to 36° E with a total area of 11.8 million ha of which over 20% is covered by water.

Malawi exhibits great diversity in terms of relief units, soils and climate for a country of its size. There are four major relief units: (1) The high altitude plateaus (1350 to 3000 m asl) dominated by Lithosols and some weathered Latosols, (2) The medium-altitude plain (750 and 1350 m asl) with deep, well drained Latosols on upland sites and poorly drained hydromorphic soils, (3) The Lakeshore Plain (450 and 600 m asl) characterised by calcimorphic alluvial soils and hydromorphic soils and (4) The Lower Shire Valley (35 to 105 m asl) dominated by calcimorphic alluvial soils and Vertisols, and some hydromorphic soils in dambos.

The climate is semi-arid in the Lower Shire Valley and some parts of the Lakeshore Plain; semi-arid to sub-humid in the Medium Altitude Plain, and sub-humid to humid in the high altitude plateaus. Although most parts of Malawi receive adequate total rainfall for rainfed agriculture in most years, its distribution is poor and erratic, leading to maize failure in some years.

Population and agricultural production

The population of Malawi is estimated at 8.7 million people with an average density of 84 persons per km², and a growth rate of 3.7% per annum. About 90% of the population is rural and derive its livelihood from small landholdings of between 1.0 and 2.0 ha per farm family.

Agriculture dominates the economy. It contributes well over 40% of the GDP, and accounts for about 90% of the foreign exchange earnings. Smallholder farmers contribute about 85% of total agricultural production, and 30% of the export trade.

The major food crops are maize, groundnuts, cassava, sorghum, rice, beans and various other pulses. Principal cash crops include tobacco, tea, sugar, coffee, groundnuts, cotton, macadamia nuts and maize. Maize is the major food crop grown on about 65% of the total cultivated land area (estimated at 1.8 million ha). About 94% of this is grown in association with legumes, and 6% is planted in pure stands.

Although good progress has been made in soil fertility research in Malawi, most of the technological

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innovations have not been taken up by smallholders. With increasing population pressures on land, and limited land that can be put to agricultural production, there is a clear need to develop appropriate crop production technologies that are practical, stable, environmentally sound and adoptable by resource-poor smallholders. These systems could be based on increased fertiliser-use efficiency, improved varieties, soil and water conservation strategies, and the use of indigenous and organic fertiliser materials as alternative sources of nutrients. It is within this framework that the maize modelling work was initiated in Malawi.

Implementation of the Maize Modelling Initiative

The translation of research findings into technology packages that can be widely adopted and utilised by farmers constitutes a major problem in the development of agriculture. Generally, field experimentation, either in outlying research stations or in farmers' fields, is the basis of this development, identifying suitable technology (research) and demonstrating its usefulness (extension).

The results of experiments are heavily dependent on the rainfall pattern in the particular season in which they are carried out, the specific soil type on which the experiment takes place, and numerous management factors under the control of the researcher. The critical issue to be addressed is whether the results from such crop experiments can produce technical advice appropriate to farmers' fields in a different place, in a different year, on a different soil type, and where farming operations are constrained by socioeconomic factors not present at the research station where most field experiments take place.

Agricultural research, wherever it is undertaken, tends to be highly location-specific. It is simply not possible to cover an entire country with field trials in an effort to derive appropriate cropping practices for the wide variety of soil types and climatic conditions that are found in any region. The challenge is to develop methodologies that allow scientists to transfer technology effectively from one area to another, given the constraints of time, money, and other resources.

One tool that offers considerable potential is the use of crop simulation models. The provision of a validated crop model for Malawi would allow the problem of site-specificity to be relaxed to some degree, without incurring the resource expenditure that would be necessary for large-scale field experimentation. Computer-based assessment of various varieties and management packages in different regions of the country would yield information to help ensure that only the most promising technologies would be selected for field testing in particular areas, thereby enhancing the efficiency of the research process.

This modelling effort was conceived, therefore, to be a step in the direction of helping to increase the efficiency of the transference of technology, both in the design of appropriate packages for smallholder farmers and in the extension of the results. This might be achieved through the integration of an existing crop growth simulation model (CERES-Maize) within the maize research programs for particular maize-producing environments in Malawi. It was hoped to demonstrate that a simulation model could be a useful tool for complementing field research.

The specific objectives were: (1) to build a database of soil and weather variables for some maize-producing areas of Malawi, (2) to validate and calibrate an already existing simulation model of maize growth and development for representative cultivars in a number of study areas, (3) to predict maize production and its variability between sites and between years in the study locations and in the other regions of the country, and (4) to illustrate how the CERES-Maize model can be used to improve on the traditional approach to agricultural research based on field experimentation.

This paper summarises model validation results for field trials conducted from 1989–1992 crop seasons at three experimental sites.

Experimental Program

Model selection

The CERES-Maize model (Jones and Kiniry 1986; Ritchie et al. 1989), originally developed for conditions in the United States of America, was selected for the present modelling activities because it has also been adapted for a wide variety of locations and environments in the tropics (e.g., Kenya, Keating et al. 1991). Since the mid-1980s, CERES-Maize has been tested in at least 25 countries around the world in latitudes ranging from the northern fringes of the United States corn belt to South America.

Field trial locations

To generate the data required, a series of field trials was conducted over three seasons: 1989–90, 1990–91 and 1991–92 at three experimental sites:

(1) Chitedze (13° 59'S, 33° 38'E, 1100 m asl) on the Lilongwe soil series (medium-textured sandy clay loam ferruginous Latosols) of the medium-altitude plain, (2) Mwimba (13° 05'S, 33° 27'E, 1050 m asl) on the Kamphuru series (coarse-textured sandy clay loam ferallitic Latosols) of the medium-altitude plain, and Chitala (13° 41'S, 34° 17'E, 600 m asl) on the Chitala series (medium-textured sandy clay loam low-altitude ferruginous Latosols) of the Lakeshore Plain; and on farmers' fields in the vicinity of these stations. (Further details on these are given elsewhere, Thornton et al. 1993.) The annual total rainfall at these stations generally ranges from 750–1100 mm at Chitedze, 750–1050 mm at Mwimba, and 700–950 mm at Chitala. For the present paper, data obtained from the three experimental sites will be used to validate the CERES-Maize model.

Experimental design

There were 12 treatment combinations in a factorial design involving two maize varieties (one local and one hybrid), three nitrogen levels (0, 60 and 240 kg N/ha), and two phosphorus levels (0, 150 kg P_2O_5). Treatments were arranged in a randomised complete block design with three replicates. Maize was planted on ridges spaced 90 cm apart, with 30 cm between planting stations (one plant per station), giving a plant population of 37 000 plants. The plots measured 15 m by 6.3 m. The experimental design did not change throughout the life of the project; the same design was used on-station and in farmers' field trials.

Fertiliser N, in the form of urea, was applied in a band about 7.5 cm away from the planting stations in two equal split applications, a basal dressing at or near planting and a topdressing when the crop was 0.6 m height. Fertiliser P, in the form of single superphosphate, was also applied in a band about 7.5 cm away from the planting stations as a basal dressing. To ensure that other nutrients were not limiting maize growth and development, a blanket basal application of K, Mg, Ca, S, Zn and B was applied on all plots except the Chitedze experiment in 1989–90.

The varieties planted were those felt to be appropriate for each area. The hybrid maize varieties were SR-52 for Chitedze, MH-16 for Mwimba, and NSCM-41 for Chitala. Appropriate local varieties were chosen, referred to as Local-1 for Chitedze, Local-2 for Mwimba, and Local-3 for Chitala. Treatment combinations, planting dates, and dates of top dressing are given elsewhere (Thornton et al. 1993). Soil and plant samples were collected from selected trial sites to characterise N and soil-water dynamics in the crop root-zone.

The CERES-Maize Model

The CERES–Maize model allows the quantitative determination of growth and yield of maize. The growth of the crop is simulated with a daily time step from sowing to maturity on the basis of physiological processes determined by the crop's response to soil and aerial environmental conditions. For phasic development, CERES–Maize quantifies the physiological age of the plant and describes the duration of nine growth stages. Potential growth is dependent on photosynthetically active radiation and its interception as influenced by leaf area index (LAI), row spacing, plant population, and photosynthetic conversion efficiency of the crop. Actual biomass production is constrained by suboptimal temperatures, soil-water deficit, N deficiency, and P stress. The crop's development phase dictates assimilate partitioning on a per-plant basis for the growth of roots, leaves, stems, and grains.

The model also simulates surface runoff, evaporation, drainage, N and soil-water uptake, turnover of organic matter with the associated mineralisation and/or immobilisation of N, nitrification, denitrification, hydrolysis of urea, and ammonia volatilisation, for a variety of different N sources, including chemical fertilisers, green manures, and other organic N sources. Nitrate and urea movement is simulated as a function of water flow through a soil layer. It also simulates the effects of both N and P deficiency on photosynthesis, leaf expansion, tillering, senescence, assimilate partitioning, and, in severe cases, delay in phenological development. More details of the model may be found in Ritchie et al. (1989), Singh et al. (1993); together with a brief description of its associated input and output files.

Validation

To validate the CERES–Maize model we compared the simulated yield outcomes with the measured yields obtained from the N and variety treatments of the field experiments. The model's performance for the different varieties and N rates is shown in Figure 1 for the 1990–91 season. At Chitedze, on relatively fertile soils, the local variety (Local-1) showed little response to N application. The model successfully simulated a similar response. The observed and simulated grain yield responses for hybrid SR-52 were also closely matched. Both simulated and measured results showed no significant response to N fertiliser beyond 60 kg N per ha. However, at Mwimba, on a sandy soil with low inherent soil fertility, both the

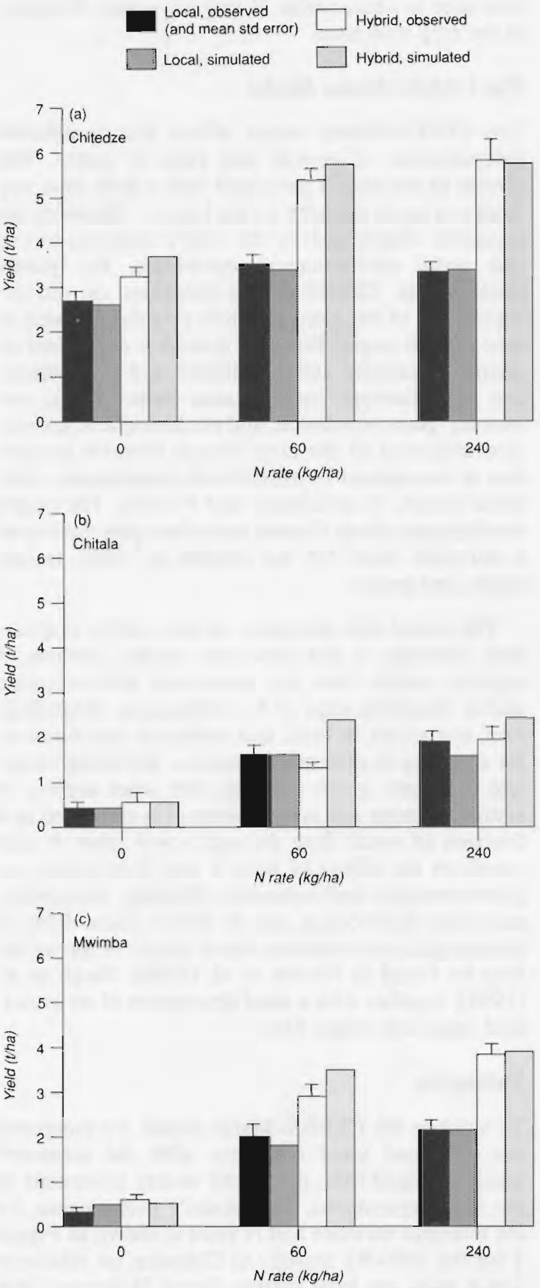

Figure 1. Performance of the CERES-Maize model with different varieties and fertiliser rates at three locations in the 1990–91 season.

local variety (Local-1) and the hybrid MH-16 showed marked response to N fertiliser application. This effect was accurately captured by the model, as shown by the simulated results. At Chitala, a drier site, the two maize varieties (Local-2 and NSCM-41) behaved similarly, with only small response to N application beyond 60 kg/ha.

A comparison of observed and simulated maize grain yields for the eight experiments run at Chitedze, Chitala, and Mwimba over the three seasons from 1989–90 to 1991–92 is shown in Figure 2. The spread of the treatment points around the 1:1 line can be explained as a combination of model and measurement errors, and also the presence of uncontrolled factors in some plots to which the model is not sensitive, for instance, weeds and termites. Generally, however, the fit is quite good. The two outliers at the top right-hand side of Figure 2 were high N treatments from one experiment at Chitedze, and the model substantially overpredicted yields in these cases. Also shown in Figure 2 is the linear regression of predicted on observed yields; the intercept is not significantly different from 0, nor is the slope of the line significantly different from 1, at the 5% level using Student's t-test. The regression accounts for approximately 94% of the variance in simulated grain yield. The CERES–Maize model is thus sensitive to combinations of genetic, management, soil and weather conditions that lead to yields in the range 0.5 to over 6 t/ha, all these factors being taken into account in the model and using the same genetic coefficients for each variety in all trials across all years.

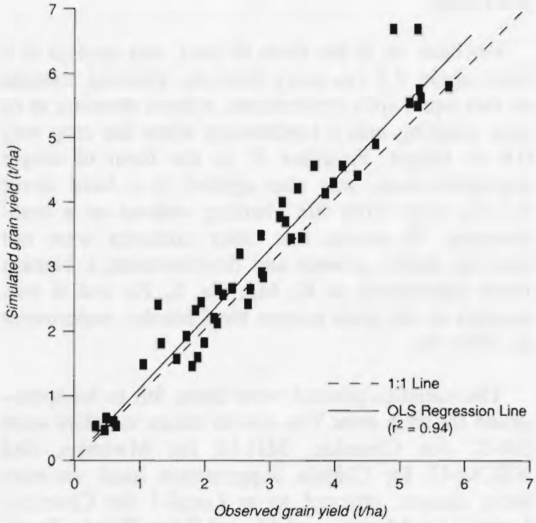

Figure 2. Observed maize yeilds compared with yields simulated with the CERES-Maize model. Data drawn from 8 experiments at 3 sites in 3 seasons (1989–92).

Discussion

The CERES–Maize model appears to predict yields with a reasonable degree of accuracy over the range of conditions that pertained in Central Malawi during 1989–1992. A feature of Figures 1 and 2 that lends more support to this assertion is that the regression lines of simulated versus observed yields lie above the 1:1 line. Slight overprediction of yields by the model is generally seen as a desirable trait, because control of experimental factors to which the model is not sensitive can never be complete. Slight overprediction is thus to be expected. By contrast, consistent underprediction by the model is generally taken to be a sign that there is a fundamental problem with the model, in that field conditions will usually be somewhat worse than the 'ideal' (no pests, diseases, etc.) conditions under which simulation runs are carried out on the computer.

On the other hand, there is some evidence that while yields may match fairly well, other internal workings of the model may need some adjustment. The entire model calibration and validation procedures will be repeated once the results of further field trials carried out in the region during the 1992–93 season have been analysed. It may well be that some small adjustments to initial soil conditions and genetic coefficients will be made, in an attempt to improve the match between simulated and observed data, not only for final yield but also for other growth and development parameters such as biomass and N uptake. This highlights the importance of the validation process, and demonstrates that whether or not a model can be deemed valid relates largely to the slow buildup (or evaporation) over time of confidence by the researchers in its predictions.

Future Activities

Future modelling activities will include validating the N and soil-water balance sub-models, simulating maize grain yield response to planting density, planting windows and N fertiliser management scenarios based on soils and historical climatic data. Concerted efforts will also be directed at linking the CERES–Maize model to a Geographic Information System for selected major maize growing areas in Lilongwe, Salima and Kasungu Agricultural Development Divisions.

The data collection procedures for validating and calibrating the CERES-Maize model are detailed and time-consuming. Once the genetic coefficients have been derived for the varieties of interest, the data collection procedures can be made much simpler while still providing field data of use for testing the model. One of the advantages of the detailed data sets collected for CERES-Maize is that other nutrient (such as NITROSIM, Rao et al. 1981) and crop models could also be evaluated under the same conditions. Ultimately, data collection procedures for model use could be simplified substantially.

Since most of the maize is grown in association with legumes, future modelling initiatives will have to consider evaluating the forecasting ability of intercropping simulation models. The development and evaluation of intercropping models will contribute greatly to improved understanding of farming circumstances under smallholder conditions.

Acknowledgments

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Rates of Adoption of New Technology and Climatic Risk in the Communal Areas of Zimbabwe

P. Huchu* and P.N. Sithole*

Abstract

Poor soil fertility and climatic risk are major factors that directly affect Zimbabwe farmers' ability to produce enough food for subsistence and for cash. Much research has been carried out towards minimising these problems at farmer level. Farmers themselves have their technologies that they have used for generations in alleviating these problems. This paper describes past and present technologies for managing soil fertility and climatic risk, their levels of adoption, and the major factors affecting adoption.

Background

Soil fertility problems in Zimbabwean communal areas

About two-thirds of Zimbabwe is covered with sandy soils that are derived mainly from coarse-grained granites. These soils are almost without exception very infertile and deficient in N, P and S. Only in a few areas, mainly in the northwest, where there are intrusions of basic rocks such as basalt or dolerite, the soils have a higher fertility than those of the surrounding areas.

Where there are human settlements, conditions of poor soil fertility have been worsened by human and livestock pressure and poor farming practices.

More than 67% of the communal areas exceed their recommended carrying capacity in respect of both human and livestock populations.

Population pressure has meant that there is very little or no virgin land to be allocated to the younger generation. The same depleted pieces of land being passed on from generation to generation in smaller and smaller sizes per family.

Increased human and livestock population has resulted in loss of topsoil and nutrients associated with it as soils are eroded after deforestation. Trees have been felled in communal areas:

- to extend crop fields;
- to provide domestic fuel;
- for beer brewing and burning bricks;
- for building houses;
- for making kraals;
- for fencing poles; and
- making wooden carvings.

Loss of soil fertility may have come about also as a result of mechanisation, particularly the use of the mouldboard plough. Deep ploughing overworks the delicate communal soils, making them loose and easily eroded by wind and water.

Use of land, year after year, with little or no fertiliser being put into the soil has resulted in soils being depleted of almost all their nutrients.

Consequences of low soil fertility

The low soil fertility results in poor crop yields. Major crops such as maize, cotton and groundnuts have given consistently low yields over the years (see Table 1).

Table 1. Estimated communal area yield (t/ha).

Year	maize	cotton	groundnuts
1985–86	1.3	0.9	0.4
1986–87	0.6	0.6	0.3
1987–88	1.4	0.9	0.5
1988–89	1.2	0.8	0.5
1989–90	1.3	0.7	0.5
1990–91	1.1	0.7	0.4

Source: Crop Forecasting Committee and National Early Warning Unit, AGRITEX and Central Statistics Office (1992)

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According to information from the Department of Research and Specialist Services (DR&SS) (Grant 1981), satisfactory grain crops cannot be grown on any of the soils of Zimbabwe without some improvement of fertility. Farmers are compelled to spend large sums of money on fertiliser to improve the nutrient content of their soils and hence their output.

In another effort to get sufficient produce from the land, people have tried to increase their cropping land by moving into areas generally considered unsuitable for cropping.

Encroachment into grazing areas has reduced available grazing for livestock. With no corresponding reduction in livestock numbers, grazing lands have been overgrazed. In most areas overgrazing has resulted in the depletion of palatable grass species as they make way for less nutritious, unpalatable species like *Sporobolus pyramidalis*. In times of drought, more livestock have died due to lack of grass.

Encroachment into vleis and other wet areas has resulted in the formation of gullies due to erosion as well as siltation of rivers and dams.

Climatic risk

There are five agroecological or Natural Regions (NR) in Zimbabwe classified on the basis of rainfall pattern topography and soil depth (see Fig.1 Waddington, these Proceedings). Almost 90% of the communal areas are found in the drier NRs 3, 4 and 5. Average annual rainfall in NR 3 and NR 4 is about 725 mm and 525 mm respectively. In NR 5, total rainfall can be as low as 200 mm. Details on natural regions are given in the Appendix.

Table 2. General comparison of seasons in NRs 3, 4 and 5.

Season parameter	NR 3	NR 4	NR 5
median start to season	10 Nov	18 Nov	3 Dec
median end of season	31 Mar	28 Mar	24 Mar
median length of season (days)	131	121	96
% occurrence of 'drought season'	18	16	18
% occurrence of 'intermediate season'	5	15	30
% occurrence of 'no season' (i.e. no rainfall)	0	1	5

Source: Workshop on cropping in the semi-arid areas of Zimbabwe. (DR&SS, and Agritex 1987)

Table 2 shows the worsening conditions for arable farming as one moves from NR 3 to NR 5. In moving from Region 3 to Region 5 trends are clearly established which indicate the later start, earlier end and shorter length of season. There is also a marked increase in the percentage incidence of 'intermediate' and 'no' seasons in moving from Region 3 to 5.

All three natural regions experience severe mid-season breaks in the rains, particularly around January. These, combined with excessive heat at this time of the year, cause field crops to be severely stressed.

Technologies for Managing Soil Fertility and Climatic Risk

Traditional techniques

Shifting cultivation

Shifting cultivation was traditionally practised until recently as a way of managing soil fertility. In Zimbabwe, two to three crops would be taken before each area of land was allowed to revert to bush for about 15 or more years. After this period, branches cut to clear the land would be heaped on particular patches of the land and burned. In this process, nutrients, particularly P, K and Ca, and absorptive charcoal, were added to the soil from the ashes. Sterilisation of the soil by heat could increase the availability of nutrients including N and S and reduce competition from micro-organisms and weeds.

This practice has been discontinued because it was hard work, and required 150–200 ha for the subsistence of a family (Grant 1981). Such large areas of land are now not available to communal farmers.

The modern adaptation from shifting cultivation is fallowing. Here, a farmer would deliberately rest part of his field for one or two seasons to give the land time to recover. This practice is again limited to those farmers who have access to large pieces of land. Sometimes fallowing will be done due to resource constraints, particularly lack of draught power, rather than a desire to restore soil fertility. Studies by DR&SS (Grant 1981) however indicate that in overworked lands which form only a poor grass cover under fallow, there is little or no evidence of improvement of fertility during the fallow period.

Leaving trees and shrubs in the field

Soil erosion can be reduced by leaving trees in the field, particularly in waterways. Trees slow down the movement of water or wind, causing soil particles to be deposited. Some trees can also provide useful shade, fruit and recycling of nutrients from the subsoil via fallen leaves that rot easily and add humus to the soil. Conversely, trees often also compete with crops for nutrients, water and light.

However, leaving trees in the field has generally been discouraged by agricultural extension agents. The main disadvantage is that the trees interfere with tillage operations. Only a low percentage of farmers till their lands by hand, suggesting that preservation of trees on cultivated fields cannot be widely practised. Only 10% of communal farmers were found in an Agritex 1991–92 survey to cultivate by hand. The majority used draught animals; a few used hired tractors.

Instead of being left inside the field, trees can be left on contour banks, between fields or at field boundaries, with soil conservation benefits.

Use of leaf litter

Another traditional soil fertility management practice is the use of leaf litter collected from under trees in the vicinity. This litter can be thrown directly onto the field to help improve soil structure and provide nutrients, or it can first be composted, either in a pit or mixed with manure in a kraal.

However, litter is not widely used for soil fertility management, because litter is now less plentiful due to deforestation. Another reason is that suitable equipment such as scotchcarts or wheelbarrows to transport the litter is not available to many farmers. Only 28% and 16.5% of farmers own scotchcarts and wheelbarrows, respectively, in communal areas (Sithole and Shoko 1993). Labour is another limiting factor.

Antheap

Antheap-soil spread over the field helps improve the structure and fertility of sandy soils. It also increases the soil pH. It improves water holding capacity of sands and prevents leaching. Like leaf litter, widespread use of antheap-soil is discouraged by the high labour requirements and limited availability.

More recent techniques

Crop rotation

Crop rotation is vigorously promoted by extension agents for improving soil structure and facilitating the transfer of nutrients between crops via the soil. It also helps control pests and diseases.

Adoption of crop rotation is high, possibly because there are no direct cash costs associated with the practice. In studies carried out in Wedza in 1991, 74.8% of communal farmers interviewed were found to practise crop rotation in their fields. The figure for Gokwe and Nyanga was found to average 76% in 1992 for both areas.

The main factor restricting adoption of crop rotation is poor access to resources such as land, labour and agricultural inputs. All these constraints can combine to result in the planting of just one crop, usually maize.

Contour ridges

Contour ridges are strongly supported by extension agents for the control of soil erosion and conservation of water and soil nutrients. Adoption of contour ridges was very high in communal areas before Independence, because of Government enforcement, and close to 100% of communal farmers dug and maintained contour ridges. The present approach of the extension department is in educating farmers to realise the need for contours. Studies carried out in Gokwe and Nyanga communal areas (Mudiwa 1993) show that farmers in mountainous areas (e.g. Nyanga) where soils are most susceptible to erosion are more likely to dig and maintain contours. (Table 3).

Table 3. Incidence of contour construction in farmers' fields (% of total sample of farmers) of two communal areas.

	(% of farms)	
Utilisation of contours	Nyanga	Gokwe
No contours in the field	20	68
Contours in part of field	26	20
Whole field contours	54	12

Tied-ridging

The creation of tied-ridges on red soils (derived from paragnesis) has been shown to ensure little or no runoff by promoting water runoff into the furrow, and concentrating it in this zone. The concentrated water penetrates deeper into the soil where it is protected from loss by evaporation from the soil surface (Vogel, these Proceedings).

Tied-ridging and sowing in the furrows between the ridges have been shown to have beneficial effects on yields of various crops in studies in Vertisols at Chiredzi (DR&SS 1987).

Table 4 shows that sowing in the furrow produced higher yields of all three crops in the four seasons except for the failed maize crop in 1983–84. In percentage terms the increases were least in the good

Table 4. Yields of sorghum, maize and cotton sown on the flat over 4 years at Chiredzi and in furrow.

Crop and tillage	(kg/ha)			
Planting technique	1983–84	1984–85	1985–86	1986–87
Sorghum				
Sown on flat	413	2771	2018	
in furrows	+159	+121	+612	
Maize benefit				
Sown on flat	0	34	23	0
		68	10	
in furrows	0	+1	+5	+1
		66	66	26
Cotton benefit				
Sown on flat	30	+2	94	54
	0	43	0	0
		0		
in furrows	+1	+4	+4	+4
	90	20	20	00

Source: Workshop 'Cropping in semi-arid areas of Zimbabwe'. (DR&SS and Agritex, 1987)

year 1984–85 and greatest in the poor years 1983–84 and 1986–87.

Tied-ridging to conserve moisture is used in cotton-growing areas of Gokwe and Nyanga (Mudiwa 1993). However, on sandy soils, crops do not respond well to tied-ridging as a means of conserving water.

In a Coordinated Agricultural and Rural Development (CARD) pilot crop project in Gutu, use of a mechanical ox-drawn ridger was promoted in the mid-1980s. Adoption by project members dropped from almost 100% in 1987 to 10% in 1992 (Chipika 1988, Huchu 1992). The reason for the drop was given as heaviness of the ridger. Ridging using a plough is not often done by farmers because it is time-consuming. Ridging using a cultivator is not always practised, since only 31.5% of communal area farmers own cultivators (Sithole and Shoko 1993).

Winter ploughing

Winter ploughing, when done immediately after harvesting, helps to retain moisture. It also adds to soil fertility by burying weeds and crop residues. It facilitates dry planting at the start of the next season, and thus allows communal farmers to make maximum use of the first effective rains.

Adoption of winter ploughing depends on availability of equipment (mouldboard plough) and reliable draught power immediately after harvesting while the ground is still moist. In studies carried out in eight randomly selected districts throughout the country (Sithole and Shoko, 1993) only 53.3% of farmers owned the draft animals they used. The rest of the farmers either borrowed or hired animals. This figure agrees with the 55.8% of farmers found to winter plough in Wedza communal area (Maboyi 1988).

Soil fertility inputs

Manure

Application of manure is recommended by extension agents for improving soil fertility and structure. Adoption of manure use is very high in communal areas. Studies carried out in Shurugwi-Chiwundura (Huchu 1993) and Wedza (Sithole and Shoko 1991) show level of manure use to be 83.4% and 63.5% respectively.

Substantial use of manure for soil fertility management is limited to those farmers who own a large number of livestock. Swift and co-workers (1989) estimated that a farmer would need roughly 14 animals to provide sufficient N from manure for one ha of arable land. In a survey carried out September–October 1992, in the middle of the drought, 60.5% of communal farmers were found to own cattle. The average number of cattle owned per communal farmer was only four, meaning that although the number of users of manure is high, quantity used per farmer is very small due to limited quantities.

The effectiveness of manure in improving soil fertility and structure and hence plant growth also depends on nutrient content. Manure in communal areas has been found to be very low in N and high in

K and Mg. The low nutrient content of manure appears to be related directly to the quality of forage consumed by the cattle. The manure also contains very high quantities of sand, sometimes as high as 80% (Mugwira and Shumba 1986). This is due to cattle trampling manure into the soil in the kraal.

The poor nutrient content of manure and low rates applied because of scarcity make it ineffective in increasing the growth of maize plants after about 12 weeks. This means that farmers need to supplement the nutrients from manure with a topdressing fertiliser.

Inorganic fertiliser

Inorganic fertilisers are highly promoted by extension agents as a means of improving soil fertility. Although most farmers have seen the benefits of using fertilisers, adoption is limited by uncertainty about the season's rainfall, presence of substitutes (e.g. manure to some extent) cash constraints, and the economic importance of the particular crop to the farmer.

Farmers have discovered that if they use fertiliser and it fails to rain, they will be worse off economically than if they did not use fertiliser at all. For this reason, many do not use fertilisers at planting (basal fertilisers). Topdressing is better adopted because, by the time it is applied, farmers will have observed the rainfall pattern for the early part of that season. Table 5 illustrates the point.

Table 5. Fertiliser use on maize in Wedza and Shurugwi-Chiwundura.

Fertiliser application	% of users in Wedze	% of users in Shurugwi-Chiwundura
Basal	48.8	41.7
Topdressing	78.9	90.9

Farmers who have livestock substitute manure for basal fertiliser. In a study in Wedza communal area, 40.8% of farmers who used manure on maize in the 1990–91 season did not use initial fertiliser. Topdressing, on the other hand, has no substitutes, which could also partly explain higher adoption of topdressing relative to initial fertiliser.

The adoption of the practice of fertiliser application is also affected by access to cash. Poor farmers simply cannot afford to buy it. In a study carried out in Wedza (Sithole and Shoko 1991) lack of money was given by 60.4% of non-users as the main reason for not using fertilisers. There is a facility for communal farmers to get credit for inputs from the Agricultural Finance Corporation (AFC). However, many farmers, particularly those in NRs 4 and 5, are afraid to take the risk.

Fertiliser usage also depends on the importance of a particular crop to the farmer. For most communal farmers, their most important crop is maize. This is where a large number of farmers will apply fertiliser (Table 6).

Table 6. Adoption of basal fertilisers in certain crops in Wedza and Shurugwi-Chiwundura in the 1990–91 season.

Crop	Wedze (% growers)	Shurugwi-Chiwundura (% growers)
maize	48.8	41.7
sunflower	19.6	21.5
groundnuts	4.4	3.8

This table may be misleading in that it defines an adopter as one who uses **any amount** of fertiliser. When actual amounts of fertilisers are considered, the majority of fertiliser users in communal areas apply less fertiliser than recommended by researchers and extension agents. In studies carried out in Wedza communal area in 1991, 82% of inorganic fertiliser users applied far below the recommended amounts.

Adoption of inorganic fertiliser also depends on farmers' attitudes. Informal interviews in Mutoko Communal Area (Carter 1993) revealed that some farmers will not use inorganic fertiliser, particularly Compound D, because they believe that it makes the soil structure weak and sandier. In Gokwe, although cotton is an important cash crop, the majority of farmers were found not to use basal fertiliser (76%) or topdressing (77%) on this crop (Mudiwa 1993). The main reason given for not using fertiliser was that the soils are still fertile. Apparently Gokwe farmers' belief that their soils were still fertile is incorrect because the extension agents in the area actually advised farmers to apply fertiliser. There was also a large difference in yield between farmers who used fertiliser and those who did not. Average yields of cotton were 38% higher where basal fertiliser was used, and 30% higher after topdressed fertiliser.

Table 7. Effect of fertiliser on average farmers' yields (kg/ha) of cotton in Gokwe 1990–91.

Used basal fertiliser	No basal fertiliser	Used top-dressing	No top-dressing
723	523	704	542

Seed and grain

Hybrid seed

Hybrid seed, particularly early maturing varieties, is strongly recommended for communal areas with poor rainfall. The advantage is short growing season and it will usually reach maturity before the rains cease.

Adoption of hybrid seed, particularly maize, has been very high in communal areas. Studies carried out in Wedza (Sithole and Shoko 1991) showed that 98% of the communal farmers used hybrid seed.

Grain storage

Variability in seasons and the effects of that variability on yield require farmers to be able to store the bounty of the good years to ward off famine in the poor years.

In studies by Koza (1993), the majority of farmers in communal areas were found to keep grain for a maximum of one season. Most of the storage structures (granaries) were found to be durable, and could keep grain in good condition if proper storage management was practised. About 40% of structures were found to have the capacity to facilitate long-term storage with a duration of a minimum of two years.

There are several reasons why farmers with a durable structure of adequate capacity do not store grain for long periods. These include optimism about the coming season, failure to control pests and diseases due to lack of knowledge of pesticides or lack of cash, and low yields obtained, or the need to sell surplus grain to meet cash needs.

Discussion and Conclusion

In general, technologies will be adopted by farmers if they fit into the farmer's production system, and are compatible with available resources, as well as providing a solution to immediate problems. This is true of most of the highly adopted technologies, such as crop rotation, manure, winter-ploughing, inorganic fertiliser and hybrid seed all of which have effectively increased farmers' yields. These technologies fit in well with the farmer's available resources.

Other technologies, such as leaf litter, antheap, and ridges (including contour ridges) have not fitted well into communal farmers' production systems, in that they place a heavy demand on draught cattle, labour, and equipment, all of which are very scarce resources in communal areas. Technology needs to be relevant to a farmer's requirements, production system, and available resources.

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Appendix: Rainfall characteristics of the natural regions (NR).

NR 1. Rainfall in this region is high (more than 1000 mm per year in areas lying below 1700 m altitude, and more than 900 mm per year at greater altitudes), normally with some precipitation in all months of the year.

NR 2a. Rainfall is confined to summer and is moderately high (750–1000 mm). This region receives an average of at least 18 rainy pentads per season and normally enjoys reliable conditions, rarely experiencing severe dry spells in summer.

NR 2b. Rainfall is confined to summer and is moderately high (750–1000 mm). This region receives an average of 16–18 rainy pentads per season and is subject either to rather more severe dry spells during the rainy season or to the occurrence of relatively short rainy seasons.

NR 3. Rainfall in this region is moderate in total amount (650–800 mm), but, because much of it is accounted for by infrequent heavy falls and temperatures are generally high, its effectiveness is reduced. This region will receive an average of 14–16 rainy pentads per season. The region is also subject to fairly severe mid-season dry spells and therefore is marginal for maize, tobacco and cotton production, or for enterprises based on crop production alone.

NR 4. This region experiences fairly low total rainfall (450–650 mm) and is subject to periodic seasonal droughts and severe dry spells during the rainy season. The rainfall is too low and uncertain for cash cropping except in certain favourable localities.

NR 5. The rainfall in this region is too low and erratic for reliable production of even drought-resistant fodder and grain crops. Included in this region are areas of below 900 m altitude, where the mean rainfall is below 650mm in the Zambezi Valley and below 600mm in the Sabi-Limpopo valleys.

(A rainy pentad is defined as the centre one of three 5-day periods (pentads) which together receive more than 40 mm rainfall and two of which receive at least 8 mm.

Source: Surveyor General Map: Natural Regions and Farming Areas (1983).

Management of Soil Fertility in Climatically Risky Environments

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Abstract

In this paper the focus is on the maintenance of soil fertility under cropping, and especially the economics of using nitrogen fertilisers, in semi-arid farming systems. The dominant theme is how subsistence farmers in semi-arid regions of Africa might improve the nutrition of their croplands. A number of possible options and strategies are reviewed, and the economic risks are explored, with examples from Kenya and Australia.

CROPPING systems differ from natural ecosystems largely in the removal of produce and the nutrients contained therein. Soil erosion may also be higher under cropping and this will also contribute to the loss of nutrients from the soil. Sustainability of farming practices depends, inter alia, on keeping the soil in place and being able to continue to meet crop requirement for nutrients, using strategies that are attractive to the farmer and acceptable to society.

The ability of a soil to supply nutrients is finite. When a natural ecosystem is first brought into agriculture, the soil may be able to meet crop demand for nutrients. However, cropping with inadequate replenishment of the nutrients being removed in the crops (and through other loss mechanisms) must inevitably result in the degradation of the soil resource and, ultimately, crop yields declining because of the soil's inability to satisfy the crop's requirement for one or more of the essential elements. The nutrient most frequently limiting is nitrogen.

The problem of declining soil fertility under cropping is most alarming in the semi-arid regions of the world. The risk involved with cropping in these regions, due to possible failure of the rains, results in returns from fertiliser inputs being less assured than in areas of higher potential. This risk is a strong disincentive for investment in soil fertility by resource-poor farmers. The result is that fertilisers are not used and soils become progressively depleted of nutrients.

Stoorvogel and Smaling (1990) have assessed the nutrient balances of N, P and K for 38 sub-Saharan African countries. Estimates for 1983 indicate that the output of nutrients exceeded inputs in almost all of the countries, depletion rates being greatest (more than 40 kg N/ha/year and 5 kg P/ha/year) in densely populated and erosion-prone east and southern Africa, especially Ethiopia, Kenya, Malawi and Rwanda. Forecasts for the year 2000 suggest that rates of depletion will be higher than in 1983 because predicted increases in yields will remove more nutrients than the expected increase in use of fertiliser. The problem of nutrient mining is being aggravated rather than alleviated.

The problem is just as serious in cereal cropping systems in sub-tropical Australia (Dalal et al. 1991). When first cropped, the soils were highly fertile and produced wheat with high protein content, but as the period of cropping lengthens, the protein content of wheat declines and crops are now responsive to nitrogen in seasons when moisture is plentiful. Despite this, few farmers have begun to use fertiliser.

Sources of nutrients

Potential sources of nutrients for the crop are the soil, manures, symbiotic fixation of atmospheric nitrogen by legumes, and fertiliser.

The soil. The fertility of virgin soil is determined by soil-forming factors, notably the parent material and climate, together with the vegetation it supports. It

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supplies N to plants through the mineralisation of soil organic matter, which is maintained by the inputs of plant residues. Under cropping, less residues are returned to the soil so that soil organic matter decreases (Fig. 1), and the soil's ability to supply N is reduced. Declining soil fertility (especially the N status of the soil) is intimately linked with soil organic matter. The rate of decline of soil organic carbon was shown by Dalal and Mayer (1986) to be correlated with the reciprocal of the soils' clay content and it was inferred that association between organic carbon and clay protects the organic carbon against microbial attack. Soil organic matter decline was not restricted to the surface layer alone, but the rate of decline was generally lower in the subsoil.

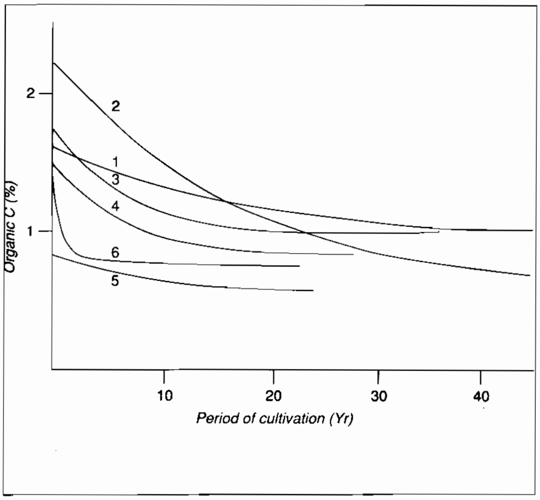

Figure 1. Decrease in soil organic carbon (0-10 cm layer) with increasing period of cultivation for six soil types in sub-tropical Queensland. Soil 2 is the Langlands–Logie clay that once carried Brigalow vegetation. (Reproduced from Dalal and Mayer 1986).

Manure. Application of manure can have beneficial effects on both the physical properties (e.g. structure, infiltration rates) and chemical fertility of soils. A large part of the response obtained to the application of manure is undoubtedly due to the nutrients it contains. In many subsistence farming systems, manure is an important resource and may be the only input of nutrients to croplands. Crop productivity can be maintained with adequate inputs of good quality manure, and where it is used there seem to be no problems with soil acidification as can occur when fertiliser is the N source of (Nambier and Ambrol 1989). The major problem that confronts the farmer is insufficient manure available to meet the nutrient requirements of the cropping lands.

In studies on farms in eastern Kenya (Probert et al. 1992), a number of factors that influence the effectiveness of manure use were identified. Firstly, the manure that farmers remove from enclosures (bomas) where animals are kept for much of the day is of poor quality (Table 1); ash content is high and nutrient concentrations are low. Mugwira and Shumba (1986) also reported low nutrient concentrations in manure for communal areas in Zimbabwe. It seems that in the bomas the manure becomes mixed with soil, which dilutes the concentration of nutrients.

Table 1. The nutrient content of manures sampled from six *bomas* in Mwala location, eastern Kenya. Concentrations reported on oven-dry basis. Data from Probert et al. (1992)

	Range	Mean
Ash (%)	88–94	91
Nitrogen (%)	0.17–0.63	0.42
Phosphorus (%)	0.08–0.20	0.14
Potassium (%)	0.26–1.10	0.72
Calcium (%)	0.58–1.94	1.17

Leaching of K and Ca into the soil beneath the bomas was found to be a significant loss pathway for these nutrients. Apparent recovery of N from the bomas was much lower than for K, which suggests that denitrification and/or ammonium volatilisation contribute to losses of nitrogen. Measured pH in the soil and the manure (which is essentially the uppermost soil layer before it is dug from the boma) was very high (pH > 9) and would be conducive to ammonium volatilisation.

Secondly, on some of the farms where this study was conducted, manure was being applied at seemingly high rates (up to 168 t/ha of dry matter). Median rates of application of nutrients in the manure were 302 kg/ha of N, 104 kg of P and 482 kg of K. Mugwira and Shumba (1986) reported that in two communal areas of Zimbabwe the rate of manure application was between 14 and 72 t/ha, the average being close to the recommended rate of 37 t/ha every four years.

In general, manure was being applied to terraces that were closest to the home site and the boma, although the farmers asserted that they did rotate the terraces to which they applied manure. In a study of the fertility of croplands (Okalebo et al. 1992), much variation was found between terraces in extractable soil P (Fig. 2) with higher values on terraces closer to the home site. It seems logical to associate this with these terraces receiving more frequent applications of

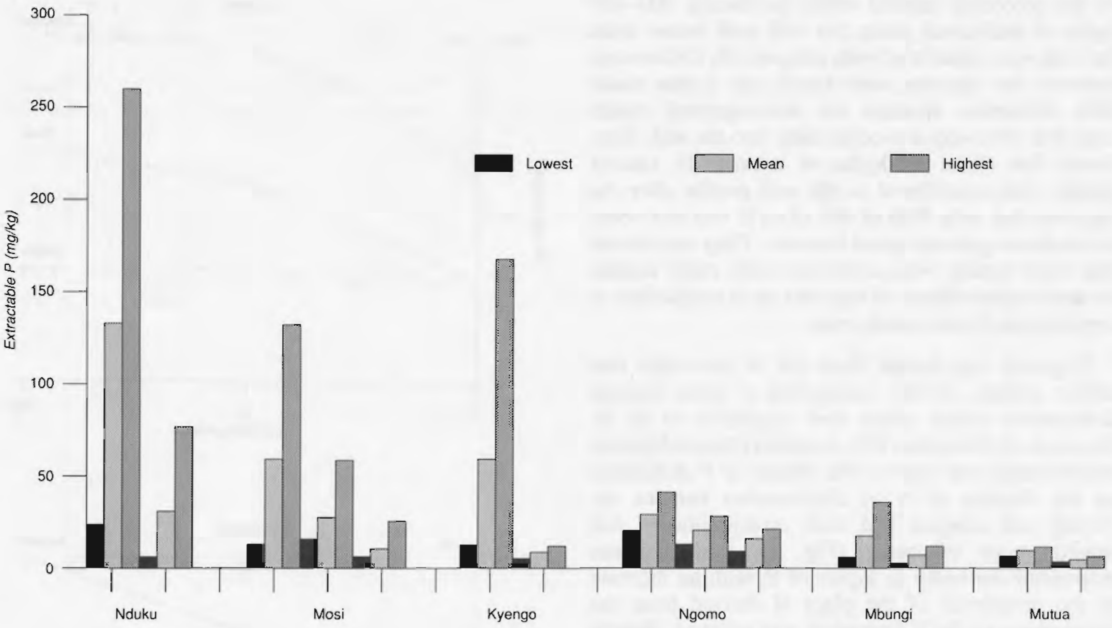

Figure 2. Range and means of extractable P (Bray No 2) in surface soils sampled from terraces on farms in Machakos and Kitui Districts. (Two or three terraces on each farm).

manure. There was also great variation within a terrace which may be indicative of uneven spreading of manure. The importance of manure in the enrichment of soil P was highlighted in the review of Mokwunye (1980).

There is little information on the availability of nutrients in poor quality manure. Tanner and Mugwira (1984) showed in a pot experiment that low-nutrient manure (0.66–0.86% N) depressed plant growth in the first four weeks whereas manures with a higher N concentration increased growth; in a second crop, all manures increased growth but increases were greater for the manures with higher N concentration. At present in eastern Kenya manure and fertiliser are seen as alternatives, though it seems that the low quality of the manure must result in it being a poor source of N for crops. It is to be noted that in Zimbabwe supplementary applications of fertiliser N are used in conjunction with manure (Mugwira and Shumba 1986).

It might be possible to improve the quality of manure by reducing the losses of nutrients (especially N) through better management of excreta within the boma system. This could be achieved by more frequent removal of dung from the boma and protecting it from the effects of weather. However, more effective use of existing manures should be possible once its limitation as a source of nutrients is recognised. Indications are that manure may be an effective means of correcting P deficiencies, but it would need to be supplemented with additional inputs of N. As the terraces most deficient in P tend to be furthest from the home site, a more uniform distribution of the manure would be needed.

Legumes. Cowpea, beans and pigeon pea are important components of the farming systems of semi-arid eastern Kenya, and are normally grown as intercrops with maize or sorghum. Their grains are important as part of the human diet, and the residues are used for feeding livestock during the dry season. Undoubtedly on N-impoverished soils these leguminous crops fix much of their nitrogen requirements, but it is less clear what their benefits are to accompanying or subsequent cereal crops. Much of the N in grain legumes is harvested in the seed and, where residues are also removed, the contribution to soil fertility is limited to dropped leaves, roots and nodules (Eaglesham et al. 1982).

The effects of legumes (cowpea, pigeon pea and lablab) grown in rotation with maize were studied at a site in the Machakos District of Kenya (Simpson et al. 1992). Yields of maize were increased as a result of the preceding legume crops, producing 300–400 kg/ha of additional grain, but still well below what the crop was capable of with adequate N. Differences between the legumes were small, and it also made little difference whether the above-ground lablab crop was removed or incorporated into the soil. They found that about 40 kg/ha of mineral N, mainly nitrate, was contributed to the soil profile after the legumes, but only 30% of this extra N was recovered in the above-ground cereal biomass. They considered that their results were consistent with other studies on the residual effects of legumes on N availability to cereal crops in semi-arid areas.

Legumes can escape from the N starvation that affects cereals, but are susceptible to other nutrient deficiencies which affect their capability to fix N. Research at Katherine, NT, Australia (Simon Nguluu, unpublished) has studied the effects of P deficiency on the fixation of N by *Stylosanthes hamata*, cv. Verano and cowpea and their contribution to following crops of maize (Fig. 3). Both legumes responded markedly to inputs of P, with an increase in the proportion of the plant N derived from the atmosphere as the P limitation was relieved. Benefit to the maize crop from the improved P nutrition of the legumes and the extra N fixed was small. Although N uptake did increase, only a maximum of 13 kg/ha of the extra N fixed was recovered in the maize crop, which was inadequately supplied with N even for the plots that had grown the largest legume crops. This low figure for legume N contribution will have been caused, in part, by the management of the legume residues, which in this experiment were removed with a forage harvester.

A fertiliser-augmented soil enrichment (FASE) strategy. Past farming practices have failed to replenish the removal of nutrients. In reviewing the sustainability of African agriculture, Okigbo (1991) concluded that population pressure has generated a rate of depletion of soil nutrients that cannot be supplied by any conservation or biological strategy, and that sustainable production, at an acceptable level, is achievable only with inputs external to the farm or country, namely mineral fertiliser. The best prospects for food security and sustainable agriculture is a strategy of augmenting traditional soil enrichment practices with modest amounts of fertiliser (McCown et al. 1992). A FASE strategy depends on maximising the effectiveness of current strategies based on manure and legumes, which are basically sound but quantitatively deficient in their ability to meet the demand for nutrients, and demonstrating that such a strategy is economically attractive for the farmers.

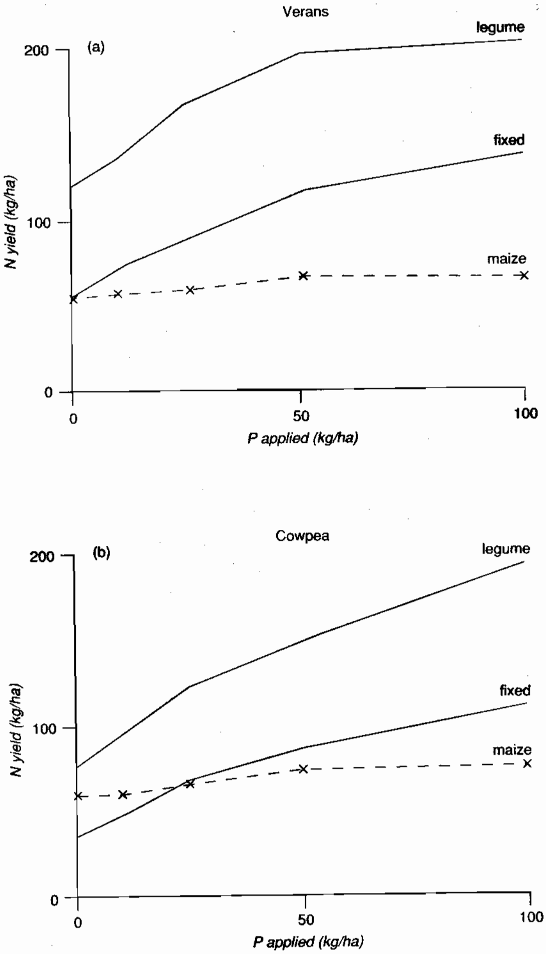

Figure 3. Effect of phosphorus deficiency on the total nitrogen yield (tops and roots) of Verano (a) and cowpea (b), nitrogen fixed from the atmosphere, and nitrogen uptake by a subsequent crop of maize. (Unpublished data of Simon Nguluu).

Response to fertiliser

Reported response to fertiliser in smallholder systems tends to be highly variable, and this may mask the general importance of soil fertility deficiencies. The two main factors determining response to inputs of nutrients are the potential yield of the crop (the demand) and the nutrient status of the soil (its capacity to supply). In environments with a variable climate, the potential yield of the crop varies greatly from season to season with the result that fertiliser responses also vary. It seems obvious, but response to fertiliser also depends on the site; for example, there may be great differences between the fertility of farmers' fields and what is found on land attached to research stations. Multiple nutrient deficiencies may also occur. Response to N is often low unless deficiencies of other nutrients (most commonly P, but possibly S, K, Zn, etc.) are corrected. Responses may also be lessened if other management practices (e.g. good plant stands and control of competing weeds, pests and diseases) are not right. Improving crop production through better crop nutrition is not as simple a technology for farmers as we would sometimes like to believe.

Use of a suitable model for maize growth that deals with water and nitrogen (Keating et al. 1992a) permits the simulation of yields over a larger range of seasons than can be obtained experimentally, though it assumes there are no other limitations to production. We have used the modelling approach to investigate the prospects for growing maize on two soil types, a chromic Luvisol and an Acrisol (see Appendix), at seven sites in Machakos and Kitui Districts, Kenya, where long-term rainfall records are available. These sites are in different agroecological zones (Jaetzold and Schmidt 1983) and encompass the rainfall variability of the region; mean average rainfall for the sites are summarised in Table 2.

Response to nitrogen interacts strongly with plant population density (Keating et al., these Proceedings). We therefore evaluated a factorial combination of plant density (1.1 to 6.6 plants/ m²) and nitrogen application rate (0 to 160 kg/ha of N as calcium ammonium nitrate applied at sowing). The results are illustrated in Figure 4 for the Katumani site, plotted as the mean grain yields in response to changing plant population and nitrogen inputs.

Table 2. Average seasonal rainfall (mm) for seven sites in Machakos District, Kenya used in simulation studies. Short rains (SR) and long rains (LR) defined as November–January and March–June inclusive.

Site (length of record) (years)	AEZ[1]	SR	LR
Iveti (44)	LH2	579	556
Kitui (60)	UM4	475	432
Katumani (25)	UM4	295	293
Makueni (25)	LM4	330	300
Makindu (60)	LM5	298	201
Zombe (32)	LM5	369	236
Konza (60)	UM6	173	252

[1] Agroecological zone (Jaetzold and Schmidt 1983)

Table 3 compares performance at each of the seven sites for selected treatments chosen from plots similar to those in Figure 4 to have near-maximum average grain yields at a constant N input of 40 kg/ha. The desirable plant density is lower on the less productive Acrisol and at the drier sites. At the

Table 3. The prospects for maize production at seven sites in the Machakos–Kitui district on two soil types in terms of average grain yields (kg/ha) and the proportion of seasons when crop failures occur (yield <300 kg/ha). Nitrogen fertiliser rate = 40 kg/ha.

		Long rains		Short rains	
Site	plants/m²	yield	% failure	yield	% failure
a) *Chromic Luvisol*					
Iveti	3.3	3446	3	3951	3
Kitui	3.3	2903	11	3491	4
Katumani	3.3	2560	24	2512	9
Makueni	3.3	2390	20	3223	9
Makindu	2.2	1303	36	2023	9
Zombe	2.2	1639	20	2176	4
Konza	2.2	1741	32	1039	43
b) *Acrisol*					
Iveti	2.2	1419	8	1740	8
Kitui	2.2	1430	13	1625	4
Katumani	2.2	1483	20	1501	4
Makueni	2.2	1462	16	1902	4
Makindu	2.2	802	40	1377	13
Zombe	2.2	781	37	1460	12
Konza	1.1	1045	18	944	24

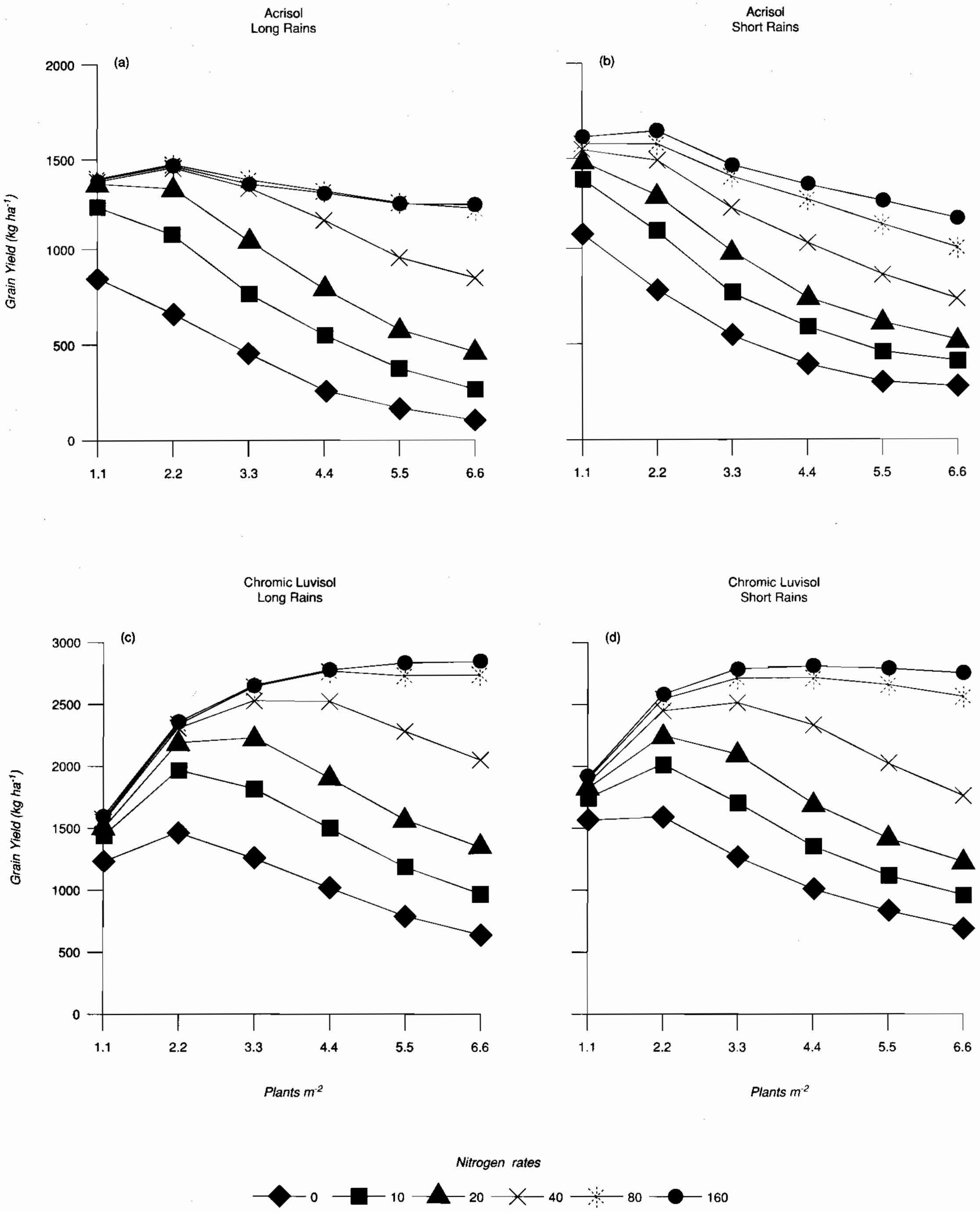

Figure 4. Average maize yields on two soil types simulated at Katumani for varying plant density and with different fertiliser inputs.

wetter sites (Iveti, Kitui and Katumani), there is little difference between the two seasons in terms of the average grain yield, whereas at Makindu and Zombe the short rains are relatively more dependable, with the opposite being true at Konza. At all the sites, production is noticeably worse on the shallower, lighter textured Acrisol than on the chromic Luvisol, largely because it holds much less available water and is thus more susceptible to water stress when there are extended periods without rainfall.

The average yield (Fig. 4) is not a very satisfactory means of comparing the sites as it gives no indication of the riskiness of the climate for crop production. As a measure of this, Table 3 presents the proportion of seasons when crop failures would have occurred (defined as a yield of less than 300 kg/ha). The risk increases markedly at the drier sites, the short rains at Konza being particularly unreliable. Reducing the plant density to 1.1 plants/m^2 at this site for the chromic luvisol in the short rains still resulted in crop failures in 31% of the seasons.

Economics of fertiliser N use

(i) Sensitivity to price of fertiliser. Keating et al. (1992b) examined the economic returns from using N fertiliser on maize crops at Katumani based on the price of maize and fertiliser in 1990. Since then, adjustments to the value of the Kenyan currency (Ksh) have resulted in large changes in the value of both commodities. In mid-1993, maize grain is valued at approximately 7 Ksh/kg (up from 3 Ksh in 1990), while the purchase price of calcium ammonium nitrate fertiliser is approximately 60 Ksh per kg N (16.3 Ksh was the assigned value in 1990). The relative increase in the price of fertiliser has been greater than that of maize. It is of importance, therefore, to consider the sensitivity of the economics of fertiliser use against variation in the cost of fertiliser.

The situation considered here is a set strategy of 3.3 plants/m^2 grown on the chromic Luvisol at Katumani with varying inputs of N (see Fig. 4). The LR and SR seasons have been combined so that simulations of yield are available for 48 seasons. Gross margins, for different fertiliser prices and a constant maize price (7 Ksh/ha), have been calculated without any allowance for planting, weeding or harvesting costs.

In Figure 5(a) the results are shown as the average gross margins plotted against the standard deviation of the gross margin, which is a measure of the season-to-season variability. Highest returns are obtained at around 40 kg of N/ha for fertiliser price varying from 40 to 100 Ksh/kg of N. However the standard deviation increases with fertiliser rate. A 2:1

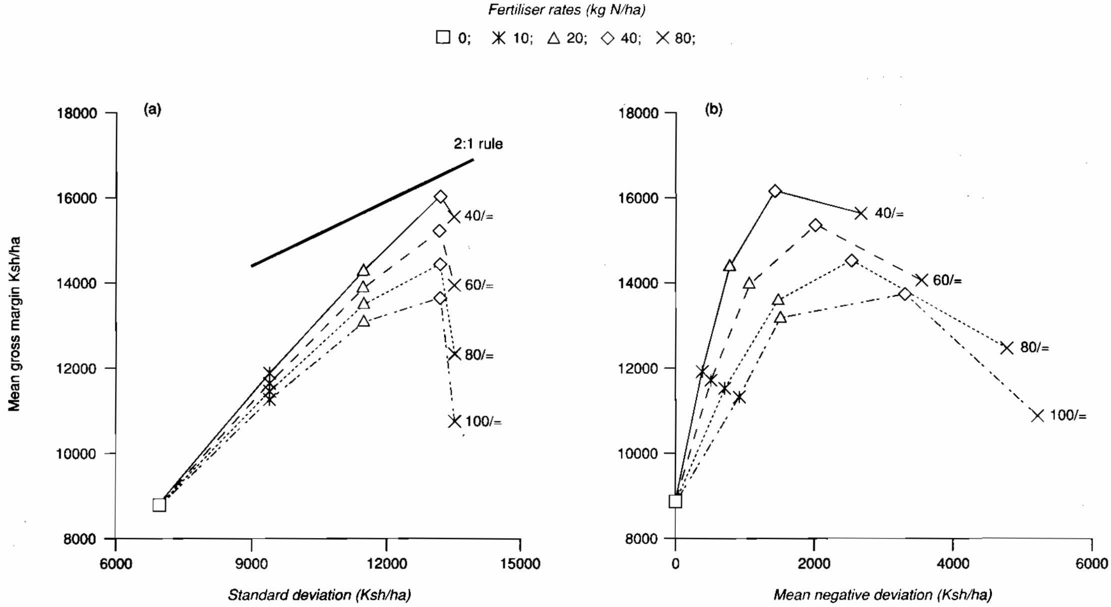

Figure 5. The sensitivity of the economics of nitrogen fertiliser use to changing fertiliser price simulated for the chromic Luvisol at Katumani and a plant density of 3.3 plants/m^2. The average gross margin, based solely on value of maize grain and fertiliser, is plotted against (a) the standard deviation of the gross margins, and (b) the probability weighted sum of deviations for those seasons when losses are incurred. The value of maize grain has been set to 7 Ksh/kg; fertiliser prices (Ksh/kg of N) as shown.

rule has been suggested (Ryan 1984) as an approximation to farmers' attitude in incurring added risk in conjunction with increased gross margin; they are willing to accept an added risk accompanying increased returns as long as the increase in the standard deviation is no more than double the increase in the mean. On this basis, use of fertiliser should be attractive to risk-averse farmers even if the price of fertiliser goes above 100 Ksh/kg. However, by the time the price reaches 100 Ksh (relative cost of fertiliser to maize = 14), a rate of application of 20 kg/ha may be more attractive, even though gross margins are less than with 40 kg/ha.

While there are clearly good prospects for farmers getting a return on investment in fertiliser N, losses are incurred in some seasons and the frequency and magnitude of such losses increase with fertiliser rate and price. Where the desire of the farmer is to minimise the loss of money in any season, it is appropriate to examine the expected returns against the negative deviation of the gross margins - that is, the losses that might be incurred (Fig. 5(b)) (Parton 1992). The maximum loss that has to be carried arises in the seasons when there are total crop failures, and amounts to the cost of the fertiliser applied. Although such fertiliser does have some value for crops in the next season, this is not considered in the analysis. The frequency of loss increases because there are occasional seasons when use of fertiliser reduces yield. For the situation presented here, the probability of negative returns was 0.15 (7 seasons out of 48) when 10 kg/ha of N at 40 Ksh/kg was used increasing to 0.19 (9 seasons) as the rate of application was raised to 80 kg/ha; at 100 Ksh/kg of N, these probabilities rise to 0.17 and 0.31 (8 and 15 seasons respectively). On this basis, there is a very strong disincentive to using higher rates of fertiliser especially as the fertiliser price increases.

(ii) Should fertiliser recommendations vary with site? We return to the simulated results for the seven sites. Using current prices for maize and fertiliser N (7 and 60 Ksh/kg respectively), average gross margins can be calculated for every combination of fertiliser rate and plant density and plotted against the standard deviation of the gross margins. Figure 6 illustrates such plots for the Katumani site and contrasts the

Table 4. Strategies of plant density and fertiliser rate for risk-averse farmers at seven sites on two soils. Within a cell, strategies are listed in decreasing order of attractiveness. Values shown are plant density (plants/m²), N rate (kg/ha) and average gross margin (Ksh/ha).

	Chromic Luvisol						Acrisol					
	Long rains			Short rains			Long rains			Short rains		
Site	density	N	margin	density	N	margin	density	N	margin	density	N	margin
Iveti	2.2	40	20983	4.4	80	27453	1.1	40	8397	1.1	40	8922
	2.2	20	20140	3.3	80	25643	1.1	20	8246	1.1	40	8474
	3.3	40	21723							2.2	40	9777
Kitui	3.3	40	17921	4.4	80	25526	1.1	40	6693	2.2	80	9699
	2.2	40	16474	3.3	80	24302	1.1	20	6659	1.1	40	7460
	3.3	80	18333				2.2	40	7612	2.2	40	8974
Katumani	2.2	20	14232	2.2	40	14838	1.1	20	8380	1.1	10	9116
	3.3	40	15520	2.2	20	14640	1.1	10	7996	1.1	20	9231
				1.1	20	11582						
Makueni	2.2	40	13781	3.3	80	20803	1.1	20	7168	1.1	20	9304
	2.2	20	13126	3.3	40	20158	1.1	10	6705	2.2	40	10915
	3.3	40	14333	2.2	40	18019	1.1	40	6546			
Makindu	1.1	10	5649	2.2	40	11761	1.1	10	4362	1.1	20	7175
	1.1	0	4991	2.2	20	11408	1.1	0	3647	1.1	10	6843
Zombe	2.2	20	7984	2.2	40	12829	1.1	20	3407	2.2	40	7821
	2.2	40	9074	3.3	40	14494	1.1	10	3132	1.1	20	6343
Konza	1.1	10	8669	1.1	0	5619	1.1	10	6312	1.1	10	5760
	1.1	0	8163	1.1	10	5810	1.1	20	5987	1.1	0	5331
	2.2	20	10237	1.1	20	5513				1.1	20	5430

outcomes for the two soils in the long rains. The 2:1 rule provides a frontier for evaluating what should be attractive options for risk-averse farmers. Such an analysis identifies the strategies shown in Table 4 as being the 'most attractive' for each of the sites. Within a site, these are arranged in order of decreasing attractiveness. The simple economic analysis highlights, even more strongly than the average grain yield, that lower density should be used at the drier sites and on the less productive Acrisol soil. Use of fertiliser is shown to be an attractive strategy even at the most risky sites, though the preferred rate of application decreases as the sites become drier, and is also lower for the less productive soil. In some cases opportunities exist for raising gross margins but at the expense of increased risk; some examples of this arise among the strategies of Table 4, but many others do not appear.

Response farming. Although there are good prospects for increasing gross margins by use of set strategies involving fertiliser and appropriate plant density, risks as measured by season-to-season variation in the expected returns also increase. Any means of reducing such risk would improve the attractiveness of fertiliser use.

Farmers frequently vary their management in response to their perception of the rainfall prospects for the current season. 'Response farming' was developed in Kenya to forecast the potential of the pending growing season using rules based on time of season onset and early cumulative rainfall (Stewart and Faught 1984). The scheme includes tactical responses involving adjustments to fertiliser input and crop density.

By using a model of maize production and historical rainfall records, it has been possible to separate the value of the response farming forecast from the value of fertilisation (McCown et al. 1991; Wafula et al. 1992). In terms of average returns, the value of

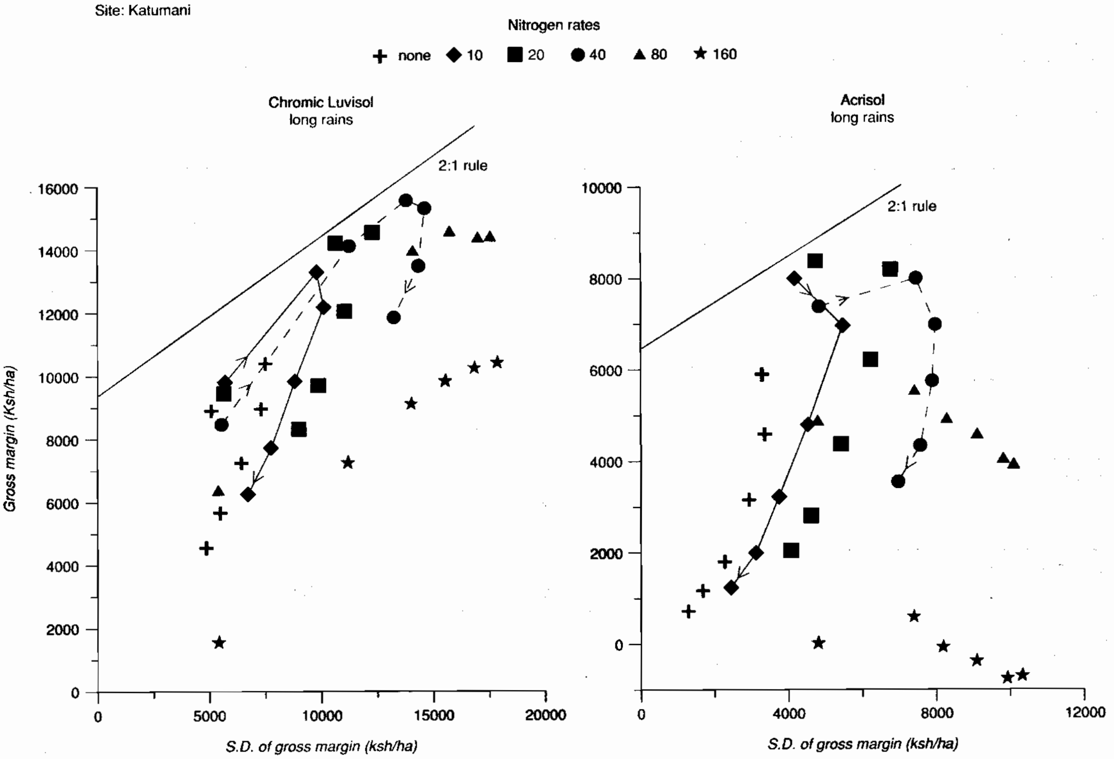

Figure 6. An evaluation of the attractiveness of using fertiliser on two soil types in the long rains at Katumani. Data points represent combinations of fertiliser rate (as shown) and plant density; for two N rates, the arrows indicate plant density increasing from 1.1 through 6.6 plants/m^2. Relative attractiveness of options is shown by proximity to the 2:1 rule.

the predictor was found to be small relative to the large benefits from using fertiliser irrespective of a forecast. In terms of risk, response farming had little effect as assessed in a plot of expected returns against their standard deviation, but it did have substantial benefits in reducing negative deviations (Wafula et al. 1992). This comes about by reducing the number of occasions when fertiliser is purchased but rainfall is insufficient to obtain a return on the investment. Thus it is a scheme that may be attractive to farmers pursuing strong 'safety-first' goals.

The Sustainability Issue: a Case Study from Queensland

A number of issues arise from the decline in fertility that occurs under cropping systems. These concern the profitability of the farming enterprise and the impact of management practices (e.g. fertiliser use, residue management, rotations) on the rate of soil degradation. An analysis has been made of the wheat cropping system in Queensland, using climatic records for Roma (1894–1989).

In the first instance we consider the returns from N fertiliser for three stages of soil degradation. These were taken to be the soil organic matter content of the Langlands–Logie soil of Dalal and Mayer (1986) (Fig. 1) when first cultivated (2.0 % organic C in the surface 10 cm), after 20 years cultivation (1%), and after more than 40 years (0.6%). The simulated results (Fig. 7a) show that although the response to fertiliser is greater on the degraded soil, fertiliser, applied at realistic rates, is unable completely to compensate for the decreased soil fertility. Transforming the yields into gross margins (Fig. 7b) indicates that farming on degraded soils is less profitable than farming on soils where the fertility remains high. In order to increase yield and protein content to attract premium prices, inputs of fertiliser are required and these have to be paid for at penalty to net income.

The scenarios depicted in Figure 7 assume that the soil fertility is fixed at certain levels. The more realistic situation is depicted in Figure 8 where cropping is simulated to commence in 1894 on the high fertility soil without any N input. Through time there is a loss in fertility and an increasing loss in yield compared with what would be achieved if fertility could be maintained at the initial level.

Figure 9 (a) shows that the cumulative gross margins of the exploitive system (no fertiliser and burning of residues) increasingly diverges from the constant high fertility scenario; the more conservative practice of retaining stubble and using N fertiliser is intermediate. Figure 9 (b) compares the gross margins for two rates of N input with those for the exploitive system. In the longterm, it provides justification, of sorts, for use of the higher rate of N. However, during the early years of cropping, while the fertility is still high, the exploitive system is more profitable. When a 5% discount rate is applied (to convert future profits to present values) it takes some 40 years before the conservative practice 'catches up' with the exploitive system, while at a discount rate of 15%, it never catches up.

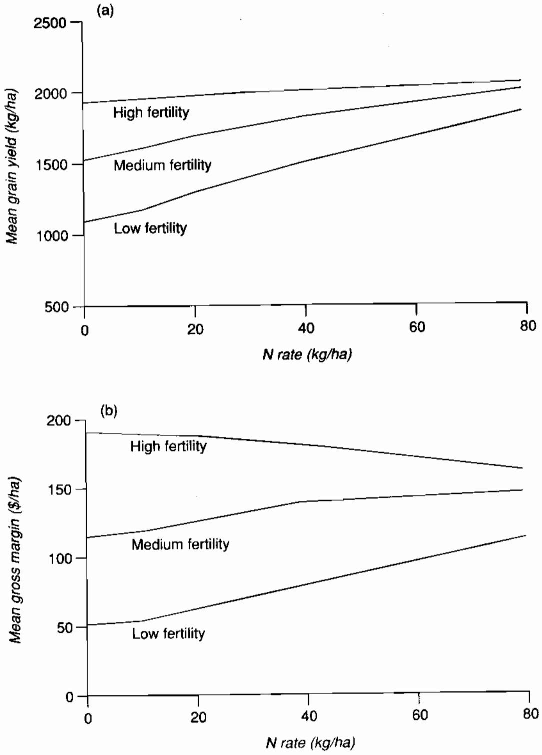

Figure 7. Simulated wheat yield (1894–1989) at Roma, Queensland on soils where the fertility has declined due to previous cropping. The high fertility situation represents the early stages of cropping when the land is first cultivated; other scenarios represent 20 and more than 40 years of cropping, (a) mean grain yield and (b) mean gross margin.

In a simple analysis of this type, the glaring omission is any value ascribed to the land. No account is taken of the fact that the degraded soil can only be farmed less profitably, and must therefore have a lower value than it had before it was exploited.

At present there are no clear answers to several key questions. How might a high fertility soil be maintained, or the fertility of a degraded soil be restored? At what stage in the degradative process

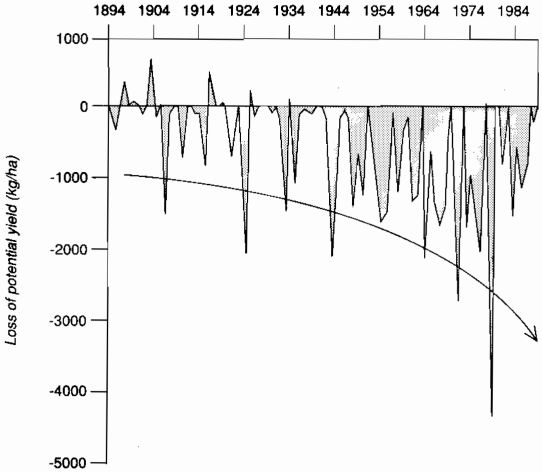

Figure 8. Impact of fertility decline on wheat yield simulated at Roma, Queensland. Yields for an exploitive system (no fertiliser, residues burnt) plotted relative to a hypothetical, constant high fertility system.

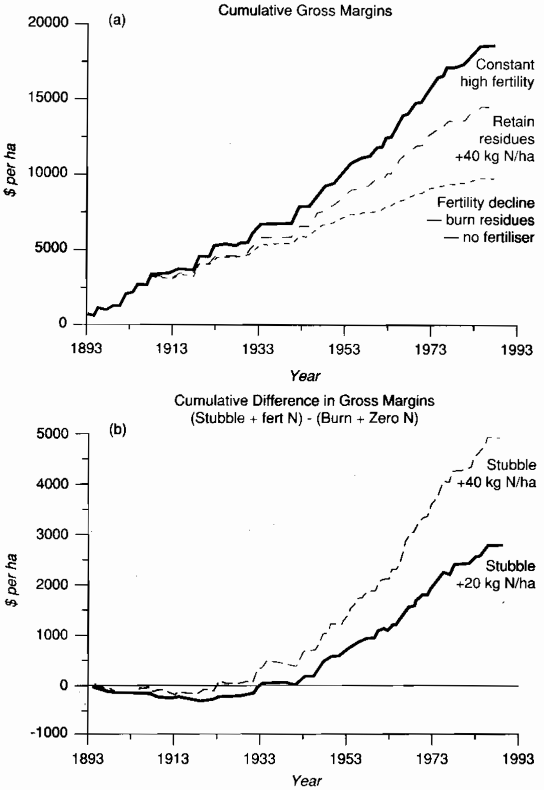

Figure 9. Cumulative gross margins (1993 prices) for wheat simulated at Roma, Queensland, (a) absolute gross margins for a constant, high fertility system, a conservative system, and an exploitive system, (b) gross margins relative to the exploitive system for conservative systems with two rates of nitrogen application.

should practices be initiated to maintain soil fertility? In the Australian context where conditions often exist for mixed livestock and cropping enterprises, legume leys may offer a means of maintaining the soil organic matter content and N fertility of the soil; a factor involved in the attractiveness of this approach is the relative profitability of the cropping and ley phases. For subsistence farmers in Africa, the legume ley approach is not likely to be a viable option (McCown, in press). Thus while the problems may be similar for the two farming systems, the solutions may be very different.

Conclusions

In semi-arid environments, the impact of drought on crop performance has been the focus of much research. Soil fertility has often been ignored because it has been considered either unimportant or irrelevant in systems where it is perceived that farmers cannot use fertilisers.

The case studies from Kenya and Australia presented in this paper both show that soil fertility cannot be ignored if the productivity of semi-arid cropping systems is to be improved in the short term or maintained in the long term. The interventions will vary, with fertilisers, manure and legumes all having roles in different circumstances. Models that can deal with the soil, crop and environmental interactions have an important place in research to identify appropriate soil fertility management strategies.

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Appendix

Standard inputs and assumptions used for modelling maize production in eastern Kenya.

The analysis assumes that pests, weeds and nutrients other than N are not limiting. The maize cultivar is Katumani Composite B. Planting was assumed to occur once onset of the season was detected, defined as the receipt of in excess of 40 mm of rain within an 8-day period with no more than one consecutive dry day. Onset windows during which planting could take place were from calendar day 276 to 320 for the short rains and 62 to 120 for the long rains. In those seasons where onset was not detected, planting was simulated at the end of the onset window.

The properties of the two soils, a chromic Luvisol and an Acrisol, are set out below. These soils are typical of soils in the region. The chromic Luvisol has an available water-holding capacity of 175 mm over its 130 cm depth and at the beginning of the onset window it contained 45 kg/ha of mineral N; comparable values for the 110 cm deep Acrisol are 82 mm of available water and 42 kg/ha of mineral N. These amounts of mineral N are typical of what is measured on farmers' land where maize is grown, together with intercrops of pulses, without fertiliser. Soil water was initialised at one-fifth of the available water range.

Residues from the previous crop were assumed to be 300 kg/ha as straw (C:N = 65) and 800 kg/ha as roots (C:N = 45) for the chromic Luvisol and 200 and 400 kg/ha, respectively, for the Acrisol.

Each season was modelled independently with re-initialisation of input parameters at the start of the onset window.

Table A1. Profile information for the chromic Luvisol. DLAYR is the layer depth (cm), LL is the lower limit of plant extractable water (volumetric), DUL and SAT are the corresponding drained upper limit and saturated water contents, WR is a rooting factor for root growth, BD is the soil bulk density, C is the organic carbon (%), NH_4 and NO_3 are the ammonium- and nitrate-N (mg/kg) at the onset of the season.

DLAYR	LL	DUL	SAT	WR	BD	C	NH_4	NO_3
10	0.14	0.25	0.30	1.00	1.35	1.10	1.0	2.0
10	0.14	0.25	0.30	0.86	1.35	1.10	1.0	3.0
10	0.14	0.29	0.32	0.64	1.35	1.00	1.0	3.0
20	0.15	0.30	0.33	0.47	1.40	0.80	1.0	2.0
20	0.17	0.30	0.34	0.35	1.40	0.70	1.0	1.0
20	0.17	0.30	0.35	0.25	1.40	0.65	1.0	1.0
20	0.17	0.31	0.36	0.15	1.40	0.60	1.0	1.0
20	0.17	0.31	0.37	0.08	1.40	0.60	1.0	1.0

Whole profile properties: SALB, the soil surface albedo = 0.13; U, the soil evaporation coefficient for stage 1 = 9 mm; SWCON, the whole profile drainage coefficient = 0.50; CN2, the runoff curve number = 60.

Table A2. Profile information for the Acrisol.

DLAYR	LL	DUL	SAT	WR	BD	C	NH_4	NO_3
10	0.06	0.14	0.24	1.00	1.45	0.41	1.0	2.0
10	0.06	0.16	0.26	0.86	1.45	0.41	1.0	3.0
10	0.08	0.16	0.26	0.64	1.45	0.30	1.0	3.0
20	0.08	0.16	0.26	0.47	1.45	0.20	1.0	2.0
20	0.08	0.16	0.26	0.35	1.45	0.20	1.0	1.0
20	0.10	0.16	0.26	0.25	1.45	0.20	1.0	1.0
20	0.10	0.16	0.26	0.15	1.45	0.20	1.0	1.0

Whole profile properties: SALB, the soil surface albedo = 0.16; U, the soil evaporation coefficient for stage 1 = 6 mm; SWCON, the whole profile drainage coefficient = 0.70; CN2, the runoff curve number = 72.

Limitations to Crop Production in Marginal Rainfall Areas of Malawi

S.A. Materechera and H.R. Mloza-Banda*

Abstract

In Malawi there is a more-or-less well-defined rainy season which begins in November and ends in April. However, the amount of rainfall received, its distribution, and its frequency are highly variable, particularly in certain areas, which are therefore marginal for crop production. Although the total of these marginal areas is small, compared to total land area (5.1%), it supports an important part of the population of Malawi because of the scarcity in arable land. This paper considers the problems associated with rainfed crop production in these areas. Possible management strategies which can be used to alleviate these constraints are discussed.

Physiography and Land Use

Agriculture dominates the economy of Malawi and production is based largely on smallholder farms of 0.5–2.0 ha which produce about 85% of all major food crops. As in parts of many developing countries, population increases in rural areas have placed extreme pressure on land in two ways: (a) population per unit of land has increased, resulting in ever-increasing demand for greater production per ha; and (b) people are moving progressively into drier areas, some of which experience recurrent droughts.

Soils and Climate

There are three main agroecological zones in Malawi:

i) the Shire Valley and Lake Malawi shoreline savanna grasslands and thickets;

ii) the miombo woodlands of the medium plateau; and

iii) the high altitude grasslands.

This wide range of relief is a major determinant of the climatic, hydrological and edaphic conditions of the country, and hence its agricultural potential.

The alluvial soils in the Shire Valley and the lakeshore plains are fertile. Most of the remaining soils in the country are heavily weathered with low to medium fertility, except for isolated more fertile areas of the Lilongwe plains and Shire highlands (Seubert and McKay 1989).

The climate of Malawi is characterised by a strong seasonality of rainfall. A climatic classification of Malawi based on the Thornwaite method is given in Table 1.

The amount and distribution of rainfall are strongly influenced by topography such that the highlands and escarpment experience greater precipitation than do the lowlands and rainshadow areas. Thus, whereas 90% of the country has a mean annual rainfall of more than 800 mm, annual rainfall rates of less than 750 mm are experienced along parts of the lakeshore of Lake Malawi with a low lying hinterland, as at south Karonga, Salima. and Mangochi; a belt covering the mid-Shire Valley from Blantyre to near Mangochi; in the Lower Shire Valley, and in more restricted rain shadow areas (ICLARM and GTZ 1991). These areas are the focus of this paper although they comprise only 5% of the total land area (Table 1).

Delineating marginal rainfall areas in Malawi

The potential growing period has been used as the basis for assessing climatic resources in developing countries (FAO 1978). In this method, the growing

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Table 1. Principal climatic divisions of Malawi.

Climatic classification	Moisture index	Type of climate	Characteristics Rainfall (mm)	Characteristics Average temperature (°C)	Locality	Total area %
Hot, dry steppe	–30 to –60	Semi-arid to arid	600–800	>21	Shire Valley Lakeshore, Mzimba	5.1
Warm, temperate	–15 to –30	Semi-arid to sub-humid	800–1050	>18	Mid-plateaux Shire Highlands	61.6
Warm, temperate	0 to +15	Sub-humid	1050–1500	>15.5	Dowa, Nyika and Vipya plateaux, Kirk range	31.2
Warm, tropical rainy	0 to +100	Humid	>1500	>21	Mulanje and Thyolo plateaux, north eastern lakeshore	2.1

Source: Pike and Remmington (1965).

period was defined as the number of days during the year when precipitation exceeds half the potential evapotranspiration (UNESCO 1977), plus a period required to use an assumed 1000 mm of water from excess precipitation (or less, if not available) stored in the profile. Jones (1987) considered an annual rainfall of 700 mm to be the minimum required for successful dryland farming in the marginal rainfall areas of southern Africa.

In Malawi, a crop agroclimatic adaptability classification, in a form suitable for matching crops with climatic and soil resources, was attempted by Johnson (1973) and is the basis of current agroclimatic reporting. Although it is difficult to delineate clearly marginal rainfall areas, this paper uses several rainfall characteristics described by Johnson (1973) to delineate marginal rainfall areas in Malawi.

Low mean annual rainfall and high temperatures

Although the use of annual rainfall as an index of moisture regime and agricultural potential is open to question, it is nevertheless a useful and commonly available measure for comparing different areas. Some of the areas with the lowest rainfall in the country are indicated in Figure 1. Most of these areas receive rainfall less than 750 mm per year. The low rainfall is accompanied by high temperatures and high evaporation during the growing season. These combine to make the areas marginal for certain crops and varieties.

Short average net season length

The length of the growing period available to a crop was analysed over a 20 year period from daily rainfall data at 69 meteorological stations around Malawi (Johnson 1973). A year was divided into 73 five-day pentades and each pentade was classified as being either rainy or dry. The results show that in marginal rainfall areas the mean net season length is 115 days with a range between 109–125 days while that for higher potential areas is up to 187 days (range 174–200 days). The 115 days season length was classified as marginal after considering that a medium maturing maize variety requires a minimum season length of 135 days.

High rainfall variability and low reliability

Spatial and temporal variability of both seasonal total rainfall and distribution of precipitation within a season are a feature of low rainfall areas in Malawi. This is probably the most critical climatic factor controlling crop yields from year to year in these areas.

Using a pentade analysis Johnson (1973) showed that the Lower Shire Valley has the most unreliable rainfall in the country. At Ngabu in the Lower Shire Valley, for example, there are only 10 pentades in the rainy season (average season length is 22 pentades) which have over 67% probability of being classified as rainy.

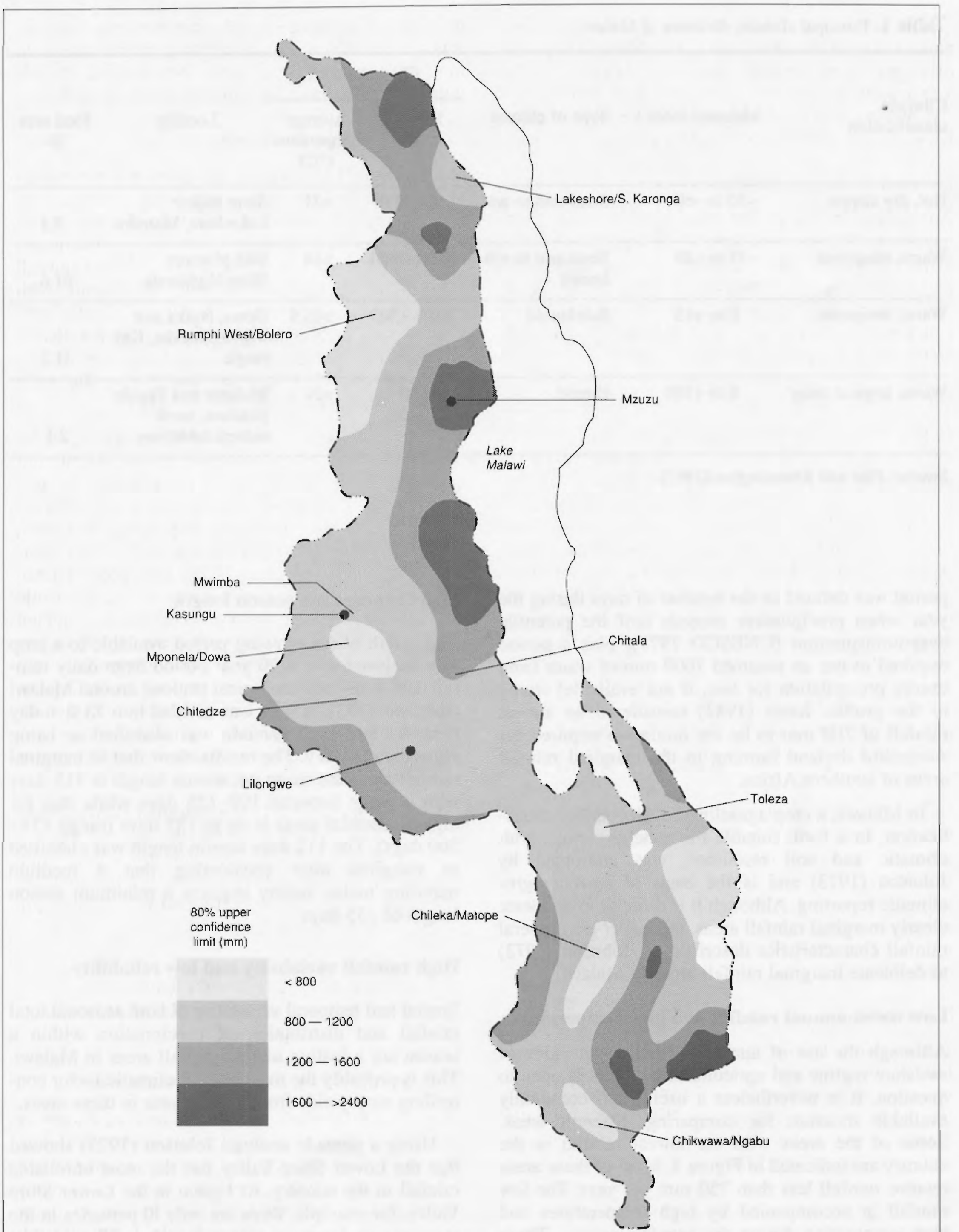

Figure 1. Major rainfall zones within Malawi.

The duration and frequency of dry spells during phases of crop growth in the Lower Shire Valley was examined using the pentade analysis (Archer 1976). The results showed that dry spells tend to occur at the two most critical stages of maize development i.e. establishment and grain filling stages.

Current farming practices in Malawi

Agronomic strategies used in higher rainfall areas have been distinguished from those used in semi-arid areas (Stewart 1988). The latter emphasise systems that involve water conservation, sustainable rather than maximum crop yields, only limited inputs for soil fertility maintenance, and addressing wind and water erosion constraints.

Land preparation

Conventional crop husbandry practices in Malawi begin with remaking of ridges and incorporation of crop residues and weeds early at the end of the harvest season. This takes advantage of residual moisture to hasten residue decomposition. Crop residues are also collected for fuel on fodder, or are burned-off during land preparation. Land preparation may be delayed for varying lengths of time till the next planting rains, particularly after the first heavy convective rains which are followed by a dry period. When cultivation must await moistening to soften the top soil, the effective length of the growing season is appreciably reduced; the farmer must conduct all required operations during a very short period, especially on the Vertisols of the Lower Shire (Panje 1986).

The remaking of ridges annually in smallholder production systems has remained one of the most important single soil and water conservation measures. Along with ridges, Johnson (1973) recommended tied-ridge cultivation for areas with unreliable season quality in Malawi. The system had, prior to 1973, long been abandoned because of its colonial background.

Soil fertility

The productivity of marginal areas of Malawi is also limited by low soil fertility. Soil organic matter remains the major source of crop nutrients, since little or no nutrients are applied. Where economically feasible, application of farmyard manure has been recommended on most Malawi soils. However, since continuous cropping has replaced crop–fallow rotations in many areas due to increasing population pressure, soil organic matter contents have declined. Apart from the high decomposition rates associated with a tropical climate the practice of removing crop residues for animal feed and other purposes has contributed to the decline of organic matter levels in most of the soils in Malawi. No solution to this important and increasing problem is yet in sight.

Crops and cropping systems

The cultivation of crops in mixtures (intercropping) is common in Malawi because such combinations reduce the risk associated with variable and unpredictable moisture situations and allow maximum advantage to be taken of both good and poor rainfall years (Edje 1979). Intercropping of cereals with pulses or oilseeds required for either domestic consumption or cash is most common. The practice is also beneficial as a means of increasing the protective cover of cultivated bare soil during the early stages of crop growth (El-Swaify 1988).

Growing of crops that can efficiently utilise the limited soil moisture is important in marginal rainfall areas. Although bullrush millet, finger millet and sorghum were the principal staple grain crops in Malawi until some 70–80 years ago, they have since been gradually displaced by maize, which is less drought-tolerant. In marginal areas of the lakeshore of Lake Malawi, maize has gradually replaced cassava, while in marginal areas of the Lower Shire and upland areas it has replaced millets and sorghum. Although pigeon pea has received considerable research attention in Malawi, other pulse crops, such as chick peas, guar beans and bambara nuts, which tolerate marginal rainfall regimes, have remained minor and underexploited compared to water-demanding pulses such as beans and groundnuts.

Overall, agriculture in the marginal rainfall areas of Malawi has suffered from the use of blanket recommendations. The recommendations have quite often assumed that Malawi is homogeneous and that technologies which have performed well in one area will perform well in all areas.

Potential Strategies for Improving Productivity of Marginal Rainfall Areas in Malawi

Crop manipulation for efficient water use

Crop manipulation involves variations in choice of species and cultivar, timing of operations, plant density, soil fertility status, pest control and other practices. The farmer's decisions are determined by many considerations, but economic factors are in many cases dominant. On the research side, optimum strategies should be developed from a knowledge of the relationship between evapotranspiration and crop production. In principle, this requires that farming practices which use water efficiently should be promoted. A maximum proportion of the rainwater received should be expended in crop transpiration, with minimum losses to evaporation runoff and drainage. Basically, this involves rapid crop establishment at the onset of the season and maintenance of a green plant canopy for as long as practical.

Choice of suitable crops and varieties

Replacement of the existing local crop varieties with new high-yielding ones provides a basis for introducing improved crops, in the dryland. While these new selections may not outperform the traditional varieties in years with low rainfall, they usually produce much higher yields during average or higher rainfall years. A farmer might therefore be well advised to select high yielding varieties and hybrids for the marginal rainfall. There is still a need, however, to develop varieties that are early maturing (short season) for the most risky environments.

Alternative crop strategies

Sowing time for dryland crops depends on the onset of rain which is often considerably in the lower rainfall areas. This results in delayed planting and often causes drastic reductions in crop yields (Lungu 1971). Basic data on crop performance as affected by different sowing dates and locations are needed by researchers in order to advise farmers on their options. Alternate crop strategies might then be developed to help deal with weather aberrations (Stewart 1988).

Midseason corrective options

If moisture stress should occur after the crop has started to grow there are certain options which could be employed to salvage some yield from the standing crop. These options include thinning and ratooning. Failing this, the crops might be replanted when moisture conditions are again favourable. Thinning sorghum by removing every third row was found to be advantageous to mitigate moisture stress in the Deccan black soils of India (Vankateswarlu 1988). Such options could be investigated for some areas in Malawi.

Conclusion

To meet Malawi's evergrowing need for food, areas with marginal rainfall must be fully utilised. The real challenge in the alleviation of soil fertility and water constraints in the cropping systems of these areas is to develop strategies which will afford the farmers better control of their resources for increased production. Research is urgently needed to develop and test technologies that can reduce the risks for crop production in these areas.

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Constraints in the Smallholder Farming Systems of Zimbabwe

E.M. Shumba*

Abstract

This paper reviews constraints to crop production, the status of technology development and future research needs of the smallholder farms in the semi-arid areas of Zimbabwe.

ZIMBABWE'S agricultural industry consists of two major sectors; the large-scale commercial and the smallholder (communal) sectors. Prior to 1980 production from the communal sector was largely for subsistence requirements. However, its contribution to marketed maize output has increased from 8% in 1976 to 48% in 1986–88 while its proportion of cotton production rose from 22% to 50% over the same period (Table 1). Such advances clearly demonstrate that, given the appropriate technical and institutional support, communal farmers have the capacity and willingness to invest in expanding the country's agricultural production.

Table 1. Proportion (%) of total crop delivered to official marketing outlets by sector, 1976–88.

Crop %	Year	Large-scale commercial farms	Communal areas*
Maize	1976–80	92	8
	1981–85	69	31
	1986–88	52	48
Cotton	1976–80	78	22
	1981–85	61	39
	1986–88	44	56

*Includes deliveries from small-scale commercial farms and resettlement areas.
Source: Agriucltural Marketing Authority and Central Statistical Office.

Unfortunately, this analysis becomes misleading when one considers that about 80% of the maize delivered by the smallholder sector to the Grain Marketing Board in 1985 came from only 20% of the one million communal area households i.e.those located in the higher rainfall environments (Natural Regions I and II). The majority of farmers contribute very little because they live in the low rainfall areas (NRs III to V). Many of these farmers experience food shortages (both in terms of quality and quantity), particularly during drought years (Fig. 1).

Constraints to crop production in communal areas

Communal areas of Zimbabwe are characterised by low levels of agricultural production and productivity. This is largely due to biophysical and socio-economic problems in this sector.

About 74% of the communal farmland is located in NRs IV and V which are characterised by low and erratic rainfall and a short growing season, and therefore are generally considered marginal for crop production (Vincent and Thomas 1960). The predominantly light textured soils are also less fertile than those found in the large-scale commercial sector. These soils have been extensively cropped with little or no addition of fertilisers, and thus are severely depleted of nutrients, especially nitrogen and phosphorus (Mashiringwani 1983). Grant (1981) demonstrated that it was difficult to obtain good crop yields on these soils without regular applications of inorganic fertiliser, manure or lime. However, moisture shortages during the crop growth cycle limit the extent to which crops can respond to inorganic fertilisers on these soils (Mackenzie 1987).

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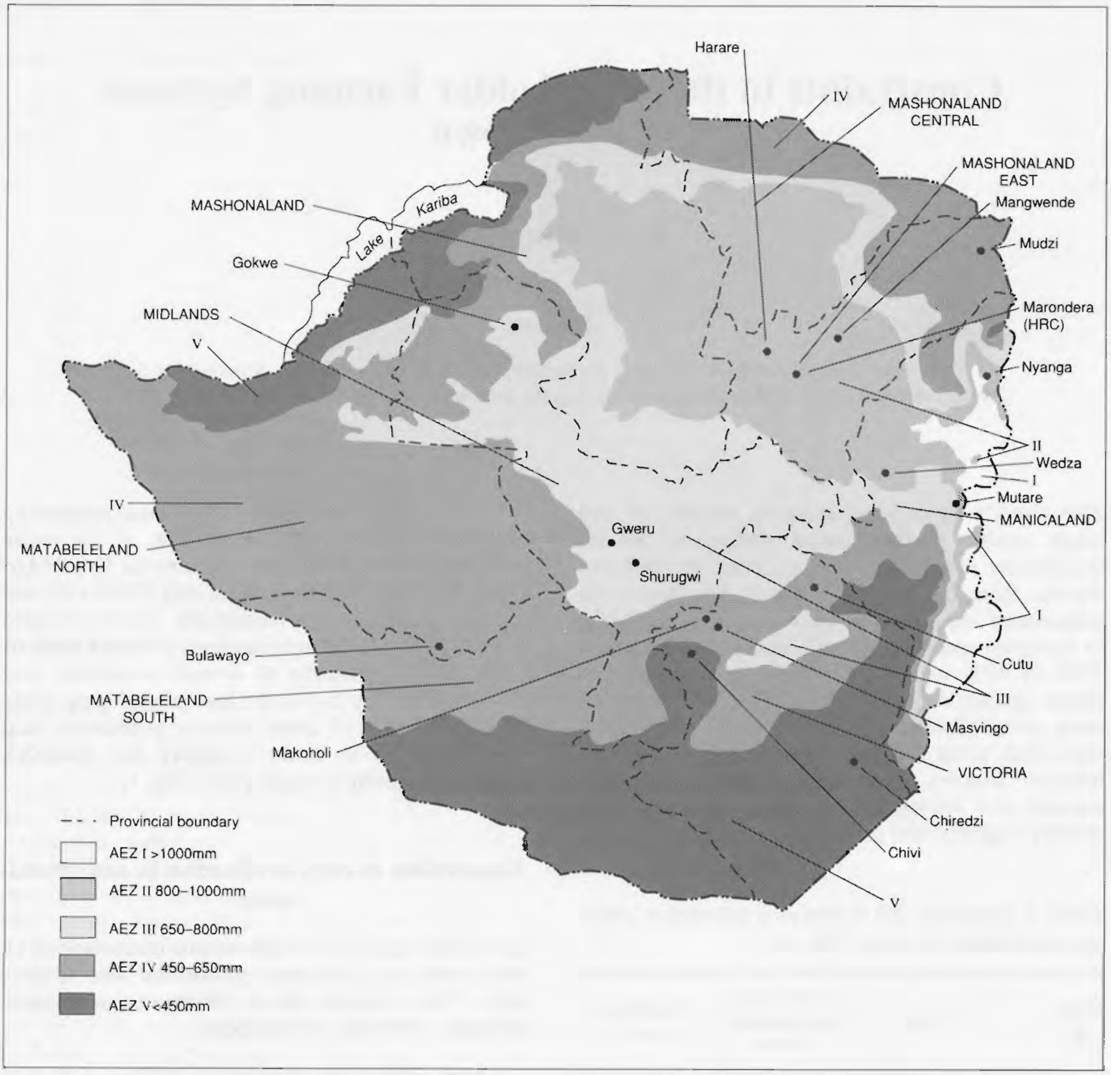

Figure 1. The Natural Regions of Zimbabwe.

The major socioeconomic constraint is the poor resource base which limits the extent to which smallholder farmers can invest in agricultural activities. Table 2 shows the resource endowments of farmers in two communal areas located in high (Mangwende) and low (Chivi) rainfall areas. The relatively high cropping intensity in Chivi, a semi-arid site, illustrates the farmers' desire to spread risk by cropping larger areas. While the large areas of 0.69 and 0.59 ha cultivated per active family member in Mangwende and Chivi, respectively, resulted in labour bottlenecks during the cropping season; such labour shortages contributed to delayed weeding and late basal fertiliser application. Both these practices have been shown to reduce crop yields (Shumba 1989; Mabasa, pers. comm.). Furthermore, weed competition has been found to be more severe if it coincides with early dry spells and in the absence of inorganic fertilisers.

Approximately half the farmers in Chivi and Mangwende communal areas do not own cattle and therefore have poor access to draught power. The situation is exacerbated by droughts and lack of dry season feed that result in a weak and reduced draught power pool available to service an increasing number of cultivators at the beginning of each cropping season. This leads to late crop establishment and a further reduction in the length of the growing season, hence low crop yields, particularly for the non owners of cattle (Shumba 1989).

Smallholder farmers in the semi-arid areas realise lower incomes than those of their counterparts in the higher rainfall areas. In fact the former get more than half of their annual cash incomes from non-farming activities. Such low incomes limit the extent to which they can invest in agricultural production, e.g. Chivi farmers invest only 14% of their annual income of $Z173 in agricultural inputs compared to 28% by their counterparts in Mangwende, a high rainfall site (Table 2).

Table 2. Resource base of smallholder farmers in Mangwende and Chivi communal areas.*

	Mangwende[a] (n=80)	Chivi[a] (n=96)
Farm size, ha	2.87	2.82
Average cropping intensity (%)	75	82
Family size (no.)	7.4	8.5
Family members active on the farm (no.)	3.1	3.9
Area cultivated per family member (ha)	0.69	0.59
Farmers hiring casual labour (%)	30	39
Farmers owning draught animals (%)	45	41
Annual cash income ($Z)	601	173
Income from off-farm sources (%)	27	57
Income spent on agricultural inputs (%)	28	14

a. Mangwende and Chivi are in Natural Regions II and IV respectively

* Source: Farming Systems Research Unit Annual Report 1985.

The foregoing biophysical and socioeconomic constraints account largely for the low crop yields achieved by smallholders in the semi-arid areas of Zimbabwe (Table 3).

Table 3. Average crop yields (t/ha) achieved in Mangwende and Chivi communal areas.*

	Mangwende[a]	Chivi[a]	National average for communal areas
Maize	2.6	1.0	1.0
Groundnuts	0.7	0.3	0.5
Finger millet	0.9	0.4	0.5
Sunflower	0.6	0	0.4
Sorghum	0	0.4	0.4
Pearl millet	0	0.5	0.5

a. Mangwende and Chivi are in Natural Regions II and IV respectively.

* Source: FSRU Annual Report 1985.

Status of technology development

Previous and current research has concentrated on developing technologies to increase and stabilise crop yields under conditions of low and erratic rainfall on depleted sandy soils. They include the following:

Crop improvement. Over 95% of the smallholder farmers buy and plant hybrid maize seed each year (Rohrbach 1988, Shumba 1990). The local breeding effort has, over the years, concentrated on drought-tolerant maize with emphasis on early maturing and high-yielding three-way hybrids. When compared to the commercially available open pollinated varieties, such hybrids are superior in both yield and yield stability under marginal conditions (Shumba 1990). Furthermore, hybrid maize seed is also widely available throughout the country. However, the adoption of the recently released early maturing and high-yielding varieties of sorghum and pearl millet has been poor due largely to the shortage and limited distribution of the improved seed and unattractive crop producer prices.

Inorganic fertiliser use. Research carried out on depleted sandy soils showed considerable variation in crop yield response to N-P-K fertiliser depending on site and season (Agronomy Institute 1985). Although the regular application of cattle manure in combination with nitrogen fertiliser has increased available soil N and P over time, crops have not benefited from the nutrient buildup during below average rainfall years. The apparent unreliability of the benefits from chemical fertiliser used under semi-arid conditions partly explains why the technology has not been widely adopted by smallholder farmers (CIMMYT 1982; Rohrbach 1988).

Moisture conservation. Although a number of moisture conservation practices such as ridge and farrow planting have been designed, tested and widely promoted (Johnson 1987), most of the smallholder farmers still plant crops in conventional seedbeds prepared by ox-drawn mouldboard ploughs. This is despite the potential of such practices to improve crop response to fertilisers under low rainfall. Among other things, Waddington (1991) has attributed the low adoption to the uncertain short-term crop yield benefits from the technologies on light textured soils.

Plant population. Work conducted by the Agronomy Institute has shown considerable site and year variation in crop yield responses to plant population in semi-arid areas. While a maize stand of 36000 plants/ha was considered optimal during a good rainfall season, it significantly reduced grain yield in a dry year.

Intercropping. Although most research conducted in the humid and subhumid areas indicated that intercropping reduces risk of crop failure from factors such as drought (Fisher 1977), some local research has established that the practice may not have a big effect on yield stability in the marginal rainfall areas. Under these conditions intercropping drastically reduced the yield of the main crop without much improvement in overall land productivity in a dry year (Shumba et al.1990).

This overview demonstrates a strong dependence of some of the technologies on soil and rainfall-related factors. To account for this, researchers have traditionally collected the relevant soils and rainfall data and used it qualitatively to interpret their results. However, the Agronomy Institute has started recently to build quantitative models of the systems under study in order to help researchers interpret results.

Future research needs

Future research could focus on the following broad areas.

- Improving upon the existing cropping systems so that they become more productive and stable through crop improvement and crop management research. Crop improvement could focus on screening germplasm for drought tolerance and nitrogen-use efficiency at sites with low rainfall and infertile sandy soil. However, because of its complexity and long-term nature, this type of work lends itself to joint research projects with international agricultural research centres such as CIMMYT, in the case of maize.

  Crop management research could concentrate on improving the researchers' understanding of the responses of key crop husbandry practices to variations in soil fertility and rainfall through modelling. The success of this approach depends on good site characterisation and maintenance of detailed records on the experiments. Given the site-specificity of crop management research and the limited funding available for such efforts, there is need to select carefully a few representative sites for this type of work.
- The development of new farming systems. The fact that more than 50% of the annual cash incomes realised by smallholder farmers in semi-arid areas comes from off-farm sources suggests that the existing cropping systems have failed to meet their needs adequately. There is therefore need to develop new, profitable and sustainable farming systems that improve the standards of living of these farmers. These could include agroforestry-based cropping systems, introduction of irrigated agriculture, and concentrating on livestock at the expense of dryland cropping.

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An Integrated Approach to Soil Fertility Improvement in Malawi, Including Agroforestry

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Abstract

Approximately 80% of land under cultivation in Malawi is planted to maize. Most maize is grown by smallholders, whose farm sizes average less than 1 ha per farm family. Because of the high population density (>75 people/km^2), most land is continuously cropped. The introduction in 1991 of flinty hybrid maize varieties, which have processing and storage characteristics similar to local varieties, has led to a sharp increase in hybrid maize adoption in Malawi. Hybrid varieties currently account for 20% of the total land area planted to maize.

The fertilisers available to smallholder farmers in Malawi contain only N and P and, in some cases, S Hybrid maize varieties currently available in Malawi have yield potentials in excess of 10000 kg/ha, but on farmers' fields average less than one-third of this amount. 'Minus one' nutrient trials conducted from 1989 to 1992 revealed potential deficiencies of K, S, Zn and B at some sites.

Soils from over 400 demonstration sites were analysed, and a nutrient supplement of S, Zn and B (and in some cases K) was added to the existing N and P fertiliser recommendation. The nutrient supplement resulted in substantial and economical yield improvement at several of the sites tested. The demonstration trials also revealed that hybrid maize performed better than local maize under zero and suboptimal rates of fertilisation. Farmers have been under the mistaken impression that hybrid maize requires substantial amounts of fertiliser to outperform local maize. The results may encourage farmers who cannot afford large amounts of fertilisers to adopt hybrid maize.

Other research indicates that the amount of P supplied in the fertiliser recommendation, 40 kg P_2O_5/ha, may be excessive, and in some cases may be detrimental to maize yields. Band application of P fertilisers has been shown to be more efficient than the current dollop method. Surface application of urea has proved as effective as dollop application at topdressing. Late application of both basal and topdressing fertilisers is suspected to cause lowering of yields. An early season dry spell characteristic of rainfall patterns in Malawi is suspected to reduce greatly the effectiveness of late-applied basal dressing fertiliser.

Agroforestry could play a substantial role in soil fertility improvement. Data from alley cropping trials indicate that trees cycle substantial quantities of calcium Ca), magnesium (Mg), phosphorus (K) and sulfur (S) to the upper 15 cm of the soil profile. However, little P is cycled, and even N-supply by the leaves is fairly limited. Adding N and P at low rates to an alley cropping system substantially improves yields, and permits maize to take advantage of other nutrients cycled by the trees. The particularly favourable S and K status is soils under alley cropping was encouraging in light of the deficiencies of these elements found in Malawi soils.

MALAWI, with 75 people/km^2, is the most densely populated country in southern Africa. Almost 90% of the population lives in rural areas, farming an estimated 1.4 million ha of smallholder lands. The average farm size per farm family (ha average/4.7 persons) is 1.1 ha, with over 75% having holdings of 1.5 ha or less (Conroy 1992). Almost all farm operations are performed manually. The existence of livestock is minimal in major maize-producing areas. Because of the high demand for arable land, fallow periods are very short to non-existent. Maize, the staple food crop, is planted on 85% of small farmer land holdings.

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Statistics on maize production accumulated by CIMMYT (1992) show the effects of population pressure on soil fertility. The population of Malawi is growing at 3.5% annually. However, land available for maize production is limited, and increased only 1.7% annually from 1981–1990. Maize yield on a per hectare basis actually decreased 1.2% annually over this same period, resulting in an annual decrease in per capita consumption of 2.3%. The decrease in per-hectare yields was in spite of an average annual increase in fertiliser consumption of 7.8% from 1970 to 1989. Clearly, increased land pressures have resulted in declining soil fertility and lower yields. With the population continuing to grow and little uncultivated land available for future production, the current agricultural system in Malawi is unsustainable and in decline.

Because of the limited land area available for crop production, the trend of declining maize yields must be reversed if food self-sufficiency is to be maintained in the face of an increasing population. Maize yields in Malawi average 1.1 tons/ha. Available hybrid varieties in Malawi have yield potential in excess of 10 tons/ha. However, hybrid seed use is low, and the yield potential of hybrid varieties can be achieved only under improved soil fertility. Because rainfall is normally adequate in the major maize-producing areas of Malawi, the key to increased maize production is improving soil fertility and increasing hybrid seed use.

One of the major obstacles to hybrid seed adoption, the lack of varieties acceptable to farmers, has been addressed with the release of the varieties MH17 and MH18 in 1990–91. Local maize has traditionally been preferred by farmers because of its harder (flinty) endosperm. The flintiness imparts considerable resistance to weevils, a major pest that usually decimates the softer endosperm (denty) hybrids in storage. Furthermore, a higher percentage of endosperm is recovered from local maize in the traditional maize processing. The new maize varieties have a large proportion of hard endosperm, giving them a flinty texture more like the local maize. Farmers perceive the new varieties as possessing similar storage and processing characteristics to local maize (Smale et al. 1993).

The area planted to hybrid maize has been increasing steadily since 1986: maize area planted to hybrids approaching 20% in 1992-93. Hybrid adoption has been hindered by a perception that hybrid varieties must be fertilised at high rates in order to yield economically. Most farmers purchase hybrid seed and fertiliser through government credit packages. Because of the high rates of fertiliser (92 kg N and 40 kg P_2O_5/ha) that must be purchased with the seed, the packages are expensive. Farmers are reluctant to accept this large credit risk.

Maize Fertilisation Practices in Malawi.

Currently, a single fertilisation recommendation exists for hybrid maize throughout Malawi. That recommendation is 92 kg N and 40 kg P_2O_5/ha. Basal fertiliser is supplied by either diammonium phosphate (DAP; 18% N and 48% P_2O_5) or 23:21:0+4S. Topdressing N is supplied as either urea or calcium ammonium nitrate (CAN; 28% N). Both basal and top dressing fertilisers are applied in two concentrated dollops, applied 10 cm on either side of each maize planting station, at a depth of 10 cm. The maize itself is planted on 90 cm rows in planting stations of three plants spaced every 90 cm. There are approximately 12 350 planting stations per ha. Thus 24 700 dollops should be applied at basal dressing and another 24 700 at topdressing. This is a very labour-intensive process.

Several shortcomings on current recommended fertilisation practices exist. These are summarised below.

(i) The rate of fertiliser in the recommendation for hybrid maize is beyond the means of many smallholder farmers.

(ii) Fertilisers available to smallholders supply only N and P, and in some cases S. Potential deficiencies of Ca, Mg, K, Zn, Cu and B are not accounted for in the recommended fertilisers.

(iii) The blanket N/P recommendation does not take into account regional soil fertility differences.

(iv) The practice of applying fertilisers in dollops is extremely labour-intensive. Farm costs for a single fertiliser application are the same as required for ridging. Because of the labour required, fertilisers are often applied too late for maximum effectiveness.

(v) Apart from being labour-intensive, dolloping can be an inefficient method of fertiliser application. Urea, when concentrated in a dollop, may convert slowly to available-N forms, and could reduce N-availability during critical growing stages. P is often more efficiently applied in a band than in a dollop because of improved root contact with the fertiliser.

The Malawi Maize Commodity Team (MCT) has been addressing these constraints in an integrated approach to increasing maize yields by improving soil fertility. This paper highlights research methodology and results. In addition, results relating to maximising returns from alley cropping are presented.

Hybrid Variety Yields Under Low Soil Fertility

The Malawi Ministry of Agriculture (MoA), the United Nations Development Program (UNDP) and the Food and Agriculture Organization (FAO) have been conducting a joint maize demonstration program on farmers' fields since 1989-90. The demonstration consists of four treatments: hybrid and local maize unfertilised, and hybrid and local maize fertilised at recommended rates (92 kg N and 40 kg P_2O_5 for hybrid and 40 kg N and 10 kg P_2O_5 for local). Details of trial results are presented in Jones (1993). Figure 1 summarises trial results from 1989–90 to 1991–92. As expected, fertilised hybrid maize yielded the highest, averaging 3300 kg/ha, including the severe drought year of 1991–92.

On average, hybrid maize without fertiliser yielded 165% of unfertilised local maize, and 85% of fertilised local maize. Because hybrid maize yields better than local maize under low fertility, it offers a way for smallholder farmers who cannot afford the full fertiliser package a way to improve their yields. The complete substitution of hybrid maize varieties for local maize would immediately increase national maize production by over 30%, without additional fertiliser use. These three years data suggest that policy should be modified to recommend hybrid maize at any rate of fertilisation, and to supply fertiliser credit packages with lower rates of fertiliser.

Supplying the Right Nutrients for Maximising Yields

Four fertilisers are available to smallholder farmers in Malawi—diammonium phosphate (DAP; 18% N, 46% P_2O_5), 23:21:0+4S ($N:P_2O_5:K_2O$), urea (46% N) and calcium ammonium nitrate (28% N). These fertilisers supply only N and P, and in the case of 23:21:0+4S, sulfur. Several essential nutrients are not supplied at all, including K, Ca, Mg, Zn, B, and Cu. Past soil and plant analysis indicated that Fe and Mn were almost always adequate.

'Minus one' type fertiliser trials conducted by the MCT indicated maize response to K, S, Zn, and/or B in some areas. Results from the average of five sites in the Dedza Hills from the 1990–91 growing season are presented in Figure 2. However, because of the limited number of sites on which the trials were conducted, it was impossible to make assessments with regards to regional nutrient deficiencies.

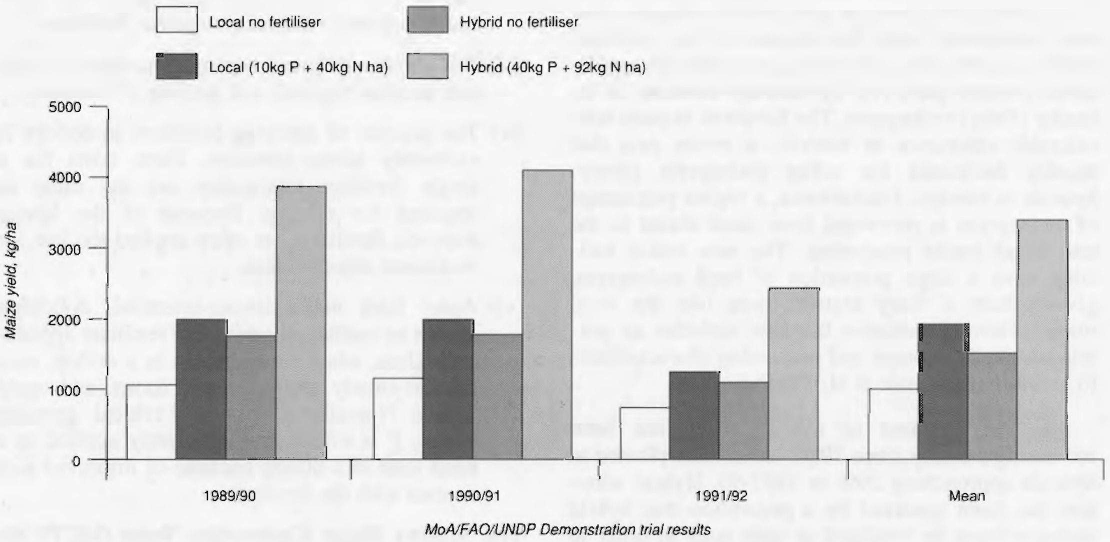

Figure 1. Effects of fertilisers on yields of local and hybrid maize varieties over three seasons.

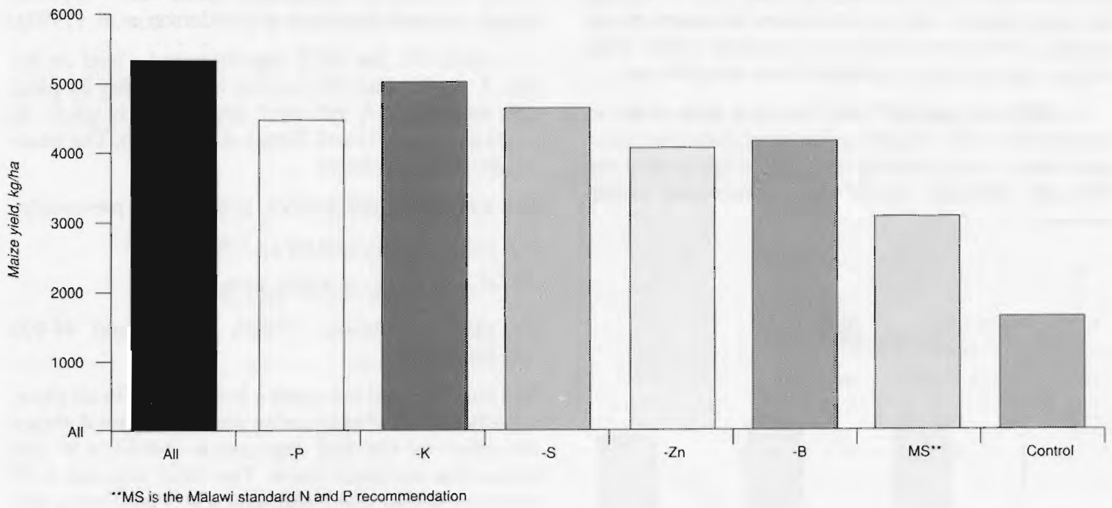

Figure 2. Maize yield as a function of applied nutrients in a missing nutrients trial, 5 sites in the Dedza Hills, 1990/91.

In an effort to deduce the degree to which nutrients other than N and P were limiting yields, the MCT collaborated with MoA, UNDP and FAO in their maize demonstration trials in 1992–93. Soil samples were taken from each of the 400 demonstration sites (all on farmers' fields) from Lilongwe, Kasungu, Mzuzu, and Blantyre Agricultural Development Divisions (ADDs). These ADDs account for 75% of Malawi's maize production. Four treatments were added to the previous 4-plot demonstrations in Lilongwe and Kasungu ADDs. These treatments were hybrid maize at the local maize fertilisation rate (40 kg N and 10 kg P_2O_5/ha), hybrid maize with 92 kg N/ha (no P), local maize with 40 kg N/ha (no P), and hybrid maize with 92 kg N, 40 kg P_2O_5, and a supplement of 15 kg S, 5 kg Zn, and 0.5 kg B/ha. Potassium was added to plots where soil tests indicated low K levels.

The final results for all these trials are not yet available. However, preliminary results indicate that the nutrient supplement increased yields at those sites where nutrient deficiencies were indicated by soil tests by an average of 20–30%. Hybrid maize outperformed local maize at the reduced fertiliser rate of 40 kg N and 10 kg P_2O_5/ha. Both local maize and hybrid maize suffered when P was not applied. These preliminary results indicate that soil tests can identify nutrient deficiencies of nutrients other than N and P, and that these deficiencies can be amended by fertiliser applications. Soil test results are described in detail in Wendt (1993).

Fertiliser application methods

Fertiliser recommendations in Malawi stipulate that both basal and topdressing fertilisers be applied in dollops. Dolloping fertilisers is very labour-intensive and often results in delayed application.

Basal dressing fertilisers are dolloped after emergence. However, an early season dry spell commonly follows planting rains. Because no water is available, applied fertilisers are not able to diffuse into the rooting zone. The young plant is therefore stressed for nutrients, which can affect its viability during the dry period and its future yield potential.

In addition, dolloping is an inefficient way to apply fertilisers. Figure 3 shows average maize yields from five sites with dollop and band application methods. While responses varied from site to site, for band applications average yields were as high with 20 kg P_2O_5/ha as with 40 kg P_2O_5/ha.

The negative consequences of applying urea in a dollop are reviewed by Jones (1993). After concentrating urea in a dollop, pH changes inhibit enzymes and microbes that permit conversion of urea into plant-available nitrate and ammonium. Concentration of urea at a point may also increase leaching losses because the adsorptive capacity of the soils in the application zone is exceeded. The maize team has conducted research (data not shown) that shows that topdressing urea on the surface rather than in dollops does not reduce, and in some cases increases, maize yields. Under these conditions ammonia losses from surface applied urea must have been insignificant.

In 1993–94, the MCT will test on a wide scale, in cooperation with Malawi agricultural extension, band application basal dressing and surface application top dressing methods, versus the conventional dollop method.

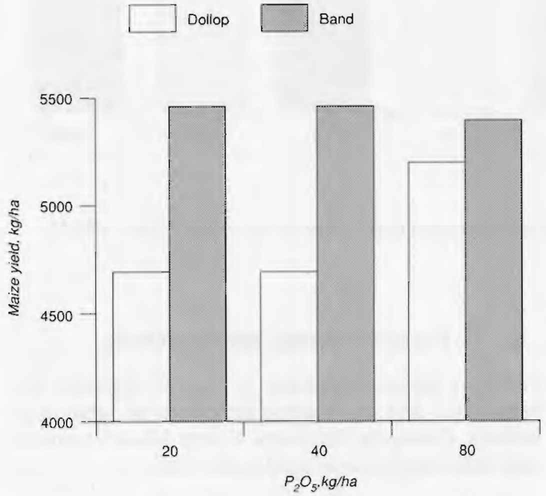

Figure 3. Maize response to P placement and rate, average of 5 sites.

Optimising Yields Under Alley Cropping

Alley cropping is the growing of crops between hedgerows of woody leguminous species. Prunings from the trees serve to fertilise the crop. Hedgerow leaves have high concentrations of N, Ca, Mg, K, and S relative to maize leaves (Kang et al. 1981). These nutrients, cycled from the soil, can contribute to maize fertility. Some nutrients may be cycled in greater or lesser quantities than others in relation to maize demand. By strategically supplementing leaf additions with appropriate fertilisers, yields from alley cropping systems can be maximised.

In 1986, an alley cropping trial using *Leucaena leucocephala* was begun at Chitedze Agricultural Research Station near Lilongwe, Malawi. Three leaf management strategies were employed: (i) leaves applied; (ii) leaves removed; and (iii) leaves removed + 100 kg N/ha applied as calcium ammonium nitrate. These treatments continued until the 1989–90 season, and are described in Bunderson et al. (1991).

In 1990–91, the MCT superimposed a trial on the site. A confounded 34 factorial design using 81 plots was employed. A full trial description is given in Jones et al. (1993) and Wendt et al. (1993). The treatments were as follows:

(i) leaf application history, as described previously;
(ii) N rate: 0, 30, and 60 kg N/ha;
(iii) P rate: 0, 18, and 36 kg P/ha;
(iv) plant population: 14 800, 29 600, and 44 400 plants/ha.

Soil analyses had indicated a low P status in all plots, regardless of leaf application history. Figure 4 shows the effect of the leaf application history × P rate interaction on maize yield. The clear response to P additions shows that P was deficient. Plots with a history of leaf application responded most to P additions. This indicates that nutrients cycled by the leaves could not be utilised by the maize crop until the most limiting nutrient, P, was supplied. Plots with a history of leaf application had higher levels of Ca, Mg, K, and S than plots where leaves have not been added. These results show that leaf application had little effect on soil P status, and that P application was necessary to get the full benefit from leaf application.

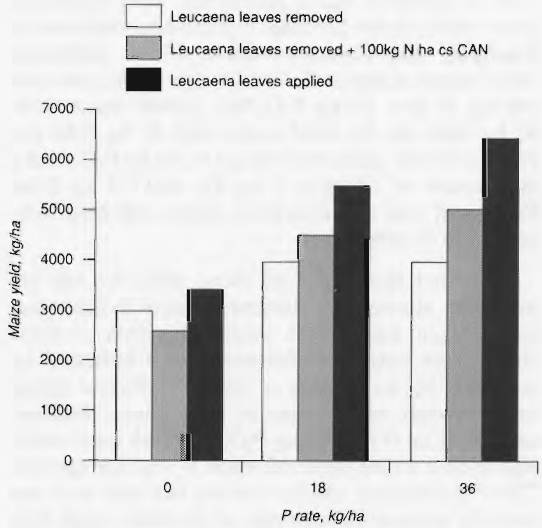

Figure 4. Effect of leaf application history and P rate on maize yield.

Figure 5 shows the effect of the N rate × P rate interaction on maize yield. Very little yield response to P additions was realised until N was added, and little response to N additions could be found until P was added. This shows that both N and P were limiting. Substantial yields could be achieved with the application of small rates of N and P.

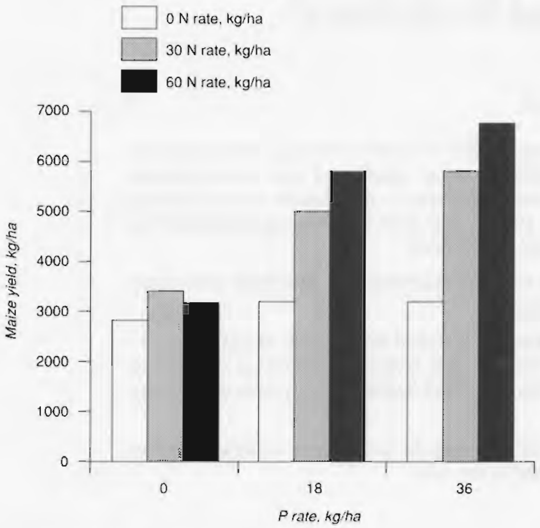

Figure 5. Effect of N and P application on maize yield.

Future Research

In the 1993–94 season, the MCT will run, in cooperation with Malawi Agricultural Extension, a series of demonstration trials that compare new fertiliser types, placement methods, and timing of fertiliser application with the current recommended methods. Trials will take place on farmers' fields. In addition, approximately 3000 topsoil samples will be taken from farmers' fields throughout the country. These samples will receive a full analysis, and analytical data will be used to locate regional nutrient deficiencies. These deficiencies will be addressed with the new fertiliser sources to be tested in cooperation with extension.

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Economic and Climatic Risks in Cropping Systems in Chivi Communal Area, Zimbabwe

B.G. Mombeshora and M. Mudhara*

Abstract

This paper describes the components of the farming systems in Chivi communal area where the climate and soils are unsuitable for intensive crop production. Studies of the socioeconomic circumstances of farmers reveal that there are serious constraints to investments in soil fertility management. Draught power and cash are in short supply. The land tenure system prevents the adoption of certain technologies. Marketing is generally inefficient.

The farmers' cropping systems are dominated by cereal crops which are combined with some leguminous crops and oil seeds. Landholdings are small.

Resources for soil fertility management are not readily available due to lack of cash for purchasing inorganic fertiliser, cattle for provision of manure; and labour for collection of antheap soil. The situation is made worse by the high variability in rainfall leading to high risks of applying these resources.

Crop modelling is postulated as a possible means of resolving the interactions brought in by the complex system in which crop production is conducted in the area.

THE information presented in this paper covers approximately 10 years of farming systems research in Chivi by the Farming Systems Research Unit (FSRU) of the Department of Research and Specialist Services (DR&SS) as well as information from other government and non-government organisations working in the area.

A summary description of the farming system component is presented, followed by observations and ideas on how these relate to soil fertility management in the area are given.

Climate

Chivi communal area is located in agroecological regions IV and V (Vincent and Thomas 1960, see also Fig. 1 Waddington, these Proceedings) between 20.0° to 20.55° south and 30.05° to 30.53° east. Regions IV and V are extensive farming areas, mainly livestock production in the commercial sector and mixed crop–livestock production in the communal areas. Chivi lies at a general altitude of 1000 metres above sea level (range 600–1300 m). The mean annual rainfall is 643 mm (range 230–1191 mm) falling between early November and May. Both the total rainfall per season and its distribution are highly unpredictable and variable with delays in the start of the rainfall season, heavy downpours over short periods of time, and severe mid-season droughts being experienced across the whole area. During the wet season, temperatures range from 18° C minimum to 30° maximum, while in the dry season (May to October) temperatures range 5–25° with occasional ground frost in some areas.

Soils and vegetation

The cropland soils in Chivi are diverse, ranging from heavy clays to sands. Spatial variability occurs at a variety of scales from landscape differences in soil type (catena) characteristics to field level variations in micro-environments due to topography and associated soil and water relations. Generally the soils are of poor to medium fertility, are shallow and of low water-holding capacity, with low levels of organic matter, associated deficiencies in micronutrients, and

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low pH less than 4.8. About 40% of the soils in the area are sands derived from granite and most of soils are kaolinitic and fersiallitic group. Nitrogen as well as P, S, and Zn deficiencies are typical in these soils. Other soils are derived from sandstones, shale conglomerates, metavolcanics, gneisses and metasediments.

The general vegetation in Chivi consists of mixed veld with light to medium woodlands with scrub understorey. The veld consists mainly of perennials (*Heteropogon* and *Eragrostis* spp.) and a high proportion of annuals. The woodlands are mainly of *Brachystegia* spp., with mopane (*Colophospermum mopane)* and acacia (*Acacia* spp.) dominant with some baobab (*Adansonia digitata)* in the central area.

Socioeconomic circumstances

Land is held under customary law. The household has the right to till the land which is allocated by the chief through his headman. (This role of allocating land has now been transferred from the traditional leaders to locally elected councillors.) In most cases the bulk of arable land is located some distance from the homesteads. Smaller patches can be cultivated around the homestead. The average arable land area per household was 4.84 ha in 1990–91. The fact that the land is not owned by the farmers has meant that they are not willing to make long-term investments on their farms for fear of losing the investment. Many farmers will be moved when the proposed Totwe–Mukosi dam is constructed. Farmers feel that the compensation they are receiving from the government is very low.

It is the responsibility of the headman (councillor) to ensure that some land is set aside for livestock grazing with all households having communal rights to the land, especially in summer. In winter, farmers are free to graze their livestock anywhere, since field crops have been harvested. Only securely fenced fields cannot be grazed. Due to resource constraints most crop fields are not fenced. This makes it difficult for farmers to adopt certain technologies that require protection from livestock, e.g. agroforestry or permanent soil structures.

Average cattle holdings are very low. In January 1991 the average cattle number per household was approximately four. After the devastating 1991–92 drought cattle numbers had fallen to approximately 1.7 per household (Table 1).

Cattle are the main source of draught power although donkeys are also used. A survey conducted before the 1991–92 drought revealed an average of one donkey per household. Draught power ownership is a critical element in the communal area farming systems. Surveys conducted 1991–92 revealed that farmers with access to draught power till more land, apply inputs on larger proportions of their fields to improve soil fertility and in general are better endowed with implements essential for farming. As a result they are able to obtain better harvests than those without draught power. Cattle are used also for payment of dowries and act as a bank account as they can be sold readily for cash.

Table 1. Numbers of cattle owned per household (before and after the 1991–92 drought)

	Before drought	After drought
Average	4	1.7
Minimum	0	0
Maximum	101	100

Households tend to be large. The average household size recorded during a survey in January 1991 was seven (minimum one, maximum 23). The members of the household also supply the bulk of the labour used for crop production. The same survey revealed that, in some years, the number of household members was directly correlated with the area planted for particular crops, e.g. groundnuts, sorghum, pearl millet and maize. However, labour becomes a constraint during land preparation and weeding.

Due to the low agricultural output in Chivi remittances from family members play an important role. Information from the survey showed that the number of family members per household was highly correlated ($p<0.01$) with the amount remitted to the household over a 12-month period. The survey also showed that on average $243 had been remitted per household (minimum 0, maximum $1200).

As there is so much risk associated with crop production, insurance measures such as remittance are necessary to cushion farmers. Some remittances are provided in the form of goods (e.g. clothes, groceries, agricultural inputs). Incomes generated by members of the household who are resident in the area are an important source of income. On average $154 (minimum 0, maximum $1670) was generated through various activities by family members resident at the homestead. In general the financial resources are limited.

The communal area has a growth point (development centre) which lies about 50 km and 40 km from its southern and northern borders respectively. Most agricultural inputs can be obtained from the growth point. However, due to the exorbitant prices charged by local traders, farmers prefer to procure most of their inputs from Masvingo, the provincial capital even though it means travelling further. In some instances farmers are not given an adequate range of inputs from which to choose. In such cases they end up buying whatever is available on the market. This is especially the case with seeds, to the extent that inappropriate varieties are being used. Also due to the input supply bottleneck, farmers use seed obtained from the previous season's crop.

Due to low crop productivity, there are no Grain Marketing Boards (GMB) depots in the area. In some instances mobile depots have been put in place. In most cases crops are sold through private buyers who are authorised by the GMB. However, under this system farmers realise lower prices than they would if they had sold directly to GMB.

An all-weather road runs through the communal area but feeder roads tend to be bad. Local transport is generally inadequate and expensive and this, combined with the low prices realised by farmers from approved buyers, drastically reduces the revenue per unit output.

Cropping systems

Farmers in Chivi rely on a mixture of rainfed farming, a few irrigation schemes, livestock rearing and off-farm income to support themselves. The cropping system is dominated by grain crops, e.g. maize, sorghum, millet, which are combined with sunflower, cotton, finger millet, groundnuts and a range of other minor crops such as cowpeas, pumpkins and bambara nuts. Field sizes are generally small (average 4.8 ha/household) due to high population density (around 30 people/km^2) and 63% of the arable land is planted with the grain crops, which are staple starches. Farmers also grow a variety of vegetables (cabbage, tomatoes, onions, beans, etc.) in the dry season, on small gardens usually situated in the wet vleis and near wells or boreholes, for domestic consumption and cash.

Although some cowpeas, pumpkins and, sweet sorghum are mixed with the grain crops, monocropping is the main practice recommended by extension. Crop-to-crop rotations are practised to a limited extent and crop-to-fallow rotation is practised where shortages of labour or draught power exist. These are insufficient for effective fertility management. Cereal monocropping dominates because of the preference for grains and the small field sizes available. Farmers who have draught power practise winter ploughing to conserve soil moisture while those without power plough only during the wet season. Planting of grain crops, especially maize, is staggered to early mid and late season to minimise the risk of mid-season droughts. The full potential of the rainy season is thus not captured, resulting in low maize yields (<1.0 t/ha) by the late planted crops.

Soil fertility management

There is a range of fertility management options in Chivi. These include inorganic fertilisers, livestock manure, ash/household compost, antheap soil and leaf litter (FSRU 1993). These may be combined with a variety of other management options including fallowing, crop rotation, use of leguminous crops and intercropping. In spite of these options, during the period 1988–89 to 1992–93, between 75% and 90% of the total area planted did not receive any form of fertilisation. This reflects a number of factors:

(i) the lack of cash for inputs like inorganic fertilisers, as well as low availability (marketing and transport constraints);

(ii) low or uncertain returns to fertiliser inputs;

(iii) lack of manure due to low livestock numbers in relation to arable area; and

(iv) labour constraints on leaf litter collection, antheap soil collection and composting, etc.

Only 9% of the farmers use inorganic fertilisers (both compound D and top dressing). This is not only due to cash shortages but because of the realisation that recommended fertilisers and rates of application are uneconomical. Responses to fertilisers are related to the crop–soil moisture relations, which often are not favourable, resulting in poor results from soluble fertiliser applications (FSRU 1993). Other forms of fertility management, used by 70% of farmers (manure, litter etc.), are constrained by labour requirements and the limited quantities available in the area. The overall situation is that only a small percentage of the arable areas receives either inorganic fertilisers or other forms of nutrients, the remaining area being depleted of soil nutrients without replacement and recycling. Table 2 shows the rankings by Chivi farmers of the advantages and disadvantages of various fertility improvement inputs.

The current situation of crop production and soil fertility in Chivi is complex and results from the interaction of factors already outlined, including the political situation. Soil fertility and crop yields are declining; erosion is on the increase. Several factors contribute to this situation.

Table 2. Preference for alternative fertility inputs.

Input	Ranking			Advantages	Disadvantages
Livestock	A	B	C		
manure	1	2	1	Increased germination and yield. Residual effect improves soil structure. Good moisture retention.	Crop may 'burn'. Encourages weed. Needs large cattle numbers
Antheap soil	2	3	4	Reduces water logging. 2-3 years residual effect	First year application not effective, excess kills crop, much labour needed
Leaf litter	3	3	2	Increases growth. Improves structure. Reduces salinity.	Crops burn with insufficient rains. Much labour needed
Ash compost	4	5	4	Increases growth. Good for vegetables.	Needs plenty of moisture.
Inorganic fertiliser	3	1	2	High crop growth.	Yearly application, Needs high rainfall. Expensive.

Note: A = rank of actual current use; B = preference under good rainfall; C= preference under poor rainfall.
Source: FSRU 1993.

(i) Over-cultivation and soil nutrient depletion associated with increased population, high cropping intensity, reduced fallow periods (less than three years, up to continuous cropping), and limited crop rotations;

(ii) poor vegetation cover and heavy downpours, favouring high rates of runoff and soil erosion;

(iii) limited use of fertility inputs associated with high costs of inorganic fertilisers, inadequate supplies of alternative inputs and low crop responses to conventional inputs due to soil types and low rainfall; and

(iv) the communal land tenure system, which prohibits use of fertility-improving agroforestry practices such as growing trees for green manure.

Crop modelling in Chivi

Experiences by the FSRU during crop research have highlighted the difficulties of climatic variability. Replanted crops often fail, placing farmers in a critical position as they do not have the necessary resources for further replanting.

The variability in seasons has often meant that on-farm trials are conducted without enabling conclusive agronomic recommendations to be achieved. At each stage in the experimentation process, some issues have remained unresolved. Crop modelling can be used for deriving better decisions on how to cope with soil and climatic variability. It is likely to be the best way of handling the time series data which, in most cases, are not fully utilised by other methods, due to variability. The main cost of using the modelling approach is the requirement for detailed experimental and meteorological data.

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Recent Developments in Systems Modelling

Peter S. Carberry*

Abstract

In July 1990, an International Symposium was held in Australia to review the application of simulation models in managing climatic risk in crop production in the semi-arid tropics and subtropics. In looking back on this symposium as a reference point for modelling activities up to the end of the 1980s, one is impressed by the general endorsement given to modelling as a means of problem-solving in agricultural production systems. Notwithstanding this, the progress in development of systems modelling since 1990, both in the enhancement in software capability and in the application and interpretation of simulation results, has been extensive.

Recent efforts in Australia have been directed towards creating a modelling capability that (i) simulates agricultural production systems, (ii) includes a portfolio of simulation models for a range of crops and pastures, and (iii) encapsulates rigour in software development, programming and maintenance, and provides a user-friendly operating environment. The Agricultural Production Systems Simulator (APSIM) has been designed and developed to meet these criteria and now represents a core technology of systems research in northern Australia.

A second area of advancement in system simulation is the extension of model output beyond the simple presentation of simulated yields or gross margins. Combining the tools of system simulation with those of economic decision analysis provides a powerful means of evaluating economic returns, their associated risks and farmer preferences for the trade-off between return and risk.

This paper reports on these recent developments in systems simulation and provides an example of a relevant application study in northern Australia.

MODELLING is not new to research on agricultural systems. In fact, it goes back to at least the 1940s. Since then, investment in simulation modelling has grown in line with the rapid advances in computers and, over the years, one can identify a number of significant milestones in the development of crop and soil models (Angus 1991; Ritchie 1991). The question that this paper addresses is whether dynamic simulation of agricultural systems has made significant progress over more recent years and, if so, in what ways?

In answering this question, the status of modelling at July 1990 is taken as a benchmark against which developments since then can be evaluated. At this time an International Symposium was held in Australia, the purpose of which was to review the management of climatic risk in crop production in the semi-arid tropics and subtropics, with particular emphasis on the application of simulation models (Muchow and Bellamy 1991). Contributions were drawn from a cross-section of the modelling fraternity and collectively represented the achievements at that point in time in both model capability and application. The status of modelling in both semi-arid Kenya and Australia was presented.

This paper takes the somewhat narrow view of models in adopting the definition that a model is 'a combination of mathematical equations and logic used to conceptually represent a simplified crop production system' (Ritchie 1991). Such models are used to predict the changed state of the system being simulated, given input of initial system conditions, management interventions to the system and the daily weather variables that drive the system. Crop yields are a primary output of such predictions, although changes in other state variables, such as soil loss from erosion, are also often of interest. Ritchie

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(1991) provided an excellent review of crop simulation models and their make-up at this level of relevance.

Progress in systems modelling is addressed under two broad headings: improvements in the development of simulation models, and greater relevance in modelling applications. Models improve by either (i) increased accuracy in predictions, (ii) broadened simulation capability, or (iii) better software. More relevant applications encompass the need for models to make significant impacts on agricultural decision-making. This paper reviews the state of system modelling at July 1990 and identifies the scope for advancement in each of these areas. In particular, the progress being made in Australia by the Agricultural Production Systems Research Unit (APSRU) in addressing these areas is highlighted.

The Status of Modelling in 1990

1990 Climatic risk symposium

Three papers at the Symposium were of particular interest in helping to define criteria against which the status of modelling in 1990 could be judged. Firstly, Ritchie (1991) dealt with the specification of the ideal crop model, then Penning de Vries and Spitters (1991) addressed prospects for improvements in prediction accuracy in the future. Ritchie (1991) gave seven criteria against which models can be judged (Table 1(a)). Although open to argument, simulation models being used in 1990 were judged to have achieved significant advancement in only three criteria. Take either CERES-Maize (Jones and Kiniry 1986) or the less-detailed soybean model of Sinclair (1986) as examples. On the whole, the level at which processes are simulated in these models has been endorsed by the similarities between them and other models (cf. Rosenthal et al. 1989; Carberry and Abrecht 1991; Monteith and Virmani 1991; Chapman et al. 1993). Both approaches have been widely adopted (Hodges et al. 1987; Carberry et al. 1989; Liu et al. 1989; Keating et al. 1991; Hammer and Muchow 1991; Meinke et al. 1993) suggesting that the data requirements for running the models were attainable and that predictions were generally applicable, although on this last point, the need for local adaptation was identified by almost all such groups. On the contrary, by 1990, there were few if any examples of models that were well programmed or user-friendly. The more likely situation was that model code was written by researchers and reflected a lack of input from professional programmers. Likewise, the person that built the model often was the only person that could drive the model. Few models by 1990 had been linked to pest models nor indeed dealt with weeds or diseases.

Table 1. Criteria suggested for (a): the ideal model for predicting crop yields (Ritchie 1991) and (b) improvement in simulation (Penning de Vries and Spitters 1991).

(a) Ideal model
- balance between all components of a model
- general applicability in space and time
- realistic data requirements
- ability to be linked with pest models
- structured programming
- user-friendliness

(b) Improved simulations
- matching of problems to simulation ability
- computers and software
- skilled modellers
- models of relevant systems
- model parameters
- data — physical
  — biological
  — climate

In general, the crop models represented at the 1990 Symposium demonstrated improved prediction accuracy over the first crop models developed prior to the 1980s. Coefficients of determination (R^2) for predicted versus observed grain yields ranged from 0.88 to 0.63 (Keating et al. 1991; Hammer and Muchow 1991). In contrast, the validation of the widely-used SORGF sorghum model (Arkin et al. 1976) initially did not display good prediction accuracy for grain yield ($R^2 < 0.40$) (Vanderlip and Arkin 1977), although accuracy improved with further developments over time ($R^2 = 0.74$) (Huda 1987). Of the criteria (Table 1(b)) of Penning de Vries and Spitters (1991) to improve simulation ability, all were met to varying degrees by the models around in 1990, the point being that simulations have improved by advances in each of these areas. For example, the advances in computers and software have greatly improved the ease of computer modelling. Access to reliable long-term climatic data has often been one of the greatest hindrances, yet the recent development of weather data generators is seen as a solution (Hutchinson 1991). The availability of experienced modellers and of models of relevant agricultural systems has been more limiting, but interest in modelling is on the increase. However, the usual sampling errors contained in experimental data will continue to impact on reliable estimation of model parameters and on the accuracy of validation data, meaning that models will probably not achieve accuracy much greater than that achieved by the 1990 vintage models ($R^2 \sim 0.90$).

Anderson (1991) provided a framework of a farming system against which the usefulness of models could be judged (Table 2). The framework suggested that the utility for farming consists of the economic performance of the farming system plus the personal preference of the farmer. The economic component of this socioeconomic model is a function of farmer decisions, of the probability distributions of yields attained and prices received, and of the effects of any policy interventions to the system, such as by governments or financial institutions. Anderson's (1991) assessment was that, judging by the papers presented at the Symposium, the great majority of interest by modellers concentrated on yield prediction alone. In fact, only two papers (Keating et al. 1991; McCown et al. 1991) effectively considered the economics of farming practices, by addressing the trade-off between simulated gross margin (GM) return and the associated risk, although most papers presented simulated yields and several presented simple GMs.

Table 2. A framework for the farming system (Anderson 1991).

Utility	= U (economics, personal preference
Economics	= f (management,P(Y),P(p),policy)
P(Y)	= f (management, climate)
P(p)	= f (demand,policy,supply)

The terms P(Y) and P(p) refer to probability distributions for yield and price respectively

The other notable deficiency of modelling with regard to Anderson's (1991) framework was a concentration on the management of single crop enterprises as opposed to enterprise combinations, and following on from this, simulating single-season effects, not long-term consequences. Only three papers fell into this latter category. Carberry and Abrecht (1991) simulated components of a ley-farming system, Freebairn et al. (1991) presented long-term simulated yield decline due to erosion from a wheat–fallow cropping system and Clewett et al. (1991) simulated components of a farm dam system for irrigating sorghum. A major reason for this deficiency was the limited availability of models that could simulate system phenomena. Of the system models around in 1990, EPIC (Williams et al. 1983) traded-off prediction accuracy (Steiner et al.1987; Williams et al. 1989) for scope in simulating a broad range of systems using a generic crop model, whereas DSSAT (Uehara and Tsuji 1991) consisted of a set of full crop models (e.g. CERES-Maize, SOYGRO) but was limited by not dealing with crop sequences. PERFECT (Littleboy et al. 1989) was positioned somewhere between the two ends of the capability/accuracy tradeoff, being limited to wheat, sorghum and sunflower but dealing with long-term consequences of crop sequences.

Where was modelling 'at' in 1990? Judging from this review, models were mostly of single crops, predicting yields with reasonable accuracy, but consisting of poor software coding and reliability, operated from limited computing environments and containing the single ability to produce probability distributions of yield. To progress it was clear that what was needed were models of agricultural systems, embodying professional software development and reliable operation, a user-friendly computing environment and the ability to produce applicable economic analyses. Finally, to justify such developments, modelling had to become relevant to the research needs of the farming system.

Improvements in Model Development

APSIM—Agricultural Production Systems Simulator

In January 1990, the Agricultural Production Systems Research Unit (APSRU) was formed in Australia to undertake research on the farming systems of northern Australia. The core technology of APSRU is operational research (McCown 1989 1991). In forming APSRU, two distinct efforts in developing system simulation capacities in Australia, PERFECT (Littleboy et al. 1989) on the one hand and AUSIM (McCown and Williams 1989; Carberry et al. 1992) on the other, were amalgated. This amalgamation of effort has resulted in the development of the Agricultural Production Systems Simulator (APSIM), consisting of a user interface (APSIM shell) and model code (APSIM model). How APSIM addresses the criteria of model capability, model accuracy, software programming and user environment is briefly outlined in the following sections. More detailed descriptions of APSIM are provided elsewhere by Hammer et al. (1993) and McCown et al. (1994).

Model capability

APSIM is a flexible software system for simulating agricultural production systems, which it asks the user to specify rather than a model of a particular cropping system. That is, the APSIM model is a collection of modules, each describing specific physical and biological processes, that are combined in meaningful ways to represent agricultural systems.

Figure 1 graphically represents this concept. Here, there are a number of modules, grouped as either biological, environmental, managerial or economic, that are linked only via an 'engine'. The 'engine' is a communication system that passes information between modules according to a standard protocol. The fact that two modules are not directly linked allows modules to be plugged in or pulled out of the 'engine' depending on the specifications for the simulation task. For example, if one wished to simulate a rotation involving crops A and B, modules for crop A and crop B would be plugged into APSIM along with modules for a soil-water and nitrogen balance. While modules for alternative crops or water balances exist within APSIM's libraries, there would be no need to link them into APSIM for this task. In this way, the simulation capacity of APSIM is limited only by the availability of modules to simulate the processes peculiar to the system of interest.

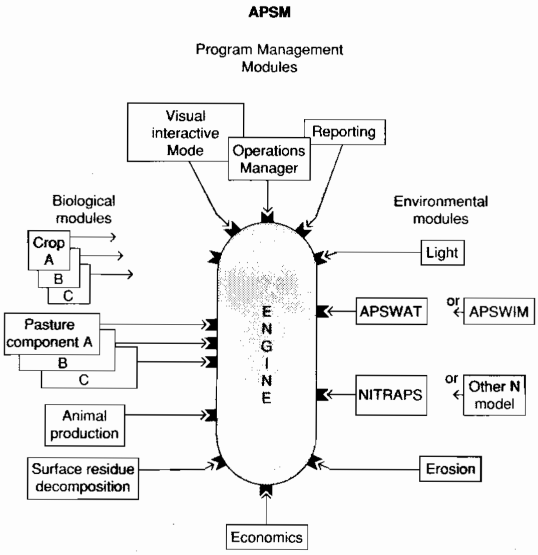

Figure 1. Schematic diagram of the APSIM simulation model (Source: McCown et al. 1994).

Given current access to modules, APSIM has the ability to simulate a range of crops in response to management options and whether grown in rotations, in mixtures or interacting with pastures and livestock. Importantly, this is accomplished in a way by which the soil accrues the effects of agricultural practices such as cropping, fallowing, residue management and tillage. In this way, APSIM can simulate long-term trends in soil productivity due to fertility depletion and erosion.

The initial emphasis of APSIM is to deal with the dryland cropping systems of semi-arid and subtropical Australia. However, such an emphasis does not preclude APSIM being configured for other agricultural systems, e.g. sugar production in the Australian humid tropics (B.A. Keating 1993 pers. comm.) or intercropping systems in sub-Sahelian Africa (Adiku et al. 1993).

Model accuracy

By using an approach that allows almost any existing model of a crop or soil process to be easily interfaced with the APSIM 'engine', there has been no need to compromise simulation accuracy for modelling capability. Therefore APSIM has adopted many of the existing models that simulate crop, pasture, soil or animal processes in Australia and elsewhere (Table 3). The accuracy of APSIM therefore derives from the validation accuracy of each original module plus the degree to which such validations are affected by the module combination linked into APSIM for a particular application. While the use of existing validated modules provides for confidence in APSIM, the effect of module combinations on prediction accuracy is the focus of APSIM's on-going development and testing processes.

Software programming

A major aspect of the development of APSIM has been the emphasis placed on high standards in software development and rigour in coding correctness. The software development of APSIM has represented approximately 10 person-years of professional programming. The programming objectives of APSIM are grouped into three broad requirements. Firstly, there was the need to implement APSIM's protocol which permits the modular plug in/pull out interface with the APSIM 'engine'. Secondly, programming standards were developed to ensure program reliability and maintainability by implementing a disciplined approach to subroutine design, to readability of code, to program testing and to version control of source code. Thirdly, a modelling environment was created to facilitate the use of APSIM for both program development and maintenance and for operational research purposes.

User environment

The APSIM shell uses a Microsoft Windows™ operating environment. The APSIM window is made up of a number of buttons, each representing a module that can be accessed from the APSIM library. Source code of a module, if available, can be accessed in an

Table 3. List of current and planned modules within APSIM and references to their origin.

Group	Module	Original Model	Reference
Crop	cotton	OZCOT	Hearn and Da Rosa (1985)
	cowpea	APSIM-Cowpea	Adiku et al. (1993)
	maize	AUSIM-Maize	Carberry and Abrecht (1991)
	peanut	QNUT	Hammer et al. (1992)
	sorghum	QSORG	Hammer and Muchow (1991)
		AUSIM-Sorghum	Carberry and Abrecht (1991)
	sunflower	QSUN	Chapman et al. (1993)
	wheat	CERES-Wheat	Ritchie et al. (1988)
		Woodruff-Hammer	Hammer et al. (1987)
		Sinclair and Amir	Sinclair and Amir (1992)
Pasture	grass	GRASP	McKeon et al. (1990)
	legume	GRAZPLAN	Moore et al. (1991)
Soil	water	CERES	Ritchie (1985)
		PERFECT	Littleboy et al. (1989)
		SWIM	Ross (1990)
	N	CERES	Godwin and Jones (1991)
	erosion	PERFECT	Littleboy et al. (1989)

editor by selecting the appropriate button. As part of the APSIM installation process, users specify their own software development tools such as compilers, linkers, file viewers and editors. These tools can be accessed via pull-down menus from the menu bar of the APSIM window.

Within the APSIM shell, a module is incorporated into (or omitted from) APSIM model executable code by marking (unmarking) the checkbox of the module button, then compiling and linking the combined modules into executable code. This APSIM version can be run by selecting a control file, which defines a simulation run, and, where appropriate, climate, soil and experimental databases. These activities can be undertaken by using pull-down command menus, although the APSIM model can also be simply run under DOS or other operating systems. After running the model, output can be interrogated by viewing output reports and graphing output variables using the custom-developed graphics package.

The basis of APSIM's operating environment is to provide easy access to all the activities that users would normally undertake in modelling.

Relevance in model applications

Over past years, the continued development and/or refinement of models often has taken precedence over their application. For example, in a search of the literature since 1986, 283 publications were found on the topic relating to maize (corn) models. Of these, roughly 83% could be classified as papers where model development was the major research activity. Model development in this case included activities to define functional relationships, calibrate or validate models or functions within models. Only 17% of papers were classified as papers which used models in some way and only a fraction of these papers addressed outcomes in terms other than crop yields. This survey is obviously an oversimplification, as many applications may not be published in scientific papers. Nevertheless, in the current research environment in Australia, and probably elsewhere in the world, a disproportionate effort in developing new models cannot be justified. It is of little benefit to clients of agricultural research continually to explore new ways of prediction if the predictive tools are not used to help them make decisions. This is especially so if the scope for improved accuracy in predictions is not great. Therefore, a culture of using models in operational research is clearly needed in the future development of system modelling.

Arguments for models to be used in operational research have been well put by several others in these Proceedings. Clearly, in many cases, models are the most appropriate means of generating yield distributions for alternative strategies. But much of the past work in applying models has stopped at simulating yield production, where the relevance of such applications would have increased significantly if predicted yields were transformed into economic returns. The following sections firstly describe several of the economic analysis tools that are easily applied to simulation output, secondly, outline an example of where these economic tools have been recently applied in Australia, and finally, briefly introduce the use of model output in computerised decision support systems (DSS).

Economic analyses

When making decisions in climatically variable environments, no strategy or practice is best in all years. Typically there is a trade-off between the economic return of a strategy and its riskiness. Strategies that have the potential to produce large economic returns in the good years also represent the risk of greatest losses in the poor years. Alternatively, strategies that are tailored to minimising losses in the poor years forgo profit when the seasons are good. In these situations, techniques commonly employed in economic analyses can assist in comparing strategies which differ in their trade-off between returns and risk. Two useful tools are stochastic dominance and mean variance (E, V) analysis (Anderson et al. 1977).

Stochastic dominance is a means of comparing plots of cumulative distribution functions (CDF), which specify the cumulative probability (y-axis) of obtaining less than a specified outcome (x-axis) (Fig. 2a). First-degree stochastic dominance (FSD) assumes that a decision-maker will always prefer more to less economic return, and occurs when a dominant CDF (e.g. curve G) is never less than another CDF (e.g. curve F) at any probability level. Second-degree stochastic dominance (SSD) further assumes that the decision-maker is risk-averse. When two CDFs cross over (e.g. curves G and H), SSD occurs when the area between two CDFs at the low probability levels is greater than the area between the CDFs at the high probability levels (Fig. 2a). A third approach is stochastic dominance with respect to a function (Meyer 1977), which has much greater discriminating ability than FSD or SSD but requires knowledge of the degree of risk-aversion of decision-makers. When comparing a number of strategies, stochastic dominance does not necessarily select one dominant strategy, but more probably identifies a set of risk-efficient strategies. Risk-inefficient strategies can be discarded as being inferior options due to the existence of alternative strategies with higher probabilities of return.

In (E, V) analysis, the assumption is that risk can be equated with variance. Risk-efficient strategies within an (E, V) analysis dominate others by having either higher mean economic return or lower variance (or standard deviation in (E,s) analysis) of return. A subset of risk-efficient strategies can be delineated by plotting mean against standard deviation of return for a number of strategies to create a mean-standard deviation (E,s) space (Fig. 2b). A convex 'efficiency frontier' is defined by fitting a curve through points with the highest mean at each given standard deviation. Strategies which fall below this efficiency frontier are regarded as inefficient, i.e. alternative practices exist which produce greater returns at lower or equivalent levels of variability. Resource combinations falling on the frontier are equally risk-efficient and choice between them depends on attitude to risk. A decision-maker can trade-off a high return/high risk strategy for a strategy with lower returns and lower risk. A derivative of (E, V) analysis is a mean-negative deviation space (Parton 1992), where mean return is plotted against a probability weighted sum of deviations below a target return; the target is set to a value

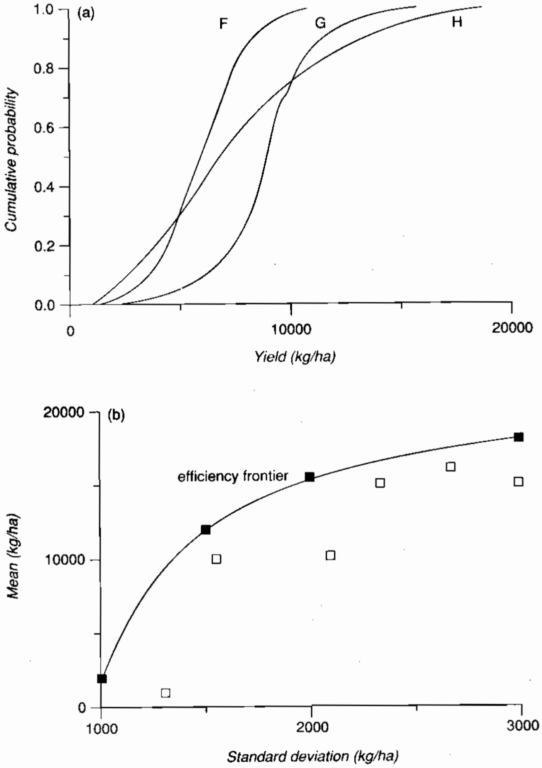

Figure 2. (a) Cumulative distribution functions of obtaining less than a nominated yield showing first degree stochastic dominance of curve G over curve F and second degree stochastic dominance of curve G over curve H; comparison of curves F and H requires knowledge of the risk preference of decision-makers.

(b) A mean-standard deviation (E,s) space showing risk-efficient (■) and risk-inefficient strategies (□) and the efficiency frontier.

below which a farm business will not survive. Mean-negative deviation space better accounts for a safety-first approach to the return/risk trade-off that decision-makers face.

An example application

Is cropping profitable in semi-arid northern Australia?

In the semi-arid tropics of northern Australia, there has been limited commercial dryland crop production. Despite past experiences being generally unprofitable and short-lived, there continues to be sporadic investment into cropping, encouraged by the favourable reports of the soil and climate resources of the region (Weston et al. 1981; Huda et al. 1990). The question of how representative were these commercial experiences is difficult to answer in a highly variable climate. In addressing this question, Carberry et al. (1991, 1993) used simulation models to predict crop yields for the long-term historical climate data of representative sites in order to estimate the economic prospects of rainfed cropping systems in this climatic zone.

From Carberry et al. (1991), dryland crop production for two potential cropping regions in this climatic zone can be compared. By simulating maize yields for the historical climate record and by calculating GM returns and plotting the mean against their standard deviation of return, *(E,s)* space was used to examine the tradeoff between expected returns and the riskiness of different levels of resource management for two representative sites (Fig. 3). At the site in north Queensland (NQ), few risk-efficient strategies produced returns higher than the break-even return (taken as an estimate of fixed costs) and their selection involved a high level of risk. In contrast, at the site in the Northern Territory (NT), only the lowest input strategies were risk-efficient and no strategy, on average, produced profitable returns.

On-going research over a decade in the NT has suggested that the prospects for dryland cropping can be improved by implementing a legume ley farming system (McCown et al. 1985, 1993). In such a system, several years of a legume ley pasture provide valuable forage for cattle grazing as well as reducing the costs of production through the supply of mineral nitrogen to a subsequent cereal crop. During the cropping phase, the legume pasture is allowed to form an understorey intercrop with the cereal in order to set seed from which the pasture ley can be re-established. The question here is whether the enhanced soil nitrogen status after the legume ley increases the profitability of cereal cropping, given the likely reductions in cereal yield due to competition from the legume intercrop. By developing a model of this proposed system (Carberry et al. 1992, 1993), simulation analyses were able to demonstrate that the probability of achieving high maize yields from cropping after a ley pasture increased over conventional cropping but so did the probability of achieving low yield due to competition in the water-limiting seasons (Fig. 4). At the world export price for maize, neither system resulted in profitable returns for the maize crop in any season (Fig. 5). However, when the value of the intercropped legume pasture as hay was considered, maize/pasture production during the wet season was stochastically dominant (FSD) over conventional maize production and resulted in returns greater than the break-even cutoff in 40% of seasons. Profitability increased markedly at the NT import parity price for maize although failures still occurred in about one in 10 seasons (Fig. 6).

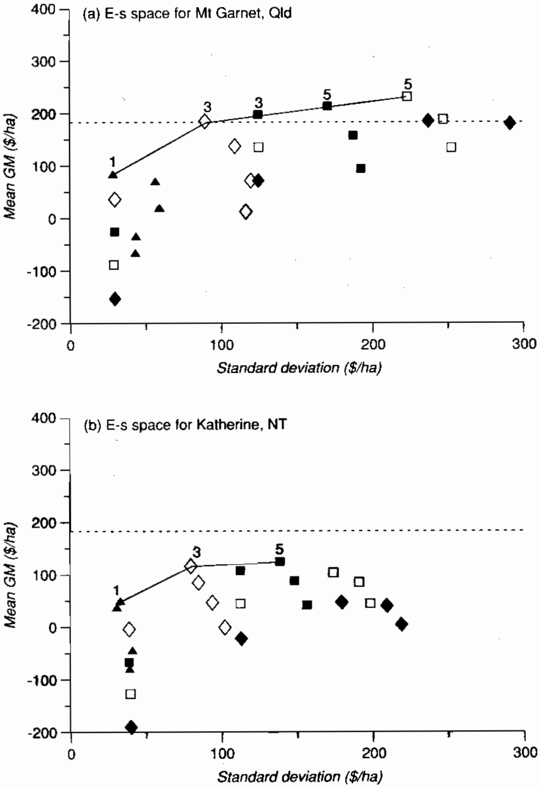

Figure 3. *(E,s)* spaces for maize at (a) Mt Garnet, Qld; and (b) Katherine, NT. Symbols refer to rates of nitrogen fertiliser applied - 0( ) 40(◇) 80(■) 120(□) 160(◆) kg/ha numbers on the efficiency frontier (———) refer to plant populations/m², and the estimated level of fixed costs (- - - - -) is shown.

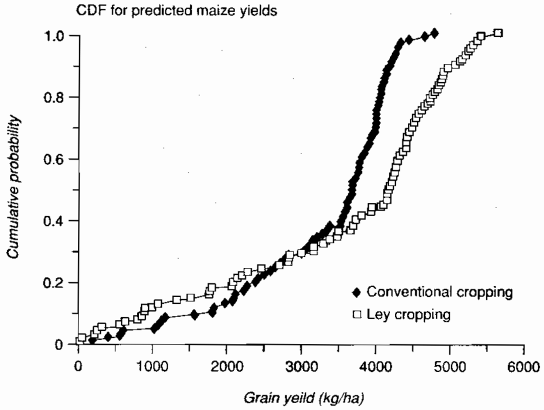

Figure 4. CDFs for predicted grain yields for maize grown at Katherine, NT, as a conventional crop (♦) or in an intercrop following a legume ley (❑).

The analyses of Carberry et al. (1991, 1993) confirmed that profitability is marginal and cropping is very risky for dryland maize production at these sites in northern Australia. Similar conclusions were reached for other sites and when alternative crops to maize (sorghum, peanuts) were used in the simulation analyses (Carberry et al. 1991). Adoption of an integrated crop/pasture system in the NT did improve GM returns but, at world grain prices, not to a sufficient level to encourage cropping investment. However, returns from the current cropping of small areas to supply the local NT grain market have been sufficient to support a viable industry.

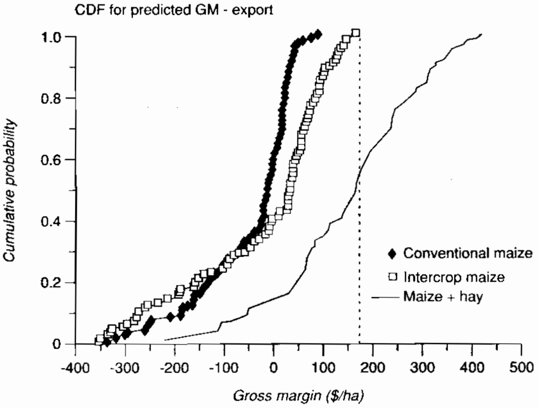

Figure 5. Using the world export price for maize, CDFs for predicted gross margins for sole maize grown as a conventional crop (♦), for the maize component of the intercrop (❑), and for the combined maize and legume hay components of an intercrop following a legume ley (—).

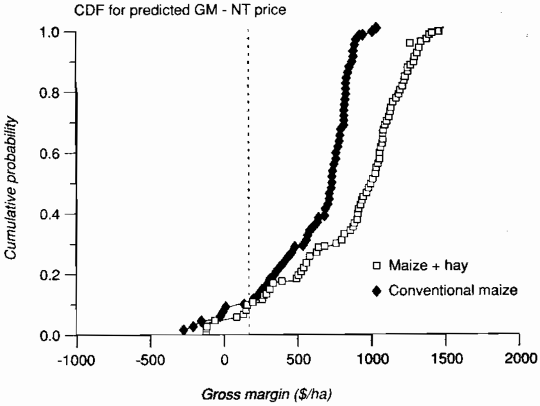

Figure 6. Using the NT import parity price for maize, CDFs for predicted gross margins for sole maize grown as a conventional crop (♦) and for the combined maize and legume hay components of an intercrop following a legume ley (□).

As a result of the operational research undertaken in northern Australia, decisions on new investment in cropping, on the farming system currently practised and on the resources placed in agricultural research in the region have been significantly influenced. In fact, clear demonstration of the poor profitability over the longer term of cropping in semi-arid northern Australia was a major contributor to the decision to transfer research capability from the region into the subtropics as part of the formation of APSRU.

Decision support systems

The argument for models to be put to use is well justified, but exactly how is another matter. Hamilton et al. (1991) put the case for information generated by models to be incorporated into computerised Decision Support Systems (DSS) to assist clients in their decision-making. Although relatively few Australian farmers use computers to assist their farm management, Hamilton et al. (1991) argued that DSS have not been oversold, but just underdeveloped. They suggested that, for new DSS products to become more widely accepted, they must be better designed. While Cox (1993) agrees that much of the blame for the non-adoption of DSS lies with the absence of any accepted design criteria, he goes further in his criticism and points to the lack of analysis of the value of alternative approaches to decision support, particularly a comparison against much simpler practical measures. The suggestion is that computerised DSS may not be an appropriate medium for information transfer at the farm level. If this is, in fact, the case, one of the principle conduits in making models more relevant to agriculture disappears. Certainly, computerised DSS continue to be refined and developed in Australia (Woodruff 1992), and their acceptance by farmers will be assessed with great interest.

Conclusions

The recent development of APSIM has extended the capabilities for simulating agricultural systems far past what was available in 1990. Now, APSIM provides the ability to simulate a range of cropping systems in a user-oriented environment using well-developed software. Efforts elsewhere in the world have likewise been moving in similar directions (Jones 1993). The challenge now is to use our modelling capability in meaningful ways.

In these Proceedings, McCown and Cox explore ways in which the recent developments in system modelling, as discussed in this paper, can be applied in research on farming systems both in Australia and Africa.

Acknowledgments

The development of APSIM, as reported in this paper, is a result of a team effort by all members of APSRU. I thank Bob McCown for the useful comments concerning the manuscript.

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Linkages between Australia and Africa in Agricultural Research for the Semi-arid Tropics

R K Jones*

Abstract

African countries with semi-arid lands in the tropics and sub-tropics have much in common with Australia. The common problems are climatic variability, infertile soils, extensive soil erosion, poor quality forage, poorly educated farmers, transport and communication difficulties, and marginal profitability. These problems are set against a background of broadly similar climates and soils.

The various phases of two research programs—one in northern Australia based mainly in Katherine in the Northern Territory, and the other in Kenya in the Machakos and Kitui Districts—are described. Both moved progressively over a 10–15 year period from a more empirical exploration of options and technology development phase, through an understanding and model-building phase, to a phase of integration and extrapolation in space and time using the modelling tools developed in phase 2.

The common problems can be aggregated into three larger issues: those concerned with climatic variability, with complexity, and with extrapolation and efficient use of scarce R&D resources. Crop and farming system modelling in a farming systems research context are seen as the way of dealing with these issues.

MOST of the Australian scientists involved in this workshop have had a strong interest in the semi-arid tropics of sub-Saharan Africa for the last 10 to 20 years. While the principal countries with which they have had in-country involvement are closer to the equator than SADC countries, namely Kenya, Ethiopia, and Nigeria, they have also been very interested in the progress of R&D in the SADC countries and are anxious to learn more about it.

The involvement and interest results from recognition of the similarity of the problems and of the scientific principles behind these problems in the two regions. Research in the African semi-arid tropics (e.g. in West Africa, Jones and Wild 1975) is relevant to tropical and subtropical Australia, and the researchers firmly believe that the reverse is also true, despite the contrasting socioeconomic environments. Figure 1 shows Australia, superimposed at the appropriate scale and latitude, on a map of Africa. The broad latitudinal similarities between Australia and parts of tropical and sub-tropical Africa are obvious, both to the north and the south of the Equator.

As a broad generalisation, many of the following problems are shared (Fig. 2).

- Climates are highly variable. Rainfall and, at times, temperatures are unfavourable for vigorous and continuous plant growth even during the short growing seasons.
- Soils are often infertile and suffer from widespread deficiencies of nitrogen and phosphorus and sometimes other major and trace nutrients.
- Soil erosion is widespread because rainfall intensity is high, and soils are often poorly-structured and hence highly erodible.
- Forage for grazing animals is generally of low quality, particularly during the long dry seasons.
- Farmers are often poorly educated and, in some regards, relatively unsophisticated.
- The areas are relatively remote from population centres, so transport and communication services are often poor.

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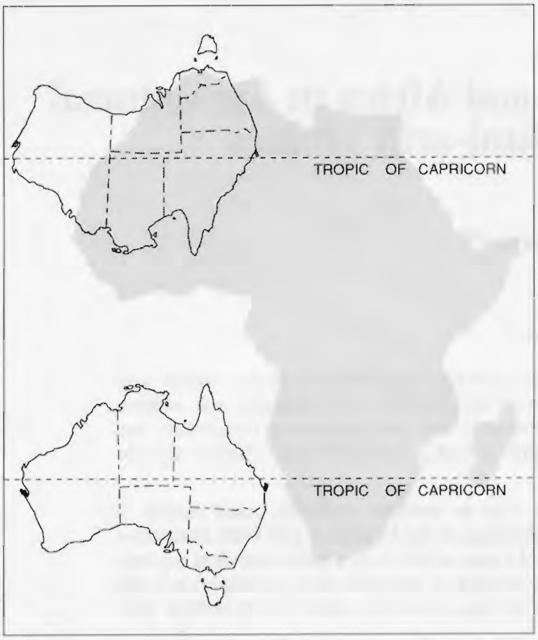

Figure 1. Maps of Australia, superimposed, at appropriate scale, orientation, and latitude, on a map of Africa.

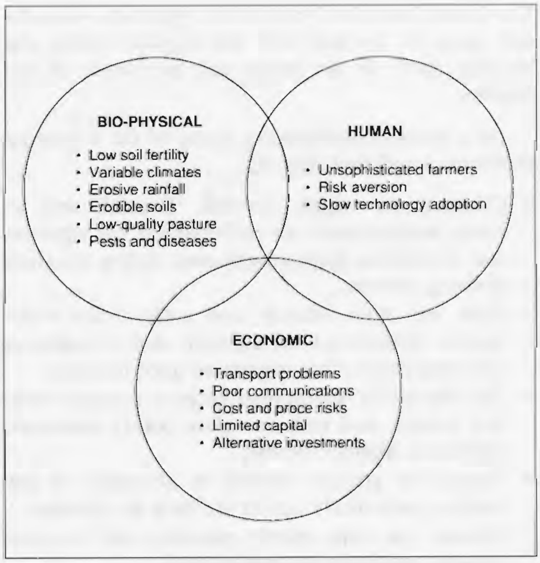

Figure 2. Biophysical, human, and economic problems common to the semi-arid tropics of Africa and northern Australia.

- Profitability of farming is marginal because of high production and price risks.

Australia has been actively involved in concurrent research programs in the semi-arid tropics of Eastern Kenya and Northern Australia over the 10-year period 1984–1993. The purpose of this paper is to describe the environments of the two regions in broad terms and to give an overview of the main thrusts of the two research programs. Three other papers in these Proceedings (Keating et al., McCown and Cox, Probert et al.) elaborate on the climatic and soil fertility aspects of the research. The final paper takes a broader perspective and looks at recent developments in Operations Research or Farming Systems Research in Australia and elsewhere.

The Australian Semi-arid Tropics

Australia has extensive areas of agricultural land in the semi-arid tropics and sub-tropics (Fig. 3). Parts of it are already used for broad-scale cropping and other areas have the potential for cropping (Fig. 4). There is an enormous range of soils in an area as large as this, but Vertisols and Alfisols are probably the most widespread. Climatically, there are strong similarities between parts of Africa and Australia. To take a Zimbabwean example, analyses of climatic similarities between four locations in Zimbabwe and climatic surfaces for Australia have been conducted by Booth (1989), an Australian forester, and are shown in Figure 5.

A considerable body of R&D for farming systems involving the integration of cropping and grazing in the Australian semi-arid tropics has been conducted at Katherine in the Northern Territory of Australia (Fig. 4); some has also been done in North Queensland and will be reported in the paper by Carberry (these Proceedings). A climate diagram for Katherine is presented in Figure 6a and shows the uni-modal rainfall concentrated over a 4-month period, high levels of radiation, and high maximum and minimum temperatures except during a short (3-month) 'winter'. This region of Australia is sparsely settled and is used predominantly for grazing cattle on large properties or cattle stations varying in size from 10 000 to 500 000 hectares. Agriculture here suffers many of the problems mentioned earlier of climatic variability, infertile soils, extensive soil erosion, poor quality forage, poorly educated farmers, transport and communication difficulties, and marginal profitability.

Research to develop a new type of integrated farming system based on legume leys was initiated in 1978 and has been described by McCown et al.

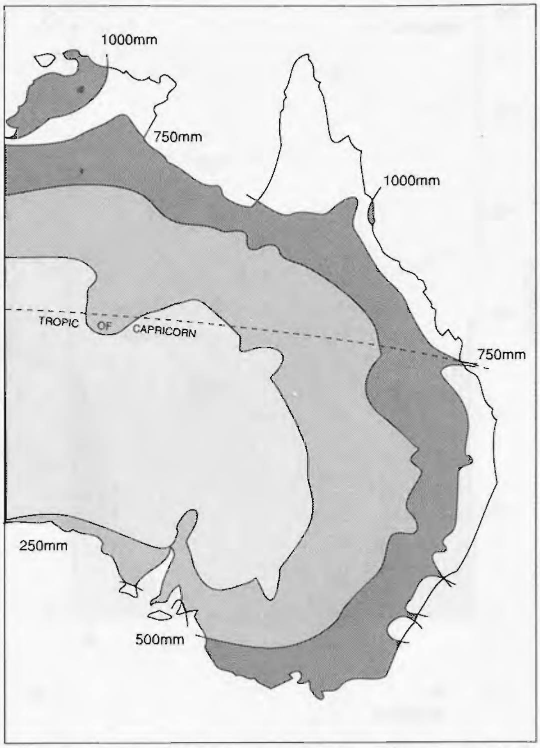

Figure 3. Map of isohyets for 'mean effective rainfall' (rainfall minus estimated runoff) for central and eastern Australia. (From Warner 1977).

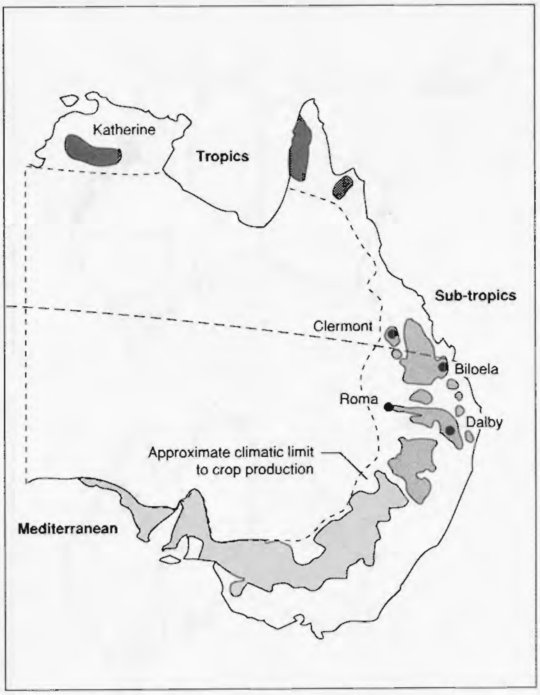

Figure 4. Land under crops in central and eastern Australia; areas in the tropics at low latitudes are not currently cropped extensively, but have potential for dryland cropping.

(1985). The main features of the Hypothetical Farming System researched were:

(i) self-regenerating legume ley pastures of 1–3 years duration are grown in rotation with maize or sorghum;

(ii) cattle graze native-grass pastures during the green season and leguminous pastures and crop residues in the dry season;

(iii) crops are planted directly into the pasture which is chemically killed at or shortly before planting; and

(iv) the legume sward which volunteers from hard seed after the pasture is killed is allowed to form an understorey (intercrop or live mulch) in the main crop.

The progress of this research since 1978 is shown in Figure 7. The first phase took a 'best-best' approach using various adapted legume species, but particularly *Stylosanthes hamata* cv Verano, and demonstrated that up to 60 kg of N could be provided to subsequent crops by a vigorous legume ley. The beneficial effects of a mulch of chemically-killed pasture material on soil temperatures, rates of drying, infiltration, and trafficability, and hence on establishment and yield of maize and sorghum were striking. This realisation necessitated a great deal of very successful R&D (particularly D) to optimise the weed control chemicals and application technology, and the zero-till planting machinery necessary for such a system to operate in a mechanised agricultural context. Towards the end of this phase, a pilot trial of the hypothetical Legume-Ley Farming System involving 2-year leys of pure legumes, one year of maize, and dry season grazing of pasture and crop residues was commenced in order to look for deficiencies in or problems of the system not apparent from the component research.

The second phase of the R&D program concentrated on understanding and quantifying the effects of ley legumes and mulch on the soil physical and chemical conditions which, in turn, influenced crop establishment and growth. It was realised that some sort of systems modelling framework was required in order to be able to address the problem of climatic

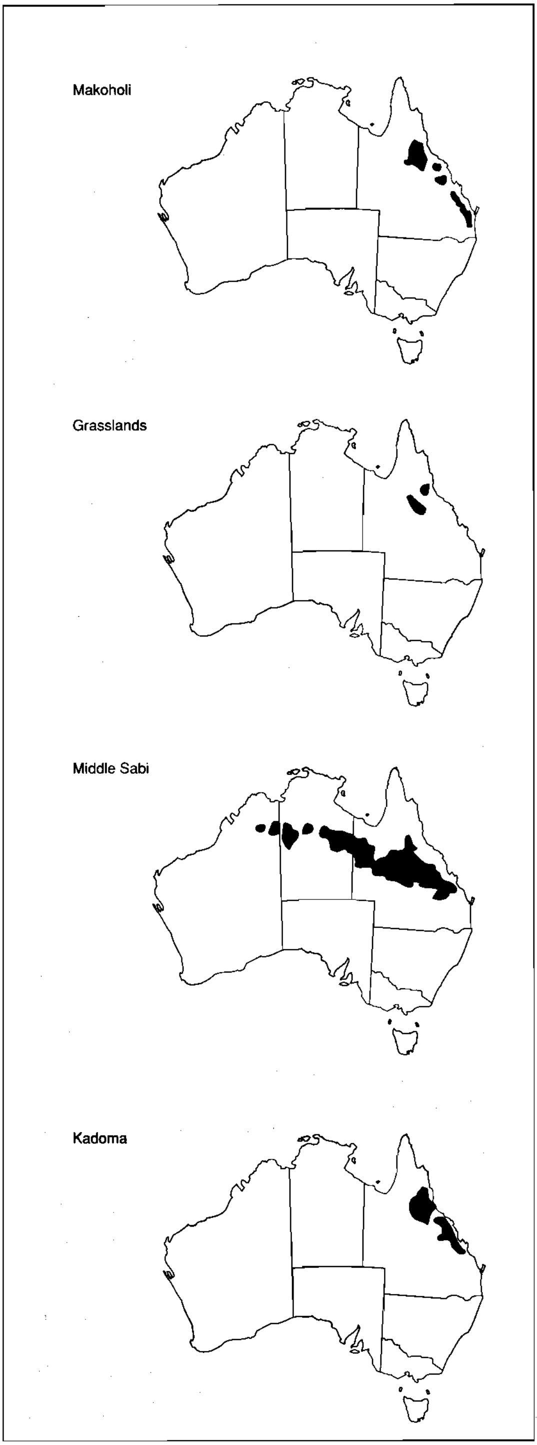

Figure 5. Areas within Australia most climatically similar to four sites in Zimbabwe. (From Booth 1989).

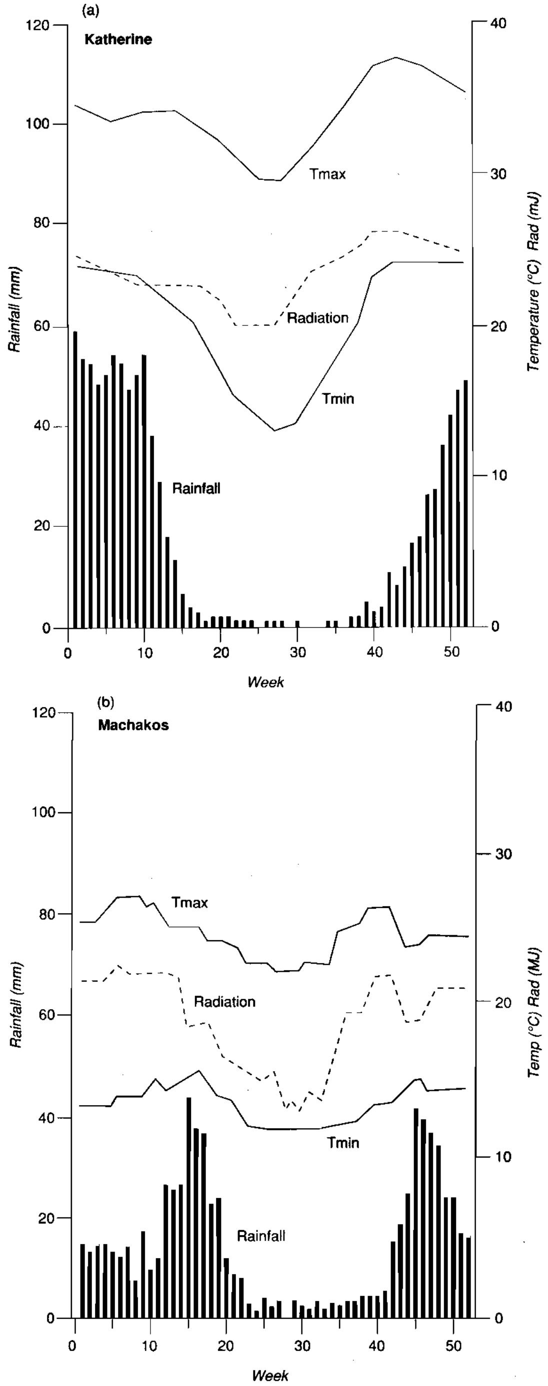

Figure 6. Mean weekly rainfall, solar radiation, and maximum and minimum temperatures at (a) Katherine, Northern Territory, Australia (lat. 14°S; elev. 120 m; annual rainfall 871 mm); and (b) Machakos, Kenya (lat. 1°N; elev. 1600; annual rainfall 890 mm).

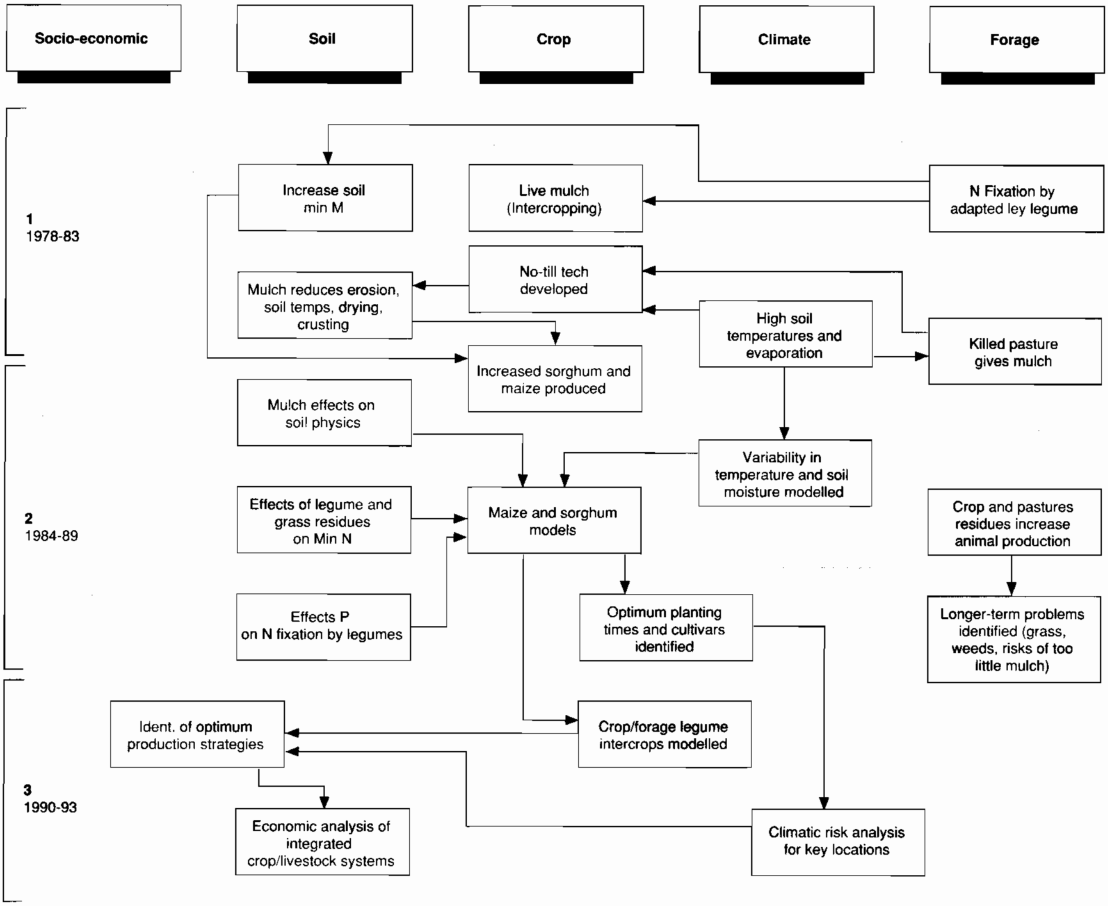

Figure 7. Schema of research activities, disciplines, and phases in the CSIRO project on cropping systems for the semi-arid tropics conducted at Katherine, NT. 1978–1993.

variability and to extrapolate the results to other soil types, locations, climatic conditions, and management combinations. Existing maize and sorghum crop models of the CERES family were therefore modified for use in the semi-arid tropics and further developed in order to store and make accessible the understanding acquired from the research both here and elsewhere in the world. This modelling activity was synchronous with that in the Kenyan semi-arid tropics research program and is described more fully by Keating and Carberry and their collaborators (these Proceedings).

During this phase, the pilot trial of the hypothetical system was concluded (McCown et al. 1986). It demonstrated that the system worked well. Excellent maize crops could be produced on biologically-fixed N alone, and animals on this system, at a high stocking rate of 0.3 ha/head during the 120-day dry season, then on native pasture at a low stocking rate of 15 ha/head during the remainder of the year, gained about 35 kg more live weight per annum than those on native pasture continuously. At turnoff, the 100 kg per head live-weight advantage represented a very significant improvement in animal productivity and financial return. The trial did, however, achieve its objective of acting as an 'early warning system' of problems in the hypothetical system as a whole. It encountered some management problems in relation to grass weeds and decision-making about when to remove the cattle from the ley pastures at the end of the dry season. However, the system is now used commercially on several thousand ha in the Northern Territory, with great success.

The third phase of the R&D program provided the opportunity to draw together all the threads of the earlier research and to use the by-now validated sorghum and maize models to examine various climatic and management scenarios from a probabilistic point of view. Thus Carberry and Abrecht (1991) simulated the effects of date of pasture kill (hence amount of surface mulch), sowing date, crop duration, and plant population of sorghum and maize at Katherine over the 100 years for which rainfall data was available. This enabled them to identify optimum production strategies for that environment. Similar work at a range of sites in north-east Queensland (Carberry, et al. 1991) incorporated economic data on variable and fixed costs and evaluated strategies on the probabilities of the gross margins rather than simply the grain yields.

Overall, it can be seen from Figure 7 that the Australian research in the semi-arid tropics moved steadily from a more empirical and technology development phase, through a phase of detailed understanding and modelling of the processes involved, to a final phase where the 'tools' developed (models) were used to extrapolate the production and economic risk analyses in space and time. The R&D at Katherine has now terminated but the more applied R&D by the Northern Territory authorities continues as commercial development, fuelled by a rapid expansion in the live cattle export trade.

The Kenyan Semi-arid Tropics

Like northern Australia, Kenya also has extensive areas of agricultural land in the semi-arid tropics, particularly in the Machakos and Kitui districts of the Eastern Province, where our collaborative project with the Kenya Agricultural Research Institute was conducted. Populations are expanding rapidly in these districts, as a result of a natural increase which is high on a world scale, together with migration from the overpopulated (higher potential) lands in the Highlands and the lands nearer Lake Victoria on Kenya's western border. This is putting excessive pressure on the productivity of these semi-arid lands under current management and inputs. Many farmers are in a downward spiral involving nutrient depletion, and soil erosion leading to reduced yields and ending in a 'poverty trap' from which it is difficult to escape.

Climatically, the area has no direct counterparts in Australia, because of the unusual bimodal rainfall regime (Fig. 6b). From a radiation and temperature point of view, however, there are strong similarities to locations on the Atherton Tableland of north Queensland. Despite differing rainfall regimes, all the problems mentioned earlier for northern Australia are evident in the Machakos and Kitui districts.

The joint ACIAR–CSIRO–KARI research project also had three recognisable phases (Fig. 8). In phase one, we studied the farming systems practised on a range of farms, evaluated about 150 pasture legume species for use as ley plants, and researched a number of agronomic issues on maize, namely planting time, water supply, nitrogen fertiliser, plant populations, and their interactions. A start was also made on testing and modifying the temperate maize model (CERES-Maize) as a framework for the results of the agronomic research.

The on-farm studies helped us understand the biophysical and economic problems faced by farmers in the region and set the scene for research in phase two. It became clear that farm yields were extremely low, even in favourable seasons (when they seem to be limited by nutrient deficiencies). Many farmers used farmyard (or *boma*) manure but the supply was inadequate for the areas of crop land involved. Very few used fertiliser of any sort. The pressure on land was so great that our earlier idea of using legumes in leys to restore nitrogen fertility in rotation systems now seemed inappropriate in many situations. Finally, it was clear that soil erosion was an important problem on the usually-terraced crop lands, but a massive problem on the grazing lands which were usually part of the average farm.

In phase two of the R&D program, the crop research concentrated on the validation and development of the maize model and its application to important agronomic and management problems faced by farmers. The results were able to be expressed as gross margins and, by running the model using climatic data from past seasons, estimates of the long-term probabilities of various management strategies were produced. This work is reported by Keating and co-workers (these Proceedings) and linked with the large body of research which had been conducted in this region in the previous 25 years. Soil fertility also received considerable emphasis during this phase and large responses to farmyard manure and to N and P fertiliser were documented and the problems and possibilities of each understood. This work is reported by Probert and colleagues (these Proceedings). In relation to the situation on the grazing lands, the adapted forage legume species found in phase one were an important component in a novel pitting system developed to rehabilitate and protect eroded these lands. Long-term research on runoff and soil loss on crop lands and its impact and interaction with plant population,

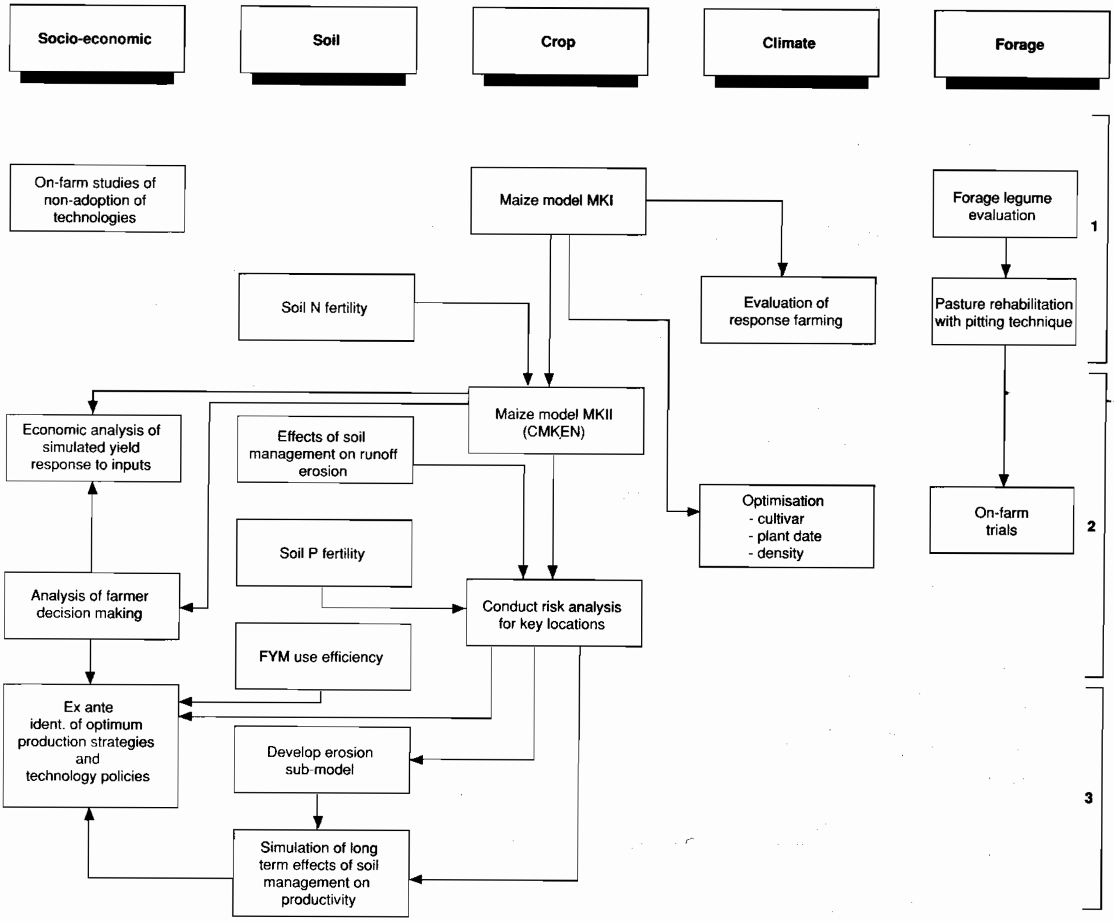

Figure 8. Schema of research activities, disciplines, and phases in the ACIAR–CSIRO–KARI collaborative research project on farming systems in the Machakos and Kitui Districts of Eastern Kenya.

surface mulch, and N fertiliser was also commenced at the National Dryland Farming Research Centre, Katumani, and is continuing in order to sample a wide range of rainfall/runoff situations. Finally, farmers' perceptions of, and attitudes towards, risk were studied to provide the understanding required for devising ways of getting the technologies required to raise productivity adopted by the farmers.

The third phase, as in the Australian work, allowed us to integrate the results of the research in both space and time. Thus risk analyses were done on the effects of various crop management options using climatic data from a large number of stations in the two districts. The understanding of the problems and the 'tools' developed during the project to address these problems allowed us to examine the long-term effects of a Fertiliser-augmented Soil Enrichment Strategy (FASE) devised to help farmers escape from the poverty trap.

Problems of R&D in Semi-arid Environments

The problems faced by farmers, agricultural R&D workers, and indeed National Agricultural Research Services (NARS) in semi-arid environments can be aggregated into a smaller number of classes of major problem. Two of these, climatic variability, and complexity — are particularly important in the semi-arid tropics, while the third, efficiency of use of the R&D resources, is a universal problem, regardless of climate.

Climatic variability

Agricultural R&D in semi-arid environments is faced with far greater problems than that in more equable climates of Europe or North America because of the much greater climatic variability. Thus, it is not possible in the semi-arid tropics to make advances in understanding the factors driving production or to develop sensible recommendations for farmers simply by repeating an experiment in a number of seasons and averaging the results. To illustrate this, Figure 9 shows the results of experiments conducted by Nadar (1984) in Kenya on the response of maize to N fertiliser in different seasons. The shape of the response curves varied enormously, from linear depressions in yield with increasing N rates to strong sigmoidal responses up to the highest rates. Virtually any shape of response curve seemed possible, and simply averaging the results would produce meaningless results.

We found that the shape of the response curve was very dependent on the seasonal rainfall experienced, so it is interesting to look at how the seven seasons sampled in the experiment compared with the larger sample of seasons available in the historic rainfall record for this location (Fig. 10). It appears from this larger sample that the years sampled by Nadar were towards the more favourable end of the spectrum of possible seasons. If he had conducted his experiments in a different set of set of seasons the results should have been quite different.

This example makes the point that agricultural R&D workers in semi-arid environments need a way of setting the results of their experimentation, done in a particular season and under particular management conditions, in a wider context so that the probabilities of occurrence of a particular outcome can be estimated.

Complexity

The second class of problem common in the semi-arid tropics is that of the complexity of the interactions between factors affecting agricultural productivity and profitability. The response curves of Nadar, for example, were obtained from experiments planted on a particular date and grown at a particular plant density. As Keating demonstrates (these Proceedings), they would have been of different shapes if these factors had also varied because of the fact that, in these semi-arid environments with their ubiquitous N deficiency, there is a complex water supply (rainfall less runoff) × plant population × time of planting × N supply interaction operating, and variation in any one of these factors can affect the outcome.

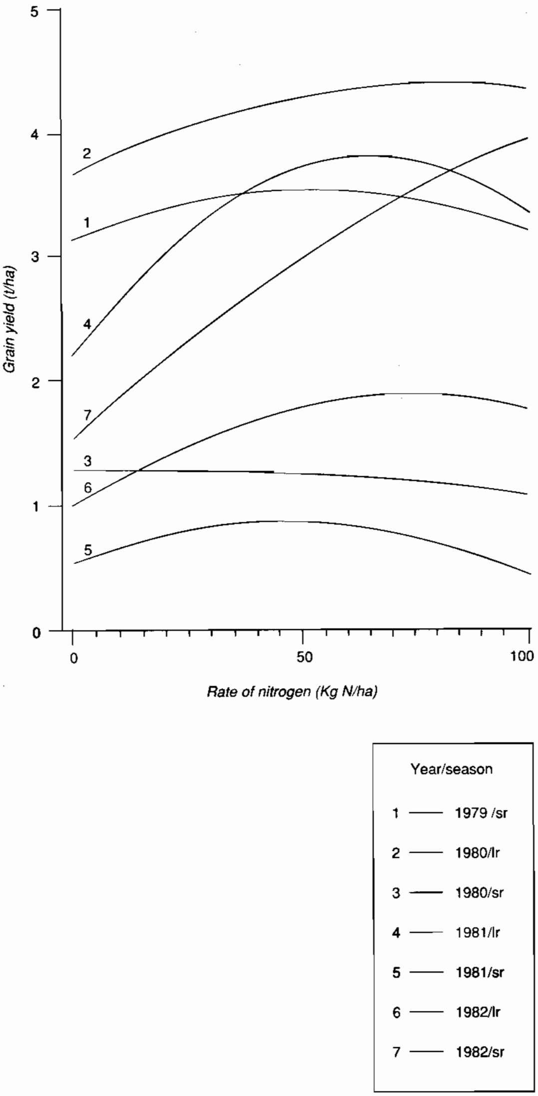

Figure 9. Response for maize grain yield to nitrogen fertiliser at Katumani (near Machakos, Kenya) 1979–1982 (after Nadar and Faught, 1984).

This complexity problem which plagues agricultural R&D in the semi-arid lands of both continents is too great for the human mind to comprehend and too great to be handled by the traditional experimentation approach. The human mind can handle two-factor interactions fairly easily. Three-factor interactions are much more difficult, but four-factor and above interactions are virtually impossible for it to comprehend. It is not possible to experiment with all the possible permutations and combinations of the factors known to be affecting production. Clearly, we have to find new ways of getting better value from the information we have from the combinations we are able to sample experimentally, and from our understanding of the biological processes involved.

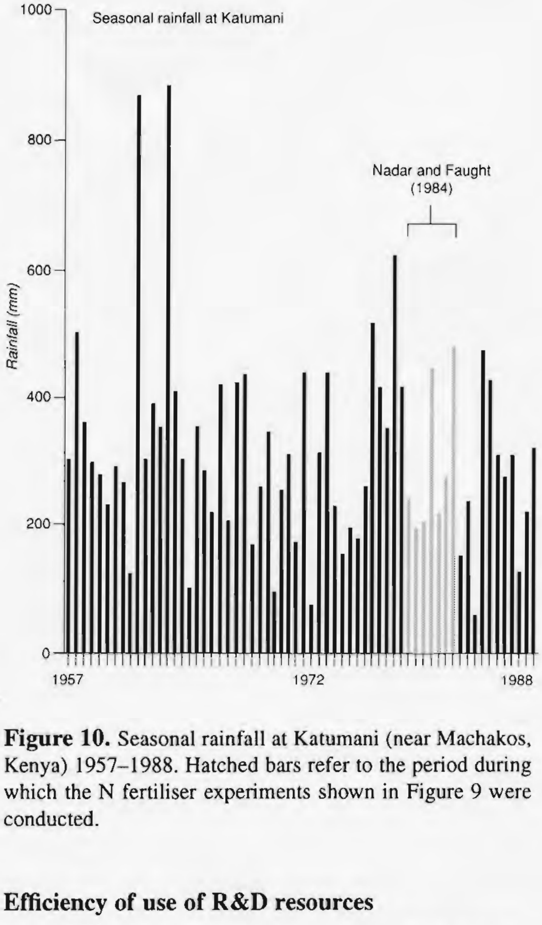

Figure 10. Seasonal rainfall at Katumani (near Machakos, Kenya) 1957–1988. Hatched bars refer to the period during which the N fertiliser experiments shown in Figure 9 were conducted.

Efficiency of use of R&D resources

The third class of problem requiring a common approach in our two continents is that of efficiency of use of the R&D dollar. The priority accorded to agricultural R&D versus other science and technology investments is steadily declining in Australia as it is in many parts of the developed world. While the priority for agricultural R&D might still be high in SADC countries, it would seem that the total resources available are often severely limited. We therefore have the responsibility of finding ways to make the R&D more effective and more efficient.

One aspect of this is to conduct fewer experiments but get more value from them by collecting more comprehensive information and ensuring that it is in a form which enables it to contribute to the further development and application of crop and cropping system models. Another aspect concerns the extrapolation of results of experiments conducted at one location on one soil type in one series of seasons to other locations, soil types, seasons, and economic circumstances. This is particularly relevant for expensive long-term experiments investigating the effects of rotations and management practices. Even in a relatively affluent country like Australia it is out of the question to have more than a few such experiments.

Other papers in these Proceedings (Carberry, Keating et al., McCown and Cox, Probert et al.) attempt to relate our experiences in wrestling with these three classes of problem in both Australia and Kenya, including some new approaches to the modelling of agricultural systems and its use to address real-world problems of farmers.

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Dealing with Climatic Risk in Agricultural Research—A Case Study Modelling Maize in Semi-arid Kenya

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Abstract

Rainfall variability is a dominant feature of crop production in semi-arid regions. Soil fertility is also a major constraint, and much of the research effort has been directed at agronomic or genetic factors that impact on either or both the supply and demand for water or nitrogen. This paper reports on the application of models to research aimed at improving maize productivity under the highly erratic rainfall regimes of semi-arid eastern Kenya. Steps undertaken to test and adapt the CERES-Maize model are described, and a revised version called CM-KEN is shown to provide a realistic description of the major issues of concern in maize production in the region, i.e. responses to plant population, planting time, location, nitrogen and water supply and the interactions between these factors.

The additional insight such a modelling approach provided in terms of the prospects for improving maize productivity in the region is examined. Current germplasm is shown to be well adapted to the limiting rainfall regimes of the region. The major gains in productivity are likely to come from improved management of soil fertility and soil surface management. Indications are that nitrogen fertilisers should have a place in more productive systems in the region.

Insights pertaining to the conduct of agronomic research in regions of high climatic risk are also examined. Between 10 and 20 seasons of fertiliser rate trials were shown to be necessary to identify an optimum N fertilisation rate with any degree of confidence (i.e. to reduce coefficients of variation of the optimum rate to 25 and 15% respectively). In contrast, application of a validated model to the historical weather data enabled 63 seasons to be 'sampled' and coefficients of variation of optimum N rate to be reduced to approximately 1%.

SEMI-ARID tropical regions dominate the agricultural production systems of Africa, India and northern Australia (Troll 1965). These regions are characterised by highly variable rainfall regimes in either or both the timing, amount, or within-season distribution (Monteith and Virmani 1991). Variability in other climatic factors such as temperatures and radiation is small and relatively unimportant in comparison with rainfall. One exception to this generalisation is the occurrence of high soil and air temperatures which can have significant impact on crop establishment and productivity for some crops in some regions (Herrero and Johnson 1980; McCown et al. 1985; Carberry and Abrecht 1991).

Coefficients of variation in total seasonal rainfall are in the order of 30–40% for locations with a single 'rainy' season (Jones, these Proceedings). Variability in seasonal rainfall is even larger in semi-arid regions of Kenya, which, because of their equatorial location receive two rainy seasons each year. At Katumani Research Station where much of the research reported in this paper was conducted, an average annual rainfall of 700 mm is split into two very short (approximately 3 months) and unreliable seasons averaging approximately 300 mm each (Keating et al. 1992). Coefficients of variation are in the 40 to 50% range for seasonal rainfall at Katumani.

Historically such bimodal rainfall regions have been better suited to pastoralism since the dry season is shorter than unimodal rainfall regimes. The two

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'dry seasons' in semi-arid eastern Kenya are, however, sufficiently pronounced that two very short-season crops have to be grown each year. Long-season pigeon pea is the exception to this, being sufficiently drought-tolerant and having a lifecycle that allows it to be grown across both rainy seasons and the intervening dry season (Nadar 1984b). In Kenya, these two seasons are referred to as the short rains (late October–December) and the long rains (April-June) but the relative extent and reliability of the two seasons varies from location to location. An examination of the rainfall record for the Katumani National Dryland Farming Research Centre in Machakos Kenya indicates the magnitude of the variability in seasonal rainfall (Fig. 1). It is obvious that mean seasonal rainfall provides little information on the nature of the rainfall regime that exists in such areas.

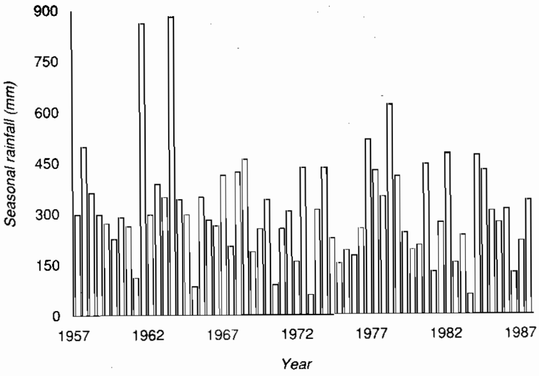

Figure 1. Seasonal rainfall at Katumani NDFRC, Machakos, Kenya. (Rainfall is accumulated over the period of growth of KCB maize as estimated by the CM-KEN Maize Model).

Agricultural research in areas such as this needs to confront the issue of climatic risk from both relevance and efficiency perspective. Firstly, there is a strong incentive for research to be relevant by identifying strategies that reduce the occurrence of low-yielding or failed crops associated with low rainfall years. Secondly, temporal variability in results from experimental work makes interpretation difficult and research time-consuming.

The KARI–ACIAR Dryland Farming Project sought strategies to raise maize productivity in the semi-arid lands of Machakos and Kitui Districts in eastern Kenya. The research work conducted within this project has been reported in detail elsewhere (Probert 1992). This paper reports on a modelling approach to make research more effective in addressing the constraints to agricultural production in regions of high climatic risk. It does this in terms of a case study involving research on production strategies for maize in semi-arid eastern Kenya. The paper aims to summarise this past research and reflect on the insights gained, in terms of both the likely impact of production strategies and technologies on the level and stability of maize production and, more generally, on effective approaches to research in semi-arid areas.

Maize Research in Semi-arid Kenya

There is a long history (approximately 40 years) of research into dryland farming practices in Kenya. The period from 1950 to 1985 was reviewed by Keating and co-workers (1992a). Issues such as planting times, plant populations, varietal selection, intercropping, fertiliser use, surface management, rotations and fallowing have all been examined and reported. The majority of these studies have sought to raise productivity by manipulating either or both the supplies of water and N and their demand by the crop.

Place for models

Models can be viewed as extended hypotheses put forward to describe the way in which a system will respond to various combinations of inputs. The crop production system, which was the focus in this case study, can be viewed as one which outputs crop and stover yields from soil and weather inputs. Genotypic characteristics and management decisions made by farmers modify system performance. Important non-linear interactions exist among genotypic, soil and management factors and in turn between these factors (singly and collectively) and weather. As discussed above, while radiation and temperature are important factors controlling crop growth and yield, it is interactions with rainfall that dominate the performance of semi-arid crop production systems.

Jones (these Proceedings) and Keating et al (1992) have argued that it is the complexity of these crop-soil-weather-management interactions and the variability associated with rainfall regimes in semi-arid regions that necessitates a modelling approach to the study of these systems.

Choosing an appropriate level of model

Models vary in scope and level of detail. Simple relationships between seasonal rainfall and crop yield have been in use for some time in Kenya (Glover 1957; Stewart and Faught 1984). These static models cannot capture the important interactions between rainfall distribution and crop development. Dynamic models, usually with a time-step of one day, are needed in water-limited environments where the pattern of rainfall is an important determinant of crop growth and yield.

The appropriate structure of a model also varies with the objectives for its use. Semi-arid eastern Kenya required a model that would predict maize yield in relation to the major soil and environmental factors and management options relevant to the region. This meant in particular that the model had to be able to simulate the demand by the crop for water and N, as influenced by management factors such as planting time, plant population, genotype characteristics. In addition the model needed to simulate the supply of water and N from the soil, in relation to weather, soil properties and management factors such as past cropping history and fertiliser application.

Developing a modelling capability

When this work commenced in 1985, the CERES-Maize model (Jones and Kiniry 1986) was the only model available that could deal with maize growth and development on a daily basis in relation to both water and nitrogen supply. A major international effort involving many tens of man-years of work had gone into the development of this model. Our strategy was thoroughly to evaluate this model in our region of interest, and where appropriate, make changes to model coefficients or structure to improve its predictive capability for the maize genotypes and environments of semi-arid Kenya. We started with version one of CERES-Maize, prior to its formal publication and release. Subsequent changes to the CERES crop, water and nitrogen models were either pre-empted or made after these versions were released.

CERES-Maize had been most strongly influenced by experimental data coming out of the better maize-growing environments of north America, and the major changes made related to the unique features of maize production in a low-input, semi-arid environment. These changes included addition of routines to simulate crop death and altered phenology under water and nitrogen stress and the modification of routines dealing with grain number estimation, leaf area development (Keating and Wafula 1992) and mineral nitrogen dynamics over fallow periods ('Birch' effect). Further details of these modifications are given in Keating et al. (1992a). A large number of operational enhancements were also made. These included a visual and interactive interface (Hargreaves and McCown 1988) and what is referred to as the 'response farming' routines. These latter routines enable rules to be established to effect planting, fertilisation and thinning in response to the timing and quantities of rainfall received. Such routines were essential for realistic analysis of maize production strategies utilising historical rainfall records. The modified model is referred to as CM-KEN (Ceres Maize in Kenya) to register the fact that it is different to the original CERES-Maize.

Model Performance

All data sets The model validation data set contained information from 159 crop/treatment combinations, with yields ranging 0–8000 kg/ha in response to variation in sowing date, water, nitrogen, plant population and climatic conditions. Full details of the model evaluation are given in Keating et al (1992b). The line of best fit between predicted and observed grain yield was close to the 1:1 line (slope (s.e.) = 0.94 (0.03) and intercept (s.e.) = 249 (103)) and coefficient of determination (r2) was 0.88, with a root mean squared deviation (RMSD) of 689 kg/ha.

Water × plant population interaction The model is capable of simulating the response of maize yield to plant population, under both favourable and limiting water regimes. The experimental data (Fig. 2a) show that when water was freely available (441 mm over the season), yields of the KCB cultivar increased from approximately 1500 to 7000 kg/ha as plant population was raised from 0.88 to 8.88 plants/m^2. When water was limiting (303 mm over the season), yields peaked at approximately 2800 kg/ha and declined as plant populations were raised above 3.7 plants m^2. This strong water × plant population interaction was accurately simulated (RMSD = 549 kg/ha) by CM-KEN for both the KCB (Fig. 2a) and DLC (not shown) cultivars.

Nitrogen × plant population interaction The model is also structured in such a way that the interaction between plant population and nitrogen supply can be simulated. Grain yields increased in response to increased plant population in the presence of adequate nitrogen. Yields reached a plateau or declined as plant population was increased in the presence of a nitrogen constraint (Fig. 2b). While the absolute precision of the predicted grain yields was not always as good, the model was clearly capable of predicting the general nature of the plant population by nitrogen supply interaction (RMSD = 582 kg/ha).

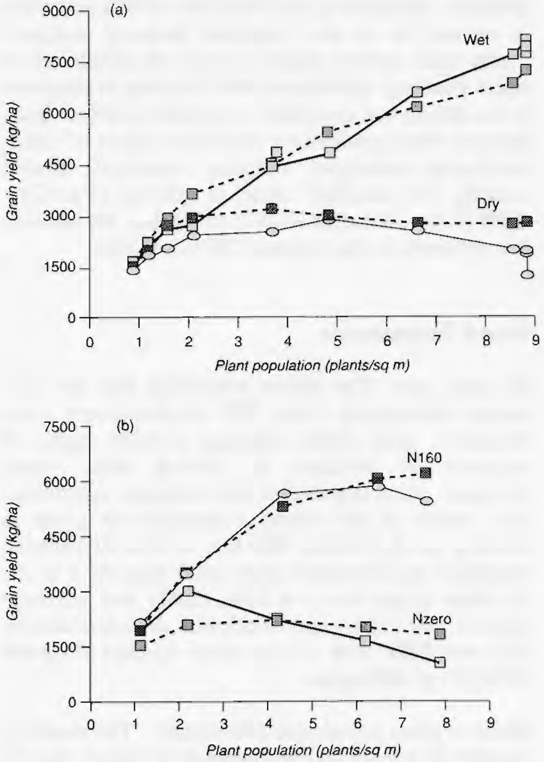

Figure 2. Observed (broken lines) and simulated (solid lines) yields of the KCB cultivar showing the interaction between plant population and (a) water regime and (b) nitrogen supply.

What New Insights for Farming in Semi-arid Eastern Kenya?

The availability of a model that dealt with the important genotypic, soil, management and environmental factors influencing maize growth meant that we could explore options for improving maize productivity without being constrained by the climatic variability that has plagued such studies in the past.

Plant populations, planting dates, genotype adaptation, losses due to runoff, nitrogen fertiliser management and tactical responses to weather patterns were all studied with the model over the historical rainfall record for Katumani (63 seasons from 1957). Analysis of the impact of single factors and the interaction between factors were conducted. Results of this work have been reported variously by Keating et al. (1991), Keating et al. (1992b), Keating et al. (1993), Wafula et al. (1992) and McCown and Keating (1992). The key findings can be summarised as follows.

- Currently available germplasm is well adapted to the rainfall patterns of the region. Gains from further selection for earlier flowering are likely only at the driest maize growing locations in the district (e.g. Agroecological Zone (AEZ) LM5) and even there, are likely to be small.
- The work confirms the widespread belief that planting as soon as possible at the start of the rainy season is desirable.
- Current plant population recommendations are generally appropriate (37 000 plants/ha = 3.7 plants/m^2) for the better maize growing locations in the districts (e.g. AEZ UM4). On shallow light-textured soils and in the drier zones (e.g. AEZ LM5), risks will be reduced with lower plant populations (1 to 2 plants/m^2).
- Productivity is very sensitive to losses of rainfall via runoff. Hence there are large benefits in crop yield available if practical methods of reducing runoff can be found. Such methods e.g. mulches must reduce runoff between the terrace banks which are a common feature on existing crop land.
- Nitrogen supply interacts strongly with plant population and lower plant populations (1 to 2 plants/m^2) reduce the risks in circumstances where N is likely to be strongly limiting.
- Some means of raising or maintaining soil fertility is a prerequisite to improving the productivity of these systems. Use of N fertilisers appears to be an economic proposition, although one that is not without significant risks.
- A nitrogen fertilisation and thinning strategy, conditional on the timing and extent of early season rainfall (i.e. 'Response Farming', Stewart and Faught 1984), does have a valid foundation in terms of the weather patterns and crop responses. The strategy has little impact on overall productivity compared to fixed strategies with similar levels of inputs, but does significantly reduce the risks of investing in fertilisers in seasons where no response will be obtained (Wafula et al. 1992).

From all these analyses together a picture emerges as to the current state of productivity in the region and the potential productivity if soil fertility is attended to and the most efficient use is made of the rain that does fall. This picture or more correctly, hypothesis, was presented by McCown and Keating (1992) as a four-step 'development pathway' (Table 1, Fig. 3).

Average maize yield (at Katumani over 1957–88) is predicted to increase from 970 kg/ha to 2740 kg/ha as inputs and associated management practices change from step 1 to step 4 (Fig. 3).

Table 1. Management inputs and parameters of the soil water balance for the simulation of four possible steps towards enhanced productivity (see Figure 4).

Step	Fertiliser N (kg/ha)	Plant population (m^2)	Soil organic matter % (0-15cm)	Runoff curve no.	Mean seasonal runoff (mm)	Soil evap. coefficient (mm)
1	0	1.6	0.9	80	62	9
2	10	2.2	1.0	70	40	7
3	20	3.3	1.1	60	23	5
4	40	4.4	1.2	50	12	4

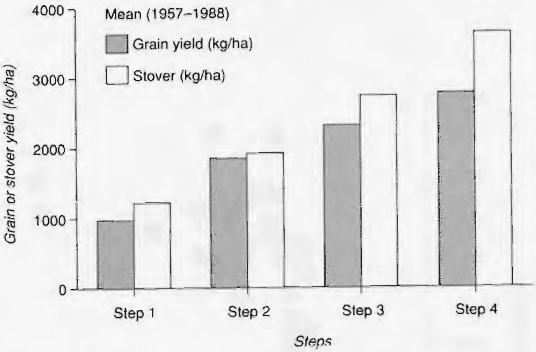

Figure 3. Mean maize yields simulated for Katumani weather over the 1957–88 period with increasing levels of inputs (details given in Table 1).

Step 1 is a scenario that approximates the present system. Maize is grown at low plant populations without fertiliser nitrogen and with high runoff losses in the absence of the return of crop residues. The mean grain yield simulated (970 kg/ha) is on the upper side of the average reported for the region (700 to 900 kg/ha, Jaetzold and Schmidt 1983) but in our case, we have not considered losses due to poor management such as delayed planting, weeds or pests.

Step 2 involves small inputs of nitrogen fertiliser (10 kg N/ha), some increase in plant population and return of the 'additional' stover produced (i.e. over and above Step 1) to the soil surface.

Step 3 involves further increases in nitrogen fertiliser (20 kg N/ha), plant population and return of stover.

Step 4, with optimal N fertilisation (40 kg N/ha) and plant population (4.4 plants/m^2) and with little runoff, is a scenario that approaches the production potential for this environment with excellent management (2740 kg grain/ha).

What New Insights for Research in Semi-arid Climates?

As a 10-year chapter of Australian and Kenyan interaction on dryland farming research draws to a close, it is appropriate to reflect on what insights the interaction has provided on the nature of agricultural research for semi-arid regions.

Addressing climatic risk — average effects

The overwhelming message for research planning and implementation from this study is that it is essential that some means of assessing the impact of climatic risk be incorporated into the research program. The model, when combined with the historical rainfall record, highlights the inadequacy of reaching conclusions from experiments conducted over short duration in semi-arid climates.

We have attempted to quantify this power of temporal extrapolation in an analysis of variability over time for response to N fertiliser. The analysis draws on the simulations reported in full by Keating et al. (1991). Briefly, the study involved KCB maize being simulated at Katumani at N rates between 0 and 160 kg N/ha over a period of 63 seasons from 1957 to 1988. Average yields and gross margins increased little beyond 40 kg N/ha (Fig. 4 a, b). Response to N fertiliser was highly variable (Fig. 4c) as has been shown experimentally in studies such as that reported by Nadar (1984a) (Jones these Proceedings). The majority of this variation can be related to seasonal rainfall amount (Fig. 4d), although the distribution of this rain in relation to crop development is also clearly important. From this analysis, optimum N rates, expressed in terms of gross margins, could be identified for each season (Fig. 5). These varied greatly over the duration of the rainfall record simulated.

If the temporal variability presented in Figure 4d is accepted as indicative of the extent of the variability in response to N fertiliser, an assessment can

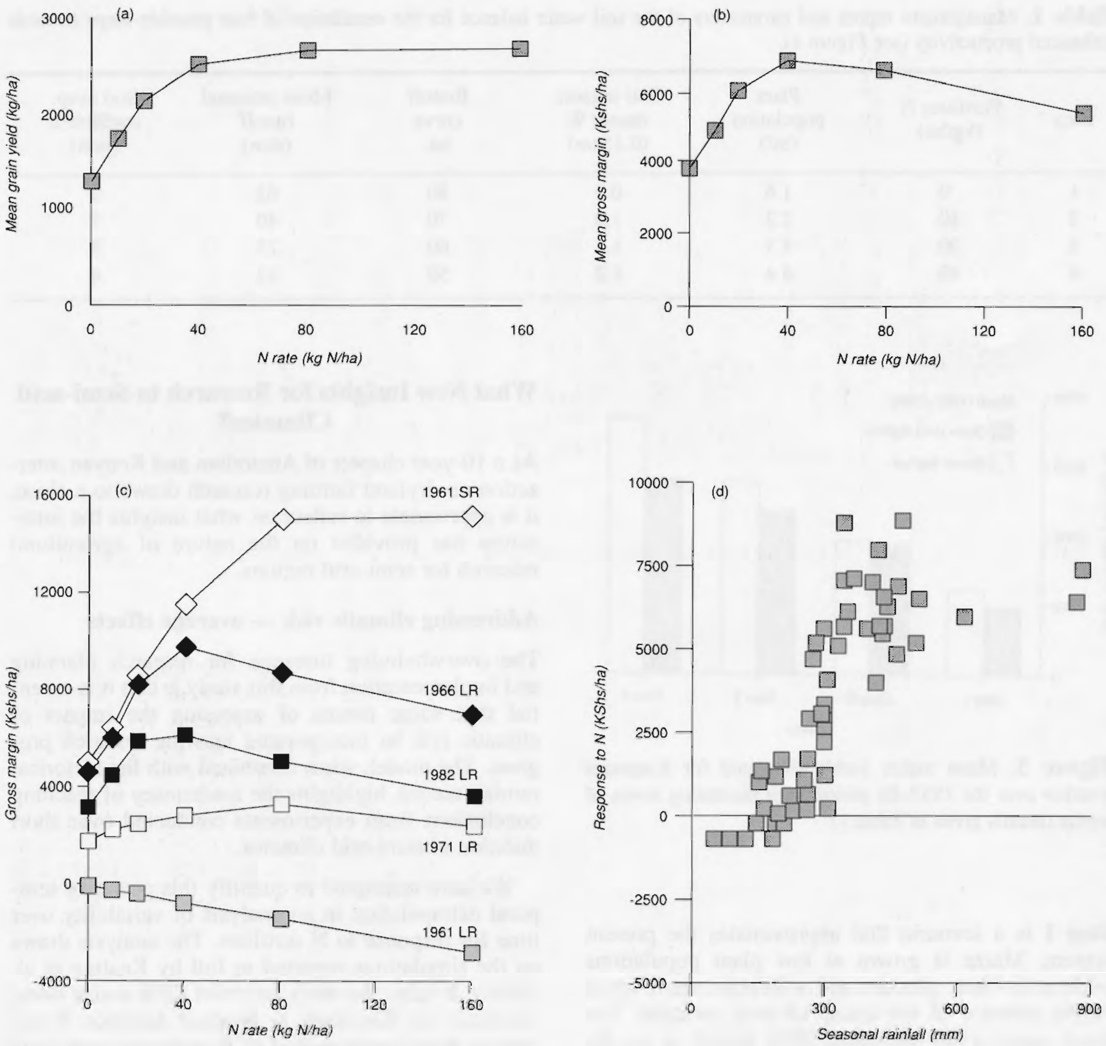

Figure 4. Effects of nitrogen fertiliser simulated at Katumani over the 1957 to 1988 period.
(a) Mean grain yield
(b) Mean gross margins
(c) Variation in response in gross margin for selected seasons (SR = short rains, LR = long rains)
(d) Relationship between additional gross margin resulting from the application of 40 kg N/ha and seasonal rainfall.

be made of the duration of experimentation needed to assess the expected returns from using N fertiliser in this environment. This has been done by sampling the population of optimum N rates depicted in Figure 5 and plotting the coefficient of variation in optimum N rate changes as a function of the number of seasons contained in each sample. Each sample was the mean of a number of seasons, ranging from 1 to 62 (sampled without replacement), and sampling was repeated 100 times. Coefficient of variation in optimum N rate decreased rapidly as the number of years sampled increased (Fig. 6). If a coefficient of variation of 15–25% was considered acceptable, and typical of much agricultural experimentation, this analysis reveals that 10–20 seasons of experimentation would be needed to identify an optimum N fertilisation rate with an acceptable degree of confidence.

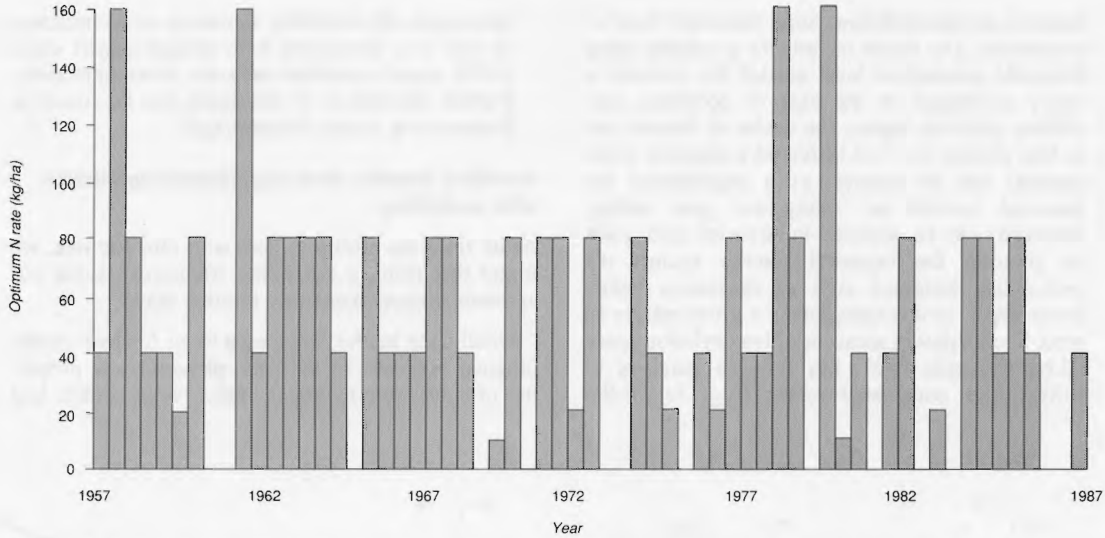

Figure 5. Optimum rate of N fertiliser (giving maximum gross margins) simulated at Katumani over 1957–88 period.

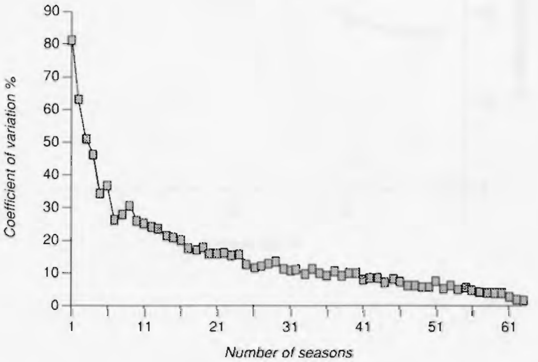

Figure 6. Reduction in coefficient of variation of optimum rate of N fertilisation with increasing number of seasons sampled. Seasonal variability in optimum N rate was derived from simulation of KCB maize at Katumani, 1957–88.

Addressing climatic risk—analysis of risks

This analysis has focused on the value of the model in assessing long-term average returns from a particular strategy. Equally important is the role the model plays in quantifying the risks associated with a particular practice.

Information on risk can be presented in a number of ways.

- The risk dimension of N fertiliser use is fully quantified in terms of cumulative distribution functions (Fig. 7a) which indicates the probability (*y* axis) of obtaining grain yields or gross margin less than the range (*x* axis) shown.
- One critical element of the complete risk profile shown in Figure 7a is the proportion of seasons when no positive returns are achieved from using nitrogen fertiliser. This was found to vary from 18 to 38% for the range of N rates shown in Figure 7b.
- If production is presented in terms of the long-term average gross margin (E), risk can be assessed in terms of the standard deviation of gross margin (SD) over the historical period simulated (Fig. 7c). Points to the upper left-hand side of such a figure maximise returns with minimum variability (or risk). A 2:1 rule of thumb has been suggested (Ryan 1984) as a first approximation to the attitudes of farmers on smallholdings to incurring added risk in conjunction with increased gross margin, i.e. such farmers would not be averse to using inputs or technologies provided they did not increase the standard deviation of the gross margin more than twice the increase in mean gross margin.
- Variability as measured by standard deviation can be a poor measure of the risks considered most important by farmers. In Figure 7d, standard deviation is replaced as a measure of risk by the

negative deviation below some threshold level of production. The desire of farmers to achieve some threshold production level needed for survival is easily envisaged. In the case of decisions concerning fertiliser inputs, the desire of farmers not to lose money (i.e. not to record a negative gross margin) can be viewed as a requirement for financial survival or 'safety-first' goal setting. Strategies can be assessed in terms of such goals by plotting the expected returns against the probability weighted sum of deviations below some target, in this case, below a gross margin of zero. Such a plot in mean-negative deviation space (E-ND) (Parton 1992) has obvious parallels to E-SD space considered earlier (Fig. 7c). E-SD space uses all variability in returns as an indicator of risk (i.e. deviations both up and down) while E-ND space considers only the down-side risks. Further discussion of this topic can be found in Probert et al. (these Proceedings).

Ancillary benefits from experimentation linked with modelling

Aside from the ability to deal with climatic risk, we found that using a modelling framework aided our agronomic experimentation in other ways.

Firstly, the model provided a focus for crop physiological research. In the past, physiological properties of crops were recorded, such as leaf number, leaf

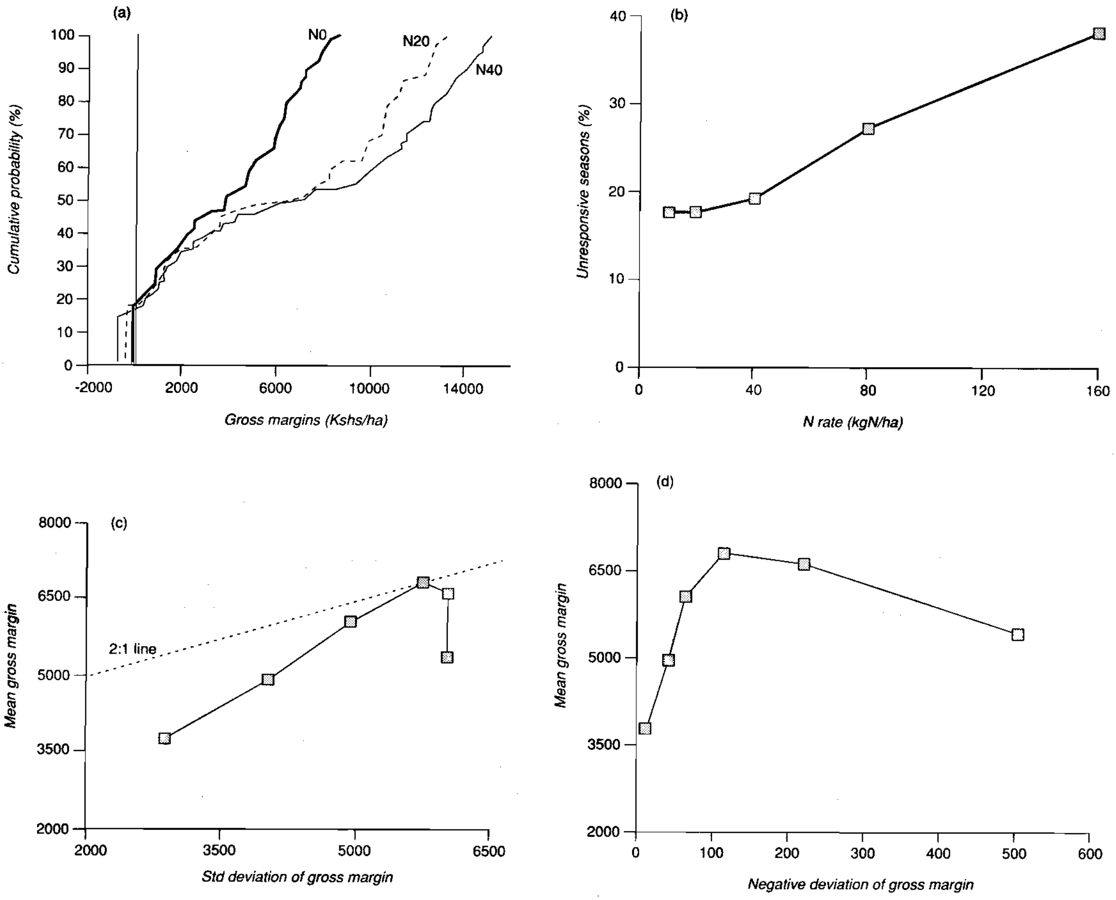

Figure 7. Measures of risk associated with nitrogen fertiliser usage.
(a) Cumulative distribution functions for a range of N rates (b) Proportion of seasons when responses are not achieved (c) Mean returns versus standard deviation of returns for a range of N rates as indicated in Figure 7(b)
(d) Mean returns versus probability weighted sum of negative gross margin for a range of N rates as indicated in Figure 7(b).

area, phenology and grain number, but researchers had little means to put such time-consuming measurements to use. Within a modelling context, such measurements serve the essential purpose of validating the accuracy of model components.

Secondly, the modelling approach promoted integration of the components of the agronomic research program. Agronomy research had been structured into components such as 'plant populations', 'fertilisers', 'intercropping' and 'agroclimatology'. There were also divisions between research station-based programs and on-farm programs. For the modelling studies, we quickly found ourselves doing experiments, both on-station and on-farm, examining the interactions between plant population, nitrogen fertiliser and weather, as influenced by planting date and water supply. Such experiments cut across the established divisions within the agronomic research program and thus promoted the need for a 'systems' view of agronomic strategies.

Thirdly, the desire to model experiments highlights the need for quality weather data and relevant soil properties. These forms of data tend to be not well recorded in agronomic research anywhere, be it Australia or Africa. While weather data are frequently recorded, because few persons use it, little attention is paid to their quality. Incorrect calibration of radiation recording instruments has been a commonly encountered problem in our work in both Australia and Kenya. Likewise, weather data tend to be sent to some central meteorological office, and rarely will researchers working in a particular environment have access to either the current or long-term weather data in a digital form. Modelling forces agronomic researchers to take a vital interest in quality weather data. The situation is often worse on characterisation of soil properties in agronomic experimentation. While a pedological classification may sometimes be available, few researchers measure soil properties that control water and nitrogen supply, even though such information might be essential to the interpretation of experimental results. When agronomic experimentation is conducted in a modelling context, the motivation for collecting such vital soil information is increased.

Obstacles to the Development of a Modelling Capability

This paper emphasises the benefits to be gained from coupling agronomic experimentation with a modelling framework. While we see this step as the only way forward in risky climates, we do not want to convey the impression that it is straight-forward and without its own difficulties.

Need for trained teams

Effective use of modelling in research for the semi-arid regions is held back by the unavailability of teams of scientists and experimentalists with skills in model development and application. While much progress has been made over the last 10 years, this still remains the major limitation in both Australia and Africa. The importance of training has been long recognised by groups promoting the use of modelling such as the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT 1988). That project has done much to expose crop researchers around the world to the role models might play in their research. This problem cannot be addressed only in terms of short-term training in how to use a particular model. A major change in perspective is needed, together with a significant investment in developing an understanding of the component crop and soil processes and in developing the skills required in software development, maintenance and model application.

Readers should not underestimate the challenges on this front. While training was considered an important issue in the KARI–ACIAR project in Kenya, this project ends after 10 years with only two people with well-developed skills in model development, testing and maintenance, and two additional scientists with skills in model application. Several are continuing their postgraduate training programs and none would consider themselves fully proficient in this area of work.

Need for better software

Another realisation from work with models in Kenya has been the need for better software design and software development and maintenance procedures, if models are to be a sustainable tool in agricultural research. Deficiencies of current software in this area compound the skills and training problems discussed above.

In the past, professional programmers have had limited input into the development of models used in crop research and the code available was both difficult to comprehend and error-prone. This problem was compounded by a tendency to 'patch-on' code to deal with new issues as they arise. We started our modelling in Kenya with an early version of CERES-Maize (version 1.0). Over the period 1985–92, this code developed in a pragmatic fashion, to meet the expanding needs of our research. New features to deal with weather-directed crop management, crop thinning, crop death and replanting options, tactical fertiliser management, mulch effects, surface residue decomposition, fallows, long-term analyses and interactive modelling were added. Inevitably, these enhancements became 'patches upon patches' and by as early as 1989 it had become obvious that a major redesign of the model was needed as we moved from what was essentially an individual crop model to a need for a cropping systems model with the soil as the central focus, and crops and residues 'coming and going' over time. This redesign has resulted in APSIM (Agricultural Production Systems Simulator) which is discussed in full by Carberry (these Proceedings).

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Maize Root Profiles in Gleyic Sandy Soils as Influenced by Ridging and Ploughing in Zimbabwe

H. Vogel*

Abstract

Little information is available in Zimbabwe on the response of maize (*Zea mays* L.) plants to their root environment in poorly draining sandy soils. Since a large proportion of maize in Zimbabwe is grown on land frequently subject to waterlogging, a study of maize root profiles under field conditions was carried out during the 1992–93 rainfall/growing season. The prime objective of this field study was to characterise the distribution and to quantify the length of maize roots in gleyic sandy soils under a ridge till-plant system compared to conventional mouldboard ploughing. Concomitant plant analyses and monitoring of soil water contact provided further information on plant–soil interactions.

Although the study was limited in scope, the relationship between tillage, certain soil physical factors and rooting by maize plants could be fairly well defined. The results confirmed that ridging increases soil rooting volume and thus root length per unit volume of the soil resulting in significantly higher yields (6.6 t/ha compared with 5.1 t/ha).

GLEYIC sandy soils are widely distributed in the highlands (1200 to 2100 m a.s.l.) of subhumid (approximately 800–1000 mm/year) northern Zimbabwe where the regoliths are underlain by undulating granitic bedrock at shallow depth (Thompson and Purves 1978). Their particle size distribution ranges from loamy sand (FAO 1988) in the topsoil to sandy loam in the subsoil weathering zone and they are generally highly consolidated and compact (Vogel 1992). They are also acid in reaction (pH 4.4-5.0 in 0.01M $CaCl^{2}$) and low in both organic carbon (< 0.5% in the 0-200 mm layer) and exchangeable cations (e.g. 0.1K, 2.0 Ca, 0.5 Mg as $cmol^{+}$ kg^{-1}). The seasonally fluctuating shallow water-table, stone lines, termite activity and tillage also cause strong vertical and horizontal soil variations. The resultant heterogenous soil environment created by these natural soil formation processes and by cultivation greatly affects maize root growth and yields. The two most common problems associated with growing crops in such compacted soils are poor aeration and insufficient root length (Stirzaker and White 1991).

Four years (1988-89 to 1991-92) of tillage trials showed that a system called no-till tied ridging (Elwell and Norton 1988) successfully addressed the problems of waterlogging and compaction best by providing additional and less densely packed rooting volume above the original topsoil (Vogel 1993; Table 1). It was also observed, however, that during prolonged dry weather early in the season the artificial heaping-up of soil raised topsoil temperatures to above 35°C and generated wide daily temperature fluctuations of more than 15°C in the elevated ridges between 0600h and 1400h (Vogel 1994b); both of which are detrimental to maize establishment.

In this study, carried out at the onset of tasseling of maize during the 1992-93 growing season, the objective was to describe quantitatively the distribution of roots and plant nutrients within the profile of ridged and ploughed soil.

Methods and Materials

The study site is located at Domboshawa Training Centre (latitude 17°35'S, longitude 31°10'E, altitude 1560 m a.s.l.) in northern Zimbabwe, 30 km north of Harare.

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Horizontal and vertical root mapping (Logsdon and Allmaras 1991; MacRobert et al. 1991) were employed to study root profiles of maize that had been planted on 24 November 1992 in both permanently ridged and annually ploughed soil. Measurements were made 50 to 52 days after planting (DAP) at the beginning of tasseling (13 and 15 January 1993), in ongoing, long-term tillage trials where maize is grown in monoculture. Sampling at tasseling is considered the best time to obtain maximum maize root length densities (Mengel and Barber 1974).

The annual mouldboard ploughing treatment (MB) used is the conventionally practised tillage technique of Zimbabwe's smallholder farming sector. Ideally, ploughing is to the recommended depth of 230 mm (Grant et al. 1979) employing a single-furrow ox-drawn mouldboard plough. The no-till tied ridging (TR) treatment is a conservation tillage technique promoted by Zimbabwe's agricultural extension service. During the first year, the land is also ploughed to the recommended depth of 230 mm, and cross-slope crop ridges of not less than 250 mm unconsolidated height are then constructed. The ridges are not ploughed out after the first year but are permanently maintained to minimise draught power and loss of organic carbon. Surface runoff is controlled by laying out the ridges at a 0.4 to 1% gradient and by constructing smaller crossties at 1-m intervals along the furrows.

At the time the trials commenced, treatment plots were arranged in seven completely randomised blocks which are separated by contour ridges. However, prior to the 1991-92 growing season, one ridged and one ploughed plot of approximately 800 m^2 gross area each were added to two blocks for extra studies, i.e. a total of four new plots. One of the two blocks was situated in an upper catenal position, on a reasonably well-drained Areni-Gleyic Luvisol to Luvi-Gleyic Arenosol (FAO 1988). The other, located in a mid-catenal position, was characterised as poorly drained Eutric Regosol to Gleyic Arenosol with stone lines at shallow depth.

In each of the four plots, one soil pit was excavated according to the trench profile method (Böhm et al. 1977). The pits, dug across two crop rows, measured 1.8 m in width and 1.2 m in depth. The surface of the exposed soil profile wall was first smoothed with a putty knife and subsequently approximately 5 mm of soil was brushed off the profile face with a soft paint brush to expose the maize roots. A 1.0 m × 1.2 m metal frame (MacRobert et al. 1991) was positioned over the cleared maize root profiles with the maize plants always situated in the centre of the frame top. This metal frame was interwoven with thin nylon twine to form a 50 mm × 50 mm grid pattern. Within each grid square, the position of each 5 mm length of root was noted as a dot on scaled paper. The number of dots per grid square were totalled for each 50 mm depth increment across 0.9 m width (crop row spacing = 0.9 m) and converted to root length density (cm/cm^3).

Soil mechanical impedance was measured at the time of root mapping using a hand-held penetrometer (Anderson et al. 1980). The soil water content at this time was at field capacity throughout the depth of recording (= 0.52 m) in both treatments. For root conservations made between 51 and 58 DAP, cone resistance as determined during the week of root observation (and the previous week, which in our case gave the same result) produced the highest correlation with relative root abundance (Vepraskas and Wagger 1989). Five readings were taken at 35 mm depth intervals in each of the four plots within the maize rows (i.e. through the top of the ridges). Bulk density was determined as the oven-dry (dried for 24h at 105 °C) weight of 2.5 × 105 mm^3 undisturbed core samples also taken in situ at field capacity.

Soil water content was recorded weekly. Over the top 0 to 100 mm of the soil it was measured gravimetrically and converted into volumetric values by field-determined bulk densities. For lower depth levels (150 mm to 1.4 m) a CPN 503DR neutron probe was used which had been calibrated separately for the 150 mm depth level ($r^2 = 0.94$) and the lower (starting at 300 mm) levels ($r^2 = 0.96$).

One uniform fertility treatment was applied. A basal compound fertiliser totalling 24N:18.5P:17.5 K:19.5S kg/ha was applied at planting followed by two top dressings of ammonium nitrate (NH4NO3) each of 34.5 kg N/ha in mid-December 1992 and two days prior to root excavation and soil sampling.

The two maize plants from each pit were taken for nutrient analyses after root mapping. Harvested maize grain, as collected across all replications, was weighted and corrected to a uniform moisture content of 12.5% for final yield analysis.

Results

It is recognised that the results of this study are time and site-specific and also that the number of only eight maize root profiles analysed is small. Nevertheless, as will be shown, the effects of ridging and ploughing on crop growth and root distribution were sufficiently different and consistent to make up for the lack of replications. Crop height and the number of leaves per plant on the ridged plots were greater than on the ploughed plots and reflected the large differences in the respective root distributions (Figs 1-4). These results were also in full agreement with previous findings from extensive root excavation exercises which had established maximum root penetration depth below ridges (Vogel 1993, 1994a).

Seasonal rainfall pattern

At Domboshawa the 1992–93 season produced a total rainfall of 791 mm. Unlike in previous seasons (Vogel 1993, 1994a), no early-season drought occurred after planting (24 November 1992) but instead rainfall was plentiful and evenly distributed (Fig. 5a). Between the time of planting and the root mapping exercise (13 to 15 January 1993), a total of 370 mm of rain was received.

Soil water

The effect of tillage on soil water content was statistically significant (at $P < 0.05$) up to 25 November 1992 (that is until one day after planting), but only down to the 750 mm depth level (600–925 mm soil horizon) which coincides with the observed maximal root penetration depth (Fig. 2). Ridges entered the season with a significantly lower soil water content (Fig. 5b) and also kept the rooted profile considerably drier than conventional tillage throughout the growing season (Fig. 5c).

Between 10 December 1992 and 13 January 1993, overcast weather conditions prevailed. For a period of 5 weeks, soil water levels in ploughed soil remained between field capacity (ranging from

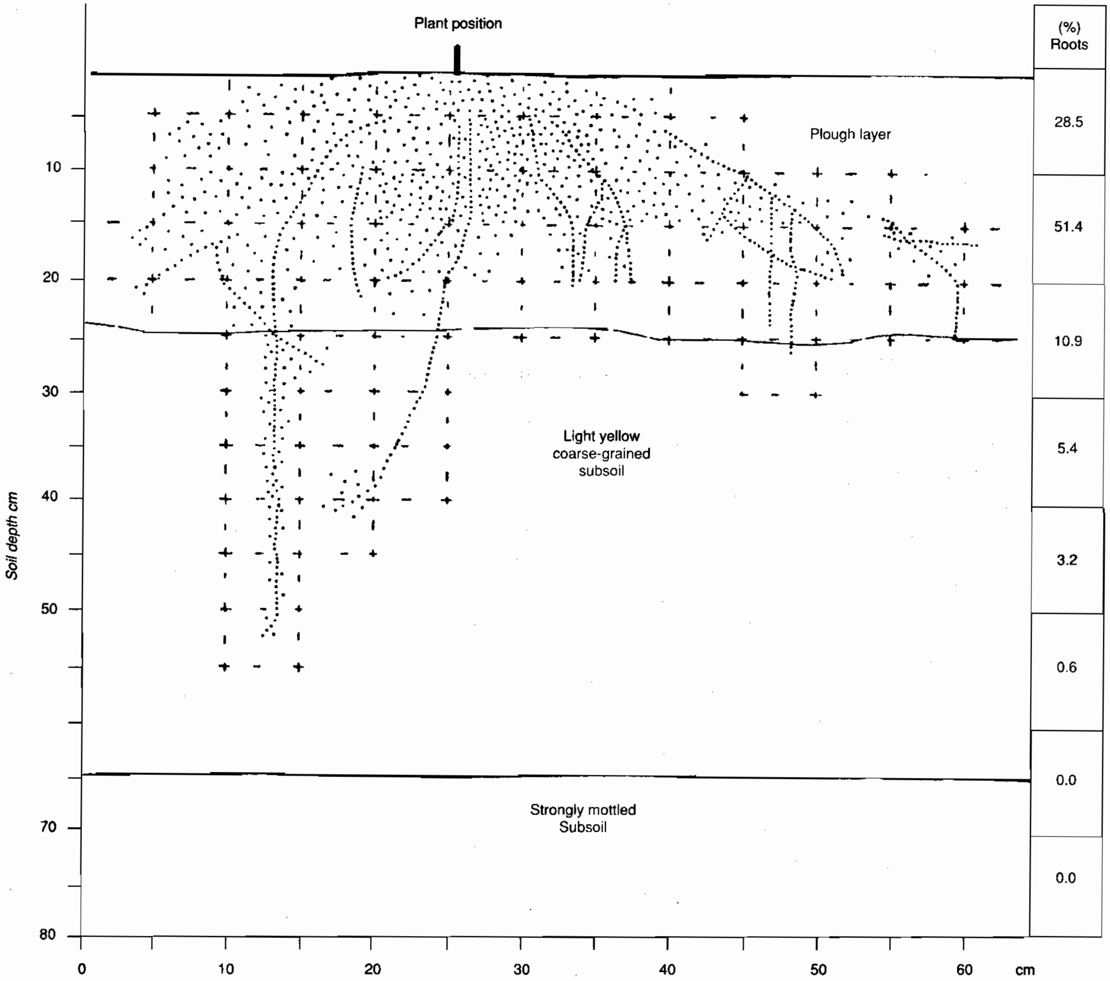

Figure 1. Maize root profile under mouldboard ploughing in reasonably-well drained Luvisol profile.

12.4% by vol. at 100-200 mm to 15.5% by volume at 450 mm depth) and approximately 20% by volume (saturation approximately 32% by volume) throughout the entire root zone. In contrast, soil water contents in the ridge tops (as measured between 0 and 100 mm and at 150 mm depth) always remained slightly below or at field capacity, and reached field capacity at 300 mm depth (14.0% by volume) during this time. Only at 450 mm depth below ridges were soil water contents recorded (15.3 to 18.9% by volume) that surpassed field capacity.

It is assumed that the prolonged wetness within 300 mm of the surface was the prime factor responsible for the stunted maize crop in ploughed fields compared to the tall crop on ridges at the time root mapping was carried out, i.e. 50 to 52 days after planting (DAP). Although it is generally agreed that a high soil water content per se has little meaning in terms of plant–water relations, it is well established that the primary effect of soil wetness within the root zone is attributable to its adverse effect on rhizosphere aeration which directly affects root growth and nutrient uptake (Van Schilfgaarde and Williamson 1965; Mackay and Barber 1985; Sojka 1985). Other research (Chaudhary et al. 1975; Hardjoamidjojo et al. 1982; Kanwar et al. 1988) also showed that maize yields are most reduced if soil wetness occurred during the vegetative stage, i.e. within 50 DAP, as was the case in 1992-93 at Domboshawa.

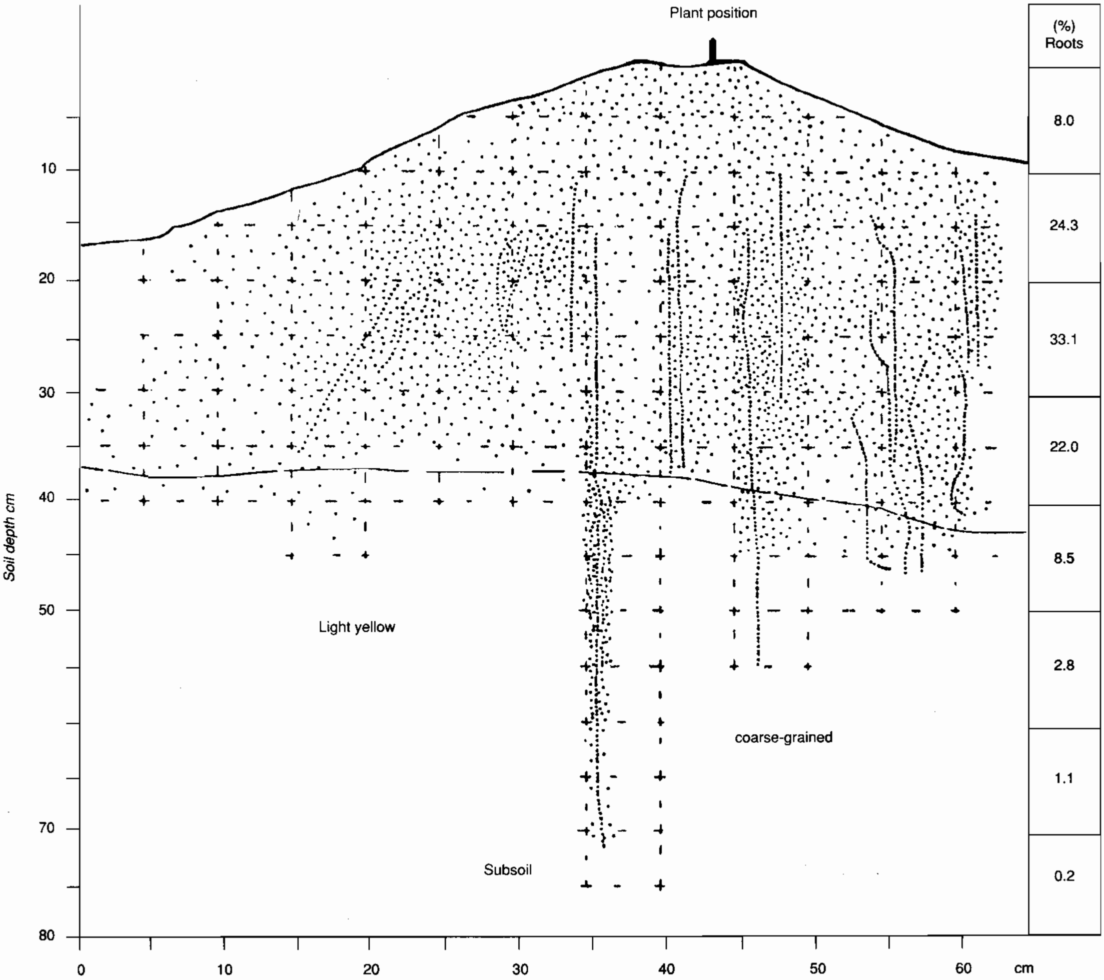

Figure 2. Maize root profile under tied ridging in reasonably-well drained Luvisol profile.

In spite of an air-filled porosity of 20–30% over the period of five weeks concerned, and although oxygen diffusion rate and redox potential data were not obtained in this study, observed and/or measured plant factors suggest aeration problems existed in the ploughed soil. Yellow leaves and a high concentration of 140 to 196 mg/kg of ferrous iron in the tissue of the maize plants taken from the ploughed fields at tasseling, as well as conspicuously less root growth in the 50-mm layer immediately above the topsoil-subsoil boundary (Figs 1 and 3), indicate the existence of transient waterlogged conditions and oxygen deficiency. In contrast, maize grown on ridges featured green leaves and the measured concentration of ferrous iron in its tissue only ranged from 118 to 126 mg/kg. There were no similar effects on the concentrations of other nutrients. The maize plants grown on ridges were significantly taller than those grown on the flat (Fig. 6). The assumption that aeration problems existed in the root zone is also supported by the results of a recent study of similarly marginal waterlogged soils in South Africia which showed that the oxygen (O2) to carbon dioxide (CO2) ratio of the soil air was improved in ridges compared to flat ground due to better internal drainage and thus unrestricted gas exchange between the atmosphere and the soil air (Myburgh and Moolman 1991). Other research also suggests that an 'aeration effect' on root growth may occur in sandy soils with up to 30% air-filled porosity (Eavis 1972, Warnaars and Eavis 1972).

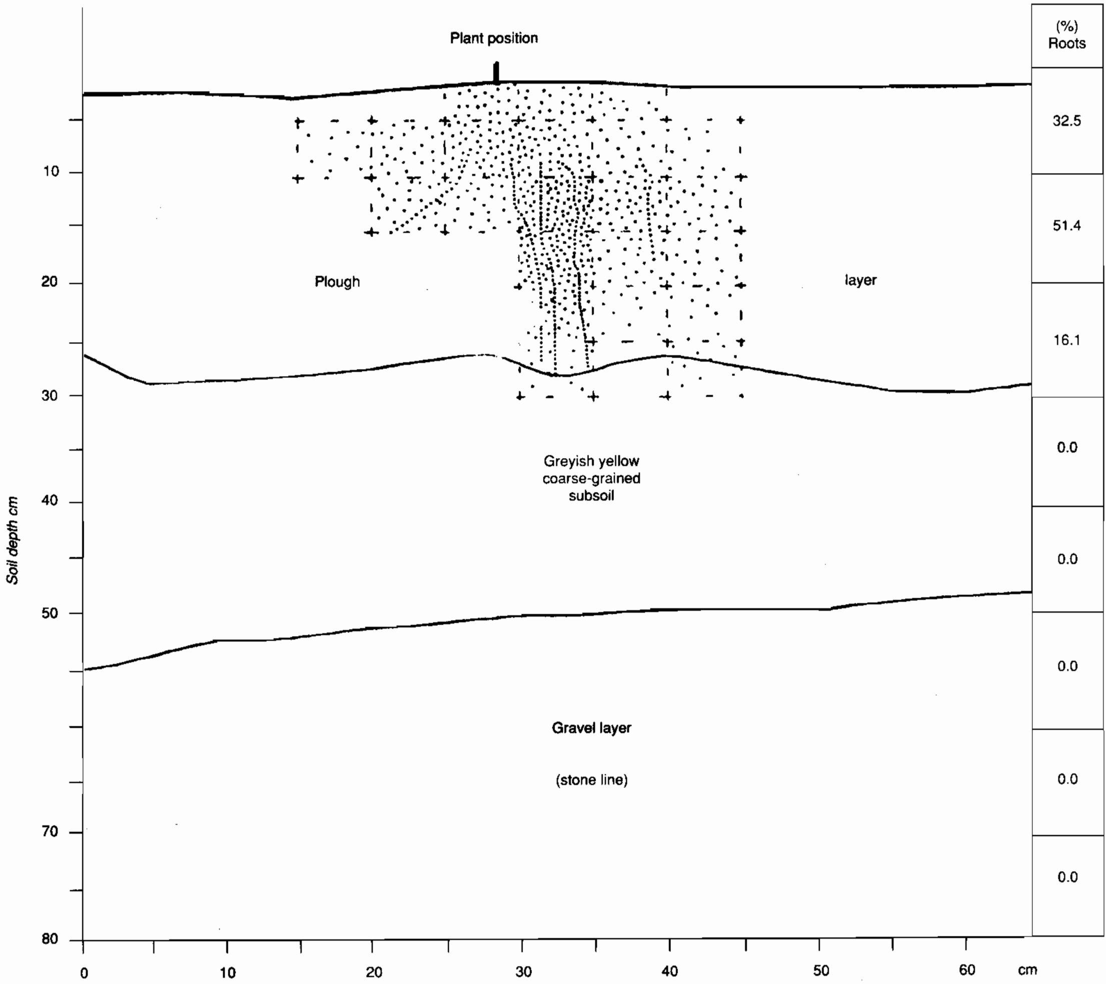

Figure 3. Maize root profile under mouldboard ploughing in poorly-drained Regosol profile.

Soil strength

It is assumed that besides poor aeration, high soil mechanical impedance played the prime role in limiting maize root growth in ploughed plots. Soil mechanical strength is assumed to be sufficient to stop bulk root growth at a critical pressure of 2000 kPa as determined by a cone penetrometer (Gill and Miller 1956, Taylor et al. 1966, Blanchar et al. 1978).). This threshold value was reached at approximately 270 mm depth under the ridges on the shallow Regosol, in both soil types under ploughing (Figs 7a,b) and at approximately 360 mm depth (Fig.7a) below the ridges on the deeper Luvisol. The penetrometry results thus fully confirm the mapping results (Figs1-4) which clearly show the vast bulk of roots confined to above these critical depths. They are also supportive of findings which suggest that a distinct reduction of root growth takes place when mechanical impedance and low oxygen concentrations occur together (Schumacher and Smucker 1981). Impeded roots were found to require more oxygen than unstressed roots which could accelerate the development of anoxic conditions. Furthermore, in field environments characterised by compact soil and frequent rains, oxygen diffusion (root elongation is more sensitive to the oxygen diffusion rate than to oxygen concentration) may drop to growth-terminating levels (< 33 m^2 s) within one day of heavy rainfall but may require one week thereafter to recover to growth-supportive levels (> 58 m^2 s) again

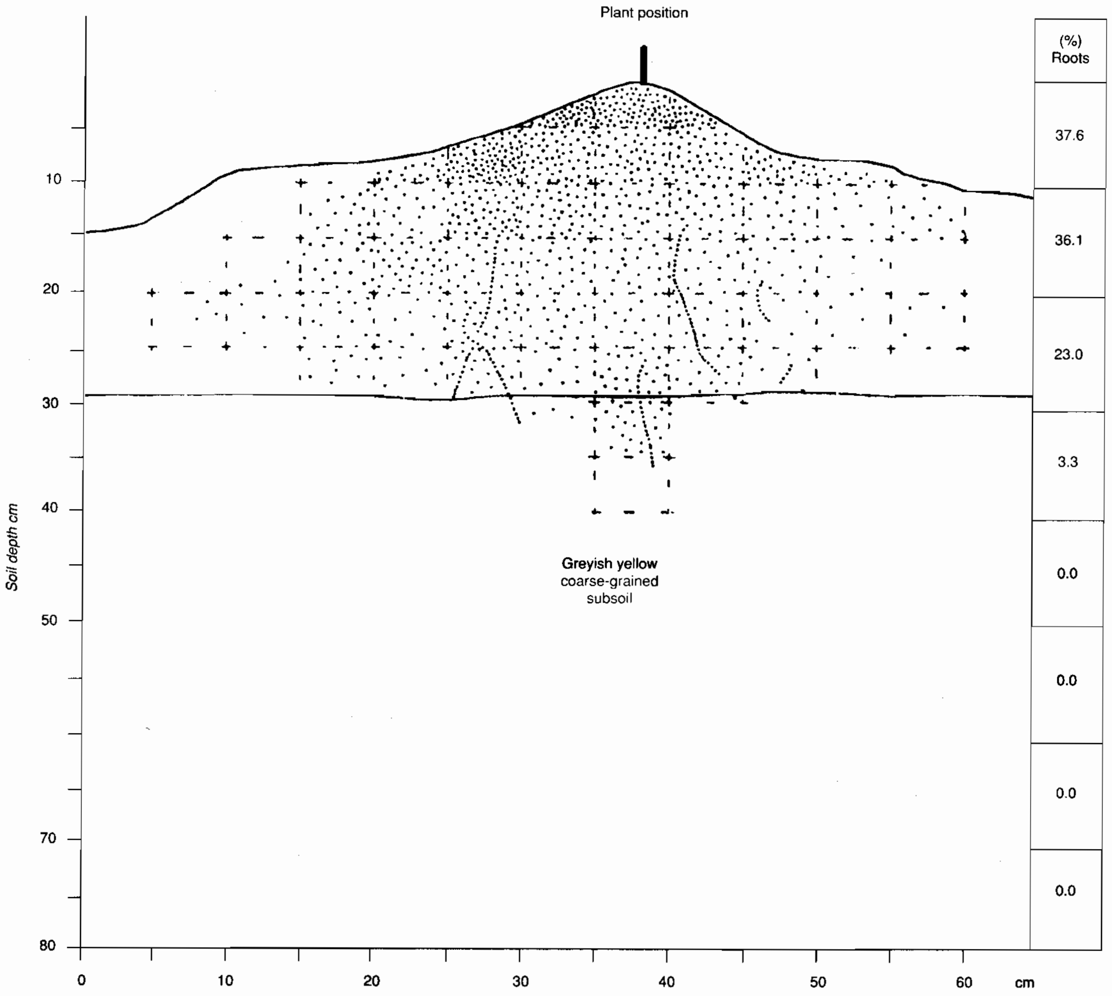

Figure 4. Maize root profile under tied ridging in poorly drained Regosol profile.

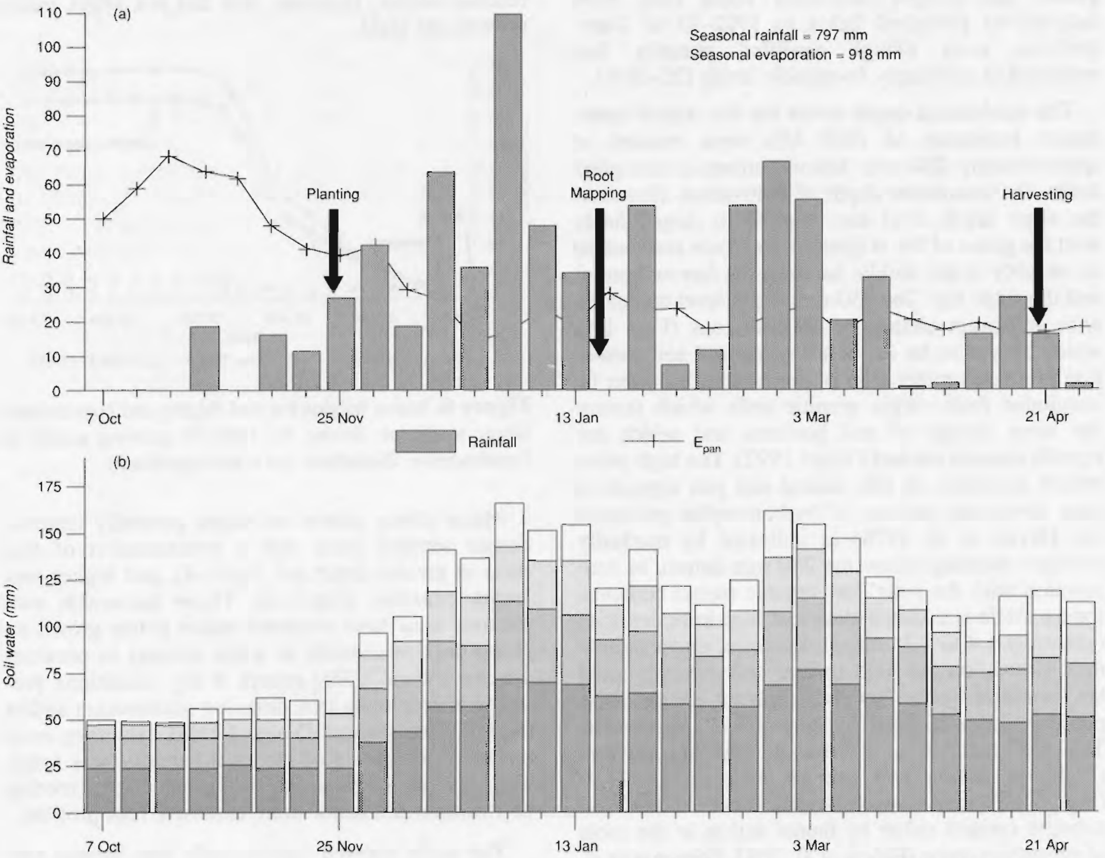

Figure 5. Moisture balance in the 1992–93 season: (a) total weekly rainfall and pan evaporation, and weekly measurements of soil water for the four depth layers, (b) under ridging (on the ridge), and (c) under conventional tillage.

(Allmaras and Logsdon 1990). Both findings suggested that oxygen deficiency could have been induced on ploughed fields in 1992–93 at Domboshawa even though air-filled porosity had remained at seemingly favourable levels (20–30%).

The established depth levels for the critical penetration resistance of 2000 kPa were reached at approximately 250 mm below surface in ploughed fields, the maximum depth of cultivation. However, the same depth level also applied to ridged fields with the plane of the original soil surface assumed to lie roughly in the middle between the furrow bottom and the ridge top. The 250-mm depth level coincided with an abrupt change of soil horizons (Figs 1-4) which appear to be the result of natural soil formation processes rather than of cultivation. This can be concluded from virgin granitic soils which feature the same change of soil horizons and which are equally densely packed (Vogel 1992). The high penetration resistance at this natural soil pan appears to have developed because of hydromorphic processes (cf. Davies et al. 1978) as indicated by markedly stronger mottling below the 250 mm datum, in conjunction with the soils' low organic matter contents, their particle size distribution and high bulk densities (generally 1.4 to 1.7 tonnes). However, under permanent cultivation the high natural soil strength could be increased further by the smearing and/or compressive action exerted by agricultural implements. The few roots able to penetrate the subsoil pan (Figs. 1–4) where soil strength exceeds 2000 kPa (Figs 7, b) may have followed zones of low soil strength created either by faunal action or the roots of preceding crops (Ehlers et al. 1983, Stirzaker et al. 1993) and/or prolific perennial weeds such as *Richardia scabra* L. and *Cynodon dactylon* (L) Pers. (Vogel 1994b).

Root length density

Soil mechanical strength (Figs 7a,b) and maize root length density (Figs 7c,d) corresponded well. For both treatments and soil types, maximum root length density was developed approximately 100-150 mm above the depth for which a cone penetrometer pressure of 2000 kPa could be established.

Maize root length density below the ridges was generally about 50% higher than in ploughed soil. Higher root length density for a ridge-till treatment has also been observed elsewhere (Kovar et al. 1992). However, the depth of greatest root length density differed between the two soil types for tied ridging (Fig. 7c). This must be attributed to the circumstance that ridges on the Regosol profile were not quite as high as those on the Luvisol (cf. Figs 1 and 3); consequently, the critical depth level corresponding to the restriction of root growth was reached earlier. However, this did not affect maize growth and yield.

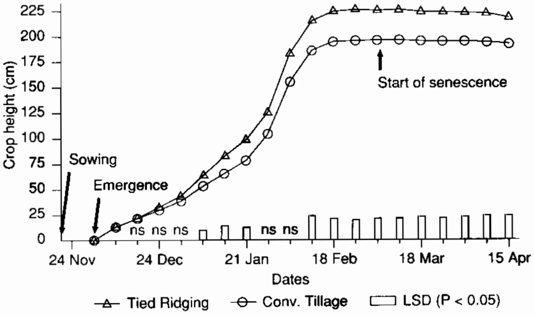

Figure 6. Maize heights for tied ridging and conventional tillage treatments during the 1992–93 growing season at Domboshawa, Zimbabwe. (ns = not significant).

Maize plants grown on ridges generally featured deeper seminal roots and a concentration of fine roots at greater depth (cf. Figs1–4), and higher root length densities (Figs7c,d). These favourable root features must have rendered maize plants grown on ridges less susceptible to water stresses in previous seasons (Vogel 1993) except if dry conditions prevailed after sowing thus delaying germination and/or inhibiting emergence (Vogel 1994a). However, once maize is established on ridges it becomes less sensitive to water stresses due to a much bigger rooting soil volume and hence more extensive root profiles.

The study showed convincingly that limited topsoil depth (Thompson et al. 1991) due to subsurface compaction (Oussible et al. 1992), in combination with poor aeration, determined root distribution and density. Although some penetration was observed to about 750 mm, the majority of roots resided above 300 mm in the soil (Figs1-4) as has been observed in similarly waterlogged sandy soils elsewhere (Follett et al. 1974). Tied ridging improved rooting by adding extra soil on top of the original soil profile. At maturity maize on tied-ridges yielded significantly ($P < 0.05$) more grain (6.6 t/ha) than maize on mouldboard ploughed plots (5.1 t/ha) as observed previously (Vogel 1993).

Conclusion

Although the number of root profiles analysed was limited, the relationship between crop growth, root distribution and tillage was conclusive. Ridging resulted in more prolific, denser and deeper maize root systems than ploughing; consequently, plants grown on ridges yielded significantly better. The

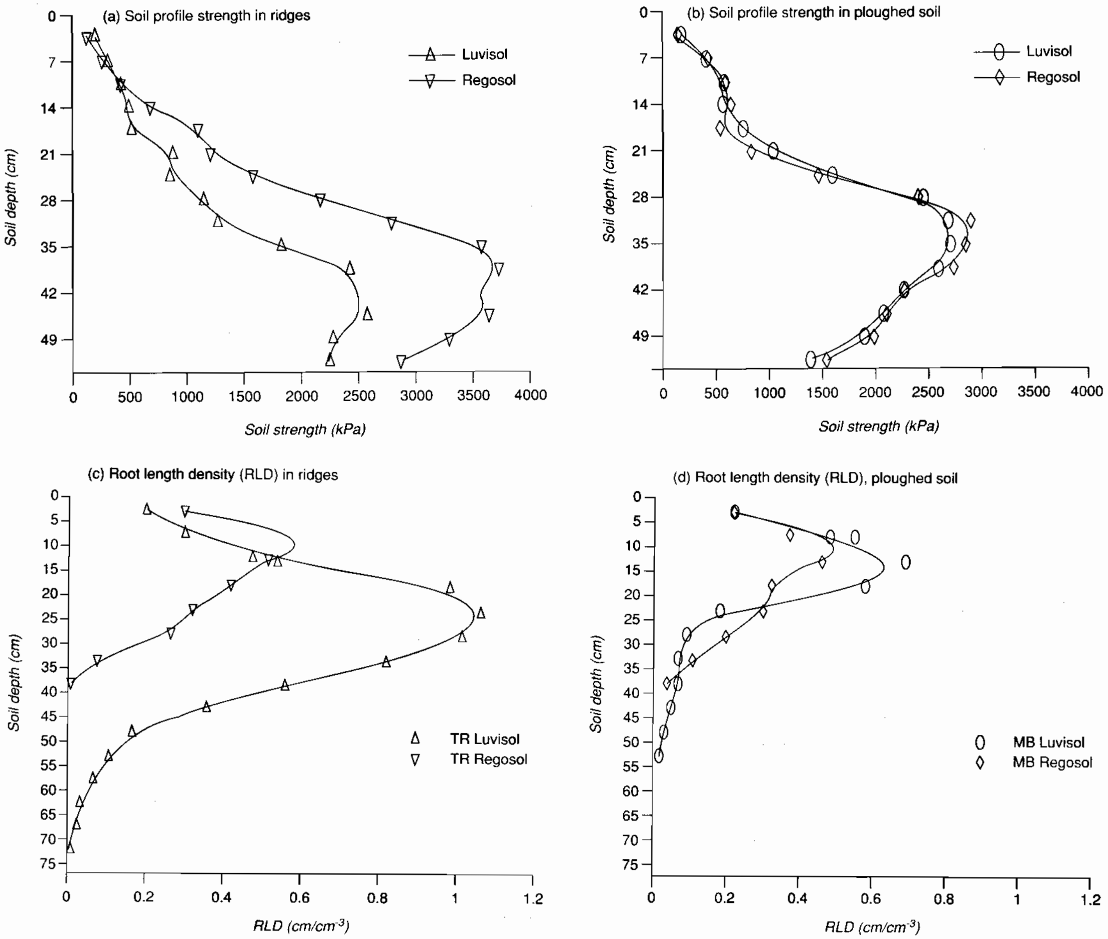

Figure 7. Soil profile strengths and root length densities in ridged and ploughed soils at tasselling in mid-January 1993 at Domboshawa, Zimbabwe.

observed root differences were ascribed to the additional topsoil layer created by the ridging which provided more favourable rooting conditions above physical restrictions of the subsoil. While the vast bulk of roots in ploughed fields were confined to the depth of cultivation (200–250 mm), ridging increased the vertical height of penetrable soil by at least 50–150 mm. Given the influence of ridge height on topsoil temperature and potential evaporation losses, future studies need to establish the optimal height and shape of ridges for the specific soil and climatic connditions prevailing in the study area. Knowledge of an optimal ridge height is also essential from a draught power point of view since high ridges require ploughing into extremely compact subsoil and/or gravel layers, a critical disadvantage in animal draught power.

Acknowledgments

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Agricultural Systems Research in Africa and Australia: Some Recent Developments in Methodology

R.L. McCown and P.G. Cox*

Abstract

Soil fertility depletion is a recurring, and increasingly urgent, theme both in sub-Saharan Africa and in Australia. It poses severe problems for a farming systems research approach that focuses on breaking constraints to production in a sequential and isolated fashion, and working with individual farmers. Additional approaches are required to evaluate the design of novel farming systems, and to change the attitudes and behaviour of groups.

When farming systems research (FSR) was getting started in Africa, Australian researchers moved down a different route towards the construction and use of crop models. These are now well developed and sufficiently reliable for use in operations research. But this activity, and the decision support products it spawns, is also increasingly seen by many as problematic and deficient.

In Australia, we are beginning to recognise that FSR and modelling are components of a wider systems approach. We shall need to bring all our system skills to bear if major problems like soil fertility depletion are to be ameliorated. But the eclectic approach we are developing is, we believe, the beginning of a reproducible and transferable research methodology which could be usefully applied more widely.

SOCIETY expects professional agricultural researchers to find out what good farming is, and to help farmers do it. But in most of Africa, and much of Australia, few farmers use the practices that researchers think necessary for efficient and sustained production. Why do we not see greater use of existing good farming methods? Is the discrepancy between good farming and much of actual farming due to a failure of researchers to appreciate sufficiently the realities which farmers face, or to our failure to help them change to something better? Is this discrepancy due to inadequate attention to technology design leading to the promotion of inappropriate technologies? Or to a failure to communicate well enough about the relative costs and benefits of alternative strategies?

In 1985, the Australian Centre for International Agricultural Research (ACIAR) hosted an international workshop 'Agricultural Systems Research for Developing Countries' (Remenyi 1985). At this meeting, these questions were addressed in the context of both eastern and southern Africa (Norman and Collinson 1985) and Australia (Remenyi and Coxhead 1985). While encouraging progress was reported, deficiencies in methodology for providing answers were obvious. The aim of this paper is to consider these generic questions and some recent developments in methodology used to answer them. We take as an example the decision to invest in soil fertility improvement in situations where soils are seriously depleted but where the economics of nutrient replacement is problematic because production is so often water-limited. This situation applies in many parts of Africa and Australia.

Soil Fertility in Sub-Saharan Africa

Probert and co-workers (these Proceedings) describe the serious problem of soil fertility depletion in a region of Kenya. In the 1970s, Ruthenberg highlighted the growing importance of the issue of soil fertility maintenance in farming systems of the African savanna zone, and predicted that soil degradation would become more general as pressure on land resources increased (Ruthenberg 1980).

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Broekhuyse and Allen (1988) describe the destruction of the productive capacity of the Mossi plateau (Burkino Faso) by its inhabitants, and the social processes of overexploitation which apply to much of the savanna zone. Lynam (1978) has described a similar process in the Machakos and Kitui Districts of Kenya. The causes of overexploitation (high rates of rural population growth, shortage of suitable land for further expansion of cropping, and poverty which precludes replacement of soil nutrients at rates that will sustain productivity) already operate over much of Africa on scales, and to degrees, varying from worrying to catastrophic.

The problems of land degradation and low productivity are now so widespread in semi-arid Africa that it is easy to forget that this is not the natural state. Broekhuyse and Allen (1988) report that while 400 kg/ha is today considered a *good* grain sorghum yield on the Mossi Plateau, an ethnographic survey indicated that this is half the *normal* yield of former times. This decline has taken place over four generations — a rate that was perceptible within each generation, but not high enough to cause alarm.

The longer the delay before investing in soil fertility replacement, the greater the nutrient response and the higher the rate of return on the investment. Matlon (1987) refers to an FAO rule-of-thumb that adoption of fertiliser requires a 100% return on investment i.e. a 2:1 benefit–cost ratio. He reports a value of 350% for sorghum in areas of Burkino Faso in the early 1980s when the rate of fertiliser use was increasing. But as population increases, fallows shorten, soil fertility declines, and poverty deepens. While the potential response to a unit of nitrogen increases under these circumstances, the financial resources needed to purchase fertiliser progressively decline. These authors rule out fertiliser as a feasible innovation because it represents such a large, and increasing, proportion of the average annual income. The only action that might break the physical resource constraint is thus precluded by poverty.

Amelioration of soil fertility decline in sub-Saharan Africa will require enormous changes in education, public policy and administration. But the confusion that exists about the nature of the problem, and the availability of technical options, is puzzling. The technical constraints on any solution are clear.

1. Nitrogen and phosphorus are the elements in most short supply.
2. Most strategies for *avoiding* the constraint actually increase the efficiency of *depletion* e.g. better-adapted plants, increased water-use efficiency.
3. Animal manure can supply the required nutrients, but there is not nearly enough manure in cropping regions to prevent further decline.
4. Chemical fertiliser needs to be supplied, but in conjunction with manure to maintain sufficient organic matter levels and prevent acidification.
5. Poor management of high input systems in industrialised countries has created specific environmental problems. But this provides no grounds for protecting the fertility-impoverished environments of the tropics and subtropics of Africa and Australia from this remote risk.
6. Grain legumes do not provide a net increase in soil nitrogen, even when P is sufficient.
7. The conditions for successful legume ley pasture systems do not exist in Africa (e.g. affordable P fertiliser for pastures, good returns in animal enterprise from investment in sown pastures). In regions with most need, population pressures are too great for this level of cropping intensity.
8. Trees in semi-arid cropping systems are a mixed blessing. Some can provide useful amounts of nitrogen (e.g. leucaena alley cropping) and others recover nutrients at depths beyond the crop root zone. But they compete so strongly for water and nutrients that they are frequently detrimental.

Farming Systems Research in Africa

Farming Systems Research (FSR) emerged as a research approach in the late 1970s and underwent much of its development and testing in Africa. At the time of the ACIAR conference in Australia, Norman and Collinson (1985) could state that 'nowhere is increasing commitment [to FSR] more obvious than in the Eastern and Southern Africa region where we work'. Although Collinson's FSR schema has been re-used by numerous authors, we do so again because it depicts the approach so clearly and succinctly (Fig. 1, adapted from Anderson et al. 1985). The aim is efficient use of scarce resources for research, development and extension in delivering practical benefits to farmers. To Remenyi and Coxhead (1985), the key question in FSR is: why does this farmer farm as he/she does? In this paper, we highlight the other side of this question: why doesn't he/she do certain things that would be, apparently, in his/her interest? In FSR, these questions about technology design are explored using a step-wise process of *on-farm diagnosis; planning*, using an operational research approach; targeted *component research* on research stations when required; and *on-farm testing* of promising alternatives.

We can consider the merits and limitations of FSR by looking at the *diagnosis* and *planning* stages and the *scale* aspects of this approach in relation to the issue of soil fertility decline.

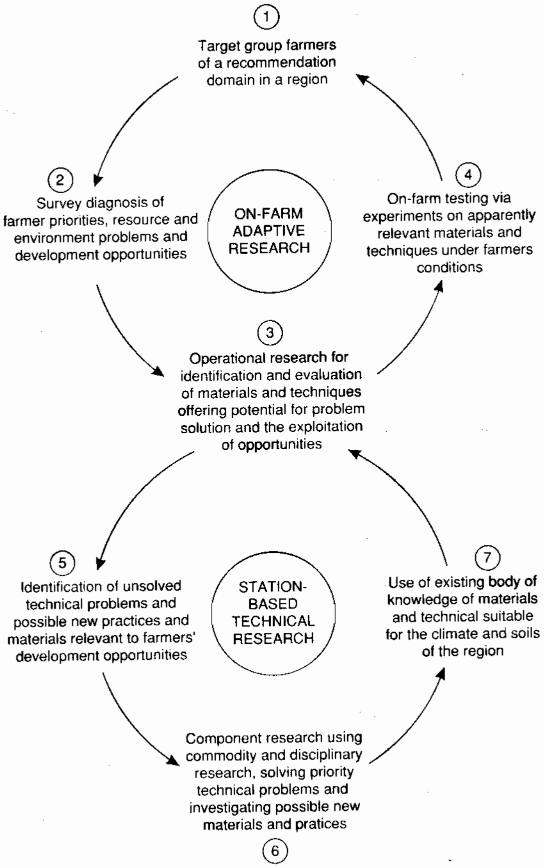

Figure 1. Schematic of Farming Systems Research methodology (Collinson 1982, modified by Anderson et al. 1985).

Diagnosis

On-farm measurement is central to the diagnosis of soil fertility decline. But measuring the status of soil nutrients such as nitrogen (N) and phosphorus (P) is made difficult and expensive by the heterogeneity of soil fertility on smallholdings due to, for example, non-uniform return of manure. Nor, in general, has experimentation on fertiliser application rates provided a reliable basis for management. Here the heterogeneity problem is compounded by the variable and unpredictable occurrence of other constraints, e.g. water deficits, pests, diseases and weed infestations, all of which result in a reduced response to added nutrients. Conclusions about the state of soil fertility in Africa based on a synthesis of large numbers of fertiliser response trials greatly underestimate the size of the problem.

While precise problem diagnosis is not easy, and perhaps not even feasible under such conditions, it is inescapable that farming cannot continue unless nutrients removed in crops, or lost in other ways, are replaced. Yet this is almost never achieved in contemporary smallholder agriculture. The common explanation is that farmers with very low incomes cannot afford to buy inputs.

Planning

At the earlier ACIAR workshop in Australia, Norman and Collinson (1985) offered two possible ways of dealing with a constraint in the farming system: relieve it, or avoid it by exploiting flexibility in the system. They observed that 'flexibility in management is enhanced when there are underutilised resources, while increasing productivity is vital to breaking constraints'. Later, Norman and Collinson state, 'if one looks at the success of FSR work to date, much of it can be attributed to exploitation of flexibility rather than breaking constraints'. And finally, 'we submit that breaking a constraint is a much more difficult problem for both researchers and farmers than the strategy of exploiting flexibility. However, major long-term increases in productivity have to come through breaking constraints'.

Seven years later, Waddington (1992) reported examples of successful on-farm experimentation by FSR teams. He observed that most examples could be regarded as 'fine tuning' of existing technologies in environments with some slack in resources. Where technologies did not already exist, and in regions with great pressure on resources, little success was experienced.

An indication that Norman and Collinson (1985) had not substantially engaged the issue of soil fertility maintenance is their statement that 'we believe that criteria used in developing improved strategies should reflect the felt needs of farming families, providing these are compatible with the needs of society (e.g. there is not a decline in soil fertility)'. This implies that an innovation with a negative effect on soil fertility would be exceptional. We think it is now clear that an innovation (such as a higher yielding cultivar) which exploits slackness in resources necessarily *accelerates* soil fertility depletion unless some of the increase in returns is invested in fertility inputs.

In the relatively favourable environments in which FSR has had its successes, relief of soil fertility constraints may be seen mainly as Norman and Collinson (1985) did, as necessary for 'major long-term increases in productivity'. However, where resources are under pressure, relief of soil fertility constraints is required to enable farming to continue to be viable as a means of sustaining low-income subsistence and not degenerate into the environmentally destructive, and ultimately self-destructive, activity of 'survival farming' (Broekhuyse and Allen 1988).

Scale

Broekhuyse and Allen (1988) distinguish the anglophone style of FSR and the francophone style, which has a more institutional, regional and long-term emphasis. They found the latter more useful when the problem was collectively destructive behaviour at the scale of landscapes by farmers each acting in his/her own best (short-term) interests. Changed behaviour did not occur unless the unit undertaking change was the village rather than the individual.

The failure of FSR to deal with issues of land degradation, such as soil fertility depletion, stems partly from its focus on the welfare of individual farmers, their perspective of their own needs, and of the choice of remedial actions within their control. While focus at this scale constitutes the strength of the FSR approach for many issues, other scales are important for the management of soil degradation.

On the Mossi Plateau, the francophone style of FSR, while casting the problem in a wider context, did not result in breaking the soil fertility constraint. The fundamental problem is a scarcity of a costly resource which is unaffordable by most farmers. In those parts of the world where sustainable agricultural systems are well developed, the means for preventing serious fertility depletion are well known and the cost of the necessary inputs is accepted (and acceptable). However, where circumstances force economically-rational farmers to farm in ways that are unsustainable and damaging to present and future society, there is a need for innovative policy initiatives. Soil erosion is a problem in political economy. Additional approaches are required (Biggs and Farrington 1993).

Systems Research in Australia

FSR has not been seen as appropriate to the R&D needs of Australian farmers. Scientists have assumed they knew their needs well enough, and that farmers could readily fit new R&D products into their systems. Systems research has mainly taken the form of economic modelling, simulation modelling and decision support systems (Remenyi 1985). But agricultural Research, Development and Extension (R,D&E) institutions in Australia increasingly recognise the value of a richer systems approach to meet the challenges presented by the complexities, uncertainties and conflicts in modern agricultural production. People-oriented systems approaches now exist alongside the 'hard' systems approaches. These have drawn heavily on Soft Systems Methodology (Checkland 1981; Checkland and Scholes 1990).

Another development has been to combine simulation modelling of agricultural production systems with the client-orientation of FSR (McCown 1991). The establishment of the Agricultural Production Systems Research Unit (APSRU) by the CSIRO Division of Tropical Crops and Pastures and the Queensland Department of Primary Industries is an example of this. APSRU is a team of 17 professionals with a charter to facilitate collaboration and convergence of R, D&E effort for dryland agricultural production systems.

APSRU's primary mandate region is the subtropical grain-growing areas of eastern Australia. Although it is more variable than for the cropping regions of Africa, the climate of this region of Australia is similar to that of southern Africa. In spite of high yield variability caused by unreliable rainfall, the region developed into a major producer of both winter and summer grains and the most important source of prime hard wheat. Rain rarely allows double cropping. Rain stored during a previous clean fallow provides much of the water for most crops. Grazing of cattle or sheep is also important on most grain farms, but ley pastures are rare. In recent years, dryland cotton has become an important crop.

Total nitrogen in the pristine black cracking clay soils was originally high (> 0.3% on some soils). In some areas, cropping had been practised without nitrogen fertilisation for 50-80 years before crop decline became evident. R,D&E during this period focused primarily on relieving biological and physical constraints to the exploitation of the rich soil resource through new crops and cultivars, and improved water conservation and utilisation.

But it has become clear, with a dramatic decline in protein content of wheat and consequent loss in financial returns, that the 'honeymoon' is over. Soil nitrogen, and particularly the economics of nitrogen supply, are amongst the most important issues in this farming system. Soil erosion, especially during summer fallows when rainfall intensities are high and decomposition rates of surface residues are high, exacerbates the problem.

Technological components

Figure 2 depicts four technological components which are widely held by professional agriculturalists to be key ingredients of profitable and sustainable cropping in this region now and increasingly in the future: opportunity cropping, conservation tillage, fertiliser and purposeful crop sequence. Each of these is important in its own right but they also interact in a complex way to influence the supply of water and N, and their use by crops.

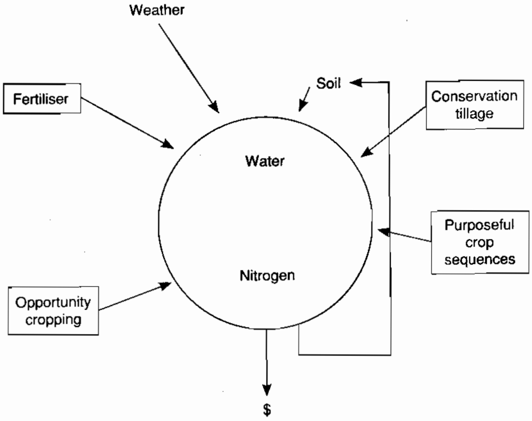

Figure 2. Technological components that contribute to improved strategies for managing scarce soil water and nitrogen supplies in subtropical eastern Australia.

Opportunity cropping is the strategy of planting whenever there is adequate soil water for the establishment and growth of a crop. This is a flexible response to the weak seasonality of rainfall. This strategy has been promoted as a soil conservation measure because it maximises crop cover of soil. Even though average crop yields are reduced vis-a-vis regular winter or summer cropping and fallowing, more crops are produced. The need to plant large areas quickly following a rain makes reduced or zero tillage techniques an attractive companion practice to opportunity cropping.

Conservation tillage is the strategy of reducing tillage and retaining stubble. It is an important means of increasing the efficiency of capture and retention of rainfall, as well as an effective measure for conserving soil, especially during fallow. The technology is well-developed and, while costs are somewhat higher than conventional tillage, yields are often higher in dry years. In good seasons, yields may be more N-limited than with conventional tillage unless additional N is supplied.

Nitrogen fertiliser use is gradually increasing, but there are still many farmers who have never used it. This is despite abundant evidence that grain protein and/or yield is depressed by N deficiency in many seasons on their farms. Its use is seen as expensive and risky.

Legumes in rotations are increasingly being viewed as an alternative source of N for cereals. Whereas grain legumes are well established cash crops, they do not leave much N behind. Except in the more favourable areas where lucerne is well adapted, there are major uncertainties about the technical and economic feasibility of pasture legume leys.

While these strategies are widely viewed by professional agriculturalists and some farmers as the most promising ingredients for good farming, only a few farmers appear to combine these imaginatively in the search for the 'ideal' system for managing soil water and nitrogen in this difficult environment. The situation is analogous to that in Africa. A major part of APSRU's research involves asking the 'why?' questions raised in our opening paragraph, and seeking answers in a number of ways.

APSRU's developing systems approach

APSRU's framework for R,D&E is shown in Figure 3. Although we have drawn heavily on Collinson's figure (Fig. 1), there are significant differences between APSRU's approach and Collinson's FSR processes. We see these as enhancements that both suit the needs of our farming and institutional environments, and utilise our particular research strengths.

We view farmers as our primary clients, but we are also concerned with the decision problems faced by a range of other decision-makers (Fig. 3 top) who have a stake in the performance of agricultural production systems and whose decisions influence, and are influenced by, farmers. These clients experience many of the same uncertainties as farmers, especially those concerning rainfall and prices.

Our aim is to contribute to better management and planning decisions (Fig. 3 right). In order to do this, we believe that professional agriculturalists must have sufficient understanding of the context and structure of decisions (Fig. 3 left). In general, farmers have evolved simpler rules for the management of key technological components that are as effective as the more complex rules generated by professional R,D&E (Cox et al. 1993a). In many cases, the farmers' rules are likely to be more effective because they recognise better the interdependence between the use of different components, and the open character of agricultural production systems. What we do needs to fit in with farmers' existing models or clearly demonstrate just how our way of doing things is better.

Simulation of agricultural production systems is an important ingredient of our approach (Fig. 3 bottom). Other papers in this workshop provide a comprehensive account of where we are in the development of this capability. We take a utilitarian approach to modelling: we use process models when and where this provides a research advantage. As was clear from the paper by Jones et al. (these Proceedings), we have been conducting experiments in farming systems research longer than we have been using models, but we found that experimentation has serious limitations in addressing many of the important issues.

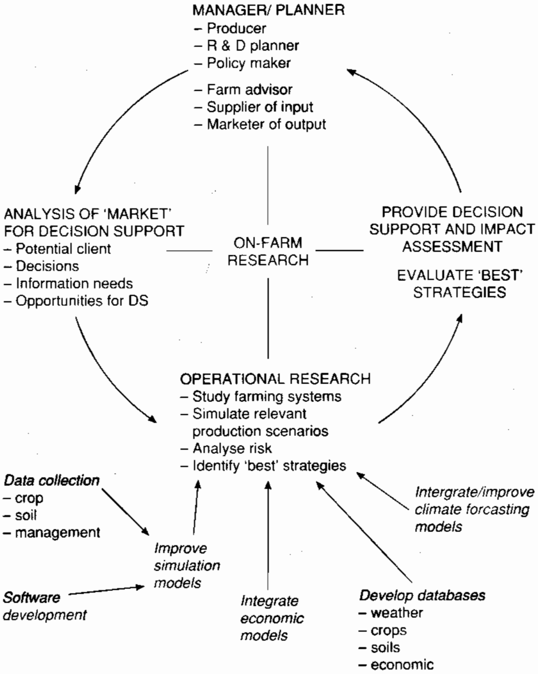

Figure 3. APSRU's framework for client-oriented R,D&E aimed at improving management of production and associated processes in an agricultural system.

An example is the difficulty of using experiments to assess the economics of N fertiliser where seasonal water supply is variable and unpredictable. Fertiliser response and net returns vary from strongly positive to strongly negative, and repetition for long sequences of years is needed to find an optimal strategy. Using historical weather records and models of maize and sorghum to predict grain yield under widely differing water and soil N conditions, Carberry et al. (1991) showed that the economic prospects for dryland cropping in a region of northern Australia are not sufficient to warrant further agricultural development. The provision of equivalent information experimentally would have required 400 000 plots (locations, times, years).

Recognition that simulation models can complement and add value to field experimentation in FSR has been recognised by others (Collinson, in Ruthenberg 1980; Anderson et al. 1985; Waddington 1992). But practitioners of FSR have judged, with rare exception, that the cost of getting models to a stage where they could do the job reliably was prohibitive (Collinson 1982). Like some before us (e.g. IBSNAT; Thornton 1991), we have decided to invest in the development of this capability. This has involved identifying the best biophysical models available with which to start and then testing and modifying these to improve prediction in the semi-arid tropics and subtropical regions in which we work. While adequate prediction of crop performance is critical to the utility of these models, we also have a strong focus on the simulation of soil processes (especially water balance, erosion and nitrogen balance) as they are influenced by management. We have built a novel software environment (APSIM) for developing, testing and using crop and other component models in systems research (McCown et al. 1993). This further reduces the overheads in using models in operational research within FSR (Fig. 1 centre).

We draw heavily from operational research in our systems approach (Fig. 3 bottom). This involves study of the performance of farming systems primarily in terms of production efficiencies, production and price risks, and cumulative effects on the soil resource. The emphasis is on the economic consequences of alternative actions over time. This is the starting point for addressing the question 'why don't more farmers invest more in soil fertility?'

Systems Research on Soil Fertility Management and Restoration

We are trying to find out, in the croplands of both Australia and Africa, whether farmers who appear to be underinvesting in soil enrichment understand their economics better than professional observers or whether they do not adequately appreciate the benefits of nutrient inputs and/or the penalties of continued exploitation of their soils. The answers have important implications for agricultural extension and for policy development. Achievement of this research aim is made difficult by spatial variation in circumstances between farms, and even between paddocks, which cause variation in benefits and opportunity costs. But an even greater obstacle to clarity is the variation in response to N inputs caused by unpredictable variation in seasonal rainfall.

Our approach in Australia to research on the management of soil fertility decline involves on-farm experimentation with farmers (Fig. 3 upper centre), especially on the costs and benefits of nitrogen inputs. Many farmers do experiments and even more have experiments in mind. We offer support for, and enhancements to, farmers' experiments, actual or latent. Both the content and the design of simple on-farm experiments are set by the farmers, subject to some revision after negotiation with researchers (Cox et al. 1993b). Treatments are negotiated with, and managed by, the farmers. Researchers help in planning, monitoring, interpretation of the results, and generalisation to other years and other sites. Experimental treatment areas are often simple splits of commercial paddocks. These usually involve N fertiliser rates in relation to paddock history, time of application, or crop species. Of particular interest are trends over time in responses to applied N following a legume crop or pasture, or a dry year when little or no N is used by the crop.

Although this is an attractive way of keeping research relevant to practice, there is no mystery as to why so little work of this kind has been done. First, no matter how obvious the treatment differences, variation in water supply among seasons and the interaction between N and water supply are so great that it is difficult to attach much strategic meaning to the outcomes during an inevitably short experimental period. Second, this approach violates the assumptions of classical statistical analysis required to isolate the yield variance attributable to treatments, i.e. replication and randomisation. The simulation model is used to compensate for theoretical deficiences in experimental designs. The model is configured for the soil properities and initial conditions, the crop cultivar, and for each management treatment successively run using weather data measured during the experiment. To the degree that the model successfully simulates the experimental results, both experimental and uncontrolled variation are also simulated by the model. If the experimental results are simulated satisfactorily, simulation of the experiment in all the years for which rainfall data are available provides a means of identifying superior management strategies.

A similar procedure provides a way to estimate the value for a decision about fertiliser use of the information in a seasonal weather forecast such as that based on the Southern Oscillation Index (SOI) (Hammer et al. 1991). This was demonstrated by McCown et al. (1991) for Response Farming in Kenya. The modelling approach provides a means of comparing management strategies in terms of long-term effects on productivity as influenced by erosion (Littleboy et al. 1992) or by changes in soil organic N (Probert et al. these Proceedings). While these last two effects are of interest to farmers with a long-term view of the productivity of their land, the broader community also has a stake in the way in which agricultural land is used, and is paying increased attention to these issues. In Australia, farmers are increasingly conscious of this pressure.

In Africa, several lines of research stand out as having high potential benefits for the amelioration of soil fertility decline.

1. Find cost-effective ways for more efficient capture, storage and use of manure on crops, taking into account the effects on the main source of manure, the pasturelands, which are also suffering nutrient depletion.

2. Use experiments to test various FASE (Fertiliser-Augmented Soil Enrichment) strategies (McCown et al. 1992) for combining applications of chemical fertiliser with manure, crop residues and composts; and use simulation to facilitate economic comparisons of these technologies over longer sequences of highly variable years.

3. Provide a modelling framework to extrapolate the results of research on biological strategies for soil enrichment. These include various legumes in rotations, legumes as intercrops, and trees in cropping systems.

4. Research the economics, including evaluation of the risks, of alternative soil enrichment strategies for different levels of inputs, and cost and price scenarios. Clients include farmers, R,D&E institutions and policy-makers.

5. Provide inputs to analyses that contribute to formulation of improved national policies on agricultural commodities, food security and fertilisers.

6. Communicate with policy-makers that no achievements in agricultural R,D&E can negate the need for some fertiliser inputs if farming is to be sustainable. And keep this on the policy agenda.

In APSRU, we are attempting to bring the complementary approaches of FSR and computer simulation together to address the deficiencies of both. Outstanding issues include: (1) the feasibility of constructing models of farming systems that are both sufficiently realistic for operations research and which reflect the way in which farmers see the problems of managing their systems; (2) the need to combine economic and ecological perspective; (3) the need to combine our new skills in crop modelling with more traditional economic models for operations research; (4) the need to develop and use these tools to improve communication between farmers and researchers rather than isolating them still further; and (5) to design and use tools that support intervention at different scales, ranging from individual farmers and farmer groups to local, regional and national policy.

Conclusion

It is clear that there is disappointment in both national and international R,D&E organisations that FSR has not resulted in greater change in the way farming is practiced in southern Africa. But it is most important that this be interpreted as limitations of an approach that has provided, and will continue to provide, a valuable framework for research. In Australia, we are using a version of the FSR framework to structure our research on the management of our agricultural production systems. We see the systems approach of Figure 3 as an adaptation which retains the strengths of both the anglophone and francophone FSR schools. It will become more effective as the operational research capabilities mature and as it becomes more firmly embedded in a participatory design process.

The success of Australia's APSRU approach requires models and thinking that are up to the task. Progress in development is evident from previous papers in this workshop. The main technical deficiencies of models for assisting FSR in southern Africa (Waddington 1992) are dealt with in APSIM (extreme N deficiency, rotations, intercropping, weed competition, and crop–livestock integration, as well as erosion). However, much work is needed to see how well these models predict over a wide range of circumstances. In Australia, networks of stakeholders in a better systems research approach are emerging to test and adapt these models and to develop innovative ways of using them to support both participatory on-farm experimentation with farmers and the management of experimental databases. Improved communication is an essential component of the approach.

Farming systems in northern Australia and much of Africa share important problems: declining soil fertility and productivity, and substantial risks associated with any private investment in soil fertility improvement. We believe that the eclectic approach we are developing is a reproducible and transferable research methodology that will be widely applicable both in Australia and Africa.

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ACIAR–SACCAR Workshop, Harare, 1993

Working Group Reports and Discussion

THREE working groups, each of 12-14 persons, were formed and chaired by Dr Nkwanyana (SACCAR), Dr Harmsen (ICRISAT) and Dr R. K. Jones (CSIRO). The groups concurrently discussed the following topics.

1. Defining aims and priorities for future research in dryland farming — after reviewing present activities.
2. How to develop research-extension-farmer linkages which could better utilise research output.
3. Needs for changes in OFR methods with a simulation modelling approach.
4. Training needs in the use of modelling techniques.
5. Opportunities for increased cooperation, both on a regional scale (east and southern Africa) and through broader international agencies.

Reports of each of the three groups were presented and discussed in plenary session. The following pages summarise the three reports and the discussion which was ably led by Drs McCown, Shumba and Waddington. The reports and discussions focused on smallholder farming systems in semi-arid areas of southern Africa.

1. Review of major problems of dryland farming in Southern Africa

Climatic problems

- — insufficient, variable total seasonal rainfall
- — unpredictable variations in rainfall patterns within seasons

Ecological problems (due to increasing human pressure on land)

- — deforestation
- — overgrazing
- — declining fallow periods
- — inappropriate farm decisions
- — unsustainable management of natural resources

Soil problems

- — erosion by wind and water
- — low inherent nutrient status (especially N and P), low fertiliser use, soil fertility decline
- — low organic matter and associated soil physical problems

Socioeconomic problems

- — limited cash resources
- — limited labour resources
- — limited draught power
- — poor education
- — insecurity of land tenure

Deficiencies in past research

- — lack of integration of climatic data in ongoing research
- — unexplained variations in results
- — lack of appropriate systems research on resource management

2. Current research directions

Crop improvement

Substantial progress has been made in producing improved hybrids and Open Pollinated Varieties (OPVs) of maize and of sorghum and millets. These have the potential for widespread impact on farm production, although production stability in the semi-arid regions is an elusive goal.

Agronomic practices

Varied results of experiments on fertiliser use, moisture conservation techniques, plant populations and intercropping all suggest a need for a more integrated, quantitative modelling approach. This would embrace the fluctuating levels of moisture-nutrients-plant populations and predict their interacting effects on crop growth and yield at widely different locations.

Improving research efficiency

Current assessments identified a general need to improve the impact of integrated research and its relevance to small-holder farmers. Also a need to reduce research costs and increase coverage of the problems of smallholder farmers was recognised. The introduction of a crop simulation modelling approach could have a useful place in upgrading the cost-effectiveness and overall impact of research in the drier agricultural areas of the region.

Sustainability

Future research will need to place greater emphasis on the design of sustainable farming systems, with a balanced approach to natural resources management.

SACCAR

SACCAR has been successful in coordinating commodity-based research e.g on crop improvement in sorghums and millets (SADC–ICRISAT), beans (SADC–CIAT) and cowpeas and groundnuts (SADC–IITA). The more holistic, farming systems adaptive-research approach that will be needed in the future may prove less amenable to regional coordination.

3. Aims and priorities for future research

Focus

Smallholder farming systems in seasonably dry (semi-arid) environments of southern Africa (SADC).

Goals

Improve overall natural resources management through an integrated approach:

- improve soil fertility management and arrest its decline
- reduce climatic and economic risks through better risk management
- improve soil and water conservation, with greater emphasis on water-use efficiency.

Strategies

- Improve research coordination
  - catalogue existing soil fertility projects and look for collaborative opportunities, e.g. through SPAAR, Rockefeller
  - promote networking through the SADC region.
- Promote the use of modelling techniques that will concentrate attention on soil fertility in the context of climatic uncertainties and economic risks, and so add value to on-farm research.
- Assess possible agricultural interventions in the context of overall sustainability and management of natural resources.
- Work together with end-users (farmers, extension workers, politicians and policy makers) in developing tools for deciding strategies and implementing R&D.
- Educate donors, policy makers, and politicians on the need for long-term support for soil fertility research and natural resource management, highlighting successful examples where possible.

Objectives

- Quantify the extent of (and rates of) nutrient depletion, organic matter decline and physical/structural changes in the soils of dryland cropping systems (on-farm, not on-station).
- Employ climatic variability and economic risk analyses to assess the integrated outcomes of possible interventions to arrest soil fertility decline.
- Improve crop management, plant genotypes and the effectiveness of rainfall in cereal and legume cropping systems to increase productivity and improve fertiliser use efficiency.
- Broaden the scope of soil fertility research away from a commodity or cropping focus to a broader natural resources management approach, possibly involving agroforestry and/or animal production systems.
- Build and maintain relevant databases (crops, climate, soil characteristics, vegetation) and develop modelling techniques to assist in reaching the listed objectives.
- Use the databases and appropriate simulation models to create various scenarios and options for use as decision tools by policy makers, e.g. policy analysis on fertiliser costs and supplies and grain prices. Use the same tools to guide credit organisations, e.g. AFC in Zimbabwe, in managing schemes relating to soil fertility and climatic risks in different agroecological zones. Governments could use models preferentially to target subsidies to smallholders in areas where they could have the greatest economic impact.
- Educate communities of the region on the reality of soil fertility decline and the opportunities for limitations to technical solutions, and the implications of current farming practices. Special targets would be:

- policy makers and politicians
- extension workers and farmers
- school students and teachers (with practical demonstrations of improved technologies, including fertilisers, and tree planting programs)

4. Research, extension and farmer linkages

- The problem in Zimbabwe and Malawi is the linear model, i.e. researchers–extension–farmers. Adaptive research teams in Malawi provide a means of linking farmers to the researchers. The committee for on-farm research and extension (COFRE) exists in Zimbabwe. These initiatives can be built upon.
- The problem of research-extension being divided into commodity teams and disciplinary groups has to be replaced by a more integrated approach.
- Training and visit workers (T&V) could bring back current problems to researchers for analysis using models (for short-term response). It is important to develop this linkage.
- By incorporating computer simulation into T&V programs the time it takes to answer farmers' problems (short-term response) could be reduced. Eventually, information could be provided on tactical management (through a Decision Support System). Extension workers will not expect to use the models themselves but will work with researchers. There is thus a need to train extension officers and tertiary students in the possibilities of the models.
- Modelling efforts at universities should be promoted.
- Models could therefore be used at four levels:
  - to assist learning and interaction between researchers
  - to strengthen adaptive/applied research
  - to influence policy decisions
  - to support extension in managing recommendations

5. Changes in OFR methods needed with a modelling approach

Benefits of a modelling initiative

- overcoming the site-specificity of conventional experimental approaches
- a long-term climatic perspective is possible
- overall resource management can be improved
- a scenario analysis can reduce the need for, and extent of, field experimentation
- radical new options can be examined, e.g. new systems
- linkages with networks are facilitated.

Costs–changes needed

- a few, very detailed, research station experiments in the development phase
- many 'intermediate' detailed experiments (IBSNAT, MDS approach) in the application phase
- there is still a benefit-cost advantage because, with rigorous selection of sites to represent broad production systems and agroecological zones, fewer experiments are needed to extrapolate across zones
- guidelines are needed, e.g. for rigorous collection of MDS from on-farm experiments and selection of sites
- a periodic reassessment of models is needed.

6. Training needs for a modelling approach

This can be organised through SACCAR.

Ongoing and planned activities

- course on use of models in agronomy organised by SADC–LWMP (with ACIAR/CSIRO involvement) in November 1993
- COMMCION networking with emphasis on creating a climatic database
- IFDC training on the use of CERES-Maize in Malawi and Alabama

Further needs

- build a university capacity to teach modelling and develop models in collaboration with NARS
- use of soil fertility depletion studies as a vehicle for training nationally and
- training of trainers using hands-on collaborative research and/or secondments with a modelling group
- long-term training opportunities in collection of MDS (technical training), software use and database development.

7. Scope for cooperation

National and regional (direct SACCAR involvement)

- assess what is being done currently
- improve communication (across departments and ministries)

- encourage use of common methodology, and sharing experiences and resources
- promote a modelling emphasis within the existing networks.

International

- catalogue and analyse current and planned activities
- improve Africa–Asia linkages mediated through IARCs
- assist transfer of modelling technology and networking
- Australia (ACIAR–CSIRO) could contribute training and continuing model development, exploiting its comparative advantage in research on semi-arid mixed farming systems.

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