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Project title

NUTRIENT SOURCING AND SOIL ORGANIC MATTER DYNAMICS IN MIXED-SPECIES FALLOWS OF FAST-GROWING LEGUME TREES

Project leader

Georg Cadisch and Ken Giller

Organisation

Department of Biology
Imperial College at Wye
Wye, Kent TN25 5AH

NRPSP Production System

High Potential
(formely Forestry/Agricultural Interface)

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CONTENTS

1. Executive Summary

The purpose of the project was to develop and promote improved soil fertility management systems in two target countries with most of the field work being carried out in western Kenya. The outputs of the project were i) A leaflet with practical guidelines on soil fertility improvements by fallows with particular reference to the direct, secondary (wood component, edible products, pest and risk mananagement) and economic benefits of mixed species fallow systems; ii) sources of nutrient aquisition by fallow species, e.g. from biological N_2 fixation and deep soil N capture, were quantified and complementarity of tree mixtures evaluated; iii) nutrient interactions of organic residues in tree mixtures were experimentally measured and reported and iv) a simplified mixed species fallow model was developed and an existing mechanistic agroforestry model was evaluated and improved (WaNuLCAS version 2.05), promoted and tested for the applicability in varies agroforestry applications in several countries during a workshop in Kenya. The concept and advantages of mixed species fallow have been promoted in Western Africa and Uganda and in the later country the counterpar has developed new approaches for their own fallow system in the sloppy hills of Kabale.

Several experiments have been conducted to evaluate and test improved mixed species fallows: Three field experiments at different sites to i) screen several potential species for the suitability as single fallows or components in mixed species fallows; ii) test the interactions between species in mixed fallows and iii) to evaluate options for increased secondary benefits, e.g. fodder offtake or cash cropping opportunities during fallow establishment. Biological N_2 fixation by leguminous fallow species (natural ^{15}N abundance), depth N capture (positioning labelled isotopes at various depths) and plant quality interactions were evaluated using new stable isotope approaches. Several field days have been organised for farmers and other interested groups. The existing WaNuLCAS model was tested and improved and alternative simpler approaches developed. As a result of the successful modelling workshop new demand for training has been received and has led to cross fertilization with activities under the FRP programme.

A close collaboration with the pilot project team which is evaluating agroforestry options with 1500 farmers has ensured a wider uptake and applicability of results.

2. Background

The number of poor people has been increasing in Sub-Saharan Africa in the past decade. Many people live in rural areas with an increasing population pressure and low agricultural productivity. Western Kenya has favourable conditions for agriculture with two cropping seasons and good rainfall (1200-1800 mm) particularly during the long rains (March-August). As a consequence the population density is high and landholdings are small while many men are now migrating to the town to seek employment. Pressure on land has led to continuous cropping of basic food crops such as maize and beans and yields are low and declining. The soils generally have a good physical structure but lack important plant nutrients. Phosphorus (P) is particularly limited with 80% of soil having resin extractable P levels of <3 mg P/kg (well below crop requirements) and research by KEFRI/KARI/ICRAF has been investigating fertilizer requirements and management options in these P fixing soils. Nitrogen (N) is another strongly limiting nutrient particularly once P and potassium (K) deficiencies have been alleviated. Chemical fertilizers can correct this situation but their high costs puts them beyond the reach of many farmers. To solve the fertility problem (or due to lack of labour) farmers leave land fallow for periods of 9 to 15 months. However, natural recovery of soil fertility with grass and broad leaved species is slow and hence regeneration of soil fertility limited.

While there are no alternatives to fertilizers for P and K to improve soil fertility, soils can be enriched in nitrogen by increasing the proportion of leguminous crops on their land. Legumes are capable of fixing substantial amounts of atmospheric N_2 when P and other constraints are alleviated. Impacts of legumes are largest when all the fixed N_2 is recycled as in the case of improved leguminous fallows. Thus short-term fallows of the native tree *Sesbania sesban* had become a central agroforestry technology for soil fertility recapitalization in Africa As a result of the large (2-3 fold) yield responses of subsequent maize crops *Sesbania* fallows have a high potential for adaptation. Recent surveys suggest that over 1500 farmers in western Kenya have adopted improved fallows or alternative agroforestry technologies (such as biomass transfer) and there is increasing interest from farmers in adjacent regions.

Sesbania sesban is known to nodulate and fix nitrogen freely given suitable conditions. Detailed root studies have demonstrated that *Sesbania* roots freely to depths greater than 4 m in soils of western Kenya. Whereas large amounts of nitrate-N accumulate under unfertilized maize crops due to leaching of N mineralized from the soil, little nitrate-N is found at depth beneath the *Sesbania* fallows. However there is little direct evidence to indicate how much N actually comes from N_2-fixation (to balance N removal by subsequent crops), or to what extent nitrate-N is captured from depth or simply prevented from leaching from the surface soil horizons. Also the N-rich litter of *Sesbania* results in effective N supply and substantial responses in crop growth but the fast N supply is not in synchrony with crop demand which may result in substantial losses during the early crop phase and such litter contributes little to building the soil organic matter status.

Although there is widespread current interest in *Sesbania* fallows, a number of potential problems associated with reliance on a single species have also been highlighted. In particular the susceptibility of *Sesbania* to attack by root-knot nematodes and by the *Mesoplatys* beetle is causing increasing concern, particularly in regions where important crops are susceptible (for instance tobacco in Malawi) where *Sesbania* may serve as a secondary host. Other problems include the intense insect damage which often limits seed production in *Sesbania*. Single provenances have been widely propagated and disseminated to farmers leading to concerns should new pests and diseases arise. Thus the reliance on one species not only increases the risk associated with pests and diseases but also with adverse weather conditions or establishment failure. By increasing the diversity of species and by using mixed species fallows farmers risks could be substantially reduced. Additionally, mixing species utilizing different above- and below-ground resource niches may lead to more efficient nutrient capture. Mixed species fallows also can provide a wider range of additional benefits such as wood, fodder or edible products.

3. Project Purpose

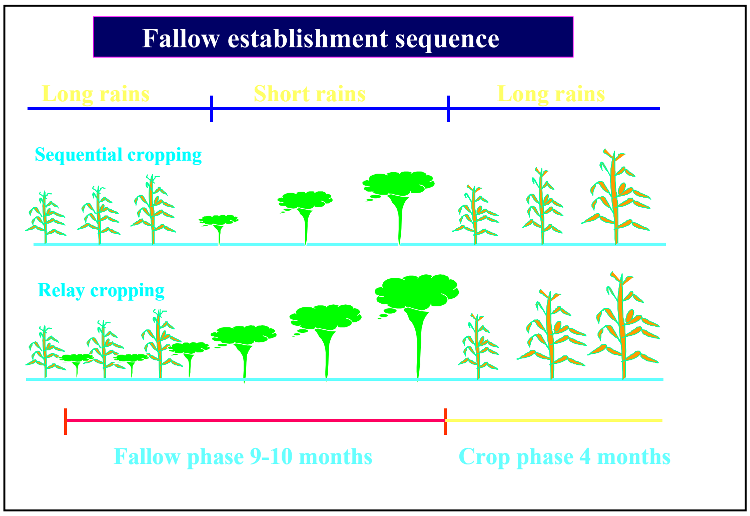
The purpose of this project was to develop and promote improved soil fertility management systems. We proposed to assess alternative mixed fallow systems on farmers' fields and to improve an existing biophysical model in order to assess a wider range of applications. The goal was to identify mixed fallow species combinations with increased nutrient acquisition efficiencies that also offer a wide range of alternative economic benefits to farmers (wood, fodder, food) thereby increasing the attractiveness of improved fallow systems.

4. Outputs

4.1 Guidelines on soil fertility improvements by mixed species fallow systems

The experience gained from several field experiments as well as from inputs from farmers, extensionists and researchers has led to the following guidelines:

4.1.1 Establishment of short-term improved tree/shrub fallows



Improved fallows should produce a large amount of recyclable biomass during the short rains (the less productive season). To increase fallow length and hence fallow biomass productivity the improved fallow species are best undersown into the long rain maize crop. The timing of the fallow planting is crucial and depends on the establishment speed of the legume. Species which establish slowly, e.g. *Sesbania sesban*, can be planted after the first weeding while faster growing species such as *Crotalaria grahamiana* are sown after the second weeding. Following these guidelines no negative effect of the fallow species on the intercropped maize have been observed.

4.1.2 Maximising fallow yields and secondary benefits

In order to increase farmers choice of improved woody fallow species we tested a range of new species for their suitability to the soil and climatic conditions in western Kenya. *Crotalaria grahamiana* and *Tephrosia vogelii* were superior to the local *Sesbania sesban* in relation to production of recyclable biomass, which included leaves, pods and litter components (Table 1).

Table 1: Production of recyclable foliage biomass yields and wood components of promising leguminous fallow species for western Kenya as affected by fallow age.

Species	9 month old fallow[1]			15 months old falow[2]		
	Foliage/litter biomass	Wood	Total N	Foliage biomass	Wood/forage	Total N
			Kg /ha			
Cajanus cajan	3400	5700	148	2700-4500	2500-13500	70-120
Crotalaria grahamiana	5200	5900	178	6400-10300	5700-10300	149-267
Sesbania sesban	2200	8000	100	2800-3200	9700-16700	78-97
Tephrosia vogelii	3900	9400	150	nd	nd	nd
Macroptilium atropurpureum	2100	0	145	5400-12800	0	102-141
Natural Fallow	6000		76	4100-7600	0	49

nd not determined; [1] using seedlings 1997/98; [2] yields at two locations 1998/1999

Crotalaria in particular has been appreciated by farmers, not only due to its high biomass production and easy establishment, but also due to the proliferous seed production and good weed suppression capabilities. The experiments also showed that sesbania provided the highest wood component together with tephrosia. Fallow wood is an essential part of the secondary benefits of fallows and much appreciated by women as a fuelwood.

Macroptilium atropurpureum (siratro) also performed reasonably well and was singled out by farmers for the benefit of fooder provision for their livestock. However, if all the biomass of siratro would be used as fodder than there might be little residual benefits. Thus its ability to be sown as an understory component into the tree/shrub species was tested (see below).

Fallow productivity and wood production was clearly dependent on the age of the fallow and the growing conditions, mainly rainfall (Table 1). Minimum time for short-term improved fallows was 9 months which produced sufficient biomass when establishment was good and rainfall was sufficient. Improved fallows are intended to replace the existing natural fallows that are planted during the less productive of the two seasons which is prone to shortage of rainfall for food production. In the second year we experienced a severe drought between November 1998-January 1999 which resulted in maize crop failure but also strongly reduced biomass production of fallows. Hence fallow time was increased for a further season in order to provide sufficient benefits and justify labour inputs into fallow establishment.

4.1.3 Residual benefits of improved fallows

Maize yields immediately after improved fallows were twice the maize yields after natural fallows and also substantially higher than with continuous maize cropping. Since maize received complementary fertilization with phosphorus and potassium the positive yield effect was mainly due to nitrogen benefits and potentially soil structural improvements. Fallow benefits did not necessarily follow biomass yield of the recyclable fallow component (Table 1), e.g. sesbania fallow resulted in equal benefits to crotalaria despite lower recyclable biomass yields. More important than species differences was the age of the fallow. 15 months old fallows resulted in substantially better yields than 9 month old fallows with yield increases over continuous maize of over 3 t/ha in the first crop after the fallow. Short duration fallows also had much reduced maize benefits in the second cropping cycle after the fallow while in the longer term fallows most of the fallows still produced as much as maize fertilized with 100 kg N/ha. Maize yields after the 15 month old fallows is still being monitored by the Kenyan counterpart (KEFRI) to establish the long term benefits. Maize yields in the first trial (9 month old fallow) were affected by striga and termites which may also partly account for the lower benefits.

Table 2: Residual N benefits of fallows or continuous maize cropping on grain yield of maize[3] in western Kenya

Fallow species	9 month old fallow[1]			15monts old fallow[2]	
	1st crop	2nd crop	1-4 crops	1st crop	2nd crop
			.t grain/ha		
Cajanus cajan	3.0	1.4	9.5	4.6-5.2	3.4-5.1
Crotalaria graham.	3.1	0.9	7.4	5.5-5.9	5.2-6.7
Sesbania sesban	3.6	1.1	8.8	5.6-5.9	5.8-6.3
Tephrosia vogelii	2.5	1.1	7.9	nd	nd
Macroptilium atrop.	2.4	1.0	7.8	5.5-6.3	5.2-7.2
Natural fallow	1.3	0.9	6.0	1.3-3.5	4.1-5.2
Continuous maize	1.9	0.7	6.9	1.7	2.5-3.8
Continuous maize + 100 kgN/ha				4.5-4.8	5.0-6.4

nd = not determined; 1 = harvest1998; 2 = harvest at two locations 1999; 3 = fertilized with P and K

The results clearly demonstrated that 9 month old fallows provide positive benefits for maize production in western Kenya, however for increased and improved long-term impact 15 month old fallows were superior.

4.1.4 Why mixed species fallows ?

The following guidelines for mixed species fallows were derived from our experiences and have also been summarized in a leaflet which is currently under evaluation by the partner organizations KEFRI/KARI/ICRAF. The conclusions and recommendations have also been incorporated in a booklet currently under development for extensionists by these organisations.

Mixed species fallows provide a range of advantages over single species fallows:
Insurance: Improved single species fallows might fail due to adverse weather conditions (drought, logging), establishment failure (poor seed quality or lack of proper seed pre-treatment). In mixed species fallows, the more resistant species will at least partially compensate for the low yield or failure of the susceptible species.
(This effect has been observed in our second experiment where sesbania established slowly and crotalaria was able to compensate in part for the reduced growth).

Multiple use of byproducts: Sesbania fallows produce a large proportion of wood (80% of biomass) which is very much appreciated by farmers which are deprived of firewood. However, the partitioning of resources into wood leads to a lower amount of foliage returned to the soil and leads to export of fixed nitrogen from the plot (30%, see Appendix). Mixing sesbania with crotalaria (Photo 1) ensures both the benefit of wood as well as a large production of foliage biomass.

Photo 1: Nine month old *Sesbania sesban – Crotalaria grahamiana* fallow mixture in western Kenya.

Improved utilization of available resources: The tall sesbania with an open canopy mixes well with the lower but dense growing crotalaria (Photo 1). This potentially also leads to a better light utilization and the deep root system of sesbania leads also to a better subsoil mineral nitrogen exploration.

Maximization of fallow yields: Yields do not necessarily increase under non-stress conditions in species mixtures. However, where siratro was undersown under sesbania, cajanus and tephrosia larger yields were observed (Fig. 1).

Photo 2: *Sesbania sesban – Macroptilium atropurpureum* (siratro) mixed fallow in western Kenya.

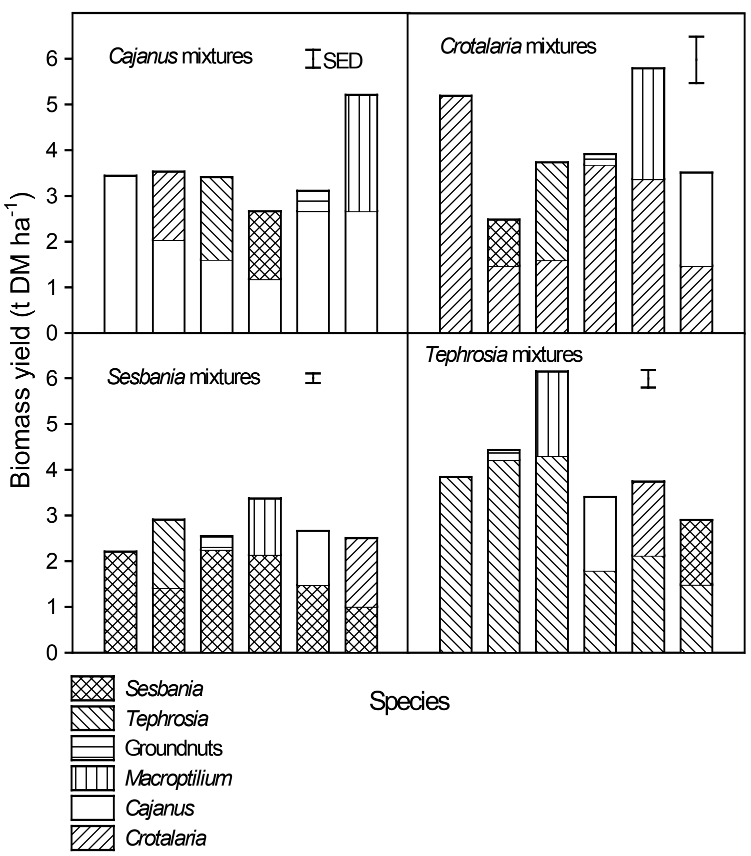


Figure 1: Folliage biomass yields of nine month old improved single and mixed species fallows in western Kenya.

Prolonged residual effect: Mixing species of different leaf qualities and decomposition rates may reduce nitrogen losses and extend the time of residual effect and hence the overall soil fertility benefit.

(However, fallow species currently available do not provide a large range of leaf residue qualities. Alternatively, crotalaria produced substantial more recyclable litter and pods which were of lower quality. *Calliandra calothyrsus*, a border hedge, had resistant residues that showed a distinctive positive pattern in soil organic matter formation. Although both of these examples showed increased contribution to long-term soil fertility indices, the medium-term net benefits in maize yields were relatively small (see Table 2) and the long-term benefits still need to be evaluated).

Photo 3: Pest attack on Crotolaria in Western Kenya.

Reduced pest pressure: The introduction of new species to the area has led also to the build up of new pests e.g. caterpilar attacks on *Crotalaria grahamiana* are now more often observed. Recent evidence even suggests that the indigenous *Sesbania sesban* together with *Tephrosia vogelii* is a host for root-knot nematodes (that are nodule like but are not easily rubbed off) which affect also common beans and hence it is recommended not to plant beans in the first season after these fallows. Mixed species fallows are less susceptible to such occurences. Thus increasing the biodiversity of the system by using mixed species fallows is essential to ensure sustainability of the production system.

4.1.5 Matching soil fertility managemnent with farmers needs: Recommendations

1. For recycling of deep soil N, high inputs from biological nitrogen fixation and a wood component: *Sesbania sesban* + *Crotalaia grahamiana* **(**Photo 1)

2. To maximise fallow biomass production or to provide a fooder (siratro, up to 2 t/ha in 6 months) component: *Sesbania sesban* + *Macroptilium atropurpurem* (siratro) (Photo 2)

3. For producing a food crop during the fallow period: *Sesbania sesban* + groundnut (Photo 4) or *Cajanus cajan* + groundnut. As sesbania and cajanus have an open canopy during the early establishment a short duration groundnut variety can be planted in between the sesbania rows during the short rains (groundnut yield is about half of pure groundnut stands, full details see in Appendix).

Photo 4: Groundnut undersown into *Sesbania sesban* fallow in western Kenya.

Farmers are however encouraged to test other combination for their suitability for their particular needs. To ensure optimal use of the fallow the subsequent maize should be fertilized with 50 kg P/ha and 50 kg K/ha as most soils of Western Kenya are strongly P deficient and some are K deficient.

If P is already applied to the maize crop before the fallow establishment then both will profit from the application.

4.1.6 Are mixed species fallows economically viable?

Recommended minimum fallow duration is about 9 months with larger yield benefits obtained for longer duration fallows. The costs of fallow establishment and loss of a maize crop are offset by the increased grain yield after the fallow, reduced labor and potential savings in N fertilizer and thereby improving the economic returns.

Table 3: Increase in maize grain yield or economic benefit over yield of continuous maize control following improved fallows in Western Kenya. (values in brackets are increased benefits in 2-4th crop after fallow).

Species	Byproduct	Increase in maize grain yield (t/ha)	Economic benefit KSh/ha/3 seasons
Sesbania + crotalaria	Wood 4-10 t/ha	1-3 t/ha (0.5-1)	15000
Sesbania + siratro	Fodder 1-4 t/ha	1-3 t/ha (0.5-1)	20000
Sesbania + groundnut	Groundnut 0.2 t/ha	1-2 t/ha (0.5-1)	23000

4.2 Sources of nutrient acquisition quantified and complementarity of tree mixtures assessed

4.2.1 N_2 fixation and N balance

In order to assess the contribution of legumes to the N balance of smallholder farming systems inwestern Kenya N_2 fixation in legumes was assessed using the natural ^{15}N abundance method and a range of non-fixing plants (maize, natural weeds, *Tithonia diversifolia* and *Lantana camara*) in 1998 (see Annex). In 1997 legumes had been established by seedlings and inoculated with USDA rhizobial strains.

Tree/shrub legumes obtained more than 50% of their N from N_2 fixation (Table 4). The proportion of N_2 fixed was related to the fallow N yield. Thus the general hypothesis that N_2 fixation increases with increased biomass production in effective symbiotic systems was largely confirmed by a positive linear relationship between fallow N yield and the proportion or amount of N_2 fixed. Crotalaria obtained the highest proportion of its N from N_2 fixation (74%) and had the highest N accumulation and hence fixed most N (132 kg N/ha/9 months). The fallow N balance can be used as a **sustainability indicator of fallows**:

N balance = Amount of N_2 fixed – N offtake (wood)

While all fallows had a positive N balance the size of the N balance was heavily influenced by the proportion of N exported in wood. In sesbania around 33% of the N accumulated in the fallow is exported from the field as wood leaving only a moderate positive N balance of 21 kgN/ha. In contrast the wood component in crotalaria was only 15% giving rise to a positive N balance of 115 kgN/ha sufficient to account for the extraction of N in 2-3 maize harvests.

Table 4. Net N contribution of 9 months old legume fallows to the overall soil N economy.

Fallow species	Above-ground N[1]	N source			N off-take (wood)[1]	N balance[2]
		N_2 fixation		Soil		
		%	(kg ha^{-1})			
Crotalaria grahamiana	178	74	132	46	27	115
Tephrosia vogelii	150	66	99	51	32	67
Cajanus cajan	147	65	96	51	37	59
Sesbania sesban	101	57	58	43	37	21
Macroptilium atropurpureum	144	47	63	81	0	63
Calliandra calothyrsus	56	27	15	41	8	7
Arachis hypogaea	18	45	8	10	0	8

In the second experiment we evaluated if N_2 fixation is increased in mixed fallow species associations. The legumes were sown directly in 1998 but were not inoculated and hence depended on indigenous rhizobia in 1998. The hypothesis that N_2 fixation increases in mixtures did not generally hold (Table 5). N_2 fixation in mixtures increased only when the mixture out-performed the single species fallows as in the case of the sesbania+pigeonpea (*Cajanus cajan* (L.) Millsp.) mixture where both the proportion and amount of N_2 fixed were larger in the mixed system. In the other mixtures sesbania suffered from competition exerted by the fast growing crotalaria due to its slow establishment. Hence, total biomass production in these mixtures was less than in sole crotalaria fallows resulting in less demand for soil N and hence reduced N_2 fixation. Evidence of stimulation of the proportion of N derived from N_2 fixation in mixtures (but not necessarily amount of N_2 fixed) has been observed where legumes were grown in the neighbourhood of non-fixing crops, e.g maize-bean intercrops and hedgerows. However, where a successful fallow mixture exploits more soil N resources than the monocrops a reduced need for complementary N acquisition through N_2 fixation could be expected.

Table 5: Comparison of N_2 fixation of nine months old single and mixed species fallows in western Kenya 1999.

	N derived from N_2 fixation			N derived from soil
	(%)	(kg N ha^{-1} species^{-1})	(kg N ha^{-1} system^{-1})	(kg N ha^{-1} system^{-1})
Sesbania:				
Sesbania alone	30	12[1]	23	61
Sesbania+crotalaria	14	2	46	87
Sesbania+macroptilium	29	12	22	53
Sesbania+cajanus	44	10	108	49
Crotalaria:				
Crotalaria alone	50	57[1]	113	117
Sesbania+crotalaria	36	44	46	87
Cajanus:				
Cajanus alone	62	36[1]	71	48
Cajanus+sesbania	73	98	108	49
S.E.D	10***	21**	25**	27*
CV (%)	38	64	54	51

[1] at same density as in mixture; *, **, *** = significant at P<0.05, P<0.01, P<0.001

4.2.2 Soil mineral N acquisition

Root sampling in sesbania, crotalaria and sesbania+crotalaria fallows was conducted on a profile wall exposed from a pit dug in one of the corners of each plot between 27th February and 1st March 1998. Roots were washed from monolith soil samples of 2250 cm^3, sieved (0.5 mm mesh) and root length measured using a Hewlett Packard scanner and Aldus photostyler image analysis software.

Root distributions within the soil profile showed that most roots were concentrated within the top 0.3 m. Crotalaria had the highest topsoil root length density but subsoil root length density was

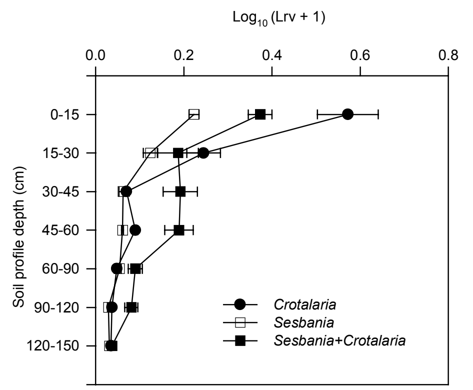


Fig. 2: Root length densities of improved fallows in western Kenya.

not different between sesbania and crotalaria (Figure 2). The root length density of the mixed species fallow in the topsoil corresponded approximately to the average of the single species values. However, there was clear evidence of changes in subsoil rooting patterns in the mixed species fallow. Root length density of the mixed species fallow below 0.3 m exceeded those of either single species. As a result of this interaction total subsoil (0.3-1.5 m depth) root length of the sesbania-crotalaria fallow was 3.5 km m^{-2} which was significantly higher than that of pure sesbania (1.3 km m^{-2}) or pure crotalaria (1.5 km m^{-2}). Full details of results can be found in the Annex. The results clearly demonstrated an increase in resource exploration of the subsoil due to increased competition in the topsoil and gave evidence of the plasticity of the root system. Other studies have suggested root plasticity effects in relation to environmental conditions or soil fertility effects and it has been suggested that species from a poor habitat tend to have higher root plasticity than species occurring in nutrient richer habitats due to a higher spatial heterogeneity of nutrient availability in nutrient poor sites. Combining species where at least one component has a high root plasticity may be crucial in taking full advantage of subsoil resources in short duration fallows.

Rooting patterns are not necessarily linked to patterns of root activity as these change with time and environmental stress. Thus we tested root N uptake activity at different depths in single and mixed species fallows (sesbania+crotalaria and sesbania+macroptilium) by placing ^{15}N isotopes at 0.15 m and 1 m (1998) or 2 m (1999). The isotope was applied in February of 1998 and 1999 at an application rate of 2 g N per application site (5 tubes) at an enrichment of around 30 atom % ^{15}N.

Substantial amounts of mineral N resources were found in the subsoil, e.g. 83 kg N ha^{-1} at 0.5-2 m with approx. 60% in the form of nitrate. Subsoil N exploration by fallows increased with time after isotope application. While at the start of the ^{15}N injection less than 10% of N was obtained from sources below 1 m this increased to >30% after 5 weeks. This was probably both due to the developing root system with plant age and size and also in response to the onset of a moderate drought. Hence too short fallows or slow establishment due to environmental stress may limit full exploitation of resources from deeper soil horizons. ^{15}N recovery data from the harvest in 1998 confirmed that sesbania had an active deep rooted system obtaining around 40% of its soil N from deeper than 1 m in 1998 and between 6-14% from >2 m in 1999 compared with topsoil N at 0.15 m (Table 6). The proportion of subsoil N uptake in 1998 at 1 m was higher in sesbania than in crotalaria. However, this was reversed in 1999 when crotalaria obtained a larger proportion of N from the subsoil than sesbania.

Table 6: Subsoil root ^{15}N uptake activity relative to topsoil (0.15 m) activity of 9 month old *Sesbania sesban* grown as single and mixed species fallows in western Kenya.

	Subsoil N uptake (%)	
	1998	1999
	1m	2m
Sesbania alone	na	14
Sesbania mixture		
Sesbania	42	6
Crotalaria	22	31
Sesbania undersown		
Sesbania	46	9
Macroptilium	42	10
S.E.D	9*	21*
CV (%)	31	46

na = not available; * = significant at P<0.05

The reason for this was not the difference in depth of ^{15}N placements but because sesbania established slowly in 1999 while crotalaria grew exceptionally well, competing strongly with sesbania in the early part of the season and resulting in reduced subsoil root activity of sesbania. On the other hand the fast growing crotalaria had a large nutrient demand, and root plasticity allowed it to root deeper and exploiting subsoil resources in this second year of establishment. The increased efficiency of mixed species fallows in extracting soil N resources was also demonstrated by the depletion in soil nitrate N over the fallow period, e.g. nitrate content under the sesbania+crotalaria mixture decreased by approx. 23 kg N ha^{-1} more over the whole soil profile of 2 m compared with the single species fallows (see Annex for full details). An important consideration is that subsoil nitrate bulges that occur in soils in western Kenya, appear to be a finite source, compared with situations where N is present in groundwater or where N is re-charged by lateral water flow fuelled from upslope leaching. Large subsoil nitrate accumulations occur after crop failure in Western Kenya. Soils in the region have an anion exchange capacity in the subsoil that assists in retarding movement of the nitrate leached below the maize root zone. The length of time needed for re-charging of these bulges is not known, but it appears that subsoil N bulges cannot be regarded as sustainable resources in efficient cropping systems. Thus fallows need to be able to access other N resources such as the ‘unlimited’ resources of atmospheric N_2 through the process of biological N_2 fixation.

4.3 Nutrient interactions of organic residues in tree mixtures measured

The fate and availability of plant available N in the soil depends on residue decomposition and subsequent net mineralization-immobilization patterns, and is influenced by litter quality of the applied residue as well as by environmental conditions. Low quality residues with high concentration of lignin, high active polyphenols have been associated with slow release of N that may not be sufficient for crop growth whereas high quality residues (high N, low lignin, low polyphenols) may release N too fast to be synchronized with crop requirements. Therefore we tested if mixing of plant materials of different qualities will provide a release N which is in better synchrony with plant demand and will maximize residue N utilization efficiency.

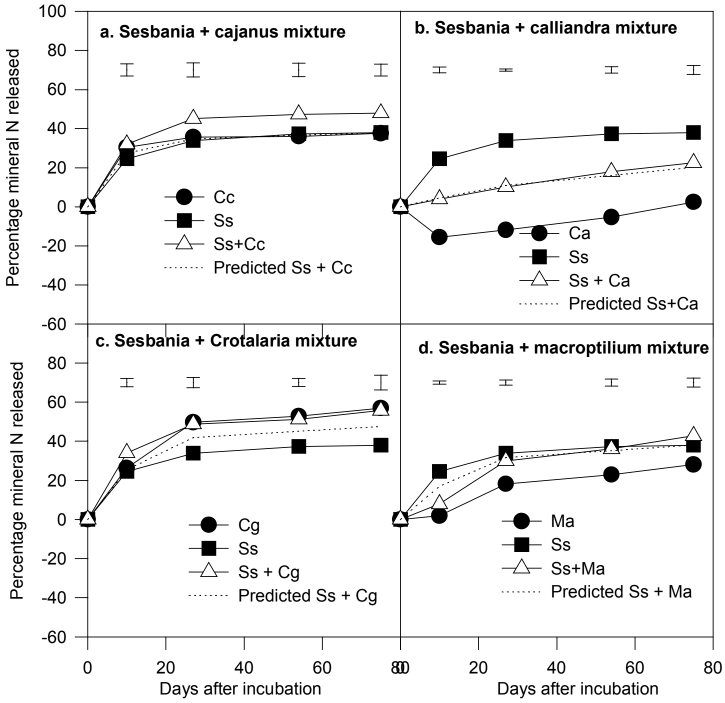
Table 7: Fallow residue chemical quality attributes and relative leaves to petioles ratio used.

Treatment	Leave:petiole ratio	N %	C %	Lignin %	TEP %	PBC
Cajanus	0.96:0.04	3.93	45.8	21.0	3.8	41
Sesbania	0.85:0.15	3.44	44.6	9.3	3.1	53
Macroptilium	0.55:0.45	3.05	43.4	10.3	1.7	24
Crotalaria	0.91:0.09	3.12	41.9	4.8	1.9	18
Calliandra	0.75:0.25	2.71	46.4	9.8	13.1	287

N = Nitrogen, C = Carbon, TEP = Total extractable polyphenols, PBC = Protein binding capacity.

To test if significant interactions occur when foliage materials of different fallow species were mixed together an incubation study was performed. The cummulative mineral N recovered from the soil amended with fallow residues varied significantly among different species both in the pure and mixed treatments (Figure 3). In the soil amended with single residues, the amount N recovered from the residue varied from 2 % for calliandra and 56 % for crotalaria at day 75. The amount of N recovered from calliandra was lower than that from unamended soil upto 54 days showing a net immobilization due to the high amounts of active polyphenols. Macroptilium also released significantly lower amounts of N as compared to the other species. However, only minor interactions (difference between mixed species mineralization pattern and dashed line) occurred in the mixed species treatments suggesting that there is limited scope for regulating N release by mixing these species.

Figure 3: Percentage of N released from foliage of single and mixed species as mineral-N in soil under leaching condition. Vertical bars represent standard error of differences between treatment means



The residual benefit effects of mixed species fallows over single species fallows was subsequently evaluated in the field. Mixed and single species fallows of sesbania, cajanus, crotalaria, macroptilium and calliandra were set up in 1998 on two farms. After 15 months fallow biomass was incorporated into the soil and maize crops were established.

At Owano farm sesbania+macroptilium and sesbania-crotalaria mixtures in the first maize crop after the fallows (SR1999) showed a slight positive interaction compared to maize after single species fallows, but in the LR2000 no interactions between these treatments were observed (Figure 4). Sesbania-calliandra mixtures and sesbania alone led to significantly higher maize yields than calliandra alone but the apparent interaction in the mixed species has to be viewed in the context of the higher fallow biomass applied in this mixtere where calliandra was added additionally to the sesbania foliage from an outside hedge source found on the farmers land. Subsequent harvests will show if mixed species fallows provide an improved long-term benefit compared to single species fallows. From the currently available short-term results there seems to be little maize yield advantage in mixed species fallows. Thus in order to be attractive to farmers mixed species fallows most provide other benefits (e.g. reduced risk, additional benefits of wood/fodder see above).

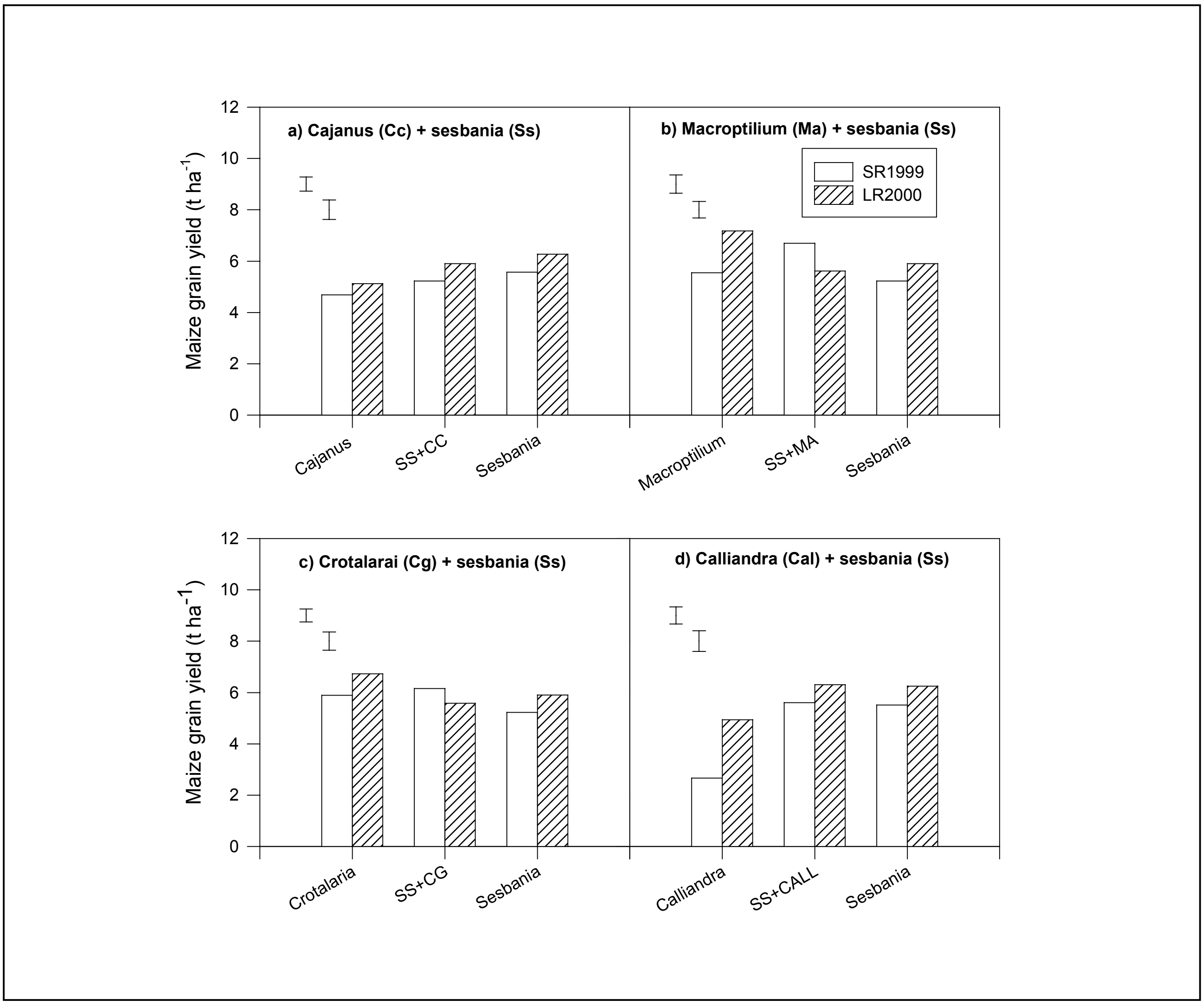


Figure 4: Effect of pure and mixed species interaction of maize grain yield at Owano farm. Note: in the sesbania-calliandra mixture the foliage of calliandra has been added from an external source (calliandra border hedge) at the same amount as the sesbania residue.

In order to assess the fate of residue N in crops and in the soil ^{15}N labelled residues were produced in separate plots. The ^{15}N labelled material was then applied in microplots in the field experiment at Owano farm.

^{15}N recovery from fallow residues in maize amounted to 15% of the applied labelled N in SR1999. Maize recovered significantly less N from the single calliandra residue treatments (3-6%). About 70 % of the residue N recovered by maize was contained in the maize grain in SR1999. In LR2000, there were no significant differences in residue-N recovery among the different single and mixed residue treatments. The percentage ^{15}N recovery of residue N by maize was significantly correlated with maize grain yield.

In LR2000 legume-^{15}N recovery in the soil at 0-15 cm depth ranged from 20 to 80% and was significantly higher for calliandra both in single and mixed treatment (Figure 5). Cumulative recoveries at lower soil depths (to 1m) were less than 20%. The high recovery of N of calliandra in the soil confirms the high contribution of polyphenol rich residues to soil organic matter build up. However, the moderate effect on maize yields suggests that this N is not becoming available in significant amounts in a time frame important to farmers.

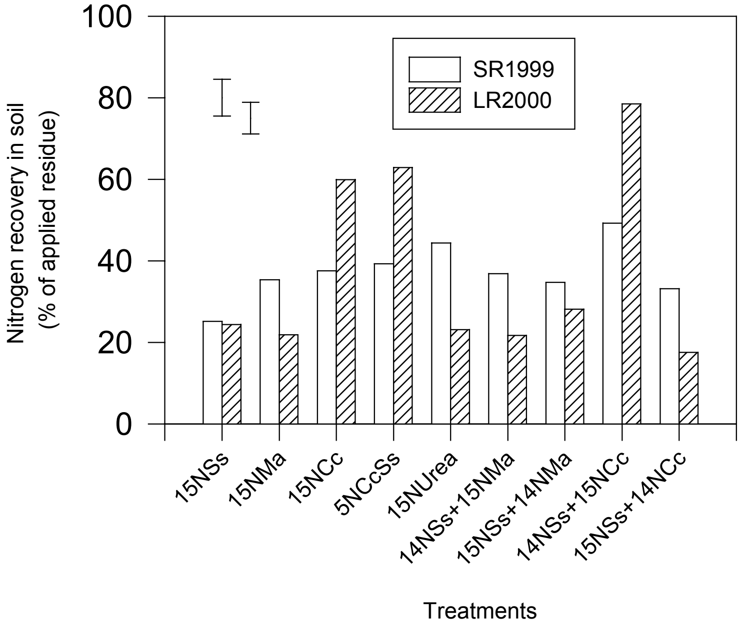


Figure 5: Proportion of the amount of applied residue N remaining in the to 0-15 cm in different ^{15}N labelled fallow treatments after two cropping seasons. Bars indicate the SED (P = 0.05) for standard error of the difference of means. (Ss = sesbania; Ma = siratro; Cc = calliandra; urea = 100 kg N/ha)

4.4 Models and sustainability of fallows evaluated and improved

A focal point in the analysis of where and how agroforestry systems work is still whether or not tree-crop systems can utilize resources of light, water and/or nutrients which would not be available in a simpler crop system. A fair amount of detail in the description of above- and belowground resource capture by the component species is needed to evaluate both competition and complementarity of mixed species fallows. In view of this increasing complexity the models discussed here are for assessing strategic options of agroforestry systems rather than for use by farmers or extensionists. Nevertheless, apart from the process orientated WaNuLCAS (Water, Nutrients, Light Capture in Agroforestry Systems) model discussed below we have also tried to devise a simpler model that captures the essential features for assessing nutrient capture in mixed species systems.

4.4.1 Simplified model of below-ground resource capture and complementarity in mixed species fallow systems

Resource acquisition of water and nutrients by plants is directly related to above-ground demand and to competition and complementarity effects. Below-ground resource capture of a mixed species fallow system (*Rcsys*, kg ha^{-1}) can thus be described as:

$$RCsys = D - C + A + BNF$$

where *D* is the resource demand (kg ha^{-1}), *C* the competition and A the advantage or complementarity effect and BNF inputs from biological N_2 fixation. *D* in a mixed 50/50 species system can be described as:

$$D = \frac{(D1 + D2)}{2} \text{ x } (1 + \Delta LAI)$$

where *D1* and *D2* are the resource demand of sole crop species 1 and 2 and where *ΔLAI* is the additional leaf area index in mixtures compared to monocultures and where the latter defines the potential for increased below-ground resource capture. Our results showed that fallow N accumulation was not significantly increased in substitution designs (e.g. in the 50/50 sesbania-cajanus mixed fallow), compared with the more productive monocrop species, likely as a result of a *ΔLAI* close to 0. Improved yields were however obtained where the *ΔLAI* increased as in the case where a second species was undersown, e.g. sesbania-siratro fallow (e.g. *ΔLAI* close to 1). Fallow duration is very important in increasing resource demand and ultimately resource capture and the overall benefit of the fallow and would act through an increased time dependent *D*. Competition between plant species is only a problem when the effects are greater than those of intra-specific competition and particularly if it affects the more vigorously growing species. Here we simplify and consider below-ground competition as occurring mainly in the topsoil (*C*) and complementary effects mainly as originating from increased subsoil resource exploitation (*A*). Below-ground resource competition in mixed species systems with complementary root systems (e.g. one species is deeper rooted) can be thus described as:

$$C = D - Rtop$$

where *Rtop* is the available amount of resources in the topsoil (kg ha^{-1}) and where *C* is zero when *D* < *Rtop*. Mixed species can have an advantage over single species where they allow exploitation of otherwise under-utilized or non-accessible resources. The potential added complementarity effect in the case of subsoil nutrients depends on the increase in the nutrient uptake potential (*Up sub*) from that soil layer and on the amount of resource available. *Up sub* depends on the proportion of subsoil roots, the nutrient demand and a root plasticity (*P*) effect (e.g. ratio of root length with mixed species over average of single species fallow) in response to resource competition in the upper soil layer:

$$Up\,sub = \frac{Lrv\,sub}{Lrv\,tot} \text{ x } D \text{ x } P$$

where *Lrv* is the average root length density (cm cm^{-3}) of the species in pure stands and *sub*, *tot* denote subsoil and total *Lrv*. Thus *P* traits of species are an important factor of increased subsoil N uptake if subsoil resources are available. Although root architecture is a trait determined by the interaction of the genetic potential of a species with the environment, certain species have been known to increase their subsoil root activity in response to competition in upper soil layer, e.g. root plasticity increased *Up sub* by a factor of 2.5 in mixed sesbania-crotalaria fallows (Figure 2). It is postulated that where *Rtop* > *D*, *P* is 1. The maximum added complementarity effect (*Amax*) is primarily a function of the amount of resources available and is equal to the effectively available subsoil resource and in the case of subsoil nutrients under nutrient limiting condition is:

$$A\max = Rsub \text{ x } \alpha$$

where α denotes the efficiency with which a resource can be utilized, α itself depends on the particular nutrient and the root length density and nutrient diffusion coefficient (*d*) in that soil media ($cm^2\ d^{-1}$), e.g. $\alpha = Lrv \text{ x } d$. Minimum *Lrv*'s for full utilization (α=1) of nitrate (0.1-1) and phosphorus (1-10) have been suggested in the literature. *Lrv*'s in our experiment where 0.2 cm cm^{-3} at 30-60 cm in the monocrop species but dropped to 0.1 cm cm^{-3} at 60-150 cm being still within the lower end of the range suggested for nitrate but certainly too low for full utilization of available phosphorus because of its lower mobility. Due to the plasticity effect *Lrv* was double in the sesbania-crotalaria mixture ensuring a faster resource acquisition than in the monocrop. Under non limiting subsoil resource conditions e.g. if Up sub < (*Rsub* x a):

$$A = Up\,sub \qquad \text{if Up sub < Amax}$$

$$A = A\max \qquad \text{if Up sub > Amax}$$

Most fallow species include at least one leguminous species and hence their N resource acquisition is enhanced by their ability to harbour atmospheric N_2 by the legume-*Rhizobium* symbiosis:

$$BNF = (C - A) \times (1 - \beta)$$

where *(C-A)* is the remaining demand for N not covered by soil N resources and β denotes the proportionally increased carbon costs, e.g. photoassimilate partitioning to nodules, for N_2 fixation compared with requirements for mineral N acquisition. Increased carbon and energy costs for N_2 fixation may reduce the growth potential and hence reduce demand for N. However, the available evidence on the real costs of N_2 fixation relative to mineral N uptake are not conclusive and it may be justified at present to set β close to zero (0-0.2). Increased subsoil N exploitation will reduce the demand for N_2 fixation but may not lead to large increases in production as increased root growth (e.g. root plasticity) or root activity may be as costly as N_2 fixation.

Diseases/pests and adverse weather conditions (e.g. drought, flooding) commonly affect plant production in tropical regions. Resource capture thus may become limited by such risk factors and further advantages of mixed species over monocrops are likely to occur where the species mixture provides a better buffered system. In fact risk or stress (*s*) management in many cases may be of greater importance than resource utilization. Resource capture thus may become limited by risk factors and it is assumed that this occurs mainly via a reduced resource demand hence:

$$RCsys = s \text{ x } D - C + A + BNF$$

where $0 =< s <=1$ and is defined as:

$$s = \frac{D1stress}{D1} \times f1 + \frac{D2stress}{D2} \times f2$$

where *D1/2stress* is growth respective resource demand under stress conditions (e.g. drought, pests) and $f1$ is the proportional contribution of each species to the resource demand e.g.

$$f1 = \frac{D1}{D1 + D2}$$

Thus impact of stress events on resource capture of the system will depend on which species is most affected and what proportional contribution it had on the overall production respective demand. On the other hand there may be some compensatory growth (ε) by the more stress tolerant species e.g.

$$RCsys = (s + \varepsilon) \text{ x } D - C + A + BNF$$
$$\varepsilon = (1 - s) \times \sigma$$

where σ is a factor (0-1) denoting the compensatory growth potential of the more tolerant species. Thus advantages of mixed species over monocrops are most likely to occur with increased environmental stress where the species mixture provides a better buffered system (Figure 6). However, risk reduction by diversity is probably less effective against abiotic ‘disasters’ but most effective (leading to the lowest system variance) when a small number of strong competitors are present, which vary primarily in relation to specific biotic stress factors.

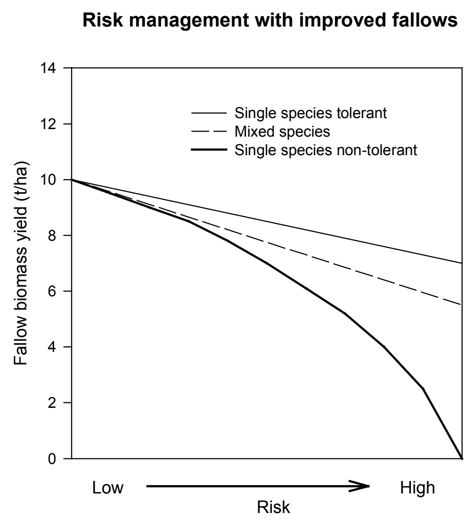


Figure 6: Risk management in mixed species fallows.

4.4.2 Assessing sustainability of fallow systems in Kenya using the the WaNuLCAS model

In modeling agroforestry systems, a balance should be maintained between 'process' and 'pattern', between temporal and spatial aspects (Fig. 7). Most existing crop growth models tend to be detailed in 'processes', but they usually do not take spatial patterns into account; they (implicitly) assume a homogeneous 'minimum representative' area, with a one-dimensional variation between soil layers. Most GIS (geographical information systems) applications do not incorporate spatial interactions and estimate the total output of an area as the summation of area times output per unit area, for grid cells which are not dynamically interacting with their neighbours (similar to a 'stratified' sampling approach). For representations of agroforestry we need both spatial and dynamic aspects, and should therefore aim at models along the diagonal line in Figure 7 and WaNuLCAS (Water, Nutrient and Light Capture in Agroforestry) provides such capabilities.

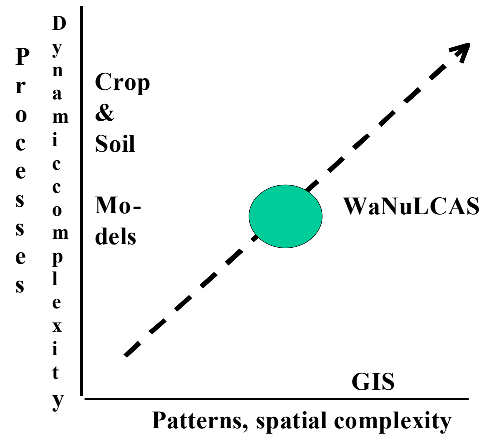


Figure 7: Schematic classification of the way crop growth models deal with spatial and temporal complexity

WaNuLCAS was used and improved to explore the long-term nutrient and soil organic matter dynamics. Many of the obtained experimental data are point measurements (mineral N, root evaluations) and it is not feasible to perform all evaluations in all treatments or over long periods. Models are an additional tool to obtain a dynamic and longer-term assessment of the systems under study and once calibrated allow to explore alternative management options.
Model input values: Production and biomass input (quantity and quality) data, canopy shapes, root length densities at different depths and initial soil mineral-N and total N and C stocks were generated by the project. Rainfall, temperature, evaporation data were obtained from nearby weather stations. Pool partitioning for the soil organic matter model were determined after running the model against long-term maize crop productivity in the area. Water use efficiencies, water movement factors and N retardation values in the soil were obtained from literature, ongoing work in Kenya (ICRAF) or by using the default values. Simulations were performed under non limiting P conditions.

Due to the heavy soil texture (clay content 50-70%) and an apparent large proportion of recalcitrant soil organic matter maize crop yields declined only slowly with continuous cropping even with no N fertilizer addition or no residues recycling (Fig. 8). Maize yield was thus strongly influenced by climatic conditions and the length of ‘fallow’ time between two crops. Thus the long rains (April-August) always led to better crop yield simulations a fact also observed in our experiments.

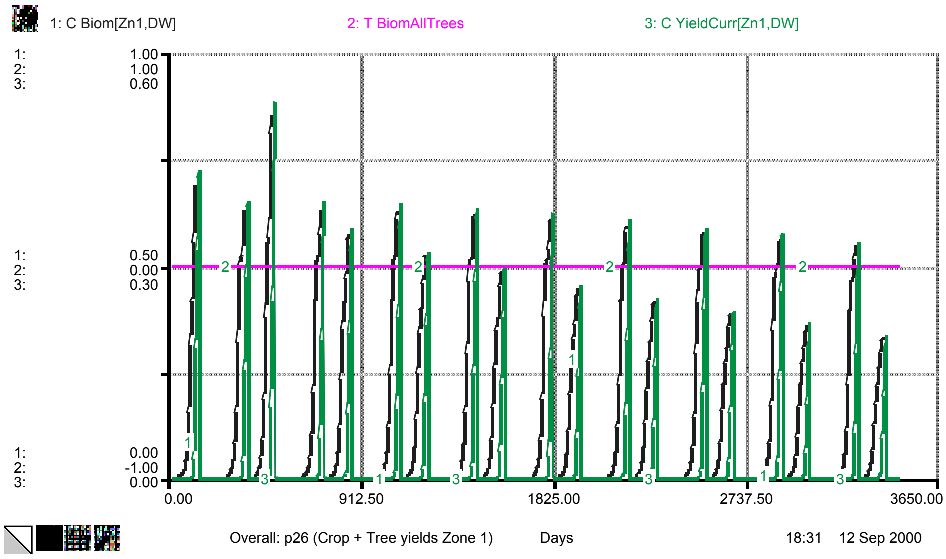


Figure 8: 10 year simulations of continuous maize cropping with no N fertilizer additions or residue recycling.

Introduction of fallows boosted maize yields but the simulated residual effect appeared to be short lived (1-3 seasons, data not presented). The simulated residual benefits depended on fallow age, residue quality and productivity as also observed in the experimental results (Table 2). To obtain longer-term sustainability with short-term (9 month) improved fallows it was necessary to introduce fallows about every second year (Figure 9). The simulation also shows that in case of a crop failure due to draught (e.g. after about 3000 days in this simulation) the subsequent crop benefits strongly from the unutilised resources. Such crop failures have also been associated with re-charging the subsoil N resources which can subsequently be accessed by fallow trees. Longer-term fallows, e.g. 15 month fallows increased residual benefits (e.g. maize yields up to 5-6 t/ha) but benefit duration was still limited with sesbania but apparently longer term benefits might be expected with crotalaria a prediction which will be evaluated in the field in the ongoing experiment.

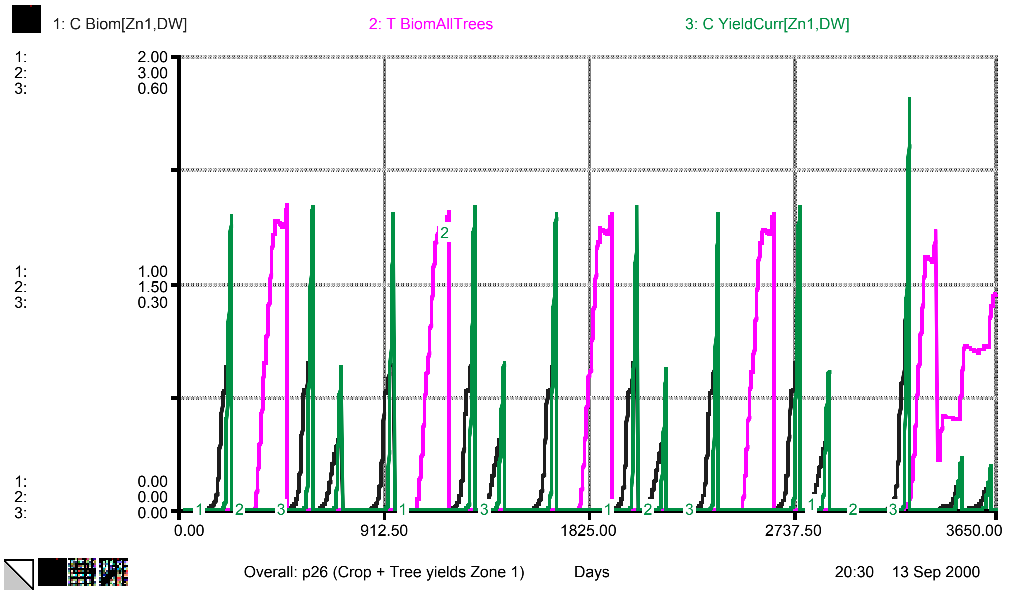


Figure 9: Simulation of maize yield performance in improved sesbania fallow system in western Kenya.

Sustainability of the improved fallow systems was evaluated by assessing the carbon and nitrogen balances in the soil. Soil organic matter increases strongly after fallow harvest and residue incorporation but declines gradually due to soil respiration losses (Table 10). Again it was necessary to introduce fallows approximately every two years in order to maintain soil organic matter levels at the initial values. Changes in soil organic matter in heavy soils are difficult to measure because of the relatively large background and the high spatial variability. Modelling thus provides an additional tool to assess potential impacts of new management strategies. As long-term data from the experiments will become available a more detailed assessment of simulated versus actual changes will be obtained.

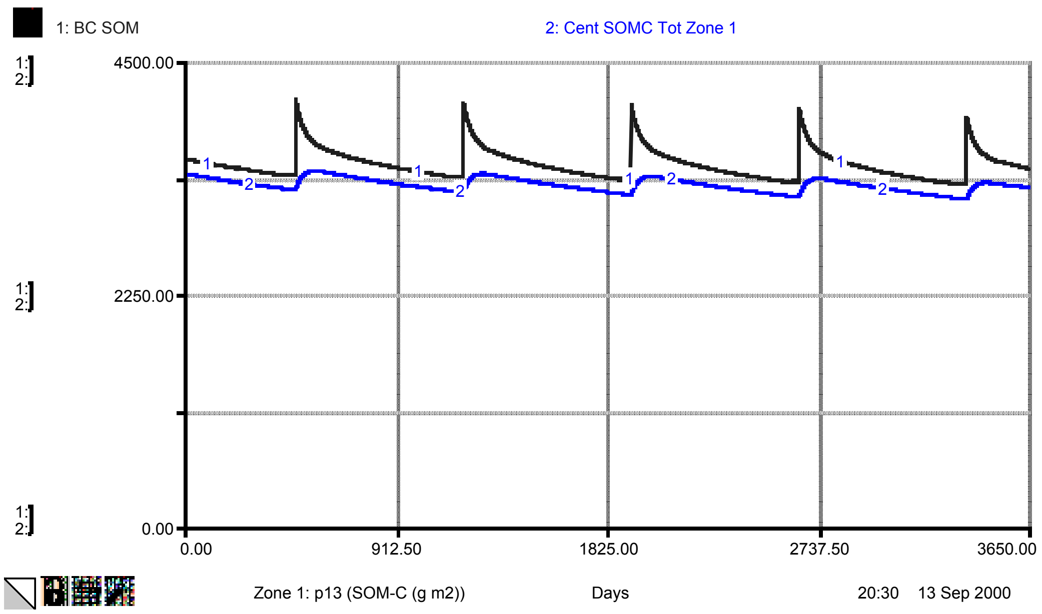


Figure 10: Introducing improved fallows every two years leads to sustainable soil organic matter dynamics in a heavy soil in western Kenya.

The model also provides a tools to assess N movement in with depth in soils and shows the effectiveness of improved fallows to recapture mineral N leached below the crop rooting zone (Figure 11).

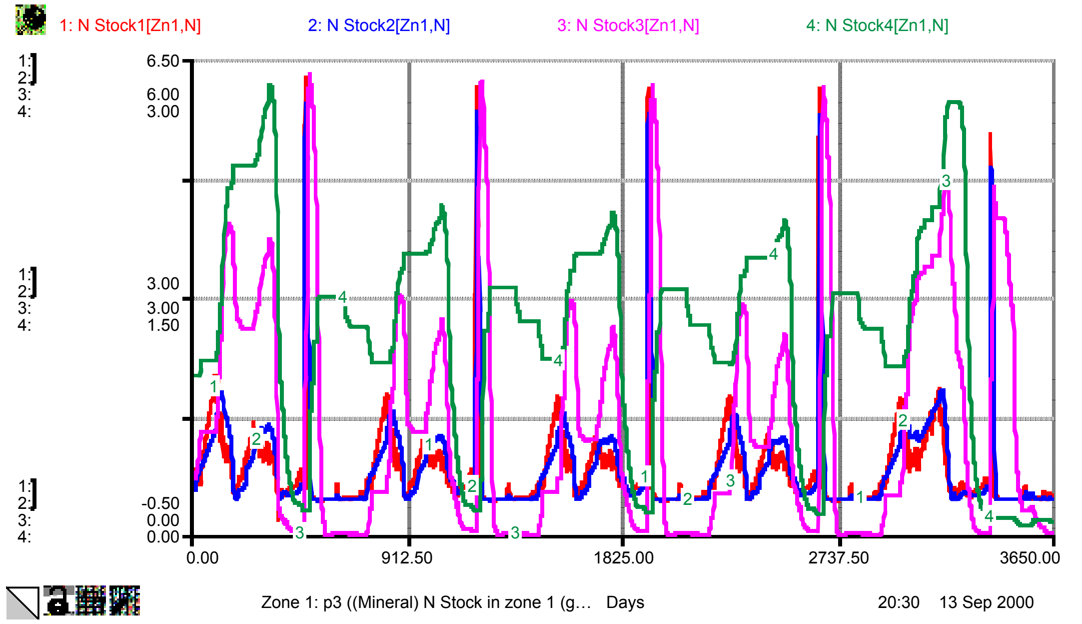


Figure 11: Simulated mineral N dynamics in improved fallow-maize rotation systems (see Figure 9). Depts 1= 0-15 cm, 2=15-30 cm, 3=30-100 cm, 4=100-200 cm.

4.4.3 Promoting and improving modelling tools (WaNuLCAS workshop)

A large effort on biophysical research on new and adapted tree-crop systems is currently underway in many African countries. The increased process based understanding of the interactions between different farming systems components and management practices needs to be captured in more generic terms in order to allow a wider applicability of the research findings than just its site specific implications. The use of process-based models is becoming more important to assist in the initial and continued evaluation of the feasibility, environmental and economic impacts of new proposed systems. They also assist in identifying researchable constraints and test hypotheses. ICRAF has recently developed several agroforestry models, which are made available to national and international research communities on the web. As part of a DFID-NRSP, UK research programme in Western Kenya on mixed fallow systems (R7056) Wye College, UK has assisted ICRAF in the testing and improvement of the Wanulcas agroforestry model. The utility of such a tool across a wider range of environmental constraints and systems necessitates its testing in other countries and environments. A tool however is only useful if it is used more widely by the national and international research community and hence needs training of interested staff and continuous support thereafter to assists users with their specific systems and assure a correct application and an understanding of the limitations of models.

Thus a workshop '*WaNuLCAS a tool for assessing agroforestry options in Africa*?' was held in Kisumu (Kenya) between 13-17 September 2000 jointly organised with ICRAF (M. van Noordwijk and C. Ong). Course participants came from Kenya, Uganda, Tanzania, Malawi, Zimbabwe and Ghana (see full report for names and addresses), with resource persons from UK and Indonesia. Research interests of the participants ranged from 'improved fallow', 'management of competition from upper storey trees', 'management of rotational woodlots', 'water use efficiency of trees at high elevation' to 'rehabilitation of upper terrace soils' and the 'restoration of soil infiltration capacity on degraded lands' (for full details see workshop report). The objective of the training course/workshop was thus to introduce the modelling tools currently available to agroforestry researchers to an audience of young African researchers and to help them develop models for their specific farming systems and research interests.

The workshop program was adapted from that of earlier courses outlined in the WaNuLCAS manual, and was based on hands-on use of models and a step-wise translation of participants interest in agroforestry systems into the steps needed to develop a WaNuLCAS application for their situation. With a highly motivated and capable group of participants as we had, this worked out very well. The workshop contained a minimum of 'lectures' and a maximum of 'learning by doing', with a high ratio of resource persons to participants.

Since the workshop we had active contacts with Paxie W Chirwa from the Forestry Research Institute of Malawi and David Siriri from Uganda (see below) on the use of the model. Also the success of the workshop has let to further demands for more training in Brazil which is due in Novemember 2001 with funding from the FRP.

As part of the validation experiences from our project and the interactions with the workshop participants WaNuLCAS was revised and a new updated verstion 2.05 is now available at: http://www.icraf.cgiar.org/sea/AgroModels/Wanulcas/index.htm

4.4.4 Promotion and validation of mixed fallows in Uganda

Using existing ICRAF network activities and through collaboration within the project relevant data is becoming available to potentially explore the suitability of promising mixed fallow systems in other countries. Originally it was intended that collaboration could be pursued either in Nigeria or Brazil. Contacts were made with IITA and our work presented at a workshop '*Balanced Nutrient Management Systems in Western Africa*' in Benin in February 1999. However, uncertainty in funding experienced by potential collaborators at the time delayed immediate actions. At the same time we received an invitation form Ugandan projects to participate in workshops in Mbale (in conjunctions with R70.. attended by James Ndufa) and field assessment of agroforestry systems in Kabale (G. Cadisch). Indeed collaborators in Mbale and Kabale were very interested in the mixed species concept which appeared to be providing some new and attracting options for their systems.

Since the initial contacts David Siriri from the ICRAF/AFRENA Project in Kabale with the assistance of the R7056 project and ICRAF has set up an experiment to assess '*Water and Nutrient dynamics in rotational woodlots in the humid highlands of Southwestern Uganda'***.** Smallholder farmers in the highlands of Southwestern Uganda are constrained by unproductive soils and inadequate production of wood on steep hillslopes. Soil scouring on terrace benches results in nutrient, soil structure and water gradients, which eventually lead to poor crop production on the upper parts of terraces. Wood production is solely dependent on eucalyptus woodlots established by wealthier farmers, which preclude cropping due to competitive effects and reduced mineralization. Promising options are rotational woodlots of *Alnus acuminata* and *Calliandra calothyrsus* and fallows of *Sesbania sesban*, which farmers have begun to establish on degraded terrace sections. A trial was set up in May 2000 with 4 tree based land use systems including single and mixed species tree combinations. Sub-treatments are four pruning regimes that will be carried out at the tree-crop interface, aimed at reducing tree competition on crops. The concept of rotational woodlots is such that trees are grown for 2 years, with crops intercropped in the 1st year. Woodlots are cut at the end of year 2 and crops grown between the alleys of the remaining stumps. Cropping continues until residual soil fertility effect of trees declines. During cropping, regrowth from the stumps are managed by removing them twice in a season. Alternatively they can be allowed to grow and be used as live stakes for climbing beans. Upon decline of soil fertility, trees are allowed to grow back into a woodlot and the cycle repeats.

David Siriri has also participated in the modelling workshop in Kenya and used this experience to model '*Impact of Alnus woodlots on upper terrace section on crop performance and water balance in the lower terrace sections'*. Woodlots of *Alnus acuminata* are promising options for these degraded areas. However, trees on the upper terrace will compete with crops on the lower terrace section. Using the Wanulcas, he was able to track changes of water availability with the development of Alnus trees and to assess their competitive effect on the crop. The initial simulations demonstrated the need to prune Alnus if this system is to succeed.

We have since assisted David Siriri in applying for some complementary funding for this work through IFS, Sweden.

5. Research Activities

The following experiments were carried out during the project:
Field experiments:
1. Screening trial: During the short rains 1997/98 new single and mixed fallow species combinations were tested for their adaption and compatibility/complementarity potential in western Kenya. N_2 fixation and deep soil N capture were evaluated using ^{15}N isotopes.
2. Mixed species trial: During the short and long rains 1998/99 interactions in promising mixed species fallows were assessed at two locations in western Kenya. N_2 fixation and deep soil N capture were evaluated using ^{15}N isotopes. Residual effects evaluations on maize yields are ongoing (currently two harvests available).
3. Fallows with integrated cash crops or fodder species trial: During the short rains 1999/00 new experimental designs for integration of cash crops or fodder species into fallows were established. Residual effects with and without fodder removal or manure returns are currently being assessed by KEFRI.
4. Decomposition of mixed species residues. Experiment established in 1999 using residues of the most promising species available.

Controlled experiments:
1. Decomposition of mixed species residues. Laboratroy leaching tube experiment using residues of the most promising species tested.
2. ^{15}N natural abundance calibration experiments: 'B' value (isotopic fractionation) and comparison with ureide method performed in the greenhouse in Wye and in Kenya.

A modelling workshop '*WaNuLCAS a tool for assessing agroforestry options in Africa*?' was held in Kisumu (Kenya) between 13-17 September 2000 jointly organised with ICRAF (M. van Noordwijk and C. Ong). 10 course participants came from Kenya, Uganda, Indonesia, Tanzania, Malawi, Zimbabwe and Ghana.

Several field visit by local farmers and NGO's were organised:
- Q1 1998: farmers visit to field trial (20 farmers) and visit by ICRAF and CGIAR staff.
- Q3 1998: visit by about 30 members of World Vision (NGO) and ICRAF staff
- Q1 1999 project visit by EU Pilot project evaluation mission
- Q2 1999: farmers visit to field trial (about 100 farmers). Interest in siratro and requests for seeds.
- Q3 1999: ICRAF board member of trustees visited field experiment.
- Q1 2000: Visit by Maseno Youth Polytechnic with regard to setting up tree nursery project. Also visit by Sakawa Global 2000 project.
- Q2 2000: Presentation of project results to extensionists and NGO's (CARE, OM-Network, etc) during workshop 'Impact assessment of fallows for soil fertility improvement' in Maseno.

Dissemination of research results at various conferences and meeting are listed in section 7.

Local facilities at Maseno were improved by providing the following equipment:
- CO_2 analyzer
- Rhizotron
- Digestion block (for plant analysis)
- Photospectrometer for ureide as well as mineral N analysis
- Laptop computer

The project also provided extensive training both at Wye and in situ for staff (James Ndufa and Stanley Gathumbi) at Maseno in:
- Use of stable isotope in N_2 fixation and N balance studies
- Modelling tools: Use of Stella environment and WaNuLCAS
- Writing publications and thesis reports

The expertise James Ndufa obtained in isotope studies has facilitated a link to IAEA, Vienna on the 'Use of nuclear techniques in agroforestry systems'. He has become a leading expert in that team in the area of ^{15}N injections into trees to study below ground processes.

6. Contribution of Outputs

6.1 Contribution of outputs towards NRSP's goals

The goals of the NRSP High Potential programme under which R7056 was developed were: ' *A suite of integrated management strategies offering improved and sustainable benefits to the poor developed and promoted'* (Note: formerly the project was initiated under the Forestry/Agricultural interface whose goal was '*Productivity of forest systems optimized and sustainable'*). The current project clearly demonstrated that improved fallow systems are technically a means to achieve improved and sustainable production in relation to N dynamics in the area of western Kenya. However, the reported benefits have been achieved by using complementary P and K fertilizers which are known to be limited in the research area. Although the limited economic evaluations may suggest that the systems appear to be economically viable poor farmers may currently not have access to such resources. Thus facilitating access to P fertilizers will be necessary in order for the promising results to be achieved by farmers. During the project it became increasingly clear that fallows must provide alternative benefits such as fuelwood, cash crop yields or fodder in order be attractive to farmers. Women were particularly interested in the fuelwood components while men were more interested in fodder components of the fallow system. However, harvesting these components will result in offtake of nutrients and hence limit the residual benefit. Mixed species fallows, however allow offtake of such components and still retain major positive benefits due to the complementary inputs by the associated species. Potential labour savings may be attractive to poor farmers who have to hire out their labour to the more richer community members or whose husbands have seeked work in the city.

6.2 Assessment of the impact of the outputs

The programmes OVI's at purpose level at the beginning of the project were: i)'*Soil fertility benefits quantified in at least two agroforestry/perennial crop based systems in 2 target countries by 2003*' and ii) '*Maize yields increased on 20% of target farmers' fields by 2003'.*

The project has quantified soil fertility benefits in one target country (Kenya). It has also initiated related work in Uganda and through the training in the WaNuLCAS model facilitated evaluation of similar systems in four other countries.

The use of improved fallows and other associated methods in western Kenya, Uganda and Zambia is increasing. Estimates by the Pilot project suggest currently between 5-15000 users in Eastern Africa. These estimates appear to be somewhat optimistic. It is clear that these techniques need to be more closely integrated with more valuable cropping systems in order to have a more widespread uptake by farmers.

Some of the limitations of the investigated approaches have been discussed under 6.1. Other limitations better documentation of improved technologies and wider distribution. Very few of the findings of the research conducted in western Kenya have been compiled in an easy accessible format for farmers. This will require joint efforts between all parties (KEFRI/KARI/ICRAF/ extensionists) involved in research in improved cropping systems in the area. Potential negative effects of certain fallow species (e.g. sesbania) on nematode populations that have detrimental effects for food crops (e.g. beans) need to be included in any promotion activities.

The project R7056 has been actively interacted with the ICARF-KARI-World Bank/Rockefeller funded 'Pilot project' scheme which covers 16 villages and about 2000 farmers, provided technical expertise and has jointly organised farmers and NGO visits. Species combinations tested in this project have also been introduced into the Pilot project. In fact farmers experimented themselves with the mixing of different species combinations. However, seed availability and seed quality have been a major limitations for more widespread testing. The link to the Pilot project has allowed the project to have a wider impact than would have been possible with its own funds and activities alone.

7. Publications and other communication materials

Headings for communication materials:

1. Books and book chapters

Cadisch, G., Gathumbi, S., Ndufa, J.K. and Giller, K.E. 2001. Resource acquisition of mixed species fallows - competition or complementarity ? In: Vanlauwe, B., Sanginga, N. and Merckx, R. (Eds.) *Balanced Nutrient Management Systems for the Moist Savanna and Humid Forest Zones of Africa*. Kluwer Academic Publishers, Dordrecht , in press.

2. Journal articles

    2/1. Peer reviewed and published

    2/2. Pending publication (in press)

    2/3. Drafted

Gathumbi, S.M., Ndufa, J.K., Giller, K.E. and Cadisch, G. 2001. Do mixed species improved fallows increase above- and below-ground resources capture? *Plant and Soil*, submitted March 2001.

Gathumbi, S.M., Cadisch, G. and Giller, K.E. 2001. $\delta^{15}N$ natural abundance assessments of N_2 fixation by mixtures of trees and shrubs in improved fallows. *Soil Biology and Biochemistry*, submitted April 2001.

Gathumbi, S.M., Giller, K.E., Buresh, R.J. and Cadisch, G. 2001. Field assessment of rooting patterns, root activity and subsoil N capture by three legumes using deep ^{15}N placement. *Soil Science Society of America Journal*, in preparation.

Ndufa, J. et al. 2002. Interactions in mixed species fallows in western Kenya. *Plant and Soil*, planed.

3. Institutional Report Series

van Noordwijk, M., Ong, C. and Cadisch, G. 2000. *WaNuLCAS - a tool for assessing agroforestry options in Africa ?* Report from an agroforestry modeling workshop. ICRAF, Nairobi, 30p.

4. Symposium, conference, workshop papers and posters

Cadisch, G. 1998. *Nutrient cycling in tropical agricultural ecosystems*. Oral presentation at workshop 'Sustainable Management of Soil Fertility in Tropical Soils', Department of Geography, University of the Estate of Mexico, Toluca, Nov. 9, 1998.

Cadisch, G. 1999. *Mixed species fallows in western Kenya*. Oral presentation at workshop 'Balanced Nutrient Management Systems in Western Africa', IITA, Benin, February 1999.

Gathumbi, S.M., Giller, K.E. and Cadisch, G. 2000. *N Fixation and N Balance in Mixtures of Herbaceous and Woody Legumes*. In: Abstracts, p. 43 of Annual Meeting of American Society of Agronomy, Oct. 1999. Madison: ASA.

Gathumbi, S.M., Ndufa, J.K., Giller, K.E., Buresh, R.J. and Cadisch, G. 2000. *Mixed Species Fallows: Complementarity or Competition in Growth Resource Utilization*. In: Abstracts, p. 48 of Annual Meeting of American Society of Agronomy, Oct. 1999. Madison: ASA

Gathumbi, S.M, Cadisch, G., Buresh, R.J. and Giller, K.E. 1999. *Subsoil Nitrogen Capture and N_2 Fixation by Legumes in Agroforestry Systems*. In: Abstracts, p. 43 of Annual Meeting of American Society of Agronomy, Salt Lake City, Utah, Oct. 31 – Nov. 4, 1999. Madison: ASA.

Gathumbi, S.M, Cadisch, G., Buresh, R.J. and Giller, K.E. 1999. *Above- and Below-ground Resource Utilization by Legume Mixtures in Western Kenya*. In: Abstracts, p. 229 of Annual Meeting of American Society of Agronomy, Salt Lake City, Utah, Oct. 31 – Nov. 4, 1999. Madison: ASA.

Ndufa, J.K., Gathumbi, S.M., Giller, K.E., Buresh, R.J. and Cadisch, G. 1999. *Mixed Species Fallows: Complementarity or Competition in Growth Resource Utilization*. Poster at: 'National Land and Water Management', KARI, Nairobi, Nov. 20-25, 1999.

Ndufa, J.K., 1999. *Mixed species fallows in western Kenya*. Oral presentation at workshop 'Methodologies for Dissimination of Research Results on Nutrient Management Strategies', Mbale, Uganda, February 1999

5. Newsletter articles
6. Academic theses

Gathumbi, S.M. 2000. *Nitrogen sourcing by fast-growing legumes in pure and mixed species fallows in Western Kenya*. Wye College, Department of Biological Sciences, University of London. Wye, Kent, UK.

Ndufa, J.K. 2001. *Nitrogen and soil organic matter benefits to maize by fast-growing pure and mixed species legume fallows in Western Kenya*. Imperial College at Wye, Department of Biological Sciences, University of London. Wye, Kent, UK. (submitted April 2001)

7. Extension-oriented leaflets, brochures and posters

Mixed species improved fallows for Western Kenya (2000). Leaflet produced by Wye College/KEFRI/ICRAF.

8. Manuals and guidelines
9. Media presentations (videos, web sites, TV, radio, interviews etc)
10. Reports and data records
    - 10/1. Citation for the project Final Technical Report (FTR)
    - 10/2. Internal project technical reports
    - 10/3. Literature reviews
    - 10/4. Scoping studies
    - 10/5. Datasets: http://www.icraf.cgiar.org/sea/AgroModels/Wanulcas/index.htm

10/6. Project web site, http:// **www.wye.ac.uk/BioSciences/soil**

8 Project logframe

NARRATIVE SUMMARY	OBJECTIVELY VERIFIABLE INDICATORS	MEANS OF VERIFICATION	IMPORTANT ASSUMPTIONS
Goal			
Productivity of forest systems optimized and sustainable.	*Improved forest resource use patterns implemented in target areas by 2005, including:- - no depletion/some enhancement of soil fertility over period of land use (measured by offtake over time).*	*National production statistics. Reports of target institutions. Research Programme reports. Evaluation of NRSP. Monitoring against baseline data.*	*Enabling environment (policies, institute, markets, incentives) for widespread adoption of new technology and strategies exists.*
Purpose			
Improved soil fertility management systems developed and promoted:	*Soil fertility benefits quantified in at least two agroforestry/perennial crop based systems in 2 target countries by 2003 Maize yields increased on 20% of target farmers' fields by 2003*	*Project reports and annual reports*	
Outputs			
1.1 Guidelines on soil fertility improvements by mixed fallow systems quantified on farmers' fields and promoted. 1.2 Sources of nutrient aquisition quantified and complementarity of tree mixtures evaluated and documented. 1.3 Nutrient interactions of organic residues in tree mixtures experimentally measured and reported. 1.4 Models and sustainability of mixed species fallows evaluated, tested and improved; recomendation domains in two target countries examined and verified.	*1.1 Maize yields increased by 20% on farmers' fields 1.2. Nutrient cycling efficiency and crop nutrient uptake improved by 20% (BNF, and deep N sources) 1.3 Improved synchrony and reduced nutrient losses quantified. Increased soil organic matter status 1.4 Set of sustainability indicators developed and promoted by the end of year 3; Improved model and system applicability tested in Nigeria and Brazil by end of year 3.*	*Research programme reports and international publications. ICRAF/AFRENA newsletter. Improved model. Observations on farmers' fields*	*Target institutions invest in the uptake and application of research results. Input and collaboration from ICRAF sustained*
Activities			
1.1 Compare single and mixed species fallows at two contrasting sites. 1.2 Positioning labelled isotopes at various depths. Evaluate tree root profiles and mineral-N dynamics. 1.3 Evaluate ^{15}N recovery from mixed residues particularly from polyphenol-protein complexes. 1.4 Evaluate soil organic matter pools. Test and improve existing agroforestry models (WANULCAS, CENTURY)	*Input / resources Staff costs: £ 64673 Overheads: £ 43066 Capital: £ 13900 Travel: £ 30340 Consumables/Isotopes: £ 27000 Miscellaneous: £ 41000 Total: £ 219,979 (over 3 years) Support from: - Wye College: K.Giller 5% of time (£8k) - ICRAF:- R. Buresh 5% of time (£10k) - 2 PhD training grants (£78k) - Support for field experimentation (£15k) Total: £111,000 (over 3 years)*	*Quarterly progress report, annual report and final report*	*- Funding and support for PhD students is maintained - No major disasters (fire, etc.) destroy field experiments - Mass-spectrometer functional*

9. Keywords

Key words (maximum of 10, excluding production system) for entry in the NRSP library accession entry for the project's FTR.

Short-term improved fallows, N_2 fixation, subsoil N capture, maize, WaNuLCAS, model, western Kenya