Modelling and measuring N and C dynamics in agroforestry systems in the humid tropics:

Test of the safety-net role of deep-rooted trees.

Final Technical Report

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Executive Summary

A very brief summary of the purpose of the project, the research activities, the outputs of the project, and the contribution of the project towards DFID's development goals. (Up to 500 words).

Including trees in a cropping system may improve nitrogen use efficiency and thus the sustainability of the system, if deep tree roots take up and recycle N which would otherwise have been lost through leaching. The project aimed to improve knowledge of below-ground crop-tree interactions in alley cropping systems through the use of isotopic tracing experiments and dynamic modelling, and make recommendations for species selection and system design. *Peltophorum dasyrrachis*, a tree with a comparatively deep distribution of fine roots, took up a higher proportion of its nitrogen from the subsoil than the shallow rooted tree *Gliricidia sepium*. Over 203 days, these trees recycled an estimated 42 kg N ha^{-1} and 21 kg N ha^{-1} respectively from this safety – net zone. The depth of rooting of a tree can be assessed by simply excavating its main roots and measuring the 'index of shallow rootedness'. Maize was even more shallow rooting than *Gliricidia* on this acid soil, and took up N from 65 – 80 cm depth only for a short period between 2 and 3 months after sowing. The soil layers where crop plants and trees take up N overlap to some extent, but deep rooting trees such as *Peltophorum* show considerable complementarity of N use. Trees increase N inputs by recycling leaching N, particularly after harvest or before crop roots have extended into the subsoil. Fixation of N_2 by trees also increases N inputs and can help maintain a positive balance for this nutrient, though only for moderate crop yields. Only around 5 % of N applied in tree prunings became available to the next crop; however, such organic inputs represent a re-capitalisation of the soil, and are likely to result in improved long – term nutrient availability as well as improving soil structure. Benefits of incorporating trees must be set against the negative effects of competition on crop yield. Fast – growing trees are likely to compete more strongly than slow growing trees and are more suitable for use in improved fallows than in simultaneous agroforestry. Much leaching takes place through subsurface lateral flow; contour hedgerows at a relatively wide hedgerow spacing may thus intercept leaching N without causing strong competition. Hedgerow spacing, the timing of pruning relative to crop growth, the quality / decomposition rate of prunings, and root distributions, all affect the productivity and sustainability of agroforestry systems.

Assessing these factors and the interactions between them will be greatly facilitated by the use of the dynamic computer model WaNuLCAS, further developed during this project. The performance of this model was verified by comparison of outputs with results of field experiments. The model will be useful for the design of locally – adapted agroforestry systems.

Background

Information should include a description of the importance of the researchable constraint(s) that the project sought to address and a summary of any significant research previously carried out. Also, some reference to how the demand for the project was identified.

Cropping systems on acid, free draining soils in the humid tropics are highly susceptible to leaching losses. The efficiency of use of soluble nutrients, particularly NO_3^-, is constrained by the shallow rooting depth of crops. It has been suggested that incorporating trees into annual cropping systems can make nutrient cycles more closed, since deep tree roots take up nutrients which would otherwise have been leached and return them to the agroecosystem (Huxley, 1999; van Noordwijk *et al.*, 1996; Young, 1997). Maintaining soil fertility depends on efficient recycling of soluble nutrients, especially where there are financial or structural constraints on the use of fertilizers. More efficient recycling also reduces the risks of environmental pollution due to leaching. However, at the start of this project this ‘safety – net’ hypothesis had been tested against few data, and modelling of below – ground interactions within agroforestry was not yet at a point where the effect could be quantified.

The benefits of tree roots in agroforestry were summarised by Schroth (1995) as follows:

a) Soil enrichment with organic matter, maintenance of the soil biomass and enhanced nutrient cycling through root production and turnover.

b) Uptake of water and mobile nutrients from the soil, thus reducing leaching losses.

c) Pumping up nutrients from subsoil layers below the main rooting zone of the crops.

d) Improvement of soil penetrability for crop roots and of other soil physical properties

e) Fixation of atmospheric N_2

The main focus of this study was to evaluate the importance of process (b), although processes (a), (d) and (e) were also quantified. The distinction between safety net uptake (b) and nutrient pumping (c) is a useful one, emphasising the dynamic nature of the process of intercepting leaching nutrients. The literature on nutrient pumping is relevant, however. Tree roots have been shown to extend into deep soil layers and bring up nutrients, which are recycled through litter (van Rees and Comerford, 1986). Woody perennials generally have maximal root length density in topsoil, and take up most of their nutrients from topsoil (IAEA 1975). The relative contribution of subsoil uptake increases, however, when the topsoil dries out (Eastham *et al.*, 1990).

Some tree species have a relatively uniform distribution of roots with depth. Such trees are likely to compete less strongly with crop plants, and thus be better suited for agroforestry associations than shallow rooting trees. Since techniques for quantifying tree root distribution are laborious, selecting deep rooting tree species or varieties, or assessing the effects of tree management on rooting pattern, can be difficult. The value of simple indicators of root distribution, such as the vertical direction of main roots, therefore needs to be assessed. Such indicators could greatly facilitate tree germplasm selection for intercropping systems.

Competition between tree components and crops in mixed systems often outweighs the benefits of intercropping trees and crops, resulting in poor results and low farmer adoption of alley cropping systems. One might conclude that the technology has not lived up to its (high) expectations and continue to focus on other options, but there may be important lessons to be learned from a proper analysis of the biophysical interactions in these relatively simple agroforestry systems. There are often relatively large inputs of organic matter in alley cropping systems but nutrients are used with low efficiency. Selecting tree – crop combinations and management techniques which overcome these constraints depends on understanding the below-ground regulation of nutrient flows. If productive and nutrient – efficient systems are to be designed for specific local situations, this understanding must be accessible to and useable by local agronomists and extensionists. Dynamic modelling offers opportunities for both improving basic understanding of agroforestry interactions, and making this understanding accessible (Caldwell *et al.*, 1996). The need for improved models of below – ground interactions in agroforestry was expressed by ICRAF; ODA-ITE-AMP

(Agroforestry Modelling Project group); and in an ODA Forestry Consultant Report (Anderson *et al*. 1992)

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Project Purpose

The purpose of the project and how it addressed the identified development opportunity or identified constraint to development.

The purpose of the project was to improve knowledge of crop-tree interaction in the below-ground environment of alley cropping systems, and incorporate this knowledge into management strategies. This lead towards the goal of increasing the contribution of trees to the productivity of tree/crop based systems.

Specific objectives of the project were:

1. To test the **'safety-net' function of roots** in agroforestry systems in the humid tropics i.e. the hypothesis that deep rooting trees are able to reduce leaching losses, and compete less with associated crops, thereby improving system productivity.
2. To identify **management options** (pruning height, frequency, etc) which improve nutrient recycling and reduce competition between tree and crop components by altering the vertical root profiles of agroforestry trees.
3. To identify **simple indicators** of below-ground tree architecture which allow a rapid evaluation of species.
4. To incorporate the improved understanding of below-ground C and N and H_2O dynamics into existing (modular) **agroforestry models**.
5. To use the new understanding of below-ground competition between tree and crop components to identify **locally adapted suitable tree-crop** combinations **and management options** which will increase nutrient use efficiency in agroforestry systems and decrease risks of environmental pollution.

Research Activities

This section should include detailed descriptions of all the research activities (research studies, surveys etc.) conducted to achieve the outputs of the project. Information on any facilities, expertise and special resources used to implement the project should also be included. Indicate any modification to the proposed research activities, and whether planned inputs were achieved.

1. Testing the 'safety-net' function of roots

Safety – net uptake of nitrogen was evaluated in established on-farm and on-station trials of hedgerow intercropping systems. The stable isotope ^{15}N was used to trace N flows through these systems in a series of experiments which aimed to:

- Quantify uptake by trees and crops of ^{15}N introduced into existing hedgerow intercropping systems at different depths and horizontal positions.
- Measure nitrogen use efficiency and leaching losses from decomposing pruning materials and soluble fertilizer applications, by ^{15}N recovery measurements from applied ^{15}N labelled prunings and ^{15}N urea.

Recovery of ^{15}N in plant and soil samples was determined using the mass-spectrometer at Wye College.

Safety – net function was related to tree, crop and soil characteristics and environmental conditions. Measurements were taken to:

- Quantify root length density of trees and crop plants at different depths and distances from hedgerows by wet sieving of soil samples.
- Monitor environmental conditions (canopy light conditions, weather data, soil temperature)
- Quantify the soil water balance and evaluate different leaching pathways (matrix flow, bypass flow and lateral flow).
- Quantify stocks of mineral N in soil.
- Assess the rate of root turnover (through the use of mini – rhizotrons).

2. Management for deep tree rooting profiles

The effects of the following management options on root distributions, nutrient recycling and competition between tree and crop components were assessed:

- Pruning trees at different times in relation to the crop sowing date.
- Pruning trees at different heights
- Establishing trees by direct seeding, transplanting seedlings or by use of stakes.
- Using fertilizers (P) and liming materials ($CaCO_3$, $CaSO_4$) to stimulate root development and subsoil exploration

3. Simple indicators of below-ground tree architecture

Two simple of indicators of below-ground tree architecture were assessed:

- The angle of descent of main roots
- Root architectural characteristics (branching proportions and length of root links)

Roots of two tree species were excavated and root branching proportions and angles were measured. These were related to fine root distributions, measured by soil coring and wet sieving of roots.

4. Incorporating below-ground C and N and water dynamics into agroforestry models

The WaNuLCAS (Water Nutrient and Light Capture in Agroforestry Systems) model, developed by van Noordwijk and Lusiana (1999), was revised and adapted to include:

- a detailed description of nutrient leaching and plant uptake, in up to 16 separately parameterised soil compartments.
- a description of soil C and N dynamics based on the soil organic matter module of the CENTURY model (Metherell, 1993).

– a more detailed treatment of leaching pathways (matrix flow, bypass flow and lateral flow).

– a ^{15}N balance, for comparison with isotopic tracer experiments.

WaNuLCAS was tested against data obtained from the experiments outlined in (1.) above.

Links with ITE-AMP were developed; project members participated in their workshops, and the WaNuLCAS model was presented to ITE-AMP members in several workshops. Comparison of the models resulted in refinements of both the HyPAR model developed by ITE-AMP, and WaNuLCAS.

WaNuLCAS was introduced to researchers from universities and agricultural institutions in a series of workshops in several countries. The model was found to be adaptable to novel situations. Examples of systems which have been simulated are:

– the effects of intercropping on growth and yield potential of rubber trees.

– the effects of rising CO_2 levels on the growth of maize, cassava and cowpea.

– erosion in coffee / shade tree systems.

– the effects of improved fallow systems using *Chromolaena* on soil organic matter.

5. Tree – crop combinations and management options to improve nutrient use efficiency

The overall effects of incorporating different tree species and management techniques on crop production and nutrient use efficiency were evaluated on the basis of experimental data and model simulations.

Competition and fertility effects were separated and assessed in a root exclusion / mulch transfer experiment. Rates of N_2 fixation by trees and / or crop plants were measured by the ^{15}N natural abundance and ^{15}N enrichment methods, and the importance of N_2 fixation for maintaining a positive soil N balance was assessed.

Outputs

The research results and products achieved by the project. Were all the anticipated outputs achieved and if not what were the reasons? Research results should be presented as tables, graphs or sketches rather than lengthy writing, and provided in as quantitative a form as far as is possible.

1. Testing the 'safety-net' function of roots

a) The concept of the safety-net

The idea that recycling of nutrients which have leached beyond the range of crop roots by trees is of benefit to the nutrient balance of a field has become known as the "safety - net" hypothesis (Van Noordwijk *et al.*, 1992, Van Noordwijk *et al.*, 1996) (Figure 1). This may be contrasted with a "nutrient pump" role, where trees are taking up nutrients from deep soil layers or groundwater which have not recently passed through the crop rooting zone (Cannell *et al.*, 1996). The distinction is based on whether the nutrients taken up would "otherwise have been leached", which may not be easy to determine on soils with substantial nutrient storage capacity in subsoil layers or groundwater. However, the term "safety-net" is still useful in emphasising the dynamic nature of the process of intercepting leaching nutrients.

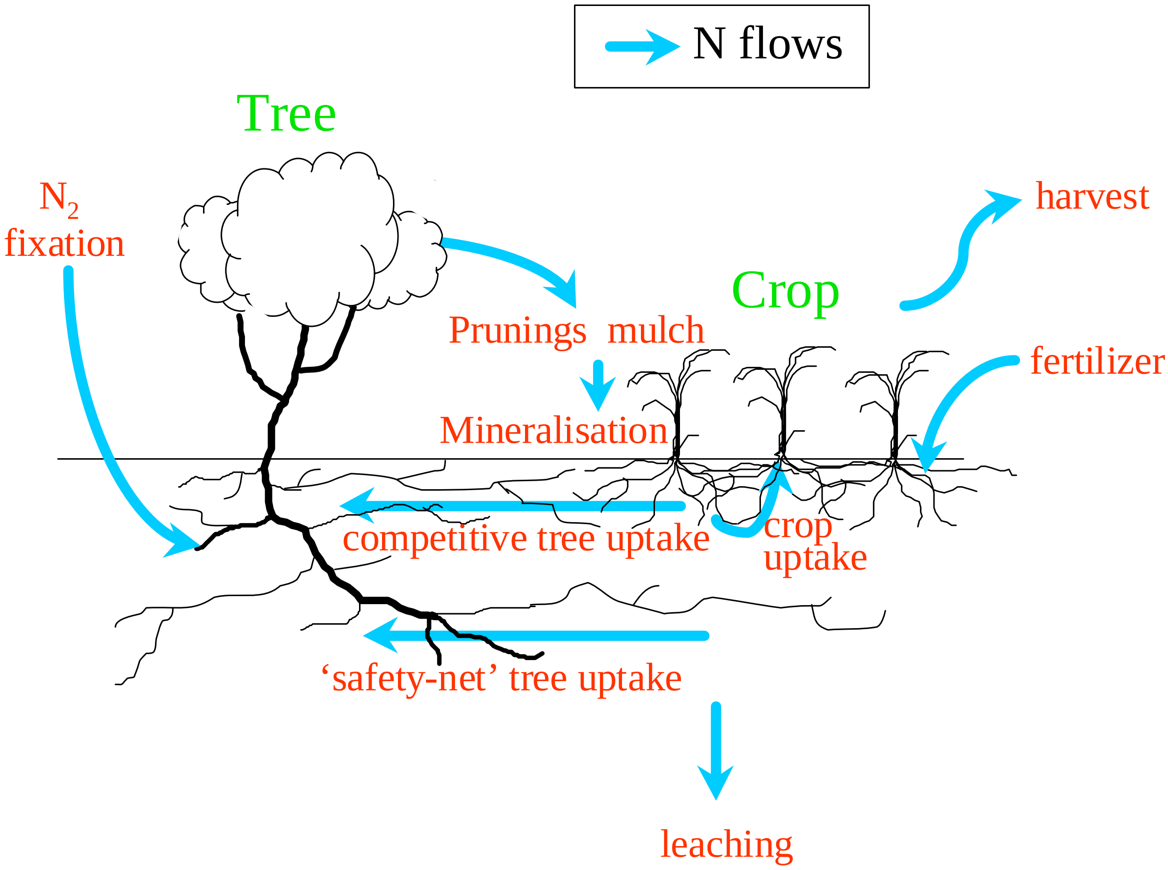

Figure 1 A simplified representation of the safety – net hypothesis.

The tree root safety-net is likely to be significant under the following conditions:-

- The effective rooting depth of crops is shallow.
- Substantial amounts of the plant nutrient in question leach through the crop rooting layer.
- Tree roots are present in soil layers beneath the crop rooting layer.
- These roots are actively taking up substantial amounts of the plant nutrient at the time when it is leached into these deeper soil layers.

Several questions arise in relation to safety-net function. Is the safety-net of agronomic significance, i.e. are large amounts of nutrients recycled in this way? Do some trees provide better safety-nets than others? What thickness of 'safety – net zone' is necessary to intercept leaching nutrients, and how dense must tree roots be within this zone? Are there ways of managing trees to minimise competition and maximise safety-net recycling? These issues were examined in relation to nitrogen cycling within established agroforestry systems on a site with free-draining acid soils and high rainfall. These are conditions where safety-net recycling might be expected to be important. Of all the plant nutrients, nitrogen is the most susceptible to loss through leaching. Crop rooting depth is restricted on many acid soils by adverse subsoil conditions, in particular high concentrations of exchangeable aluminium. Aluminium occurs in soil in a variety of ionic forms, of which monomeric ions (those containing a single Al atom) have the most deleterious effects on plant roots. High aluminium concentrations at the root surface prevent the uptake of phosphates, and high concentrations within cells may interfere with sugar phosphorylation (Russell, 1973). The proportion of aluminium in monomeric forms increases with decreasing soil pH. The degree of aluminium toxicity in soil therefore depends on pH as well as on exchangeable aluminium content, the latter being the product of cation exchange capacity and proportional aluminium saturation. Ultisols are particularly susceptible to leaching losses; a large sand fraction in topsoil leads to rapid infiltration, and the finer textured subsoil has a high aluminium content which becomes toxic at the typically low pH. Roots of plants with low aluminium tolerance, such as many crop plants, thus only have a short vertical distance over which to intercept nutrients.

Trees may compete with crops for N in the surface soil layers. Spatial and temporal patterns of N uptake will be affected by such factors as the timing of N additions, the quality of pruning materials, and the degree of synchrony of crop and tree demand (Handayanto *et al.*, 1997; Xu *et al.*, 1993). In assessing the overall effect of incorporation of trees into cropping systems, the benefit of improved N use efficiency must be set against competition for and uptake of N which would otherwise have been used by the crop (Cannell *et al.*, 1996). Synchrony of N supply and crop N demand is important if N stress is to be avoided and leaching losses minimised (Myers *et al.*, 1996; Mafongoya *et al.*, 1997). At certain stages of crop growth it may be particularly important to maintain high levels of N in soil. For instance, when crop seedlings are establishing, high concentrations of available N are necessary even though demand, expressed as kg N ha^{-1} d^{-1}, is small at this stage. Synchrony has mainly been examined in relation to mineralisation of organic inputs, but the concept can also be applied to competitive effects in hedgerow intercropping. The reduction in nutrient concentrations as a result of uptake by tree roots, and the supply of nutrients from decaying roots, is likely to vary during the cropping cycle. Anderson (1986) called for more information on the phenology of trees and crop plants in relation to spatial and temporal patterns of nutrient mineralization and uptake. Pruning events are likely to be critical, inducing periods of root inactivity and death. The timing of root uptake in relation to N leaching losses is critical to the functioning of the "safety - net".

b) Evaluation of tree and crop root distributions

To test whether trees had root distributions which were promising for safety-net uptake and limited competition with crop roots, root length density distributions in alley cropping systems in Lampung were evaluated. Maize root length density, measured in sieved samples, was greatest in the top 5 cm of soil and declined very steeply with depth (Figure 2). *Peltophorum* had a much greater proportion of its root system in the subsoil. *Gliricidia* had an intermediate distribution, more coincident with maize roots.

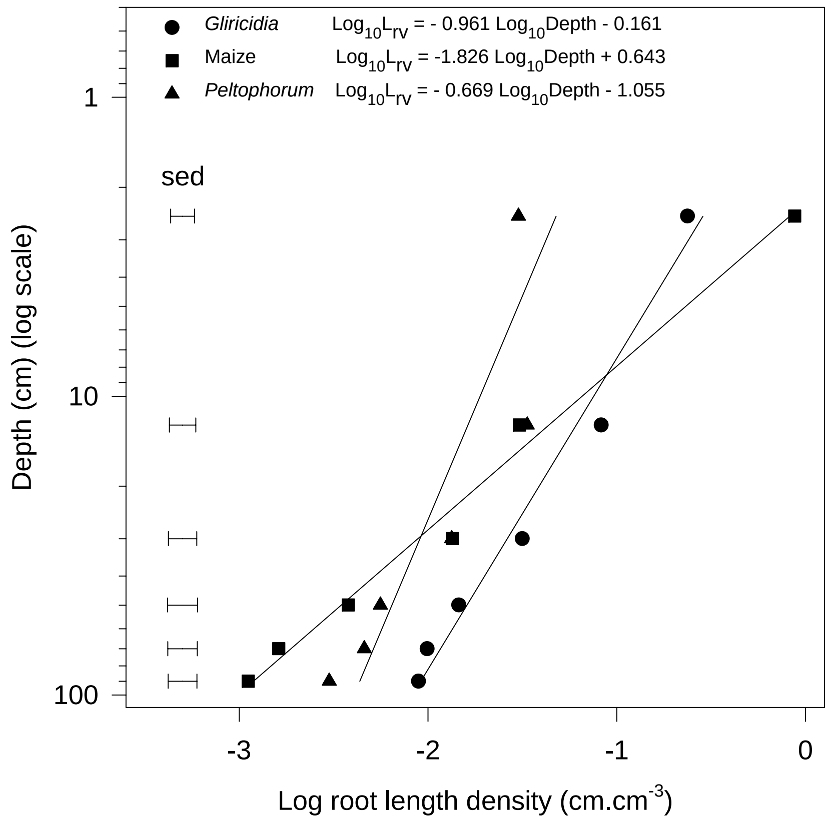

Figure 2 Regressions of log root length density (all sampling positions) of *Peltophorum*, *Gliricidia* and maize on log depth. Mean values are also plotted.

The horizontal distribution of tree roots was fairly even across cropping alleys with a 4 m hedgerow spacing (Figure 3). The ideal ‘safety-net’ distribution, with tree roots in a dense mat underneath the crop roots, was not seen, but trees had higher root length density than the crop in subsoil, and lower root length density than the crop in topsoil. *Peltophorum*, in particular, had a distribution which suggests it takes up nutrients from the deep soil but does not compete strongly in topsoil.

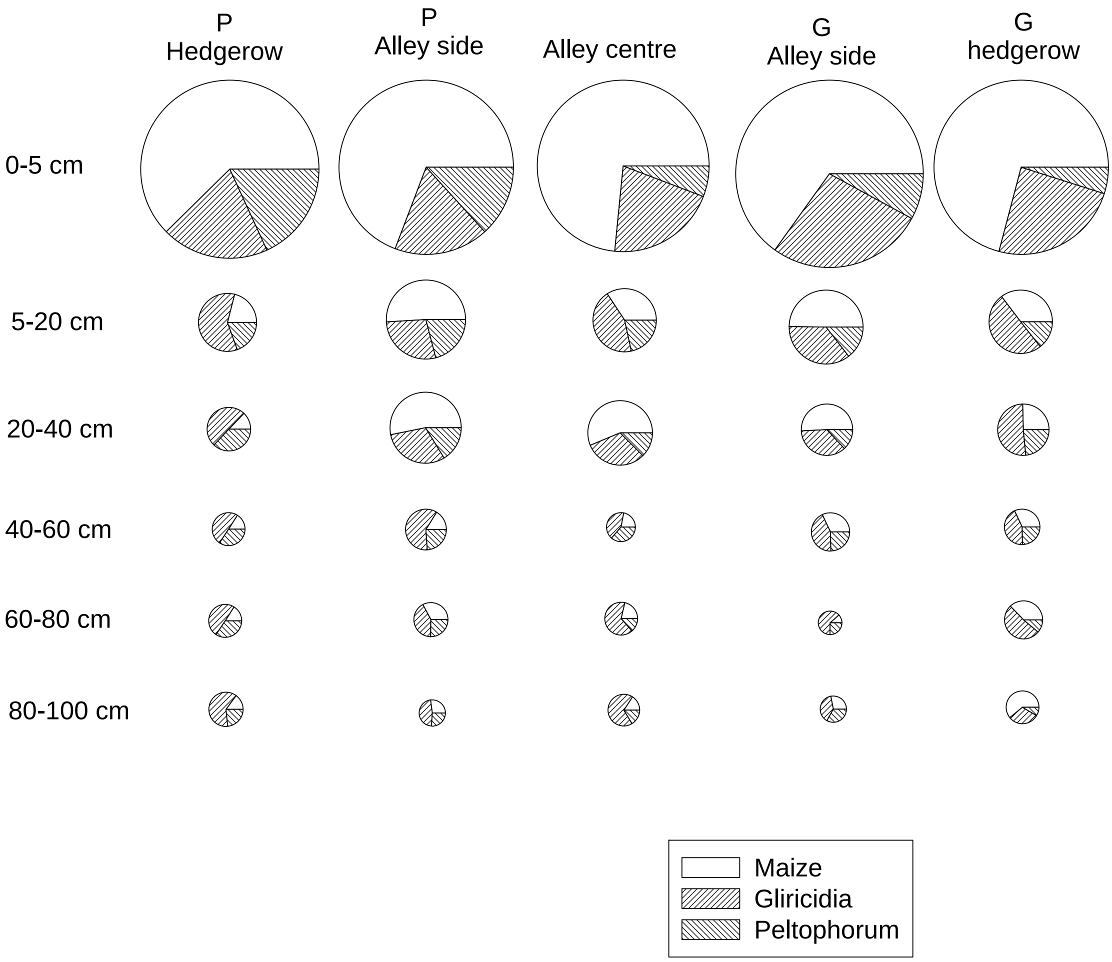

Figure 3 Relative proportions of maize, *Gliricidia* (G) and *Peltophorum* (P) root length at different positions within a mixed (G - P) hedgerow intercropping system. The area of each circle represents the total root length density.

c) Distribution of ^{15}N uptake activity: quantifying safety-net efficiency

To assess the efficiency of tree roots in intercepting and utilizing nitrogen, ^{15}N was placed at different depths and locations in soil. Patterns of ^{15}N uptake following placement at different depths generally followed the distributions of tree and crop fine roots with depth (Table 1,Table 2). There was some evidence that tree uptake took place at different depths depending on the time of pruning in relation to ^{15}N application (Table 2), but most results showed that crop uptake took place from shallower in the soil than tree uptake. *Gliricidia* trees recovered more ^{15}N from applications next to the hedgerow than from applications in the centre of the cropping alley, but this was apparently reversed for *Peltophorum* (Table 3).

Table 1 Measured total recovery of ^{15}N applied (per cent) from three soil depths by groundnut and the trees *Gliricidia* and *Peltophorum* in hedgerow intercropping systems in North Lampung, Indonesia.

^{15}N application depth (cm)	Groundnut	*Gliricidia*	*Peltophorum*
	^{15}N recovery (% of applied)		
5	13.8	0.3	5.0
35	8.9	0.2	5.6
55	3.5	0.2	7.8

Table 2 Effects of pruning time and ^{15}N application depth on ^{15}N recovery by *Gliricidia* and *Peltophorum*. Trees were pruned 25 days ("Early") or 4 days ("Late") before application of ^{15}N. *Gliricidia* trees were larger than *Peltophorum* trees.

^{15}N application depth (cm)	*Gliricidia*	*Peltophorum*
	^{15}N recovery (µg ^{15}N excess per tree)	
	1. Early pruned trees	
5	11340	142
45	847	105
80	428	403
	2. Late pruned trees	
5	2930	1003
45	1722	271
80	337	212

Table 3 Recovery of ^{15}N from different positions within the crop alley by the trees *Gliricidia* and *Peltophorum* in hedgerow intercropping systems, following application of ^{15}N at 5 cm depth.

Distance from hedgerow	*Gliricidia*	*Peltophorum*
	^{15}N recovery (% of excess applied, per tree)	
0.75 m (near side)	1.35	0.16
2.00 m (centre)	0.34	0.43
3.25 m (far side)	0.02	0.01

The percentage of *Gliricidia* N derived from fixation was estimated at 50 % using the ^{15}N natural abundance method. Assuming that the proportion of ^{15}N uptake from 55 cm depth to the sum of ^{15}N uptake from all depths was the same ratio as total soil N uptake from this depth (29% and 42% for *Gliricidia* and *Peltophorum* respectively), total soil N uptake from this safety-net zone (55 cm) was 21 kg ha^{-1} for *Gliricidia* and 42 kg ha^{-1} for *Peltophorum* (Table 4). This represents a significant amount of recycling.

Table 4 Total N production, total N uptake and estimated N uptake from the safety – net zone by *Gliricidia* and *Peltophorum* over 203 days in a hedgerow intercropping system in North Lampung, Indonesia.

	N in prunings (kg ha^{-1})	N fixation (kg ha^{-1})	N uptake from soil (kg ha^{-1})	N uptake from safety-net zone (kg ha^{-1})
Gliricidia	140 (8.9)	70	70	21
Peltophorum	99 (6.7)	0	99	42
s.e.d.	11.2**		8.1**	

The lateral safety-net

Overall effects of trees on N use efficiency were tested by applying ^{15}N urea or ^{15}N labelled prunings to the soil surface. Unexpectedly, considerably more soluble fertilizer N was taken up by downslope hedgerows, even though the slope on this field was only around 4 % (Figure 4). This effect was not seen when N was applied as tree prunings. This suggests that N leaching takes place laterally as well as vertically. Hedgerows placed perpendicular to this subsurface flow are likely to intercept N.

Nitrogen recycled via prunings is apparently less susceptible to lateral leaching, and presumably also to vertical leaching.

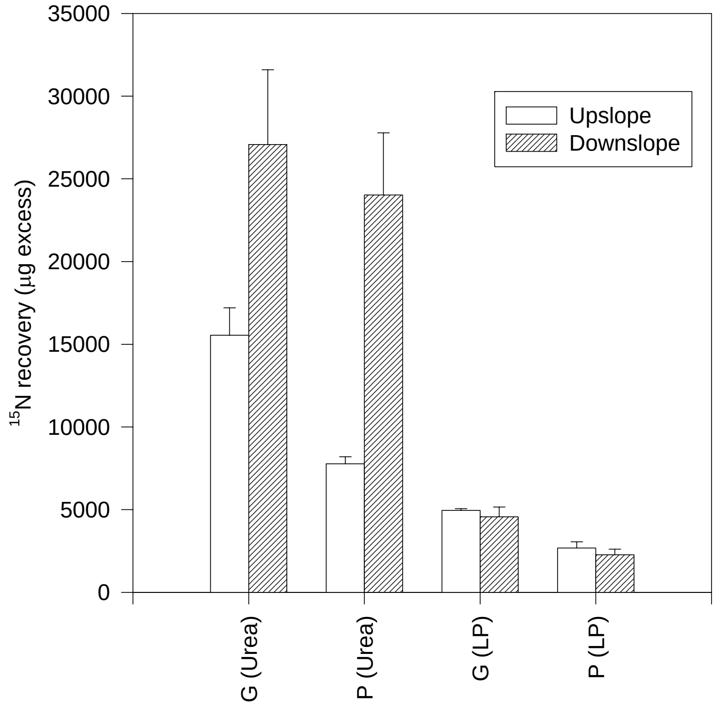

Figure 4 ^{15}N recovery totals for Gliricidia and Peltophorum hedgerows upslope and downslope from application plots, 70 days after application of ^{15}N as urea or labelled prunings (LP).

d) Temporal complementarity of N uptake

If tree and crop root activity are separated in time, competition will be reduced and trees can recycle N during periods when the crop is inactive. This is particularly likely to be useful on deep soils, where tree roots are already present at depth as the tree begins to take up N, and there is a large window of opportunity for safety – net uptake. On shallow soils, temporal separation of tree and crop uptake is likely to lead to N leaching beyond the range of tree roots.

Crop plants, and the shallow rooted tree *Gliricidia*, took up ^{15}N from deep placements later in the growing season than from shallow placements (Figure 5). The proportion of ^{15}N recovery coming from grain was therefore greater following deep placement of ^{15}N

(Figure 6). Roots of crop plants do not become active in deep soil until some 2 months after sowing. Tree roots do not need to extend down into the soil after each pruning, and so are able to take up N which might otherwise have been leached.

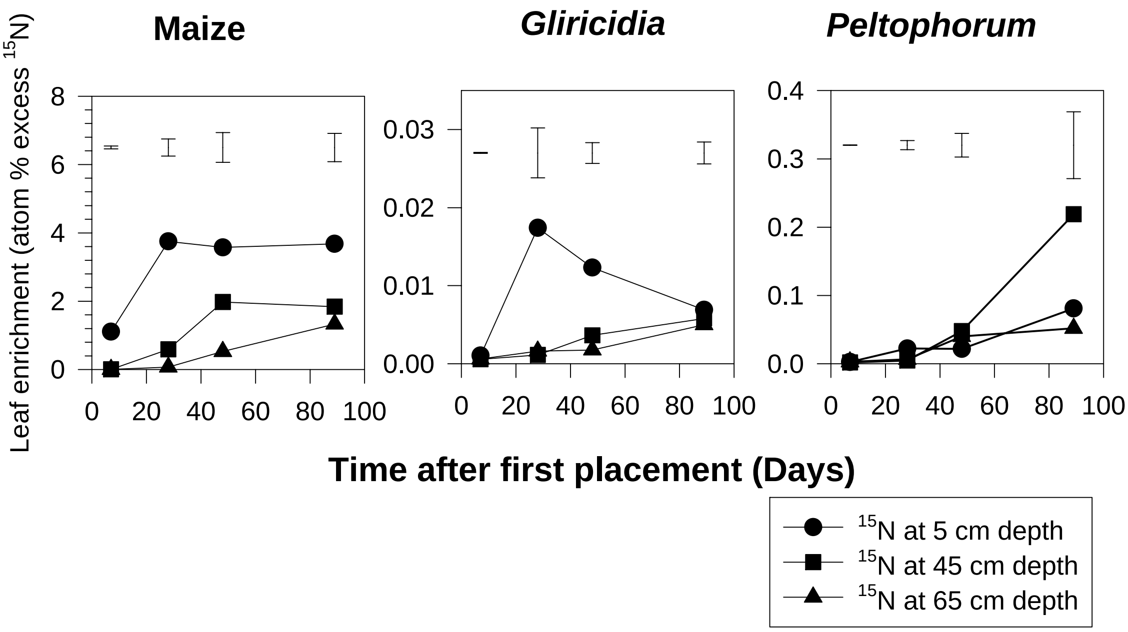

Figure 5 Time course of ^{15}N uptake by maize, *Gliricidia* and *Peltophorum* following ^{15}N placement at different depths, with first placement 9 days after sowing maize.

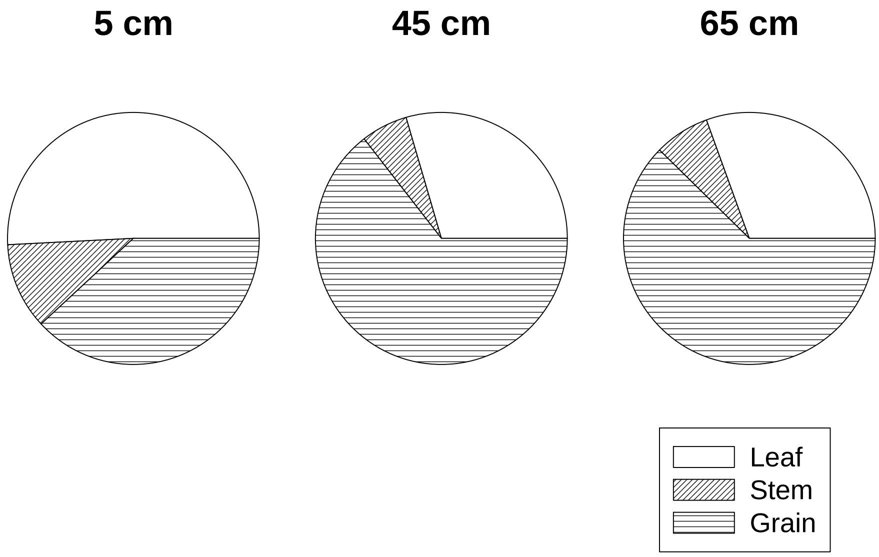

Figure 6 Effect of ^{15}N placement depth on the proportion of ^{15}N recovered in different maize parts.

The use efficiency of surface applied urea N, calculated over a single cropping season, was not improved by hedgerow intercropping (Table 5). In this experiment, ^{15}N was applied 26 days after sowing maize, and maize accounted for the majority of the uptake. It was a dry year, and *Gliricidia* in particular suppressed maize growth, presumably through competition for water.

Table 5 Location of ^{15}N in plants and in the top 1 metre of soil, 70 days after application, as % recovery of ^{15}N applied.

	^{15}N application method						
	Urea				Labelled Prunings		
	Hedgerow treatment						
	G-G	P-P	G-P	Mono -crop	G-G	P-P	G-P
Gliricidia	11.3		4.5		9.3		3.7
Peltophorum		9.2	3.5			3.1	1.6
Maize	22.3	33.5	26.5	42.0	5.8	5.1	7.4
Total plant	33.6	42.7	34.5	42.0	15.1	8.2	12.7
Litter					6.0	31.4	26.1
Soil (0-1m)	32.6	40.0	28.5	26.0	52.1	27.7	33.1
Total	66.2	82.7	63.0	68.0	73.2	67.3	71.9
Deficit	33.8	17.3	37.0	32.0	26.8	32.7	28.1

However, by the end of the second crop of the wet season, trees had taken up more of the ^{15}N (Table 6). This demonstrates the role of trees in recycling N after harvest or before the next crop has established. During the first crop, a smaller proportion of the ^{15}N was taken up by plants from ^{15}N labelled tree prunings, particularly the more recalcitrant *Peltophorum* prunings, then from ^{15}N urea. During the second crop, however, similar amounts of ^{15}N were taken up from tree prunings and urea.

Table 6 Location of ^{15}N in plants, 172 days (groundnut) or 180 days (*Gliricidia* and *Peltophorum*) after application, as % recovery of ^{15}N applied.

	^{15}N application method						
	Urea				Labelled prunings		
	Hedgerow treatment						
	G–G	P–P	G–P	Mono -crop	G–G	P–P	G–P
Gliricidia	11.5		6.0		8.2		12.5
Peltophorum		4.0	3.0			10.0	4.0
Groundnut	5.4	2.5	3.7	5.2	5.5	1.8	2.3
Total plant	16.9	6.5	12.7	5.2	13.7	11.8	18.8

During the dry season, *Peltophorum* biomass production exceeded that of *Gliricidia*, in contrast to the pattern of growth during the wet season. *Peltophorum* presumably relied on deeper water and N resources than *Gliricidia*. Such temporal complementarity reduces competition during crop growth, and increases the relative benefit of improved nutrient cycling.

e) Effects of trees on amounts of N leached

Soil macroporosity and hydraulic conductivity was greater under hedgerow intercropping systems. Increased infiltration reduced surface runoff from 5 – 10 % under monoculture to almost zero. The proportion of bypass flow was greater under hedgerow intercropping; this is likely to increase leaching rates immediately after application of soluble fertilizer, but leaching of nutrients from the soil matrix will be reduced by bypass flow.

Amounts of water draining below 0.8 m depth were estimated from changes in soil water content, measured using a neutron probe. Amounts of N leaching below this depth were then calculated from the mineral N concentration in soil solution extracted using ceramic suction cups. Little N leaching occurs while the maize crop is growing strongly, but as maize N and water demand decreases towards the end of the season, more leaching occurs (Figure 7). This leaching is considerably reduced in the presence of hedgerow trees, particularly *Peltophorum*. Reduced leaching results partly from tree water uptake which reduces the throughput of water, partly from tree uptake of N which reduces soluble N concentration in leaching solution, and perhaps partly from increased bypass flow under hedgerow intercropping.

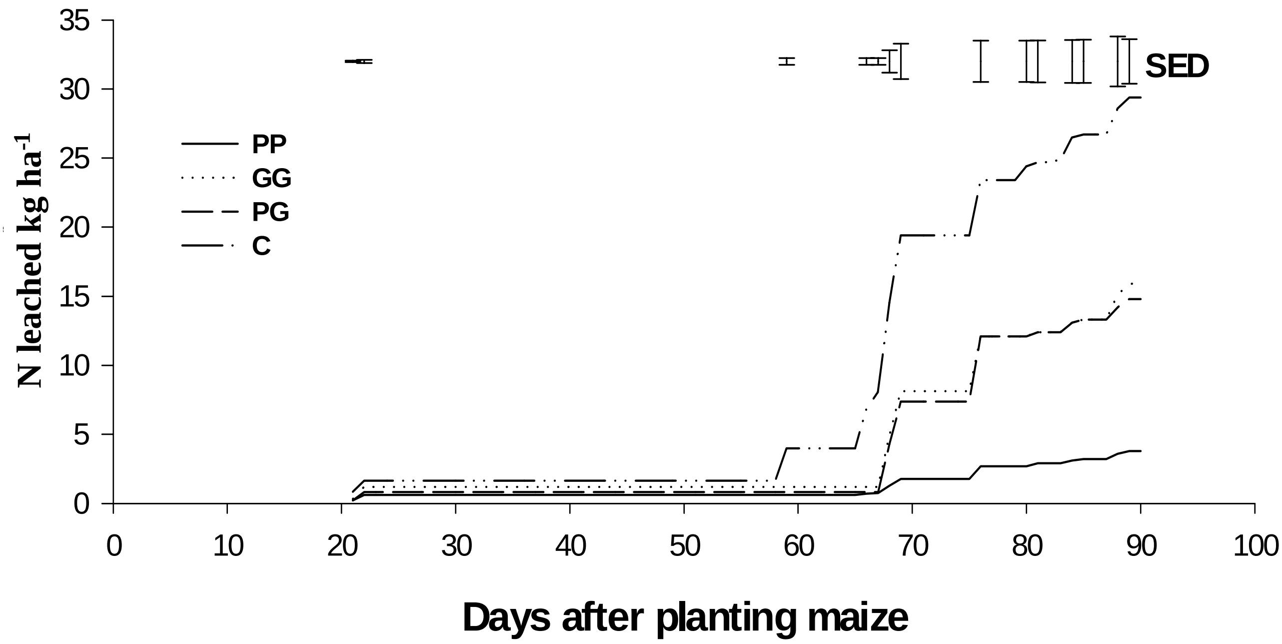

Figure 7 Cumulative amount of N leached below 80 cm depth in monocrop (C) and in hedgerow intercropping systems with *Peltophorum* (PP), *Gliricidia* (GG) or alternating *Gliricidia* and *Peltophorum* (PG); based on calculations of the water balance with WaNuLCAS and measured concentrations of mineral N.

Conclusions

In summary; considerable evidence was obtained for agronomically significant amounts of safety – net uptake. Trees, particularly *Peltophorum*, have a deeper rooting profile than maize, and this is reflected in a deeper ^{15}N uptake distribution. While trees may decrease total plant N uptake during the growth of a crop if competition restricts crop growth, total plant N uptake, taken over a whole year, is increased by trees. Trees take up N during periods when crop roots are not active. Maize roots are only active in deep soil from around 60 days to around 90 days after sowing. Tree roots actively take up N from deep soil, particularly during periods when the topsoil is drier than the subsoil.

2. Management for deep tree rooting profiles

Despite earlier evidence that decreasing pruning height leads to more but thinner main tree roots (van Noordwijk and Purnomosidhi, 1995), no effects of pruning height on tree fine root distributions were observed. Tree pruning height also had no consistent effects on the yield of intercropped maize (Table 7).

Table 7 Maize and tree prunings yield (Mg per ha of field, i.e. area of hedgerows included) in three hedgerow intercropping systems pruned at ground level or at 0.75 m height.

	Hedgerow intercropping system		
Pruning height (m)	G–G	P–P	G–P
	Maize grain yield (Mg ha^{-1})		
0	1.2	1.6	1.4
0.75	1.8	1.7	1.5
	Tree prunings yield (Mg ha^{-1})		
0	2.9	1.0	2.2
0.75	2.6	1.6	1.8

Experiments aimed at comparing the root systems of trees established by direct seeding, transplanting seedlings or by use of stem cuttings, and at examining the response of tree roots to localised applications of P and $CaCO_3$, were set up in 1997 (BMSF expts. 23A and 23B). The full evaluation of these treatments has been delayed due to civil unrest. Main roots and distributions of fine roots will be measured in 2000, when the trees have fully established, by Universitas Brawijaya / ICRAF.

Conclusion

Pruning trees is necessary to reduce competition with crops, but the temporal effects of pruning on N uptake appear to be more important than spatial effects on tree root distributions.

3. Simple indicators of below-ground tree architecture

Tree excavations showed that main roots of *Gliricidia* had a tendency to grow at shallower angles than main roots of *Peltophorum* (Figure 8). This tendency, quantified as the 'Index of shallow – rootedness' or as area – weighted mean vertical angle (Table 8) corresponded to the fine root distributions observed by wet sieving for these two tree species.

Figure 8 Excavations of main roots of *Gliricidia* (tree #4) and *Peltophorum* (tree #5).

Table 8 Mean index of shallow - rootedness ($\Sigma D_{hor}^2 / D_{stem}^2$) and area weighted mean vertical angle for *Gliricidia* and *Peltophorum* trees in three hedgerow intercropping systems.

	Index of shallow – rootedness	Area – weighted mean vertical angle
Gliricidia	0.79	45^o
Peltophorum	0.19	65^o

The value of the excavation method for quickly assessing tree root vertical distributions was demonstrated, at least for these two species.

An iterative numerical model (adapted from Spek and van Noordwijk, 1994) was used to estimate root system lengths from simple measurements of root link lengths and branching proportions. The model was able to predict coarse root length, but fine roots made up such a large proportion of total root length (Table 9) that conversions to fine root estimates were inaccurate. Calculation of tree root length density by this method therefore seems not to be practicable without further model development.

Table 9 Percentage of total root length of *Gliricidia* and *Peltophorum* in diameter classes < 1 mm, 1 – 2 mm, 2 – 5 mm, 5 – 10 mm and > 10 mm. Samples were taken 75 cm from the base of trees.

Diameter (mm)	*Gliricidia*	*Peltophorum*
	% in diameter class	
< 1	98.33	96.92
1 – 2	1.13	2.71
2 – 5	0.37	0.38
5 – 10	0.13	0.00
> 10	0.04	0.00

Conclusions

Excavating tree proximal / main roots provides a quick, low–tech and non – destructive way to assess trees' potential safety–net role and likely competitiveness. Iterative 'fractal branching' models have the potential to derive root distributions from relatively few parameters, but further studies are needed to assess branching patterns of fine roots.

4. <u>Incorporating below-ground C and N and water dynamics into agroforestry models</u>

WaNuLCAS is a competition model which can be adapted to simulate a wide range of sequential and simultaneous agroforestry systems. Uptake of water, N and P are calculated on a daily timestep on the basis of plant demand. Uptake is limited by root length density, which can be entered separately for tree and crop in 4 soil layers and 4 horizontal zones. An overview of the model is shown in Figure 9.

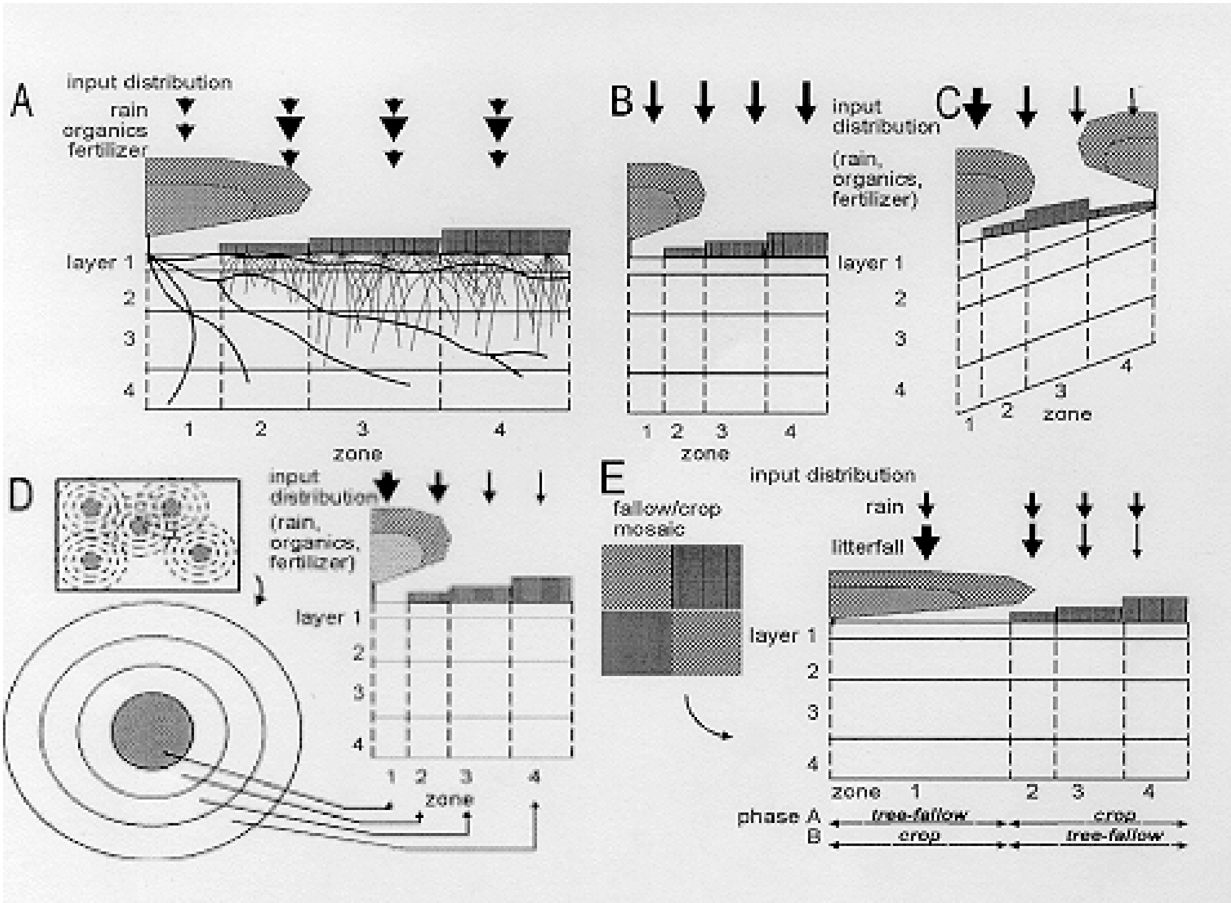

Figure 9 General layout of zones and layers in the WaNuLCAS model (A) and applications to four types of agroforestry system: B. Alley cropping, C. Contour hedgerows on slopes, with variable topsoil depth, D. Parkland systems, with a circular geometry around individual trees, E. Fallow-crop mosaics with border effects

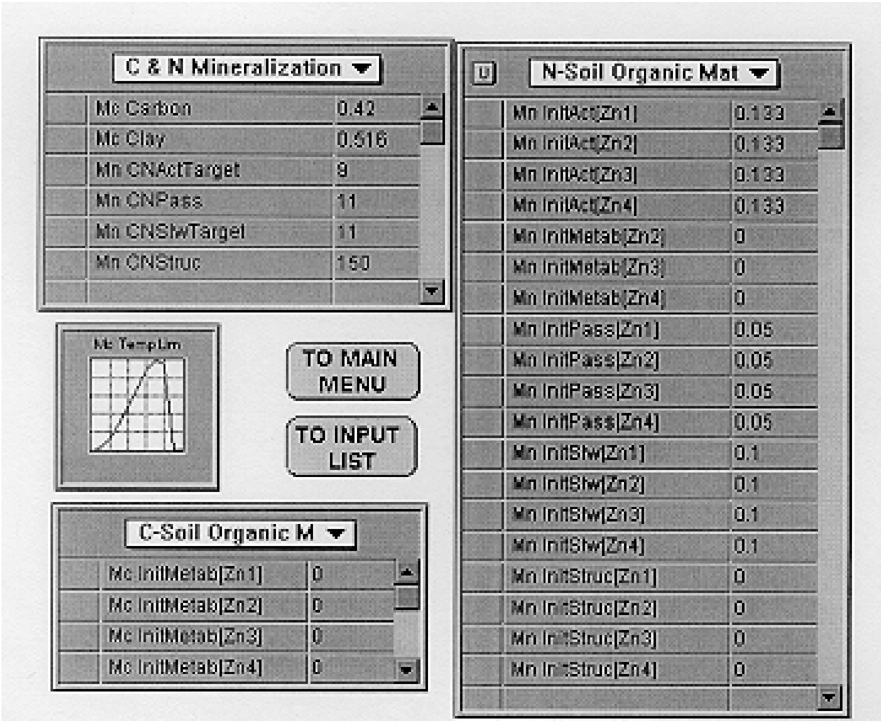

Figure 10 Upper level view of WaNuLCAS, showing options for setting input values numerically or in graph / table form. The buttons 'to main menu' and 'to input list' allow one to navigate through the input section.

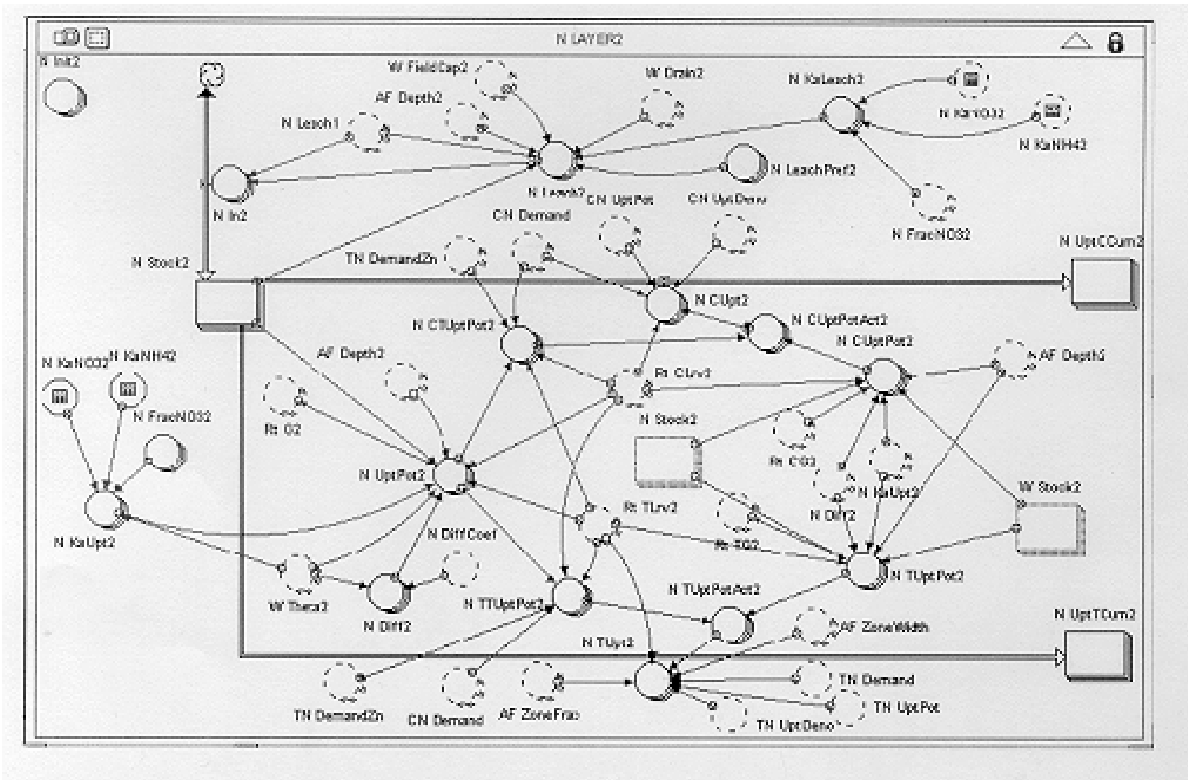

Figure 11 Middle level view of WaNuLCAS showing an example sector. Constructing new model structure is relatively simple.

Figure 10 and Figure 11 show sample screen shots from WaNuLCAS. An example of the outputs which can be obtained is shown in (Figure 12). In this case, the WaNuLCAS model was set up to simulate experimental hedgerow intercropping systems on the BMSF site. This allowed comparisons of, for example, simulated and measured crop and tree yields and enabled the accuracy of model predictions to be checked.

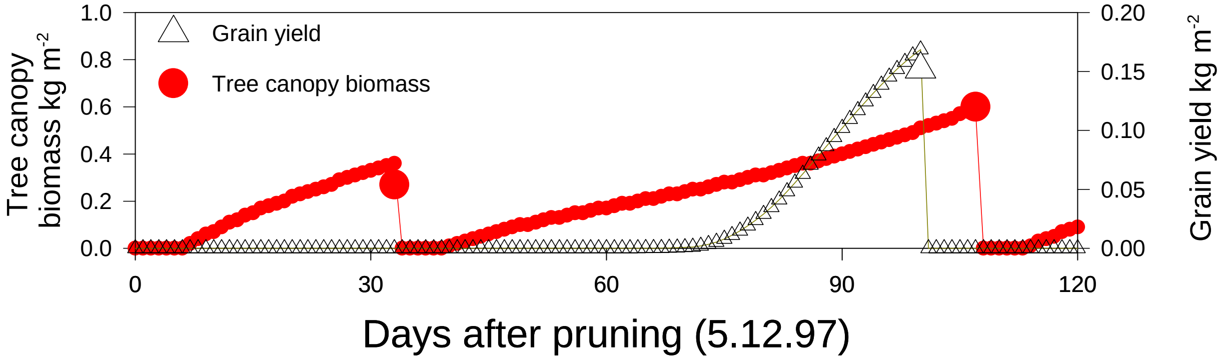

Figure 12 Simulated trajectory of growth of maize (grain component only) and tree canopy biomass within a *Gliricidia* hedgerow intercropping system. Large symbols represent measured values.

Comparisons of model predictions and measured data showed the model to be functioning with a reasonable degree of accuracy (Table 10). The reduction in maize yield by *Gliricidia* hedgerows was somewhat underestimated by the model; further model development is being aimed at refining modules describing water competition.

Table 10 Comparison of measured (microplot) yields of grain and hedgerow prunings with results of WaNuLCAS simulations for three cropping systems. Simulated results are shown in italics. Prunings yield refers to leaf plus stem. Simulated grain yields are means for zones 0.5 – 1 m and 1 – 2 m from hedgerows, weighted by zone width.

Parameter	Hedgerow intercropping system				
	monocrop	G-G		P-P	
	Urea	Urea	LP	Urea	LP.
Maize grain yield	0.33	0.17	0.19	0.28	0.25
(kg m^{-2})	*0.30*	*0.29*	*0.32*	*0.31*	*0.21*
Groundnut grain	0.128	0.069	0.083	0.090	0.098
yield (kg m^{-2})	*0.143*	*0.120*	*0.120*	*0.131*	*0.131*
Tree prunings	-	0.92	1.07	0.43	0.37
yield (kg m^{-2})		*0.88*	*0.88*	*0.45*	*0.45*
5^{th} Dec - 9^{th} July					

The range of measurements taken during this project (e.g., tree and crop dry matter and N production, changes in soil water and N content, uptake of N from particular soil locations) allows the functioning of different parts of the model to be checked. More confidence can then be attached to model outputs which are not easy or not possible to measure. The amount of N leaching below 1 m depth was not directly measured, but model predictions showed the importance of crop uptake of water and N in reducing leaching during the period of active crop growth (Figure 13).

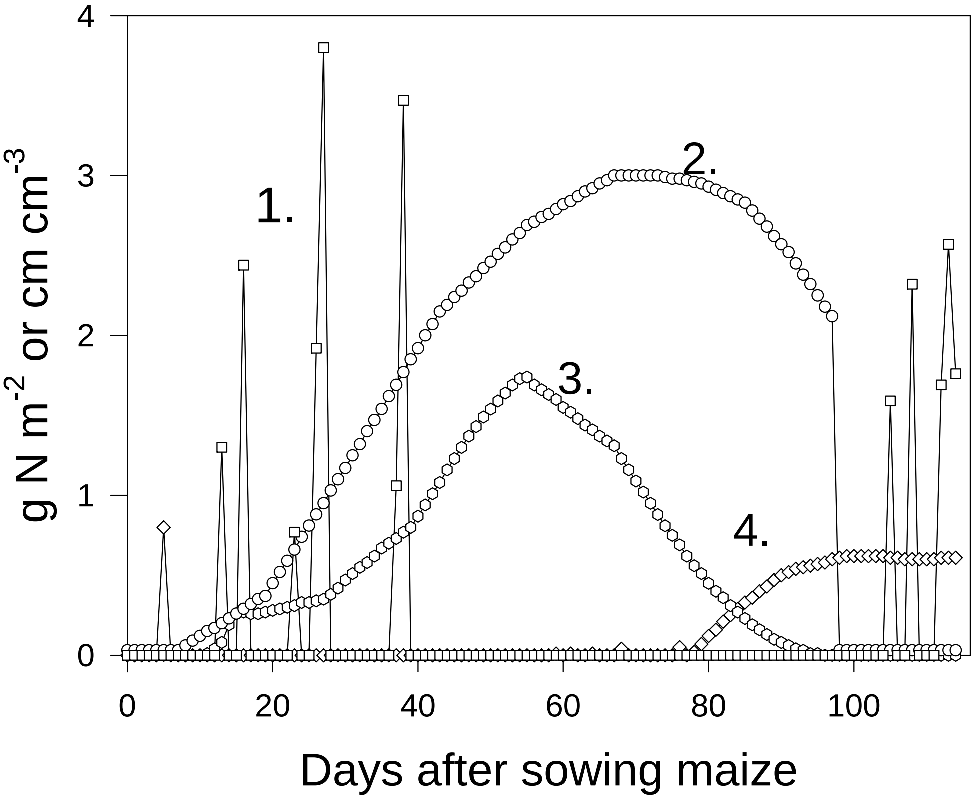

Figure 13 Leached N (1.), Crop topsoil root length density (2.), CropN demand (3.) and Tree N demand (4.), as predicted for a maize / *Peltophorum* hedgerow intercropping system by WaNuLCAS.

A variety of outputs can be obtained, and new model structure can be added relatively easily to adapt the model for new systems or to produce new outputs. Figure 14 shows a further example of model output, the simulated movement of ^{15}N tracer through different soil N pools.

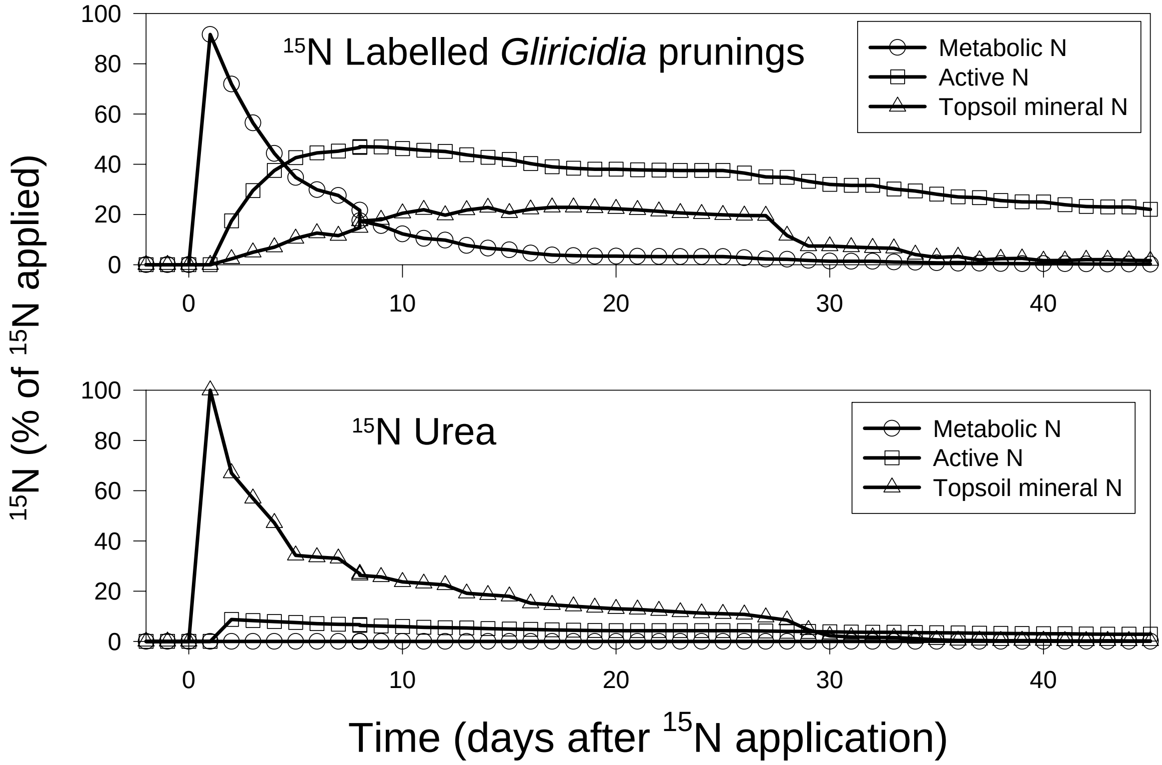

Figure 14 Movement of ^{15}N through different soil N pools following application of ^{15}N as ^{15}N urea or as ^{15}N labelled prunings, as simulated by WaNuLCAS.

5. Tree – crop combinations and management options to improve nutrient use efficiency

a) Effects of hedgerows on intercrop yield

Some hedgerow intercropping systems showed promising effects on intercrop yield. Hedgerow intercropping with *Peltophorum dasyrrachis*, or a combination of this species with *Gliricidia sepium*, had a net positive effect on maize yield in most years over a monocrop system, despite the loss of land area to hedgerows (Table 11).

Table 11 Maize grain yield (Mg ha^{-1}) in four cropping seasons in hedgerow intercropping systems (BMSF Expt 17; van Noordwijk *et al.*, 1995).

Treatment	Jan '90	Apr '90	Jan '91	May '91	Overall
Control	1.50	1.73	3.60	2.26	2.30
Erythrina	2.08	2.28	2.80	2.28	2.35
Leucaena	1.40	2.50	2.94	2.02	2.21
Gliricidia	1.69	2.59	2.56	2.46	2.33
Peltophorum	2.99	2.68	4.56	3.04	3.32
Glir. / Pelt.	2.31	2.00	3.13	2.73	2.55
Calliandra	1.08	2.70	2.99	2.42	2.30

The effect of *Peltophorum* hedgerows was similar to that of increasing fertilizer inputs from zero to 45 kg N + 60 kg P_20_5 ha^{-1} yr^{-1} (Table 12). Maize yield in monocrop was not increased by increasing fertilizer inputs from 45 kg N ha^{-1} yr^{-1} to 90 kg N ha^{-1} yr^{-1}. Other nutrients may have become limiting after N requirements were satisfied, or excessive urea application may have caused an acidifying effect. *Erythrina* did not survive the pruning regime and thus cannot be recommended for this ecosystem.

Table 12 Maize yield (Mg per ha of field, i.e. area of hedgerows included) in three hedgerow intercropping systems and in control plots receiving one of four fertilizer treatments (N0P0 = no fertilizer; N0P1 = 60 kg P_20_5 ha^{-1} yr^{-1}; N1P1 = 45 kg N + 60 kg P_20_5 ha^{-1} yr^{-1}; N2P1 = 90 kg N + 60 kg P_20_5 ha^{-1} yr^{-1}). Treatments denoted by the same letter were not significantly different (F_{pr} < 0.05).

Hedgerow intercropping systems			Control plots				
G-G	P-P	G-P	N0P0	N0P1	N1P1	N2P1	s.e.d.
Maize grain yield (Mg ha^{-1})							
1.51^{bc}	1.48^{bc}	1.66^{b}	1.04^{a}	1.29^{ac}	1.55^{bc}	1.52^{bc}	0.10

b) Choosing tree species: deep or shallow rooted ?

The goals of weak competition with the crop for N, and efficient interception of leaching N, are to some extent contradictory. Complete interception of leaching N depends on a large demand relative to availability, but these are also the conditions which lead to strong competition. Achieving both goals depends on a spatial separation of N uptake niches, so that strong demand by the trees does not deplete N excessively in the crop rooting zone. Trees with a deep root distribution are likely to take up N from deep in the soil, and are thus better candidates for hedgerow intercropping than shallow – rooted trees. A first indication of tree shallow – rootedness can be obtained by excavating and observing tree main roots (Section 3). *Peltophorum* has been identified as having a low index of shallowrootedness and a good potential for safety – net function.

c) Choosing tree species: Nitrogen fixing or not ?

The effects on crop yield of the interaction between hedgerow trees and crops can be summarised as the benefit due to fertility, minus the reduction due to competition:

$$I = F - C$$ (Akyeampong *et al*., 1995)

where I = Interaction, F = Fertility effect (direct + long-term) and C = Competition effect (light, nutrients and water).

Analysing long-term data from the BMSF site (experiment 17) clearly shows that the fertility effect alone cannot necessarily be used to identify the best tree species for intercropping. The fact that *Peltophorum* (which does not fix N_2) increased maize yield more than some N fixing species can be explained by separating these terms (Table 13); although *Peltophorum* does not have the greatest beneficial effect, its competitive effect is comparatively small.

Table 13 Effect of different alley trees on maize / rice yields (as % of crop yield in monocrop) in long term experiment 17, BMSF, Lampung.

	Pruning yield	Fertility effect	Competition effect	Interaction
	kg N ha^{-1}	%	%	%
Leucaena *	150	152	-159	-7
Calliandra *	145	120	-115	+5
Peltophorum	168	58	-26	+32
Flemingia *	165	37	-89	-52
Gliricidia *	145	19	-60	-41

*** = N_2 fixing**

Garrity and Mercado (1994) came to similar conclusions, i.e. that hedgerow systems with nitrogen fixing trees did not exert significant advantages within four years compared to non-fixing tree species. It appeared that other factors were more important determinants for the choice of hedgerow species in the investigated experimental systems, at least in the short term. However, on more sandy and less fertile soils the need for N_2 fixation inputs is likely to become apparent more quickly.

Can trees fix enough N_2 to sustain productivity?

The legume tree-*Rhizobium* symbiosis potentially provides an alternative to N fertilizers to balance N losses of agricultural systems, through its ability to fix atmospheric N_2. Hedgerow trees whose prunings are returned to the soil can theoretically make a larger contribution to the systems N balance than grain legumes as their N harvest index is zero (Giller and Cadisch, 1995). Catchpoole and Blair (1990) reported N yields of up to 700 kg ha^{-1} in 14 months old stands of *Gliricidia sepium* in the humid tropics of Indonesia. Estimates of the proportion of such N derived from N_2 fixation in agroforestry trees vary widely (0-100%) depending on species, system, management and environmental conditions (Giller *et al*., 1994). Estimations under field conditions suggested up to 274 kg N fixed ha^{-1} $year^{-1}$ by *Leucaena leucocephala* in dense stands in the humid tropics using the N difference method (Sanginga *et al*., 1986). However, the amounts of N_2 fixed by hedgerow trees are likely to be much less due to the sparse tree density in this type of cropping system.

N_2 fixation estimates of alley trees over a two year period after establishment were obtained by the ^{15}N dilution method using *Peltophorum dasyrrachis* as the non-fixing reference plant. Data were obtained from experiment 16 where *Flemingia congesta* and mixed *Gliricidia sepium – Peltophorum dasyrrachis* hedgerows were established on an Ultisol (Grossarenic Kandiudult) in North Lampung.

Table 14 Yearly tree pruning growth, N_2 fixation and soil-N uptake of a mixed *Peltophorum dasyrachis – Gliricidia sepium* and sole *Flemingia congesta* hedgerow in Northern Lampung, Sumatra (average of 2 years).

	Dry weight	Total N yield	Avg. % N derived form N_2 fixation	Amount of N_2 fixed2	Soil-N uptake
	(kg ha^{-1} $year^{-1}$)		%	(kg ha^{-1} $year^{-1}$)	
Peltophorum	3848	70	0	0	70
Gliricidia	2064	52	51	26	26
Total	5912	122		26	96
Flemingia	6014	136	25	35	101
SED	164^{ns}	9.1^{ns}	5.1*	8.7^{ns}	5.2^{ns}

Average yearly total tree dry matter and N yields of the two hedgerow systems were not significantly different although seasonal differences occurred (Table 14). *Gliricidia* obtained a larger (average 51%) proportion of its N from N_2 fixation than *Flemingia* (average 25%) the effect being consistent over the two years (Figure 15). Seasonal variation in the % N derived from N_2 fixation was associated with changes in soil mineral N availability.

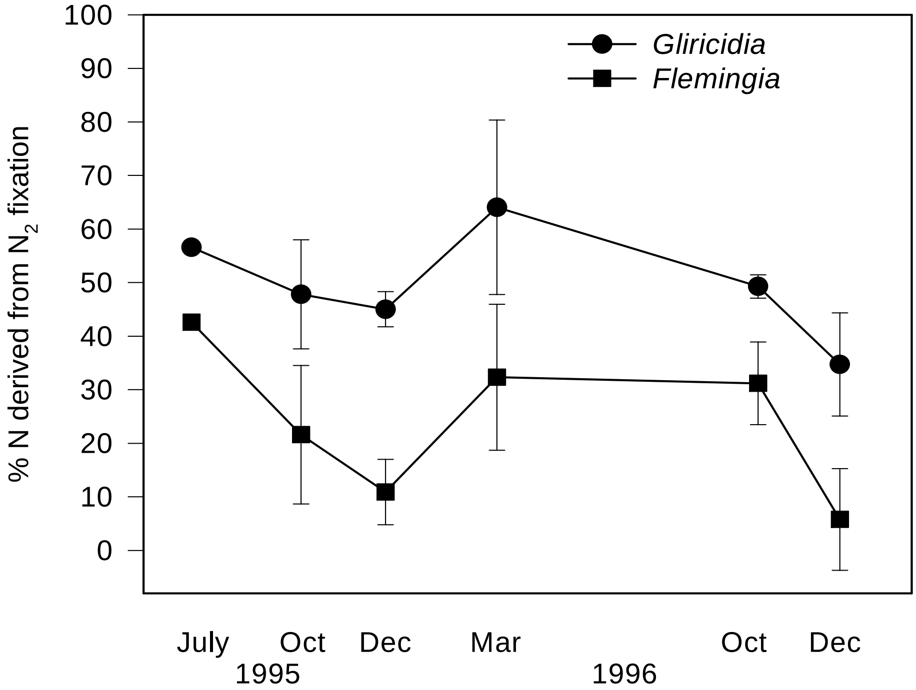

Figure 15 Percent N derived from N_2 fixation of *Flemingia congesta* and mixed *Gliricidia sepium-Peltophorum dasyrachis* hedgerows.

The amount of N_2 fixed was not significantly different between the two N fixing trees (26 vs. 35 kg N ha^{-1} $year^{-1}$ respectively). This was due to the higher total N yield of *Flemingia* compared to *Gliricidia* compensating for the smaller proportion of N derived from N_2 fixation. The amount of tree soil N uptake was similar for the two hedgerow systems suggesting that the higher proportion of N derived from N_2 fixation in *Gliricidia* was due to competition for soil mineral N by the associated non-fixing *Peltophorum*.

N balance estimates suggested that N_2 fixation inputs of alley trees were sufficient to sustain a low to moderate crop yields (<1.5 t ha^{-1}) (Table 15). However when increased production is desired as occurred in year 3 then inputs from N_2 fixation by trees were not sufficient and other legumes needed to be included in the crop rotation system (Table 15).

Table 15 N balance of 2 and 3 (in brackets) years old hedgerow or crop only rotation systems. Two years balance correspond to low-medium crop yields and 3rd years balance for medium-high crop yields.

	Hedgerow system		Crop rotation
	Peltophorum-Gliricidia	*Flemingia*	Groudnut-Cowpea
		(kg N ha^{-1} $year^{-1}$)	
N export:			
Total systems harvest N off-take[1]	34 (70)	37 (82)	77 (110)
N imports:			
N_2 fixation by trees	38	35	0
N_2 fixation groundnut[2]	20	16	34
N_2 fixation cowpea	3	8	18
Systems N balance	**+27 (-9)**	**22 (-19)**	**-25 (-53)**

[1] Hairiah *et al.*(In prep); [2] Cadisch *et al.* (In prep)

Under the given environmental conditions, additional N inputs from grain legumes were moderate and barely enough to offset increased N export in products. In the long-term under higher productivity some additional inputs from fertilizers may be required as the current calculation assume no major N losses (leaching, denitrification) from the system. However, the improved N balance in hedgerow systems has to be offset against reduced yields due to lost space, shading and competition for nutrients and water. Data from Hairiah *et al.* (In prep) suggest that the benefit of N_2 fixation inputs by trees for crop production at the study site only begins to outweigh the yield reduction due to competition more than three years after planting hedegrows.

The growth of nitrogen fixing trees is less limited than that of non – fixing trees, and so they are likely to compete more strongly for other resources. In intimately mixed agroforestry associations, this strong competition may outweigh the undoubted benefits of increased N inputs and soil N (re-)capitalisation. Nitrogen fixation rates of trees decrease with increasing soil mineral N availability, so the benefits of including N fixing trees tend to decline as soil fertility increases.

d) Choosing tree species: High or low prunings quality?

Increasing N interception by incorporating trees will only benefit crop growth if the N intercepted by trees

(i) later becomes available to crops, or

(ii) contributes in some other way to soil fertility.

The pattern of decomposition of tree litter, roots and prunings is thus important in determining whether trees will be of net benefit. Plant material characteristics which govern decomposition rate, such as C:N ratio and polyphenol content, are collectively referred to as 'quality'; high quality materials are those which decompose quickly. Prunings of low quality may not release N quickly enough for it to become available to a crop sown after pruning, and may even cause a net immobilisation of soil N. However, slow N release may be an advantage where N can rapidly be lost through leaching before the intercrop develops a strong demand for N. Slow decomposition of prunings leads to a buildup of organic matter which generally benefits soil physical and chemical characteristics, and represents an increase in soil nutrient capital (Giller *et al.*, 1997). A mulch of slowly decomposing prunings on the soil surface may provide considerable protection from rain 'capping' and erosion, although this benefit must be weighed against a possible increase in shelter for rodents and other pests (Gauthier, 1996). Both fast and slow decomposition have advantages, and the relative importance of rapid N availability and long – term soil fertility must be weighed.

Much research on prunings quality has been directed at synchronising net release of nitrogen with crop N demand. Mixtures of high and low quality prunings offer scope for moderating and manipulating the timing of N release; this was demonstrated in pot experiments (Handayanto *et al.*, 1997). Intercropping systems with alternating hedgerows of *Gliricidia* and *Peltophorum* were therefore set up at the BMSF site to exploit the effect. *Peltophorum* prunings have a larger C:N ratio, and a greater content of soluble polyphenols, than *Gliricidia* prunings. This was clearly reflected in a lower plant uptake of N from *Peltophorum* prunings than from *Gliricidia* prunings during the first crop (Table 5). In this experiment, ^{15}N labelled *Gliricidia* prunings were mixed with unlabelled *Peltophorum* prunings. Much more N from *Gliricidia* prunings remained in surface litter when these were mixed with the lower quality *Peltophorum* prunings (Figure 16). Plant uptake of *Gliricidia* prunings N was less during the first crop when *Peltophorum* prunings were mixed in, but greater during the second crop season (Table 6). This supports the principle that low quality prunings can be used to moderate the release of N from high quality prunings.

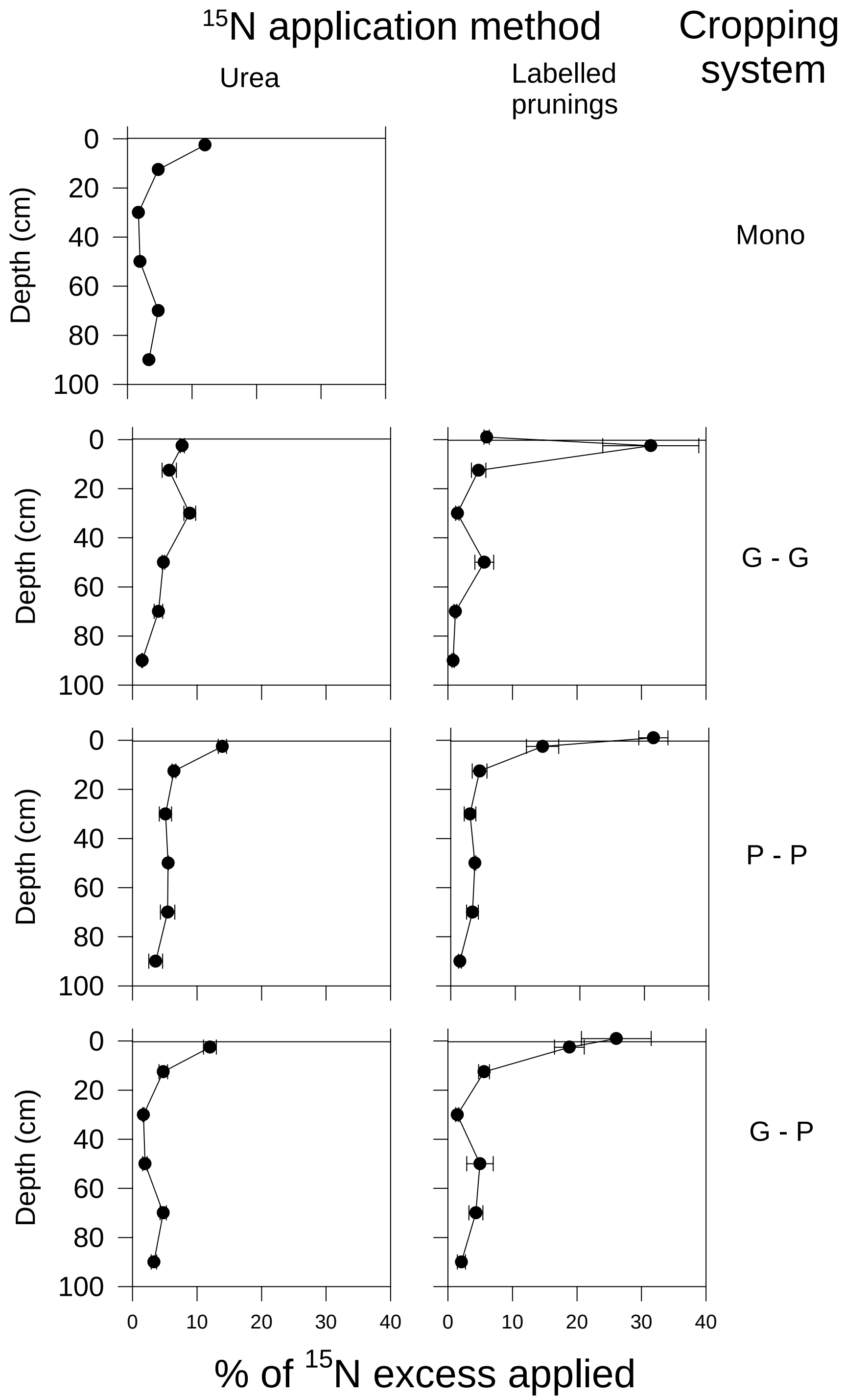

Figure 16 Location of ^{15}N in surface litter and in soil at 0-5, 5-20, 20-40, 40-60 and 60-80 cm depth, 70 days after application as ^{15}N labelled urea or prunings, as percentage of ^{15}N excess applied. ^{15}N remaining in surface litter is shown just above the soil surface.

Total N in the top 5 cm of soil was increased by 11-12 years of hedgerow intercropping with *Gliricidia* or *Peltophorum*, though apparently not when these two species were grown in alternating hedgerows (Table 16).

Table 16 Total N in soil (%) at different depths in monocrop system and in *Gliricidia* and *Peltophorum* hedgerow intercrop systems.

	Hedgerow system			
Depth (cm)	G – G	P – P	G – P	Monocrop
0 – 5	0.133	0.144	0.111	0.112
5 – 20	0.087	0.080	0.073	0.082
20 – 40	0.055	0.050	0.062	0.048
40 – 60	0.043	0.039	0.043	0.035
60 – 80	0.031	0.032	0.034	0.029
80 – 100	0.027	0.028	0.031	0.026

e) Choosing tree species: Fast or slow growing?

The growth rate of trees, and the time taken for trees to recover after pruning, have major effects on the productivity of intercrops. Trees which rapidly produce new growth inevitably have rapidly rising demands for water, nutrients and light, and are likely to compete strongly with associated crops. On the other hand, such trees are likely to reduce leaching more than slow growing trees, and inputs of soil litter and nutrients will be greater. Fast growing trees which can rapidly send roots deep into the soil and provide substantial inputs are suited for use in improved fallows, but are not suitable for use in hedgerow intercropping systems. This conclusion is similar to that reached by Schroth (1995).

Ideal trees for use in intimate agroforestry associations grow slowly during the growth of the crop. However, after the crop is harvested, competition is no longer relevant, and benefits will be greatest from trees which then grow rapidly. The ideal tree is thus one which regrows slowly after pruning, but can grow rapidly after crop harvest and exploit residual water and nutrients during the fallow period. (Such a tree might be better at preventing leaching than an improved fallow, since its roots are present in the subsoil from the start of the fallow season.) Such ideal trees seem unlikely, but the well known African tree *Faidherbia albida* provides an example, and *Peltophorum* shows a similar tendency in that its biomass production under hedgerow intercropping was generally greater during the dry season than during the wet season (Table 17).

Table 17 Prunings biomass production of *Gliricidia* and *Peltophorum* during crop growth phase (CGP) and fallow period.

Cropping season	Phase	Prunings biomass (Mg ha^{-1})	
		Peltophorum	*Gliricidia*
1993 / 1994	Fallow	6.62	4.25
	CGP	1.86	6.81
1994 / 1995	Fallow	1.85	1.14
	CGP	1.89	4.11
1995 / 1996	Fallow	6.25	2.89
	CGP	2.63	5.16
1996 / 1997	Fallow	9.85	2.77
	CGP	1.48	1.44
1997 / 1998	Fallow	6.11	6.66
	CGP	1.75	4.50

f) Management options

The species selection criteria considered above can all be influenced by management.

Evidence that trees can be made less shallow rooting by pruning at a greater height is scant, and it seems likely that any benefit of this effect would be outweighed by increased light competition. Root competition from trees in the surface soil can be reduced by periodic tillage, where this is practicable. Root barriers, or root pruning, may also have some effect, but tree roots have a remarkable ability to circumvent barriers, regrow, and proliferate in resource – rich soil, so the effect may be short – lived.

Nitrogen fixation rates vary with pruning frequency, and with soil N availability. Fixation rates are likely to be maximal when tree carbon fixation rates are high but soil N availability is low. Inputs of fixed N will thus be maximised by pruning trees infrequently and not applying N fertilizer, both of which contradict the demands of an intercrop. An appropriate compromise is to apply an amount of N fertilizer to the crop which does not exceed its demand, and so maintains available soil N at a low level during the fallow season.

Prunings quality is most easily manipulated by mixing plant materials of different quality. Prunings quality is affected by the nutrient status of the tree, with trees grown under nutrient stress producing lower – quality prunings (Handayanto *et al.*, 1995). As noted above, optimal prunings quality depends on the timescale of nutrient release required by the crop, and the rate of N leaching. There is some scope for optimising systems in this way but the interaction of several factors needs to be considered.

Tree growth rates can be influenced to a large extent by the frequency of pruning, and to a lesser extent by pruning height. More frequent pruning leads to a lower overall biomass production (Duguma *et al.*, 1988), and this can be used to regulate competition from trees. However, the use of slower growing tree species may be more practical and acceptable, since extra prunings during the growth of the crop represent additional labour costs.

In general, selecting species likely to form successful hedgerow intercropping systems, and deciding on management operations, involves weighing up a range of factors, many of which are likely to interact. Simulations provide a way of assessing the combined effects of changing a component of the system. The WaNuLCAS model was used to predict optimal pruning time for *Gliricidia* and *Peltophorum* in relation to maize sowing date; early pruning leads to tree regrowth shading the young maize, whereas late pruning leads to soil water and nutrient deficiencies (Figure 17). Pruning time is less critical for the slowly – regrowing *Peltophorum*.

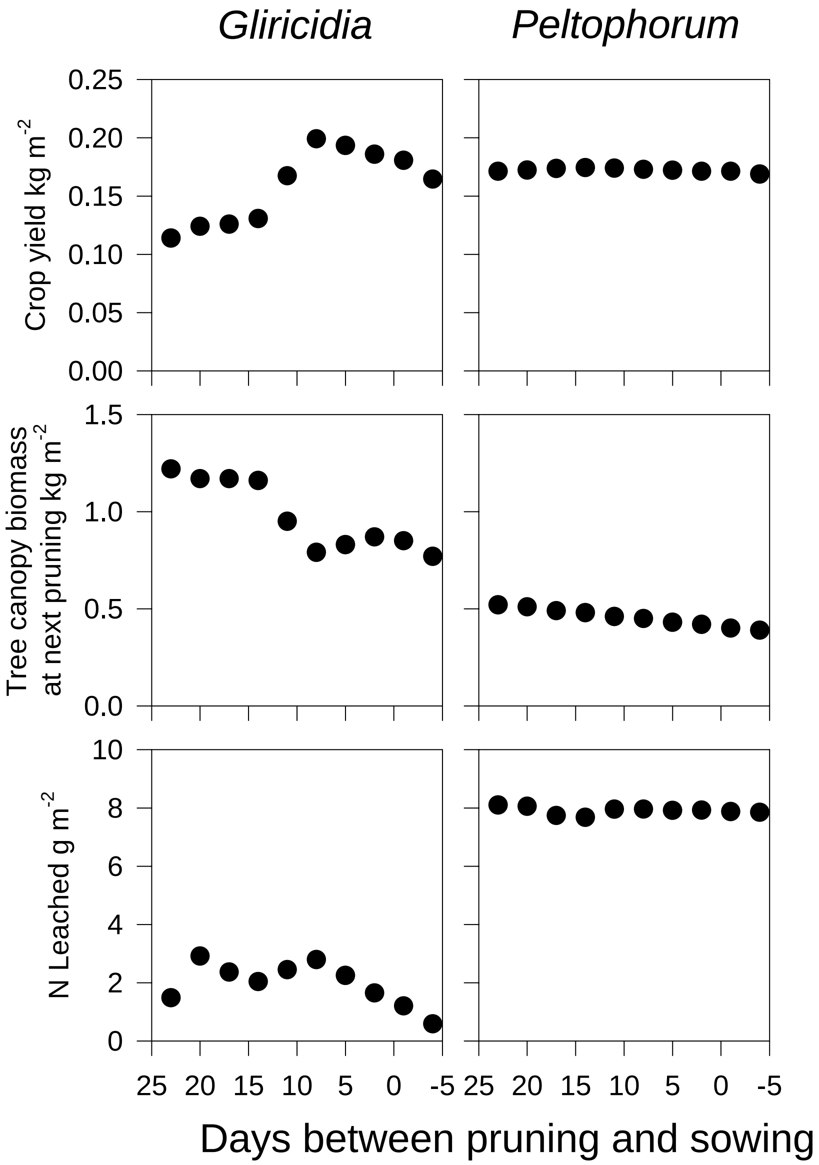

Figure 17 Sensitivity of simulated maize yield, tree prunings biomass and N leached during the growth of the first crop of the wet season (112 days) to variation in the interval between pruning trees and sowing maize, in simulated *Gliricidia* and *Peltophorum* hedgerow intercropping systems.

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Contribution of Outputs

Include how the outputs will contribute towards DFID's developmental goals. The identified promotion pathways to target institutions and beneficiaries. What follow up action/research is necessary to promote the findings of the work to achieve their development benefit? This should include a list of publications, plans for further dissemination, as appropriate. For projects aimed at developing a device, material or process specify:

a. What further market studies need to be done?
b. How the outputs will be made available to intended users?
c. What further stages will be needed to develop, test and establish manufacture of a product?
d. How and by whom, will the further stages be carried out and paid for?

a) Summary of recommendations

The improved understanding of nutrient cycling in agroforestry systems gained as a result of experimental work leads to direct recommendations for the implementation of hedgerow intercropping systems. These can be summarised as follows:

- Complete spatial complementarity of nitrogen use by tree and crop plants in hedgerow intercropping systems, as currently conceived, is an unrealistic aim; strong competition is likely to occur in closely mixed systems.
- Nevertheless, trees offer substantial benefits to soil structure and long term fertility. Trees maintain a large carbon balance; take up and recycle nitrogen during periods of crop inactivity, since they maintain a network of roots deep in the soil; and increase bypass flow during rainstorms, reducing leaching losses.
- Much nitrate leaching occurs laterally rather than vertically. Widely spaced hedgerows arranged as filters to intercept laterally flowing nitrogen compete less strongly with crops than hedgerows spaced 4 m apart, but still provide 'safety-net' benefits.
- Net benefits of hedgerow intercropping systems will be maximised if hedgerows are kept pruned short during the growth of the crop but grow rapidly during fallow periods.
- Tree species suitable for use in closely integrated agroforestry associations are likely to be slow growing during the period of crop growth as this reduces the

labour costs of pruning, but ideally this should be combined with good growth during the dry season on residual soil moisture.

- Deep rooted trees are likely to be more complementary in their use of resources than shallow rooted trees. The depth of tree rooting can easily be assessed by excavating main roots and measuring their angles of descent.
- Nitrogen fixation by trees in hedgerows spaced 4 m apart can only maintain levels of N without artificial supplements when N export in crop products is moderate, because of low to medium yield, or low harvest index. To boost system productivity and sustainability, N_2 fixing crops should be included in the rotation.

b) Current dissemination

Results of experimental work have been published in Agroforestry Forum and in the international journal Agroforestry Systems, and will continue to be disseminated through ICRAF internal publications and international journals (see attached manuscripts). A series of workshops has been held (see list of dissemination outputs below) to publicise the WaNuLCAS model, and obtain feedback on its ease of use and applicability. Groups from ICRAF, ASB, WinRock, Universitas Lampung, etc., regularly visit the BMSF site in Lampung where they are introduced to hedgerow intercropping systems and the nutrient cycling processes which we are studying.

Some of the experiments were carried out on farmers' land and therefore acted partly as demonstration plots. One field has now reverted to farmer management; interestingly, the farmer has not killed or removed the hedgerows, but cuts them back to ground level periodically during crop growth, as we would now recommend.

Highlights of research results were presented to researchers and officials from PTP Bunga Mayang, the sugarcane plantation which owns the experimental site, in a workshop held in December 1998. A proposal for a collaborative experiment between PTP and Universitas Brawijaya to compare methods for increasing organic inputs is under consideration. As a result of the meeting, and visits to the BMSF field station, the plantation has already ceased burning trash over a large area, resulting in a reduction in pollutant emissions and a potential improvement in soil organic matter content. Since many smallholder producers are associated with the PTP plantation, these changes are likely to have a wide impact if farmers perceive that the new management practices provide substantial benefits, and adopt these practices.

Due to the expertise gained through work at BMSF, project members from Universitas Brawijaya were invited to participate in a planning exercise for a new transmigrant area in Kalimantan. As a result, the planting of trees for soil fertility maintenance was incorporated into the transmigration area plans, and is now being implemented.

The use of WaNuLCAS has been demonstrated to researchers from target institutions at workshops held in Cranfield University (8 participants); ICRAF, Nairobi14-16 September 1998 (5 participants); University of the Philippines (22 participants); IITA, Benin 22 – 26 Feb 1999 (12 participants); Chiang Mai University, Thailand (10 participants); and CIFOR-ICRAF / ICSEA-BIOTROP, Bogor (29 participants). (Total workshop participants = 86).

c) Planned dissemination

Three papers will be presented by project participants from Universitas Brawijaya at a symposium to be held at Universitas Lampung in September 1999. These will cover recent results from hedgerow intercropping experiments, on N leaching; root turnover and C and N balances; and mineralisation.

The WaNuLCAS model will be used to help interpret results from experiments on improved fallows at the Kenyan Forestry Research Institute (KEFRI), as part of the DfID funded NRSP project R7056 "Nutrient sourcing and soil organic matter dynamics in mixed – species fallows of fast-growing legume trees". The model will assist with the design of locally adapted fallows.

Plans were outlined for a stakeholder workshop in collaboration with ICRAF/ASB, aimed mainly at the end users, and for production of a booklet and fact sheets on the following topics:

1. How and why did hedgerow intercropping give disappointing results? (balance of positive and negative interactions; return on labour investment)

2. What every one should know about tree- soil - crop interactions (principles of above- and below-ground interactions in resource capture, immediate and long term effects via the soil, integration in a simulation model such as WaNuLCAS)

3. How can you recognize a tree that is compatible with intercrops and increases nutrient use efficiency? (proximal roots and what we can deduce from them, in combination with aboveground phenology and vigour, with examples from fruit & timber trees in Lampung)

4. Does it matter where the trees/hedgerows are located? (moving from a 1-dimensional leaching and safety-net concept to a 2D concept with subsurface lateral flows and its implications for safety-net and filter functions, illustrated with experimental results and WaNuLCAS calculations).

A costing was made for these outputs, but partial funding requested from NRI did not seem to be available. Plans for the workshop, booklet and factsheets were therefore postponed. A Policy Brief, formed on the basis of the recommendations summarised above and aimed at Forestry and Agriculture Institutions, extensionists, GO's and NGO's, will however be produced.

d) Follow – up recommendations

The direct applicability of results of hedgerow intercropping experiments to beneficiaries is limited, since these systems are not widely used by smallholder farmers. A major conclusion of the project is that strong competition is difficult to avoid in closely mixed agroforestry systems, as currently conceived. Unless the trees provide a benefit other than that of maintaining soil fertility, such systems are unlikely to be attractive to smallholder farmers and should not be promoted.

Research results suggest a number of possibilities for designing systems which would provide net benefits to smallholder farmers, as listed in the summary of recommendations above. The growth of trees benefits soil structure and increases organic matter inputs. Widely spaced hedgerows, planted along contours or at points of egress, might provide much of the nutrient interception benefit of hedgerow intercropping without competing so strongly with crops. Periodic tillage could be used to kill tree roots which proliferate in the topsoil of areas used for annual crops. Alternatively, pruning trees to keep them small throughout the growth of the crop could be used to reduce competition; hedgerows would thus act as a rapidly establishing, deep rooted fallow during the dry season. It may be worth incorporating trees which produce fruit, timber, stakes, firewood, fodder or other valuable products in addition to their fertility benefits. If the value of such trees per unit resource use is higher than that of the crops, 'competition' for resources will not be seen as a negative effect by the farmer.

These suggestions are as yet untested. Systems must also be designed to suit local conditions, and designs must be flexible, to take account of prevailing market conditions and evolving knowledge. Socio-economic considerations are paramount, since such factors as the timing of labour availability, the presence of livestock, and the demand for different products, will determine how practical a system is. A major output of the project is thus the improved WaNuLCAS model, which allows novel systems to be evaluated without extensive experimentation. This predictive modelling approach will assist target institutions (Forestry and Agriculture Institutions, ODA-ITE-AMP (Agroforestry Modelling Project group) and ICRAF) to develop agroforestry systems suitable for use by beneficiaries (transmigrant settlers and smallholder farmers). However, a wider validation of the model is required before it can be recommended directly to give farmers specific recommendations.

Participants in the workshops held enjoyed considerable success in simulating the agroforestry systems they work on. Participants commented on the ease of use and flexibility of the model. The latter was generally considered a useful feature, though some doubts were expressed as to the danger of inexperienced users being able to change the functioning of the model. It was suggested that future model development should include collation of standard data files on tree, crop and soil types which could be easily ‘plugged in’. The adaptability of the model was generally thought to be an advantage, but it was suggested that two versions should be developed; one to retain this adaptability, the other to be based around a simple, user-friendly ‘front end’, so that it could be used by extensionists. However, these groups would need continued support, training, and a hotline to make efficient use of the model and to ensure that this tool is applied correctly.

As a direct outcome of the Bogor workshop, WaNuLCAS user groups will be set up in Universitas Lampung and Universitas Brawijaya. Participants considered that the model allowed the integration of agronomic, pedological and economic knowledge, and as such would facilitate communication between departments within their universities and enable problems of production and sustainability to be tackled in a multidisciplinary way. Future model development should aim to widen the scope of the model by incorporating plug – in modules. In particular the economic module should be refined, and a livestock module incorporated to examine the effects of incorporate animals into the system on nutrient cycling and economics. The handling of biophysical processes may also need to be refined as new knowledge develops; as for example happened during this project with the realization of the importance of lateral leaching. WaNuLCAS is still in development, and is currently aimed at researchers. If the model is to be used by non-specialists, a more user – friendly front end needs to be developed, and databases of default soil, tree and crop characteristics incorporated. Support for users, and systems for quality assurance, will also be essential. Promotion of the model by the Training and Extension Programme of ICRAF is being discussed.

e) List of dissemination outputs

1. WaNuLCAS model

VAN NOORDWIJK, M. and LUSIANA, B. (1999) WaNuLCAS: A Model of Water Nutrient and Light Capture in Agroforestry Systems. *Agroforestry Systems* 43, pp. 217-242. (A)

VAN NOORDWIJK, M. and LUSIANA, B. (1999) WaNuLCAS 1.2: Backgrounds of a Model of Water Nutrient and Light Capture in Agroforestry Systems. International Centre for Research in Agroforestry (ICRAF), Bogor, Indonesia. (C)

VAN NOORDWIJK, M. and LUSIANA, B. (1999) WaNuLCAS: A Model of Water Nutrient and Light Capture in Agroforestry Systems: Website. <http://www.icsea.or.id/wanulcas/>. English. (G)

2. Seminars and workshops

LAWSON, G. and CANNELL, M.G.R. (1998) FRP-AMP Agroforestry Modelling Workshop. [workshop included 8 participants from developing countries]. English. Cranfield University, June 19th 1998. (D)

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VAN NOORDWIJK, M. (1999) WaNuLCAS. [2 day training workshop with 10 participants, mainly graduate students working in N. Thailand and Laos]. English. Chiang Mai University, Thailand, March 11 – 12 1999. (D)

VAN NOORDWIJK, M. and LUSIANA, B. (1999) Water, Nutrient and Light Capture in Agroforestry Systems: Process Research and Integrative Models. [training workshop for researchers from Indonesian universities and the Indonesian Rubber Research Institute; 29 participants]. English. CIFOR-ICRAF / ICSEA-BIOTROP, Bogor, 20-22 July 1999. (D)

3. Publications

CADISCH, G., ROWE, E. C., and VAN NOORDWIJK, M. (1997) Nutrient Harvesting - The Tree Root Safety Net. *Agroforestry Forum*, **8**: 31-33. (A)

VAN NOORDWIJK, M., and LUSIANA, B. (1997). WaNuLCAS - A Model of Light, Water and Nutrient Capture in Agroforestry Systems. pp. 439-442. In: Agroforestry for Sustainable Land Use. CIRAD / IUFRO International Conference, Montpellier, France, 23-29 June 1997. (B).

ROWE, E. C., CADISCH, G., HAIRIAH, K. and VAN NOORDWIJK, M. (1997). The Safety-Net Role of Hedgerow Tree Roots, A Direct Test by ^{15}N Placement on an Acid Soil in Lampung (Indonesia). pp. 165-168. In: Agroforestry for Sustainable Land Use. CIRAD / IUFRO International Conference, Montpellier, France, 23-29 June 1997. (B).

ROWE, E.C., CADISCH, G. and GILLER, K.E. (1998) Root Distributions and ^{15}N Uptake Activity in a Hedgerow Intercropping System. *Agroforestry Forum*, **9**: 46. (B)

ROWE, E.C., CADISCH, G. and GILLER, K.E. (1998) Testing the 'Safety-Net' Role of Hedgerow Tree Roots. UK Agroforestry Forum meeting, Bangor, July 1998 (poster). (B)

ROWE, E.C. and CADISCH, G. (1998) Progress on WaNuLCAS Model. *Agroforestry Modelling Project Newsletter*. (B)

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HAIRIAH, K., VAN NOORDWIJK, M. and CADISCH, G. (In prep.) Biological N_2 fixation of hedgerow trees in N. Lampung. *Netherlands Journal of Agricultural Science*.

ROWE, E.C. (In prep.) The safety – net role of tree roots in hedgerow intercropping systems. PhD Thesis. Department of Biological Sciences, Wye College. (E)

SUPRAYOGO, D. (In prep.) Testing the 'safety net' hypothesis in agroforestry: Measurement and model simulation of water balance and mineral N leaching in the humid tropics. PhD Thesis. Department of Biological Sciences, Wye College. (E)