

Tree-Soil-Crop Interactions in Sequential and Simultaneous Agroforestry Systems

M. van Noordwijk,¹ K. Hairiah,² B. Lusiana
and G. Cadisch³

¹ICRAF-SE Asia, PO Box 161, Bogor 16001, Indonesia

²Brawijaya University, Fakultas Pertanian, Malang
Indonesia; ³Wye College, University of London, UK

Introduction

Perpetuum mobiles, or machines which will keep going without inputs of external energy have been a long-time dream of humankind. Over the centuries, an immeasurable amount of time and energy has been spent on the systems improvement of 'promising' technologies, which did not yet fully meet the target, but were considered to be at least halfway. Formulation of the second law of thermodynamics, which states that perpetuum mobiles cannot exist, has slowed down the efforts and has led to a situation where every 'discoverer' of a perpetuum mobile is met with a weary smile rather than excitement. Maybe recognition of the laws of thermodynamics has therefore reduced the progress in increasing the energy use efficiency of machines which were halfway meeting their target.

Similarly, agroforestry has often been expected to provide land use systems which allow sustainable outputs of high value without requiring external inputs of nutrients. Here, too, considerable efforts have been made on systems improvement of 'promising' technologies. The generalizations which can be made in ecology are not as strong as those in physics, and we do not yet have the direct equivalent of the laws of thermodynamics. Agroforestry research is largely confined to conclusions about specific systems, at specific times and locations, partly by choice (every farmer will need his/her own agroforestry system), partly by lack of understanding of underlying principles. Yet we know that there is no free lunch in resource sharing between crops and trees and that nutrient exports in harvestable

products will have to be replenished from somewhere outside the land-use unit for the system to be called truly sustainable. An apparent exception to this is nitrogen (N), where atmospheric molecular N (N_2) fixation can give land-use systems the appearance of perpetuum mobiles, even if they lead to marketable yield products, which mean both money in farmers' pockets and nutrient exports. However, the increased N availability to crops will directly increase the mining of other nutrients from the soil and will aggravate problems in the medium and longer term, unless it is part of an integrated nutrient management scheme. The more realistic, down-sized expectations of agroforestry which have developed over the last decade (Buresh, 1995; Sanchez, 1995; van Noordwijk and Garrity, 1995) now lead to weary smiles in response to many agroforestry development proposals; at least, they should - it takes time for the message to get through. Yet it should not prevent us from making efforts to increase the nutrient use efficiency of land-use systems on the basis of agroforestry systems, provided that they are based on the strategic use of external nutrient inputs, on a proper assessment of the biophysical resource (water, nutrients) base of plant production and on an understanding of resource sharing (competition) between the multiple components of an agroforestry system. Researchers can help farmers in analysing how 'promising' technologies can be improved, which tree and crop characteristics may be used to select appropriate component species and to what extent management choices should depend on climate and soil factors.

In this review of concepts and methods for studying tree-soil-crop interactions, we shall discuss an empirical approach to separate positive from negative interactions and obtain a process-level understanding of the components, and describe a framework for the synthesis of component knowledge. The final outcome of an agroforestry system for a specific farmer depends both on the nature (inherent plant qualities) and the nurture (effects of the abiotic and biotic environment, farmer management) of the system.

Simultaneous and Sequential Systems

If we ignore animal-production aspects for the time being, we can focus a discussion of agroforestry on the interactions between trees, soils and crops. None of these elements is specific for agroforestry, but their interactions as part of a land-use system are. The same components can be used in systems which have very different properties. A major distinction is between simultaneous and sequential systems (Sanchez, 1995; van Noordwijk and Purnomosidhi, 1995). In simultaneous systems, the interactions are both spatial and temporal, while those in sequential systems are only temporal: the tree and the crop communicate via the soil only (Fig. 13.1).

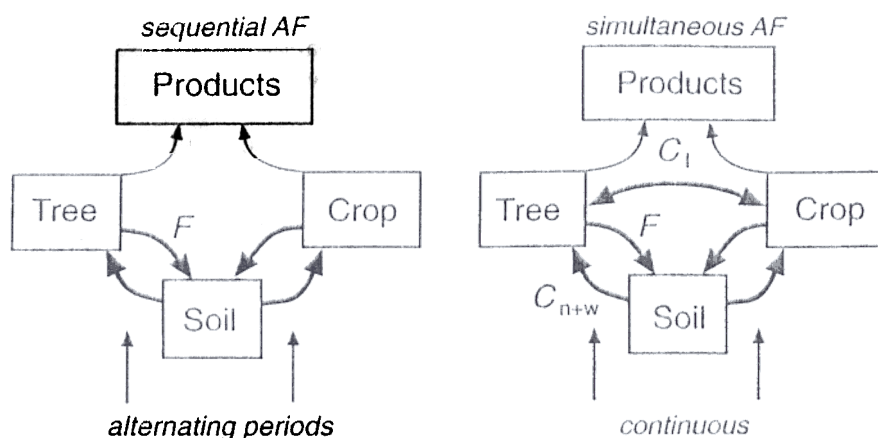


Fig. 13.1. Tree–soil–crop interactions in sequential and simultaneous agroforestry systems; F , effect on soil fertility; C_{n+w} , competition for nutrients and water; C_l , competition for light.

Direct empirical tests of improved fallow would consider a tree germplasm–soil combination as input and crop yield as output. The reason for looking at intermediate steps, such as tree biomass development, litter fall and build-up of soil organic-matter pools, is that we hope to find useful indicators of the effectiveness of the fallows, which can be used for evaluating a larger number of sites and/or fallow germplasm sources. A key aspect of the sequential systems is the potential build-up of soil organic-matter levels during the tree fallow without direct competition between tree and crop. Total organic-matter content is not a very sensitive indicator, as it changes relatively slowly under different management regimes and often has a high spatial variability, linked to variability of soil texture. Physical fractionation procedures, based on particle size and density (Christensen, 1992), allow the distinction of pools with different degrees of physical protection from decomposers. During decomposition, plant litter with an initial physical density around 1.0 g cm^{-3} becomes more intimately associated with mineral particles with a physical density of around 2.5 g cm^{-3} . A fractionation procedure developed by Meijboom *et al.* (1995) on the basis of colloidal silica suspensions (Ludox) has been successfully applied by Barrios *et al.* (1996, 1995) in the analysis of sequential agroforestry systems. The light and intermediate fractions obtained with this method appear to be the most important ones for the N mineralization in the first year after the fallow. The hypothesis that the heavy fractions are directly related with soil structure and architecture (Kooistra and van Noordwijk,

1996) and soil-water retention is speculative as yet. A possible direct role of decaying tree roots in facilitating crop root development after improved fallows was discussed by Torquebiau and Kwesiga (1996). Evidence for this is far from conclusive.

Tree-soil-crop interactions in simultaneous systems are based on the same soil fertility effect as in sequential systems, but, in addition to that, involve competition for light, water and nutrients.

Tree-Soil-Crop Interaction Equation

Akeampong *et al.* (1995) developed a simple equation for quantifying tree-soil-crop interactions (I), distinguishing between positive effects of trees on crop growth via soil fertility improvement (F) and negative effects via competition (C) for light, water and nutrients. In its most basic form:

$$I = F - C \quad (13.1)$$

Soil fertility here incorporates chemical, physical and biological aspects of the soil, in as far as they are relevant for crop growth. The interaction term is positive and the combined system is advantageous for crop production if $F > C$, and not if $F < C$. Van Noordwijk (1996) described a model which links both the mulch production underlying F and the shading, which is an important part of C , to the biomass production of the tree. The model, which assumes water not to be a limiting factor for crop growth, leads to a simple mulch/shade ratio as a basis for comparing tree species. The model also predicts that at low soil fertility, where the F factor can be pronounced, there is more chance that an agroforestry system improves crop yields than at higher fertility, where the C factor will dominate. This prediction is in agreement with the conclusion of Woomer *et al.* (1995) that the crop response to alley cropping in African network sites is negatively correlated with total soil N in the 0-15 cm layer, but positively correlated with an extractable phosphorus (P) fraction (Bray II). The tree mulch, whether from N_2 -fixing or N-scavenging trees, primarily contributes to the N and not to the P nutrition of the crop (Palm, 1995), and both the N_2 fixation by the trees and the N utilization of the crop are likely to be increased at better P supply. The suggestion of Sanchez (1995) that alley cropping is most likely to work where 'soils are fertile without major nutrient limitations' contrasts with this model. On soils without major nutrient limitations, the F term would be small (there is hardly a problem of plant nutrition to be addressed) and, although the impact of nutrient competition on the crop will be small as well, the negative effects of competition for water and light will remain on the negative side of the balance. To a certain extent, nutrient constraints on tree growth may differ from those on crop growth (especially where one of the components can fix atmospheric N_2 and the other not), and the best effects may be expected on

soils which are fertile without major nutrient constraints from a tree perspective, but with constraints for crop growth, which can be overcome by the tree mulches as organic source.

Cannell *et al.* (1996) attempted to clarify the resource base of the production by both the crop and the tree. Part of the positive fertility effect of the tree is based on light, water and nutrient resources which the tree acquired in competition with the crop (F_{comp}); another part may have been obtained in complement to resources available for the crop ($F_{\text{non-comp}}$) (Table 13.1). Similarly, part of the resources acquired by the tree in competition with the crop are recycled within the system and may thus be used by a future crop (C_{recycl}). Tree products which are not recycled may have direct value for the farmer ($C_{\text{non-recycl}}$). One may argue that F_{comp} is based on the same resources as C_{recycl} . The equation then becomes:

$$I = F_{\text{non-comp}} - C_{\text{non-recycl}} \quad (13.2)$$

The question whether or not a tree-crop combination gives yield benefits then depends on:

- the complementarity of the resource use (the distinction between the columns in Table 13.1);
- the value of direct tree products (the distinction between the rows in Table 13.1), specifically those obtained in competition ($C_{\text{non-recycl}}$) relative to the value of crop products which could have been produced with these resources;
- the efficiency of recycling tree resources into crop products, specifically for the resources obtained in competition with the crop (C_{recycl}).

The efficiency of recycling will depend on the degree of synchrony between mineralization from these organic residues and crop-nutrient demand, as well as on the residence time of mineral nutrients in the crop root zone under the site-specific climate and soil conditions (de Willigen and van Noordwijk, 1989; Myers *et al.*, 1994, 1997).

Table 13.1. Interplay of F (fertility) and C (competition) effects of the general tree-crop interaction equation.

Valuation of tree products	Resource base for tree growth	
	Competition with crop	Complementary to crop
Direct	$C_{\text{non-recycled}}$	
Indirect (recycled)	$F_{\text{competitive}}$ C_{recycled}	$F_{\text{non-competitive}}$

If tree products have no direct value, agroforestry systems may only be justified if $F_{\text{non-comp}} > C_{\text{non-recycl}}$. With increasing direct value of the tree products, the requirements for complementarity decrease. Complementarity of resource use can be based on a difference in timing of tree and crop resource demand. If the tree picks up the leftovers from the cropping period, as occurs with water in the *Grevillea*-maize systems in Kenya (C.K. Ong, personal communication), and transforms these resources into valuable products, a considerable degree of competition during the temporal overlap may be acceptable to the farmer. As light is not stored in ecosystems, complementarity in light use is easy to measure. For water and nutrients, complementarity has to consider time-scales linked to the residence times of the resources in the ecosystem; residence times tend to increase from water, via N and potassium (K) to P. For P resources used by the tree, it will be difficult to measure whether or not this P might have become available to the crop in the absence of trees. Indications of complementarity in below-ground resource use can be obtained by observing the root distribution of both components. Actual uptake of resources will, however, depend on resource and root distribution, as well as demand factors, and thus the degree of overlap in root distribution *per se* is not sufficient to predict competition.

The tree-soil-crop interaction equation can be further analysed by differentiating between short and long-term fertility effects (F_i and F_w , respectively), and by separating the competition term into an above-ground (light) and a below-ground (nutrients plus water) component (C_i and C_{n+w} , respectively).

Experimental Approach

Empirical interaction effects

A long-term hedgerow intercropping trial in Lampung, Indonesia (annual rainfall 2.0–2.5 m year⁻¹; gross arenic kandiuult soil; P and K fertilizer used in the trials) was used to quantify, understand and predict the terms of the interaction equation (Fig. 13.2). As indicated in Table 13.2, an attempt was made to separate the various positive and negative interaction terms directly and to develop a process-based model, which can be used to understand and thus extrapolate the results. In the following presentation, we shall discuss the methods used to quantify each of the terms.

Results for the overall interaction term (Table 13.3) show that the best overall effect was obtained with a tree with a moderately positive F term and a small negative C term. The two trees with the highest F term also had the strongest negative C term. The overall I term does not follow the classical preference for fast-growing trees as the basis for agroforestry systems. Maize yields in the alley-cropping system exceeded that in the

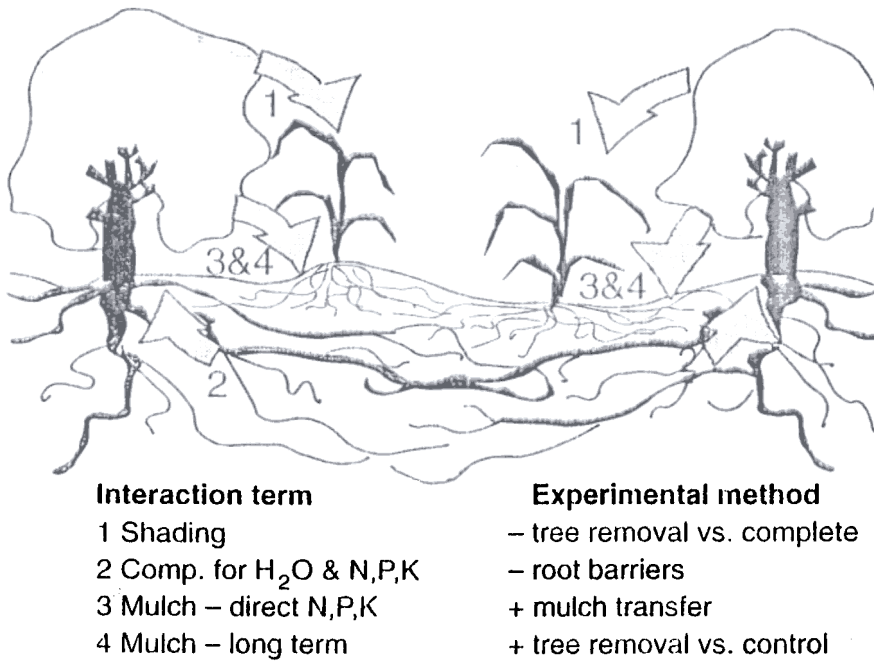


Fig. 13.2. Schematic relations of tree-soil-crop interactions in a simultaneous agroforestry system and experimental method to quantify these.

control only where the local tree *Peltophorum dasyrachis* was used (van Noordwijk *et al.*, 1995). For this specific site, process-level research can focus on the question, 'Why is *Peltophorum* so much better than the other tree species?' Explanations can be based on its relatively deep root distribution, the compact hedgerows with a high mulch/shade ratio, an appropriate timing of its nutrient mineralization, specific effects on aluminium (Al) detoxification or a combination of all these factors.

Direct fertility effect

Tests of the direct fertility value (F_1) of the mulch are based on a mulch transfer experiment. Table 13.4 gives data on the response of a maize and rice test crop to four types of tree mulch and the relative efficiency of the crop in utilizing the N contained in these mulches. Direct mulch effects can be based on nutrient mineralization from the mulch material itself, as well as on changes in (surface) soil characteristics, such as temperature, and hence mineralization of soil organic matter. The four pruning materials are

Table 13.2. Three-step approach to analysis and synthesis of tree-soil-crop interactions in simultaneous agroforestry systems. A direct experimental separation of the terms in the equation is combined with quantification of key processes and followed by model synthesis to explore management options and system-site matching.

$Y_c =$ Crop yield in interaction	$Y_0 +$ Crop yield in monoculture	$F_1 +$ Direct fertil effect	F_{∞} Long term fertility effect	$C_1 +$ Competition for light	$C_{n+w} +$ Competition for nutrients and water	M Microclimate effects
Experimental		Mulch transfer	Residual effect	tree removal	Root barriers	
Process-level understanding		Litter quality, mineralization	Functional SOM fractions (Ludo)	Canopy shape, light profiles	Root architecture (fractal branching analysis)	
Synthesis	nutrient and light capture in agroforestry systems (WANULCAS)					

1
∞
Omega
α
∞

Table 13.3. Terms of the tree–soil–crop equation for maize in the seventh year of a hedgerow intercropping experiment in Lampung (Indonesia). Data are expressed as percentage of monoculture crop yield (2.6 Mg ha^{-1} of grain); the values for *Flemingia* are based on plots where *Flemingia* replaced *Erythrina orientalis* in the fifth year of the trial.

	<i>F</i> (%)	<i>C</i> (%)	<i>I</i> (%)
<i>Leucaena leucocephala</i>	152	–159	–7
<i>Calliandra calothyrsus</i>	120	–115	+5
<i>Peltophorum dasyrrachis</i>	58	–26	+32
<i>Flemingia congesta</i>	37	–89	–52
<i>Gliricidia sepium</i>	19	–60	–41

F, fertility effect; *C*, competition effect; *I*, overall interaction ($I = F + C$).

Table 13.4. Nitrogen (N) uptake and apparent recovery (uptake as fraction of input) by maize and upland rice in response to mulch transfer of tree prunings.

	Pruning dry weight (Mg ha^{-1})	N content prunings (kg ha^{-1})	Crop N uptake (kg ha^{-1})	Apparent N recovery (kg kg^{-1})	Urea fertilizer equivalent (kg ha^{-1})	Relative N efficiency of mulch (kg kg^{-1})
Maize						
Control	–	–	45.7	–	–	–
<i>Gliricidia</i>	7.13	145	48.4	0.02	8	0.06
<i>Calliandra</i>	6.45	145	66.9	0.15	63	0.43
<i>Flemingia</i>	8.63	165	33.9	–0.08	–35	–0.24
<i>Peltophorum</i>	8.97	168	41.9	–0.02	–11	–0.07
Rice						
Control	–	–	112.6	–	–	–
<i>Gliricidia</i>	7.13	145	122.8	0.07	42	0.29
<i>Calliandra</i>	6.45	145	132.1	0.13	80	0.55
<i>Flemingia</i>	8.63	165	136.7	0.15	99	0.60
<i>Peltophorum</i>	8.97	168	116.7	0.02	17	0.10

The urea fertilizer equivalent is calculated as the amount of urea required to achieve the N uptake obtained in response to mulch; the response to urea fertilizer (50% at planting, 50% after 1 month; range: $0\text{--}135 \text{ kg N ha}^{-1}$) on plots without mulch was for maize: $N_{\text{uptake}} = 45.7 + 0.338 N_{\text{fertilizer}}$; for rice: $N_{\text{uptake}} = 112.6 + 0.243 N_{\text{fertilizer}}$. The last column gives the recovery of N (output per unit input) from prunings relative to that in urea fertilizer.

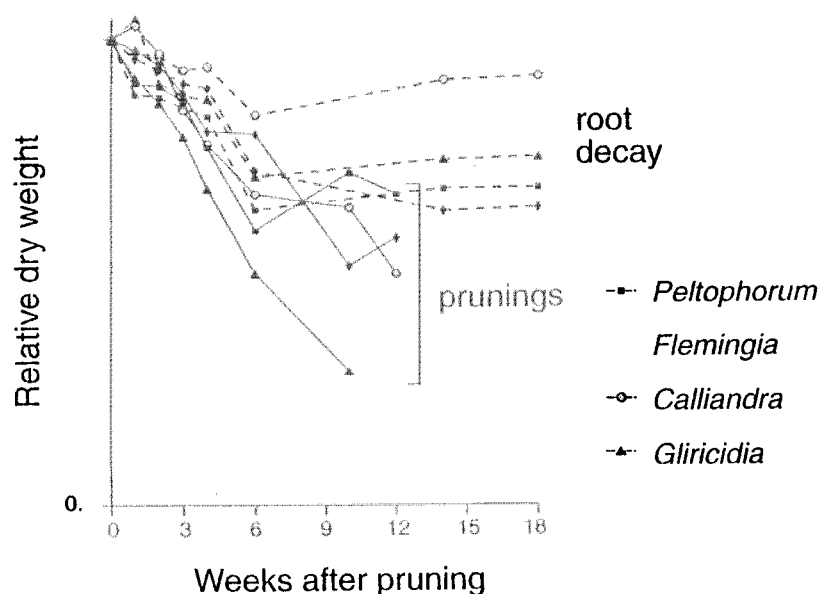


Fig. 13.3. Decomposition rate of tree prunings as surface mulch in litter bags and of root litter in ceramic pots incubated in the field.

arranged according their decomposition rate (Fig. 13.3): *Gliricidia* > *Calliandra* > *Flemingia* > *Peltophorum*. Differences in decomposition between these mulch types can be understood from their C-to-N ratios (13.5, 16, 21 and 19, respectively), lignin content (35, 28, 46 and 54) and polyphenolic content (1.1, 2.1, 1.8 and 2.2), although the role of the latter is relatively small under the high leaching rates found in the field (Handayanto *et al.*, 1994). For the shallow-rooted maize, the efficiency of N transfer was low (Table 13.4), with both rapidly (*Gliricidia*) and slowly (*Peltophorum*) decomposing materials. A reasonable efficiency was only obtained for mulch with an intermediate pattern of N release (*Calliandra*). This indicates the need for synchrony under these conditions of high rainfall and a shallow-rooted crop. For the deeper-rooted, longer-lived upland rice, the N recoveries from all mulch types was equal to or higher than that for maize. As the recovery from fertilizer N was lower for rice than it was for maize, the value of the prunings, expressed as urea fertilizer equivalent, was distinctly higher in rice than in maize. Both fast-mineralizing species can contribute (via recovery by deep rice roots) and slowly decomposing ones (because of the longer uptake period of the rice). These results are generally in line with the model of de Willigen and van Noordwijk (1989), although the difference between rice and maize in recovery of fertilizer N is unexpected.

Alternative explanations for the growth response to mulch transfer treatments exist, e.g. via their various effects on Al detoxification, rather than N supply, and we are currently testing these other possible mechanisms. Preliminary evidence indicates that *Gliricidia* may enhance soil acidification and cation leaching, possibly linked with nitrate leaching (data not shown).

Long-term fertility effect

The long-term fertility effect (F_w) can be tested in the same way as in a sequential agroforestry system, by removing the trees and comparing crop yields with those in a continuously cropped control plot. A difference is that the residual or fallow effect has now been achieved during a cropping period. The first year after removing the hedgerows in the Lampung trial, the residual effect was pronounced and it formed the major part of the F factor, given in Table 13.3. In subsequent years, the residual effect declined, while the yields in the mulch transfer treatments increased (data not shown).

At the process level, the residual effect may be linked to changes in specific soil organic-matter fractions. Size-density fractionation (Ludox) results of soil organic matter (Fig. 13.4) show a clear difference between forest and long-term cropped soil, with intermediate results for hedgerow intercrops with various trees. The small standard error of difference (SED) values allow us to differentiate between the tree species. The trees with relatively high polyphenolic contents and slowly decomposing litters (*Calliandra* and *Peltophorum*) are better at maintaining intermediate and heavy soil fractions than *Gliricidia* and *Leucaena* (*Flemingia* was included later in the experiment, replacing *Erythrina orientalis*, so their residual effects are confounded). Barrios *et al.* (1997) also found that litter sources with low (lignin + polyphenol)-to-N ratios led to higher light fraction N contents.

We tested whether or not the fractions obtained with the Ludox method differ in turnover by analysing soil changes for an extreme form of a sequential system, formed by a chronosequence of sites where forest had been converted to sugar cane in the past 10 years (Hairiah *et al.*, 1995). Analysis of the stable carbon (C) isotope ratio ^{12}C to ^{13}C of the Ludox fractions allowed us to calculate which proportion of the organic matter in the three fractions was derived from the forest and which part from the new crop. The data (Fig. 13.5) show a clearly different turnover for the three fractions. Yet the light fraction does not get back to zero in a 10-year period, probably due to its charcoal component, derived from the slash-and-burn method of forest clearance.

Maize yield in plots where hedgerows had been removed was correlated with the various soil organic-matter fractions (Fig. 13.6), except for the

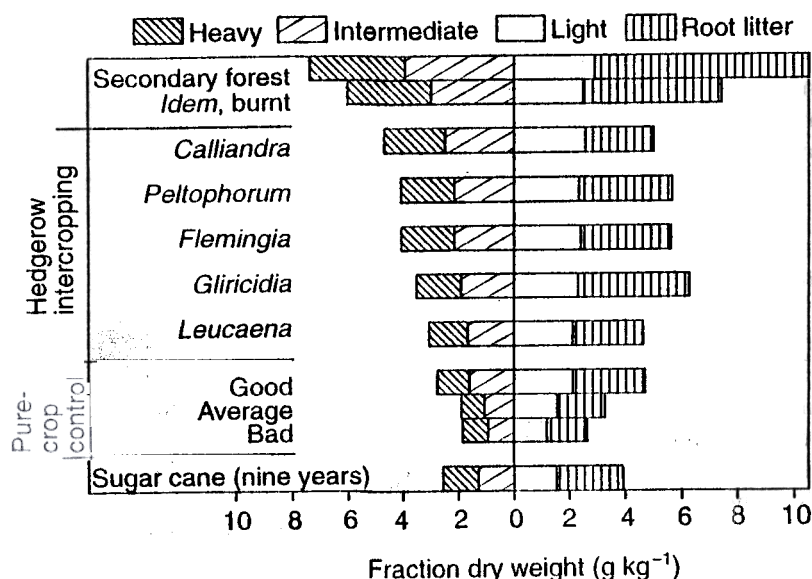


Fig. 13.4. Fractionation of soil organic matter according to size and density by the Ludox method (Meijboom *et al.*, 1995) in the eighth year of an alley-cropping experiment, its pure-crop control plot and adjacent forest and sugar-cane fields. The root litter fraction did not pass through a 2 mm sieve. The light, intermediate and heavy fraction were in the size range 150–2000 μm and were separated at physical densities of 1.13 and 1.30 g cm^{-3} . Standard errors of difference (SED) for all Ludox fractions were less than 0.4 g kg^{-1} dry weight.

Leucaena treatment. All three Ludox fractions correlate with crop yield and each other, so we cannot yet say which is the best indicator. Tree root litter did not correlate with crop yield. The *Leucaena* data are outliers deserving further attention; a relatively high N concentration in the various fractions in the *Leucaena* plots may be a partial explanation. We plan to monitor the changes in the Ludox fractions during the decline of the residual fertility effect, as well as the build-up phase, in the mulch transfer trials to obtain a more rigorous test of these fractions as predictors of crop yields.

A problem in the ongoing experiment is that the N-fertilizer treatments (urea) have acidified the soil and no longer allow us to estimate the crop N response, as they did in the first year (Table 13.4).

Competition for light

Competition for light (C_l) can be predicted from the canopy shape of the hedgerow trees, as well as measurements of the light interception by the

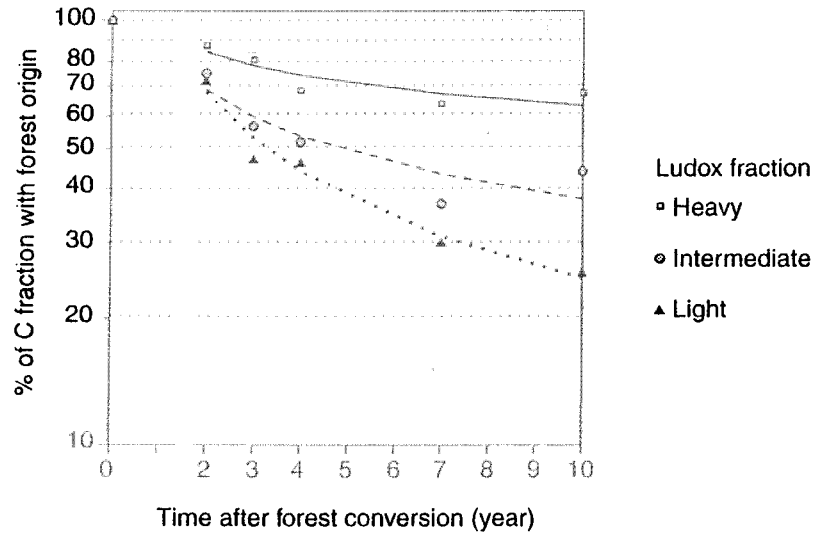


Fig. 13.5. Decomposition pattern of forest-derived organic matter in different density fractions (Ludox method) after conversion of forest to sugar cane (chronosequence). Separation between forest- and sugar-cane-derived C was obtained by stable ^{13}C isotope methodology (Hairiah *et al.*, 1995).

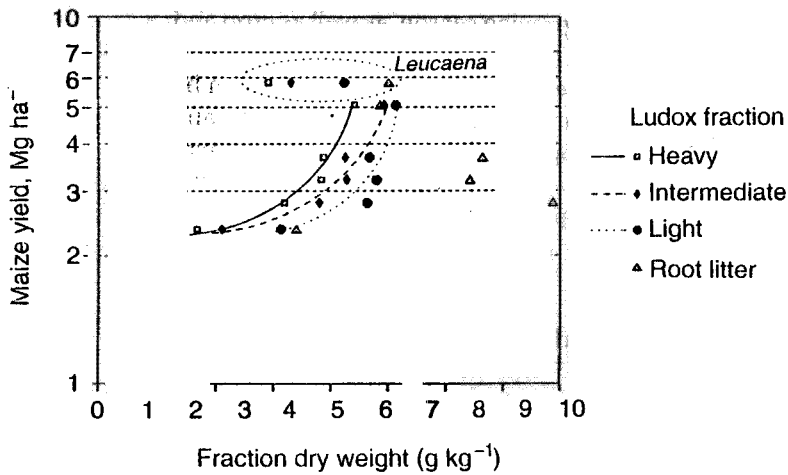


Fig. 13.6. Relationship between four organic-matter fractions (compare Fig. 13.4) and maize yield in a test of residual fertility by removing hedgerows in the seventh year of an alley-cropping trial.

canopy. Considerable differences exist between the various trees in the trial, ranging from the dense but compact canopy of *P. dasyrhapichis* to the extensive but open canopy of *Gliricidia sepium*. By recording light interception just before and after pruning, the light interception due to the tree canopy can be quantified in a mixed crop situation and compared with the amount of biomass pruned. Considerable differences were found in the mulch-to-shade ratio of the trees, with the highest (most favourable) results for *Peltophorum* (van Noordwijk, 1996).

Competition for nutrients and water

Competition for nutrients and water (C_{n+w}) between tree and crop depends on uptake demand of both components, as well as the relative distribution of the root system. Fractal root-branching models hold promise of simplifying observation methods on tree-root distribution (van Noordwijk *et al.*, 1994; van Noordwijk and Purnomosidhi, 1995). Fractal branching properties of dicotyledonous trees may be based on the process of secondary growth of the transport tissue in roots in response to the degree of local branch-root development. The system in the apparent 'madness' of a root system may be a reflection of the development history of each root axis. Root diameter may therefore reflect the number of branch roots possibly connected to that axis. Root architecture may thus allow statements about the potential competition between crops and trees; actual competition estimates at any point in time will have to come from models, which include the dynamic character of resource supply during the growing season, as well as crop and tree demand factors.

An experimental approach to complementarity of resource use can be based on using tracers (e.g. ^{15}N) injected into the soil at different depths and recording the recovery in trees and crops. We have started such experiments, including *Peltophorum* and *Gliricidia* as well as food crops. Preliminary data show that the relatively deep rooted *Peltophorum* has higher recoveries for deeply placed ^{15}N than the other components.

Integration: the Water, Nutrient and Light Capture in Agroforestry Systems Model

Integration of the various processes into a model of tree-soil-crop interactions is attempted via the water, nutrient and light capture in agroforestry systems (WANULCAS) model (Fig. 13.7), which is still under construction. The model makes use of the STELLA II modelling environment and represents a four-layer soil profile, a water and N balance and uptake by a crop and a tree. The model allows for the evaluation of different pruning regimes, hedgerow

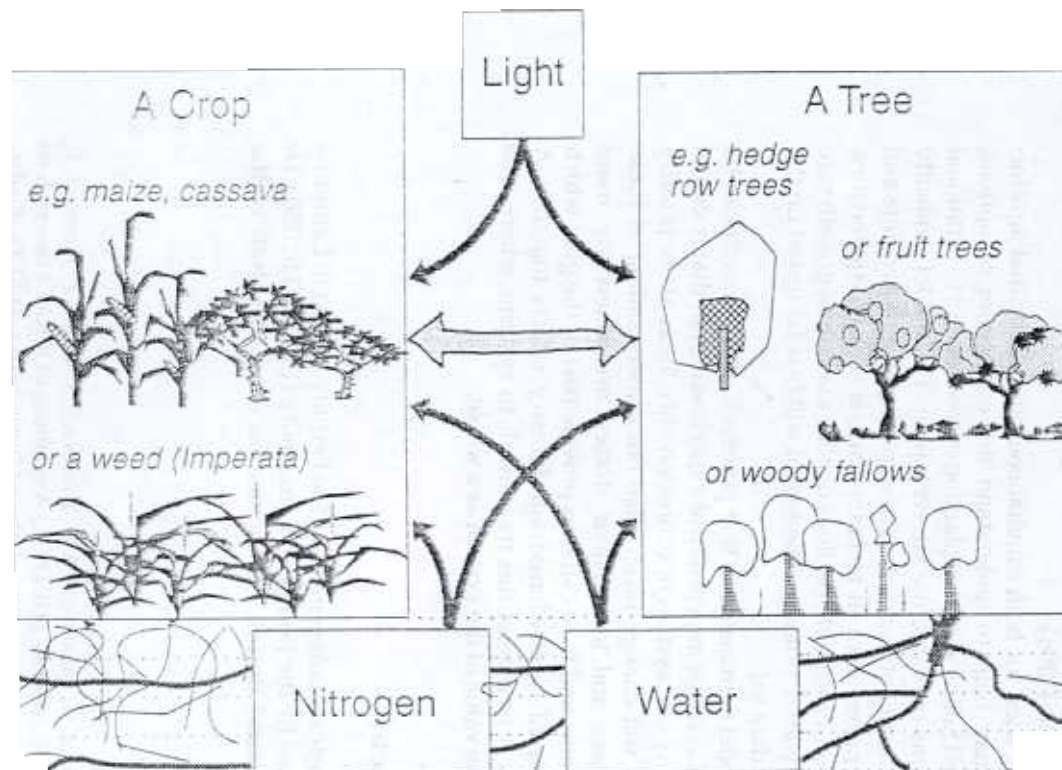


Fig. 13.7. Components of the WANULCAS model for predicting water, nutrient and light capture in agroforestry systems.

spacings and fertilizer application rates. A key feature of the model is the description of uptake of water and nutrients (at this stage, only N) on the basis of root-length densities of both the tree and the crop, plant demand factors and the effective supply by diffusion at a given soil water content. Underlying principles were described by de Willigen and van Noordwijk (1989) and van Noordwijk and van de Geijn (1996).

The model can be used for both simultaneous and sequential agroforestry systems and may help to understand the continuum of options, ranging from improved fallow via relay planting of tree fallows to rotational and simultaneous forms of hedgerow intercropping. The model explicitly incorporates management options such as tree spacing, pruning regime and choice of species or provenance. It includes various tree characteristics, such as root distribution, canopy shape, litter quality, maximum growth rate and speed of recovery after pruning. The model will first be tested on the basis of the Lampung data set.

Indirectly, the model demonstrates that process-based research can be done in the context of systems-improvement experiments, but that it should not be restricted to any one system or ecoregion only. Ideas about priority systems and regions will change faster than our understanding of these systems. The processes and interactions studied are inherently more generic than the systems and they can thus provide part of the glue which holds a large number of farmer-based agroforestry efforts together. A major challenge now is to extend this framework to systems where tree products dominate the value of the system as a whole.

Acknowledgements

Research in the Biological Management of Soil Fertility project in Lampung is financially supported by the European Community (EC-STD3 921150); Dr Chin Ong and Dr Roland Buresh commented on an earlier draft of the manuscript.

References

- Akyeampong, E., Duguma, B., Heineman, A.M., Kamara, C.S., Kiepe, P., Kwesiga, F., Ong, C.K., Otieno, H.J. and Rao, M.R. (1995) A synthesis of ICRAF's research on alley cropping. In: *Alley Farming Research and Development*. AFNETA, Ibadan, Nigeria, pp. 40-51.
- Barrios, E., Buresh, R.J. and Sprent, J.I. (1996) Nitrogen mineralization in density fractions of soil organic matter from maize and legume cropping systems. *Soil Biology and Biochemistry* 28, 185-193.
- Barrios, E., Kwesiga, F., Buresh, R.J. and Sprent, J.I. (1997) Density fractionation of macroorganic matter, inorganic nitrogen and nitrogen mineralization following

- tree fallows. *Soil Science Society of America Journal* (in press).
- Buresh, R. (1995) Nutrient cycling and nutrient supply in agroforestry systems. In: *Integrated Plant Nutrition Systems*. Fertilizer and Plant Nutrition Bulletin No. 12, FAO, Rome, Italy, pp. 155-164.
- Cannell, M.G.R., van Noordwijk, M. and Ong, C.K. (1996) The central agroforestry hypothesis: trees must acquire resources that the crop would not otherwise acquire. *Agroforestry Systems* 33, 1-5.
- Christensen, B.T. (1992) Physical fractionation of soil and organic matter in primary particle size and density separates. *Advances in Soil Science* 20, 1-90.
- De Willigen, P. and van Noordwijk, M. (1989) Rooting depth, synchronization, synlocalization and N-use efficiency under humid tropical conditions. In: van de Heide, J. (ed.) *Nutrient Management for Food Crop Production in Tropical Farming Systems*. Institute for Soil Fertility, Haren, the Netherlands, pp. 145-156.
- Hairiah, K., Cadisch, G., van Noordwijk, M., Latief, A.R., Mahabharata, G. and Syekhfani, M. (1995) Size-density and isotopic fractionation of soil organic matter after forest conversion. In: Schulte, A. and Ruhiyat, D. (eds) *Proceedings of the Balikpapan Conference on Forest Soils*, Vol. 2, pp. 70-87.
- Handayanto, E., Cadisch, G. and Giller, K.E. (1994) Nitrogen release from prunings of legume hedgerow trees in relation to quality of the prunings and incubation method. *Plant and Soil* 160, 237-248.
- Kooistra, M.J. and van Noordwijk, M. (1995) Soil architecture and distribution of organic carbon. In: Carter, M.R. and Stewart, B.A. (eds) *Structure and Organic Carbon Storage in Agricultural Soils*. Advances in Soil Science, CRC Lewis Publishers, pp. 15-57.
- Meijboom, F.W., Hassink, J. and van Noordwijk, M. (1995) Density fractionation of soil macroorganic matter using silica suspensions. *Soil Biology and Biochemistry* 27, 1109-1111.
- Myers, R.J.K., Palm, C.A., Cuevas, E., Gunatilleke, I.U.N. and Brossard, M. (1994) The synchronisation of mineralisation and plant nutrient demand. In: Woomer, P.L. and Swift, M.J. (eds) *The Biological Management of Tropical Soil Fertility*. John Wiley & Sons, Chichester, UK, pp. 81-116.
- Myers, R.J.K., van Noordwijk, M. and Vityakon, P. (1997) Synchrony of nutrient release and plant demand: plant litter quality, soil environment and farmer management options. In: Cadisch, G. and Giller, K.E. (eds) *Driven by Nature: Plant Litter Quality and Decomposition*. CAB International, Wallingford, UK, pp. 215-229.
- Palm, C.A. (1995) Contribution of agroforestry trees to nutrient requirements of intercropped plants. *Agroforestry Systems* 30, 105-124.
- Sanchez, P.A. (1995) Science in agroforestry. *Agroforestry Systems* 30, 5-55.
- Torquebiau, E.F. and Kwesiga, F. (1996) The potential role of roots in an improved fallow agroforestry system in Eastern Zambia. *Agroforestry Systems* 33.
- van Noordwijk, M. (1996) A simple model to quantify mulch and shade effects. In: Ong, C.K. and Huxley, P.A. (eds) *Tree-Crop Interactions - a Physiological Approach*. CAB International, Wallingford, UK, pp. 51-72.
- van Noordwijk, M. and Garrity, D.P. (1995) Nutrient use efficiency in agroforestry systems. In: *24th IPI Colloquium*, 21-24 February 1995, Chiang Mai, pp. 245-279.
- van Noordwijk, M. and Purnomosidhi, P. (1995) Root architecture in relation to tree-

- soil-crop interactions and shoot pruning in agroforestry. *Agroforestry Systems* 30, 161-173.
- van Noordwijk, M. and van de Geijn, S.C. (1996) Root, shoot and soil parameters required for process-oriented models of crop growth limited by water or nutrients. *Plant and Soil* 183, 1-25.
- van Noordwijk, M., Spek L.Y. and de Willigen, P. (1994) Proximal root diameters as predictors of total root system size for fractal branching models. I. Theory. *Plant and Soil* 164, 107-118.
- van Noordwijk, M., Sitompul, S.M., Hairiah, K., Listyarini, E. and Syekhfani, M. (1995) Nitrogen supply from rotational or spatially zoned inclusion of leguminosae for sustainable maize production on an acid soil in Indonesia. In: Date, R.A., Grundon, N.J., Rayment, G.E. and Probert, M.E. (eds) *Plant-Soil Interactions at Low pH: Principles and Management*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 779-784.
- van Noordwijk, M., Lawson, G., Groot, J.J.R. and Hairiah, K. (1996) Root distribution in relation to nutrients and competition. In: Ong, C.K. and Huxley, P.A. (eds) *Tree-Crop Interactions - a Physiological Approach*. CAB International, Wallingford, UK, pp. 319-364.
- Woomer, P., Bajah, O., Atta-Krah, A.N. and Sanginga, N. (1995) Analysis and interpretation of alley farming network data from tropical Africa. In: *Alley Farming Research and Development*. AFNETA, Ibadan, Nigeria, pp. 189-202.