Nutrient Use Efficiency in Agroforestry Systems

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Abstract

Agroforestry can contribute to the solution of a number of problems in the nutrient balance of agro-ecosystems. Tree products with a high economic value per unit nutrient content can reduce the risk of mining the soil without financial possibilities for obtaining external inputs. Trees may also reduce nutrient losses from agro-ecosystems and thus contribute to long term productivity and input use efficiency.

A general approach is given to optimizing agroforestry systems on the basis of tree-soil-crop interactions. Nutrient sources for tree growth can be complementary to those of crops (nutrient pumps and safety nets) or be the same, leading to competition. Soil fertility improvement through tree litter and prunings depends on the quantity, quality, timing and placement. Soil fertility improvement can be most clearly studied in sequential agro-forestry systems. On sloping lands trees can contribute to erosion control, but especially to local deposition of sediment.

1. Different types of agroforestry

Agroforestry is a collective name for land use systems and technologies in which woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately combined on the same land management unit with herbaceous crops and/or animals, either in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economic interactions among the different components (Nair, 1993). Trade-offs between productivity of the various components are normally unavoidable, but the combined productivity of a mixed agroforestry system can under certain conditions be higher than that of the best single-component systems.

Figure 1 gives a tentative classification of agroforestry systems, based on the degree of spatial and temporal overlap of the tree and crop components. Systems in the lower left corner do not fall under the definition of agroforestry, as here trees and crops do not interact.

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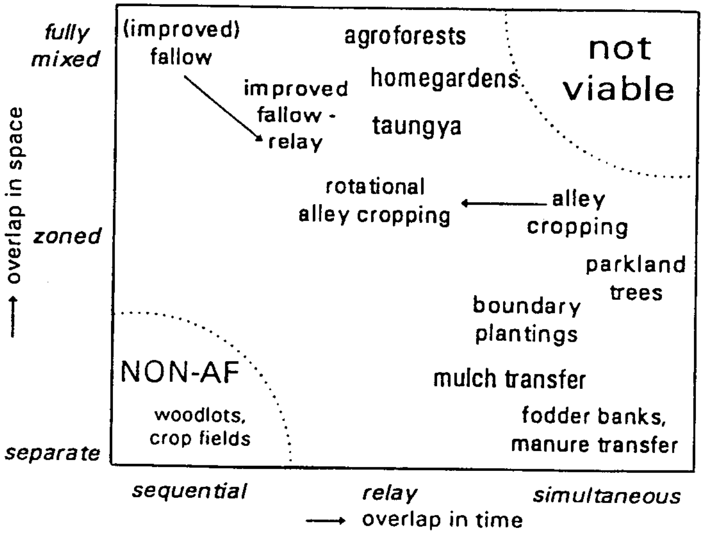

Fig. 1. Classification of agricultural systems based on both trees and crops, with regards to the degree of overlap in time (X-axis) and space (Y-axis).

Systems in the upper right corner are generally not viable as competition between the tree and crop component will be too severe. In the upper left corner we find (improved) fallow systems, where a crop and a tree phase alternate on the same land. From a biophysical point of view, such systems are fairly simple and can be successful, but farmers will hesitate to put efforts into improving the fallow phase; it is thus understandable that developments in the direction of relay-establishment of the fallow vegetation are sought (ICRAF, 1994), which move the system towards the centre of the graph. Alley cropping was first developed as a fully simultaneous spatially zoned system, but recently interest in 'rotational alley cropping' also moves the system towards the centre of the graph. Agroforestry systems with full-grown trees are either based on low tree densities (parklands, boundary plantings) or on relay systems, with a short crop and long tree phase (taungya, homegarden, agroforests).

Part of the enthusiasm generated by 'alley cropping' as sustainable alternative to shifting cultivation systems in the past decade, has been tempered by disappointing results in 'implementation' programs with the specific form chosen. There is some danger that this disappointment leads to a swing of the tree-crop balance to the other extreme of completely separated crop fields and woodlots, but there are many agroforestry systems developed and used by farmers which apparently do meet their criteria.

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As many of them are far more complex and less tidy than the neat sequence of hedgerows and crops of alleycropping, researchers face a much more challenging task in quantifying such systems and exploring the range of options to improve the systems, in support of what farmers do. Nutrient cycling and nutrient efficiency of many of the real-world agroforestry systems is poorly quantified at the systems level, as yet.

2. Trees and agro-ecosystem nutrient use efficiency

The term efficiency generally indicates an output/input ratio and thus efficiency depends on the boundaries where inputs and outputs are measured. The term 'nutrient use efficiency' is often used without specifying the boundaries of the system in space and time, and this supposes that efficiency attributes are conserved across system scales - this is not true, however. Farm level nutrient use efficiency can be understood from the nutrient use efficiency of the various components of the farm, but taking due account of which inputs of farm components are based on outputs of other components. Similarly, nutrient use efficiency at the society level depends on the farm level efficiency, but should take transfers among sectors into account. Even if the direct efficiency of using recycled wastes is lower than that of using 'new' external inputs, the overall efficiency can be greatly enhanced by recycling. Agricultural development as exemplified by W. Europe is often based on farm specialization, increased distance between production sites and markets and a reduction of recycling. Even if crop level nutrient use efficiency may have been maintained, the overall efficiency decreased and environmental concerns increased.

For an annual crop the agronomic efficiency (products per unit input) can be separated into three components: application efficiency (available/input), uptake efficiency (uptake/available), utilization efficiency (products/uptake), all on an annual basis. The relevant root and shoot parameters for predicting uptake efficiency on the single plant level (crop or tree) depend not only on the nutrient resource studied, but also on the complexity of the agricultural system (Van Noordwijk, 1987; Van Noordwijk *et al.*, 1993). In intensive horticulture with nearly complete technical control over nutrient and water supply, fairly small root systems may allow very high crop productions in a situation where resource use efficiency ranges from very low to very high, depending on the technical perfection of the (often soil-less) production system (Van Noordwijk, 1990). In field crops grown as a monoculture, the technical possibilities for ensuring a supply of water and nutrients where and when needed by the crop are far less; the soil has to act as a buffer, temporarily storing these resources, and root systems are important in obtaining these resources where present and when needed.

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Adjustment of supply and demand in both time and space (synchrony and synlocation) become critical factors. In mixed cropping systems (including grasslands), the belowground interactions between the various plant species add a level of complexity to the system; on one hand it opens possibilities of complementarity in using the space and thus of the stored resources, hence improving overall resource use efficiency, on the other hand, it means that root length densities which would be sufficient for efficient resource use in a monoculture, may not be sufficient in a competitive situation. Agroforestry systems are yet another step more complex, as the perennial and annual components have separate time frames on which to evaluate the interactions.

Economic efficiency does not necessarily coincide with biophysical efficiency. Van Noordwijk and Scholten (1994) explored how the price ratio of fertilizer inputs and yield products may influence farmer's decisions whether or not to utilize existing efficiency improving technologies; if fertilizer inputs are cheap, no incentive is given to their efficient use, if they are expensive, they may not be used at all; in an intermediate range biophysical efficiency improvement may pay off to the farmer.

Agronomic research has for a long time made the implicit assumption that results of relatively small plots, selected on the basis of their homogeneity for 'proper' experiments, were directly relevant for the field scale. Van Noordwijk and Wadman (1992) showed that the agronomic efficiency of a crop production system, defined as crop output per unit input, decreased with increasing internal variability, all other parameters being equal. Independently, Cassman and Plant (1992) developed a similar model and applied it to field results. Field heterogeneity does not affect nutrient use efficiency in the linear response range, where it may be most visible in the crop. Heterogeneity affects efficiency especially when the nutrient supply to part of the plants exceeds the requirements for maximum yield. Field heterogeneity has a direct effect on the production-environment conflict, as the amounts of inputs needed for 'economically optimum' yield increase, while the amounts of inputs which can be tolerated from an environmental point of view decreases. In heterogeneous fields, nutrient use efficiency can be improved by site specific input decisions. Technical options for such decisions are being developed for large scale mechanized farming. The small scale farmer with intimate knowledge of her land may be directly inclined to apply nutrients where needed most. This is only possible, however, if the rich and poor strata of the field can be recognized from easily observable patterns.

The time dimension also causes concern in the definition of nutrient use efficiency of agroforestry systems.

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For perennial crops, such as trees, one has to consider efficiency on the whole life span, rather than on an annual basis, as uptake and harvest will be separated in time. For the nutrient use efficiency of agroforestry systems, the typical lifespan of the trees should be used and this explains why little empirical data exist. We thus have to rely on a discussion of the component processes and on nutrient balance sheets, including losses to the environment, rather than on direct efficiency measures. The changes in the nutrient content of a system, ΔN_S, can be written as the sum of inputs and Δstorage, minus (desirable + undesirable) outputs, where storage occurs in the soil as well as the plant component. Any reduction in 'undesirable outputs' is likely to improve the long-term efficiency, even if it is based on increased internal storage, rather than direct 'desirable output'.

Figure 2 gives a schematic view of the key processes in nutrient cycling in agricultural systems, and focusses on three aspects:

1. Plant nutrient uptake from stored as well as recently added organic and/or inorganic resources; the complement of uptake is formed by losses of available nutrients to other environmental compartments.
2. Internal redistribution in the plant and yield formation,
3. Removal of harvest products, their exchange for external inputs and the recycling of harvest residues in the system.

Aspects 1 and 2 are traditionally studied in soil fertility and plant physiological research, respectively, while aspect 3 is the focus for farming systems and agro-economic studies. Without recycling and external inputs, the scheme quickly degenerates into a uni-directional nutrient flow, representing agriculture as mining operation.

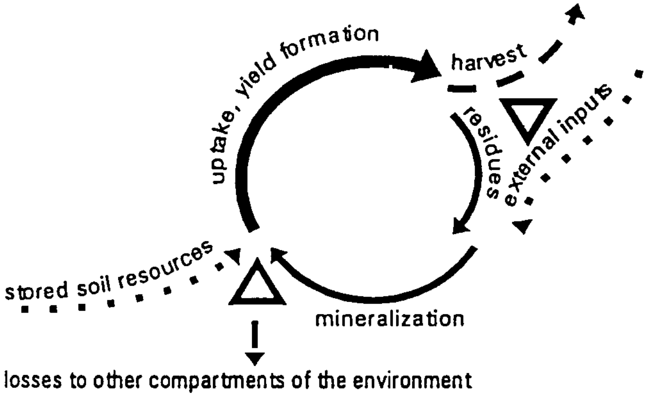

Fig. 2. Schematic nutrient flow and/or cycle in agro-ecosystems.

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Figure 3 shows that different categories of problems may reduce the nutrient use efficiency of agro-ecosystems. These problems occur at different spatial scales:

1. Chemical occlusion (and similar soil biological and soil physical phenomena) limits uptake of stored soil resources and/or the utilization of fresh inputs in the root zone at large, or more specifically in the rhizosphere.
2. A number of processes leads to spatial heterogeneity of nutrient supply at the field scale, and thus reduces the overall efficiency (Cassman and Plant, 1992; Van Noordwijk and Wadman, 1992):
   a. horizontal nutrient transfer by trees, crops or farmer's practices, creating depletion and enrichment zones,
   b. soil loss and displacement by erosion/ deposition cycles, esp. on sloping lands,
3. Leaching leading to vertical nutrient transfer to deeper layers, often beyond the reach of shallow rooted crops,
4. Losses to the atmosphere in gas form (esp N and S), dust (wind erosion) or as particulate ash during fire; the latter leads to deposition elsewhere in the landscape,
5. Export of harvest products beyond the realm where recycling is possible: increasing economic integration of farms and/or hygienically motivated reductions in waste recycling cause reduction of re-cycling as part of 'development',
6. Economic conditions which prevent the use of external inputs to replace the exported nutrients.

Potentially, agroforestry can contribute to problems 1, 2, 3, 4 and 6, but probably not to all problems at the same time, so choices have to be made.

Trees can increase nutrient concentrations on small areas of land, at the expense of nutrients elsewhere. If their source of nutrients is deep soil layers (3), chemically occluded soil nutrient sources (1), air-borne dust (4) or soil material moving downslope with surface run-off (2b) one may expect that they increase the nutrient stocks available for other components of the system, such as crops. As long as deep and chemically occluded sources last and as long as wind erosion up-wind and water erosion up-slope continue, these nutrient sources can be sustainable from the agroforest farmers point of view. None of these processes is easy to prove and quantify, however. If most of the nutrients which the trees absorb come from top soil layers (2a), and this may even extend to 50 m from the tree in some cases, the role of trees is only positive in as far as topsoil nutrients would not be utilized by other components and get lost from the system.

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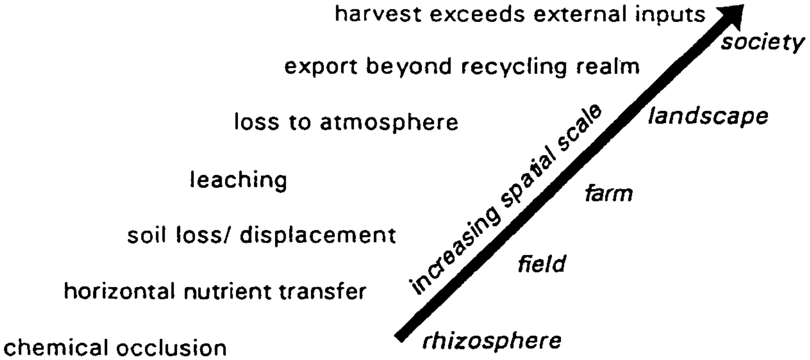

Fig. 3. Categories of problems for efficient nutrient use in agro-ecosystems.

The large horizontal spread appears to have been neglected in the design of many agroforestry experiments, and positive conclusions about increased nutrient storage and/or crop yields for agroforestry treatments, as compared to neighbouring 'control' plots, may in fact be partly due to tree roots mining the soil under the neighbouring plots as well as in their own (Coe, 1994). The direct evidence which is available in the literature may be rather suspect for this reason.

The general wisdom is that trees help to improve nutrient cycling and nutrient retention in agro-ecosystems, but the question whether or not and by which pathways this will lead to more money in farmer's pockets is less obvious. Trees in agroforestry systems are supposed to perform multiple functions, being directly productive as well as helping to conserve the soil and other resources. The 'harvest index', i.e. the harvested part of total biomass production, can serve as indicator for the tradeoff between the two functions (Cannell, 1985). If nearly all biomass of trees is removed, as happens in 'fodderbanks' (harvest index >75%), little protective effects can be expected. If trees produce harvestable products rich in nutrients, such as fruits or seeds, they will cause a considerable export of nutrients from the farm; yet, their sale may generate the cash and the incentive to buy external inputs. If trees are managed completely for their 'protection' role (harvest index 0), and all organic matter is recycled, soil fertility will be enhanced, but this will only be seen as sufficient reason for the time (and other resources) invested in them if a very valuable crop directly benefits from this soil fertility. It is clear that the question 'what is a good tree for agroforestry' will get very different answers in different conditions.

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When we compare a number of tree and crop products as regards their economic value per unit nutrient export, it is clear that especially latex-based tree products have a low nutrient content compared to their economic value, and thus may help to solve problem 6, as formulated above. Rubber and *Shorea* trees from which the damar mata kucing is collected are good choices from this point of view. Cassava is probably one of the most efficient nutrient scavengers among the crops, yet cassava based systems are not efficient in generating cash (e.g. for obtaining inputs) per unit nutrient export.

Two contrasting views exist on trees: in agroforestry trees are generally seen as 'soil improvers', especially where fast growing N_2 fixing trees are used, while in plantation forestry there is serious concern about soil depletion due to short rotation forestry, especially where fast growing trees are used (Bruijnzeel, 1992; Sanchez *et al.*, 1985). The different perceptions are partly due to different conditions (poor soils used for plantation forestry) and management practices (more damage may be done to the soil while harvesting the timber than by the nutrient export as such).

In choosing trees to optimize the nutrient use efficiency of the cropping system, a distinction should be made between agroforestry systems where trees and crops use the same land simultaneously, and sequential systems such as 'improved fallows'. Trees with abundant superficial roots and rapid growth and biomass production may not be suitable for the first, but may be desirable for the second type of system. In sequential systems soil conditions at the time of transition of tree to crop phase are the most important criterion. The tree may have left a considerable litter layer on the soil surface and a network of decaying tree roots in the soil. Effects on the subsequent crop may be based on the total soil organic matter and nutrient mineralization potential of the soil, but also on more specific facilitation of crop root development by using the old tree root channels. The latter is especially relevant on soils where soil compaction or Al^{3+} toxicity restrict crop root development. Old tree root channels provide easy pathways into a compact soil and a coating of organic matter which may help to detoxify Al^{3+} (Van Noordwijk *et al.*, 1991). In simultaneous agroforestry systems, belowground interaction are probably dominated by competition for water and nutrients. Complementarity in resource use is possible, however, especially under conditions of high leaching rates.

In this review we will focus on the nutrient aspects of the interactions of trees, crops and soils to specify environmental conditions and tree crop combinations for which positive interactions, such as conservation of nutrients and soil in the system, can exceed the negative effects of competition. We will address the following issues:

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1. What is the role of interaction terms in optimizing agroforestry systems,
2. What are the nutrient sources for tree growth: scavengers, safety nets and/or nutrient pumps,
3. How to quantify fertility improvement through tree litter and prunings (F),
4. How to quantify soil fertility improvement in sequential agro-forestry systems (ΔL),
5. How to predict and reduce competition for nutrients between trees and crops in simultaneous systems (C),
6. The role of agroforestry in erosion control on sloping lands.

3. Optimizing agroforestry systems: the role of interaction terms

Agroforestry (AF) systems as defined here are not simply farming systems where both trees and crops or animals give useful products to the farmer, but systems where tree and crop (and/or animal) production interact (Nair, 1993). Understanding and predicting such interactions should thus be at the heart of an agroforestry research program. Interactions can be ecological or economic in nature, or both, as will most often be the case because ecological interactions affecting the biological productivity will have economic consequences as well. Biological tree - crop interactions in agroforestry systems may be *indirect*, via changes in soil conditions during a tree phase affecting subsequent possibilities for crop growth in 'sequential' agroforestry systems, such as 'improved fallows', or *direct* as in 'simultaneous' systems. Direct interactions include negative ones, such as competition for light, water and nutrients, allelopathic interactions (specific inhibiting effects of chemicals released by living or dead parts of a component species) and stimulation of pests and diseases. Positive interactions can be based on soil fertility improvement (similar to the indirect effects in sequential systems), microclimate improvement (especially in harsh conditions, e.g. with strong winds) and reduction of the impact of pests and diseases (Gajaseni and Jordan, 1992; Nair *et al.*, 1994; Watanabe, 1992). Based on the relative importance of the positive and negative interactions between trees and crops, one may decide that it is worthwhile to combine them into an agroforestry system, or to keep them separate as 'woodlots' and 'cropped fields'. We will explore in general terms under which conditions agroforestry systems should be preferred over single-component systems.

In simultaneous agro-forestry systems, trees and food crops are interacting in various ways. As both positive and negative interactions occur, site specific optimization of the system may be required. The most important interactions probably are:

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a. Mulch production from the trees, increasing the supply of N and other nutrients to the food crops,
b. Shading by the trees, reducing light intensity at the crop level,
c. Competition between tree and crop roots for water and/or nutrients in the topsoil,
d. Nitrogen supply by tree roots to crop roots, either due to root death following hedgerow pruning or by direct transfer if nodulated roots are in close contact with crop roots,
e. Effects on weeds, pests and diseases,
f. Long-term effects on erosion, soil organic matter content and soil compaction.

Interactions a and d are positive, b and c are normally negative. Effects e and f are difficult to quantify in general terms, but can have a dramatic effect on the acceptability of tree-crop combinations.

Considerable efforts have been made in the past decade to quantify the tree-soil-crop interactions in one of the most simple agroforestry systems: hedgerow intercropping or alleycropping. As the initial high expectations of crop yield benefits were tuned down by often negative or neutral results, we learned more about the nature of the interactions. This knowledge can now be used to select tree - crop combinations on *a priori* knowledge and to optimize hedgerow intercropping systems. In hedgerow intercropping the following choices can be made:

1. Tree species,
2. Distance between hedgerows,
3. Pruning regime (height and frequency),
4. Crop, cultivar, crop population density and plant spacing,
5. Additional fertilizer input level.

As it is at least impractical to explore all possible combinations of such factors in simple 'trial and error' experiments, we will have to resort to 'diagnosis and design' procedures: build a coherent model of the systems, based on the major interactions and use that to define 'design' criteria for the real world, which can then be tested in limited number of experiments.

The total yield of an agroforestry system in a given year can be described as the sum of the crop yield, the yield of tree products (or increase in net present value), the yield of animal products and the change in land quality, which reflects the concerns over the long term sustainability of the system. The tree products obtained at the end of the cycle will have to be discounted for the length of the harvest cycle. If we restrict ourselves to agroforestry systems without an animal production component, we obtain:

$$Y_{tot} = E_c Y_c + E_t Y_t + E_L \Delta L \quad (1)$$

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where:
Y_{tot} = total yield, [$/ha]
E_c = price per unit crop yield, [$/kg]
Y_c = crop yield, [kg/ha]
E_t = price per unit yield of tree products, [$/kg],
Y_t = yield of tree products (or 'net present value' of future productivity), [kg/ha]
E_L = price per unit change in land quality, [$/X],
ΔL = change in land quality for future production in units X to be further specified, [X/ha].

On the basis of this equation we can explore under which conditions a maximization of total yield will lead to a choice for an agroforestry system, with both a tree and a crop component, and under which conditions pure tree or crop production will be preferred.

In the most simple case we may describe all tree-crop interactions as linear functions of the relative tree area α_t. For crop yield Y_c we may formulate:

$$Y_c = (1 - \alpha_t)(Y_{Oc} + \alpha_t F - \alpha_t C_{tc}) \quad (2)$$

where:
α_t = relative tree area (for an agroforestry system: $0 < \alpha_t < 1$)
Y_{Oc} = crop yield in the absence of trees, [kg/ha],
F = positive effect of trees on crop yield, e.g. due to soil fertility improvement, per unit relative tree density, [kg/ha],
C_{tc} = crop yield decrease due to competition by the tree, per unit relative tree density [kg/ha],

When we see the system purely from the crop's point of view, agroforestry or at least some inclusion of trees can be beneficial (i.e. lead to a higher yield than the crop monoculture), if the yield curve has a positive slope close to a pure crop system ($\alpha_t = 0$); this means that the partial derivative of crop yield per α_t at $\alpha_t = 0$ is positive:

$$\frac{\delta Y_c}{\delta \alpha_t}\bigg|_{\alpha_t=0} = -Y_{Oc} + F - C_{tc} > 0 \quad (3)$$

or, $F - C_{tc} > Y_{Oc}$. The positive effect of including trees on soil fertility F must not only exceed the competition caused by the trees ($F > C_{tc}$), but per unit area the positive effect ($F - C_{tc}$) must outweigh the crop yield per ha obtainable in a pure-crop situation. From a crop production point of view, we may conclude that combination with trees is only useful under poor soil fertility conditions (low crop production Y_{Oc}, potentially large F) and comparatively non-competitive trees.

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For the yield of tree products we may consider a negative interaction by crops through competition and a positive interaction via better weed control:

$$Y_t = \alpha_t (Y_{0t} + (1 - \alpha_t)(W - C_{ct})) \quad (4)$$

where:

Y_{0t} = yield of tree products in the absence of crops (kg/ha),

C_{ct} = decrease in yield of tree products due to competition by the crop, per unit relative crop density (kg/ha),

W = reduction in competition by weeds, due to crop cultivation, expressed as increased production of tree products (kg/ha).

The change in land quality for future production, ΔL, may be negative for a pure crop system and may become more positive with increasing relative tree density:

$$\Delta L = (1 - \alpha_t)\,\Delta L_c + \alpha_t\,\Delta L_t = \Delta L_c + \alpha_t\,(\Delta L_c) \quad (5)$$

where:

ΔL_c = (normally negative) change in land quality for future production while under monoculture crop (X/ha),

ΔL_t = (possibly positive) change in land quality for future production while under tree cover (X/ha).

If land qualities are not supposed to degrade ($\Delta L > 0$), then:

$$\alpha_t > \frac{-\Delta L_c}{\Delta L_t - \Delta L_c} \quad (6)$$

Alternatively, the costs of land degradation may be considered to be outweighed by direct benefits and be restored later, as happens in shifting cultivation or fallow rotation systems.

If we substitute equations (2), (4) and (5) in (1), we obtain a quadratic equation in α_t for the total yield, Y_{tot}. An agroforestry system ($0 < \alpha_t < 1$) as a whole is more productive then either a pure tree ($\alpha_t = 1$) or a pure crop ($\alpha_t = 0$) system, if $Y_{tot}(\alpha_t)$ has a local maximum in the range ($0 < \alpha_t < 1$). An optimum tree density $\alpha_{t,opt}$ may be found for $dY_{tot}/d\alpha_t = 0$, provided that $d^2Y_{tot}/(d\alpha_t)^2 < 0$. Only if this optimum tree density is between 0 and 1, agroforestry systems are the best choice.

$$\frac{dY_{tot}}{d\alpha_t} = E_c(F - C_{tc} - Y_{0c}) + E_t(Y_{0t} + W - C_{ct}) + E_L(\Delta L_t - \Delta L_c) - 2\alpha_t(E_c(F - C_{tc}) + E_t(W - C_{ct}) \quad (7)$$

The requirement $d^2Y_{tot} / (d\alpha_t)^2 < 0$ leads to:

$$E_c F + E_t W > E_c C_{tc} + E_t C_{ct} \quad (8)$$

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which shows that the sum of positive interaction terms on the left hand should be larger than the sum of negative ones on the right hand; otherwise it is better to have crops and trees on separate plots. Yet, it is possible to compensate a negative interaction term with a larger positive other term. A positive overall interaction can be obtained for systems where neither the crop nor the tree component shows an absolute benefit.

For $\alpha_{t,opt}$ we obtain:

$$\alpha_{t,\,opt} = \frac{-E_c Y_{0c} + E_t Y_{0t} + E_L(\Delta L_t - \Delta L_c)}{2(E_c(F - C_{tc}) + E_t(W - C_{ct}))} + 0.5 \quad (9)$$

which can be rewritten as:

$$\alpha_{t,\,opt} = \frac{X - 1 + L}{2(I_{tc} + X I_{ct})} + 0.5 \quad (10)$$

where:

$X = (Y_{0t}\, E_t)/(Y_{0c}\, E_c)$ is the ratio of financial returns on a pure tree and a pure crop system,
$I_{tc} = (F - C_{tc}) / Y_{0c}$ is the scaled net tree crop interaction,
$I_{ct} = (W - C_{ct}) / Y_{0t}$ is the scaled net crop tree interaction,
$L = E_l\, (\alpha L_t - \alpha L_c)/(Y_{0c}\, E_c)$ is the scaled relative importance of changes in land quality.

The constraint $0 < \alpha_{t,opt} < 1$ then leads to:

$$\frac{1 - L - I_{tc}}{1 + I_{ct}} < X < \frac{1 - L + I_{tc}}{1 - I_{ct}} \quad (11)$$

Outside the constraints (11), one would prefer either a pure-tree system ($\alpha_t = 1$) or a pure crop system ($\alpha_t = 0$), depending on the values of $E_c\, Y_{0c}$ and $(E_t\, Y_{0t} + E_L\, L)$. The equations also show that the choice for an agroforestry or a more simple system not only depend on the biophysically determined parameters, but also on the 'value' assigned to the various possible products (trees, crops and land).

Figure 4 gives the optimal allocation of land to trees, $\alpha_{t,opt}$ as a function of the relative value of tree and crop products, X, for different values of the interaction term I_{tc}, based on equation 11 ($I_{ct} = 0.1$ and $L = 0.1$). Figure 4 thus gives a general demarcation of the domain for agroforestry on the basis of the economic value of tree and crop production and the strength of the interaction term. The larger the positive interaction on crop production I_{tc}, the larger the scope for agroforestry (i.e. the range of price ratio's X which lead to $0 < \alpha_{t,opt} < 1$).

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For realistic estimates of the interaction term, the tree products need to have some direct value to the farmer to justify agroforestry. If trees have no direct value, the term $(F-C_{tc})/Y_{0c}$ has to be 1.0 or more, i.e. the net positive effect of trees on crop yield per unit tree area has to exceed the monocultural crop yield per unit area.

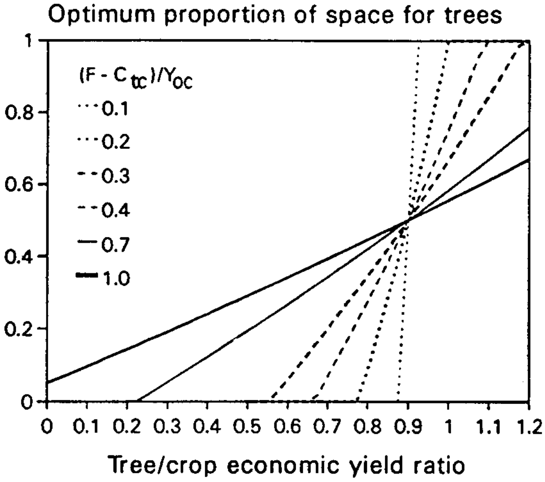

Fig. 4. Optimum allocation of land to trees, $\alpha_{t,opt}$, as a function of the economic yield ratio of tree and crop products X.

If no nutrient shortages exist, as may be expected where fertilizer is cheap, the term F will probably be small and the term Y_{0c} large. Thus, the interaction term is small and the scope for agroforestry will be restricted to tree-crop combinations with approximately equal value of the tree and crop component.

With these equations one can directly describe approximately stationary systems, as approximated in alley cropping, where the normal growth of the tree component is checked by regular pruning. For most other AF systems, however, the tree-crop interactions change from year to year. The equations can still be applied, however when annual yields are averaged over the typical lifespan of a single production cycle. If two years of food crops can be obtained after planting a slow growing tree, with a sixty year cutting cycle, or one year with a fast growing tree, with a 15 year cutting cycle, the average crop yield in the latter system is twice that in the first, when averaged over the cycle length.

The simple model approach as above appears to be restricted to modifying tree - crop land allocation ratio's, at constant plant density in the area's allocated. The production possibility frontier approach of Ranganathan (1993) overcomes this limitation and can optimize plant densities for each component.

Figure 5 (Van Noordwijk, *in press*) gives the results of a more specific model based on two types of aboveground interactions, **mulch** and **shade**. The figure identifies the domain where at least some forms of alley cropping, with a near-optimum tree spacing, may increase crop production. The upper limit of the soil N supply relative to crop N demand N_m can be related to the Mulch/Shade ratio, M/S, of the tree, which indicates the N supply per unit fully shaded area. The higher the M/S ratio of a tree, the better its prospects for alleycropping. If one wants alleycropping to work in a range where the control plots allow a crop N uptake near 50% of the maximum, the M/S ratio has to be 50-125 kg N/ha shaded, for N_m in the range 200-500 kg/ha.

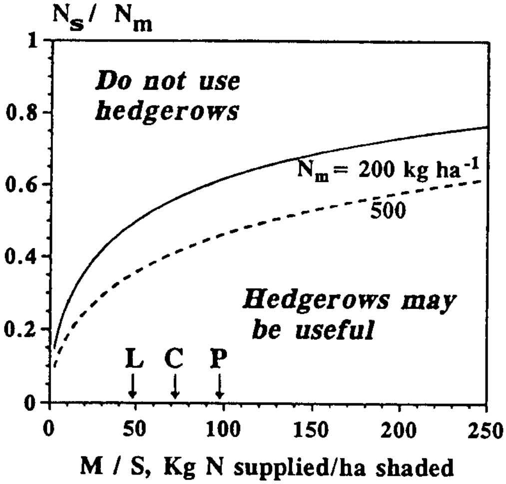

Fig. 5. Domain where at least some versions of hedgerow intercropping will give a yield advantage, as determined by the Mulch/Shade ratio of the tree and the relative fertility of the site

Apparently, hedgerow intercropping, where trees have to be a source of N to the crop, should be restricted to situations with a low soil N supply from other sources and crops which can respond to considerably higher N supply than is available. At the economic level, the labour cost of obtaining N this way has to be compared with the costs of obtaining N from other sources. So far the model ignores any positive effects on supply of P, K and other nutrients. The major part of these nutrients will probably have been derived from sources also available to the crop, but complementarity is possible. A first estimate may be that the additional benefits through other nutrients are off-set by part of the N obtained in competition with the crop, but further quantification is needed.

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Although the model suggests a rather limited 'niche' for hedgerow intercropping, considerable scope remains for selecting hedgerow trees which are most suitable. For the situation described the best hedgerow tree is one with a high M/S ratio, which can be based on a combination of a narrow but dense and compact hedgerow canopy, thick leaves, the major part of the tree canopy not exceeding that of the crop, a high N content and a suitable N-release pattern from the prunings, coinciding with crop demand. The need for fine tuning of the N release pattern increases with decreasing residence time for mineral N in the crop root zone, due to shallow rooting and/or high rainfall infiltration surplus over evapotranspiration (Van Noordwijk *et al.*, 1991).

The evaluation given may be too pessimistic on the scope for alleycropping: spontaneous litterfall from the trees (turnover of leaf biomass) will add to the mulch supply, without causing further shade. With the intensive pruning regimes required to check the tree growth during the cropping period, however, litterfall will be low for most trees. If part of the growing season can be reserved for tree growth, litterfall as well as an increased pruned biomass can be important. The prospects for alleycropping greatly improve if the crop is light saturated under full sunlight. This opens the option of 'free light interception' by an upper tree canopy, resulting in mulch supply to the crop without shade costs. In that case sparse open canopies are better than dense hedgerows. This situation is more likely to exist under the clear skies of the semi-arid tropics than under the usually overcast skies of the humid tropics, and more so for C3 than for C4 crops.

Essentially, the approach can also be used for evaluating the optimum tree density for sparse upper story trees with little or no pruning. The example of the tea gardens in Java shows, however, that shade costs of *in situ* N production, are considerable. Tea gardens used to have a complete tree cover of trees such as *Paraserianthes* as a source of N and organic matter, before inorganic fertilizer became abundantly available, but now nearly all trees are removed. This change from an agroforestry to a pure crop system was also stimulated by the availability of new higher yielding, but less shade tolerant tea varieties. It would be interesting to see at what timber prices it becomes worthwhile to reintroduce the trees, based on equation (10).

Only in specific situations are widely spaced upper canopy trees compatible with light demanding annual food crops. Peden *et al.* (1993) reported crop yield increases of about 20% in maize and beans over a monocrop control where *Alnus acuminata* was used as an upperstorey tree in Uganda, while all other tree species tested (including *Casuarina, Melia, Maesopsis, Markhamia* and *Cupressus* had negative effects. In Southern China *Paulownia* is widely grown in wheat fields, apparently with little harmful effect on the crop (Zhu Zhaohua, 1991).

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In North India *Populus* is similarly grown for timber in crop fields (Van den Beldt, pers. comm.). The specific tree characteristics which make these trees acceptable are not yet known: a relatively deep root system (*Paulownia*) and N_2 fixation (*Alnus*) probably contribute to the success.

Otherwise, upper canopy trees are usually grown on field contours. Trees such as *Paraserianthes* are widespread in Java around crop fields, *Tectona* is popular among Javanese migrants in Lampung ('North Java'); *Grevillea* is commonly found around maize fields on the lower slopes of Mount Kenya, *Gmelina* is increasingly popular in strip planting (following contour lines) on sloping land in the Philippines. In all these cases the value of the tree products to the farmer apparently compensates for the losses of crop yields. Tree management by pruning and pollarding can be used to check tree growth.

The scope for systems with simultaneous trees and crops has clear limitations. A partial temporal separation may be needed. If we uncouple the mulch production from the amount of shade cast, e.g. by having a period of the year devoted to tree growth and thus mulch production and a period in which the trees are set back severely and the crops are growing, the potential for *in situ* mulch production will increase.

4. Nutrient sources for tree growth: scavengers, nutrient pumps and safety nets

A letter to the 'Tropical Agriculturalist' (Colombo, Ceylon) in 1887 stated that: "Grevillea is valuable in the field, as its light shade, if planted at say 30 to 36 feet apart, is rather beneficial to tea. But the great good it does is the bringing up of plant food from the subsoil, and distributing the same in the form of fallen leaves, ... which, too, are useful in preventing surface wash while decomposing on the ground" (Agroforestry Today, 1990). The idea that trees act as a nutrient pump has thus been around for at least a century. Little hard data have accumulated, however, as it is no easy task to identify which part of the net nutrient uptake of a tree comes from deep or superficial soil layers. A large amount of 'circumstantial evidence' is available, however. A number of conditions should be met for trees to act as nutrient pumps:

- the tree should have a considerable amount of fine roots and/or mycorrhiza in deep soil layers,
- deep soil layers should contain considerable nutrient stocks in directly available form or as weatherable minerals in the soil or in a saprolite layer,
- soil water content at depth should be sufficient to allow diffusive transport to the roots.

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In climates, such as the (per)humid tropics, however, where rainfall exceeds evapotranspiration during the growing season, products of early mineralization will be washed into deeper layers of the soil. If crop rooting is shallow, as common on the acid soils typical of this climatic zone, nutrients will be leached beyond the crop root zone. Deep rooted (tree) components of mixed cropping systems can then act as 'safety-net', intercepting N on its way to deeper layers (Van Noordwijk and De Willigen, 1991).

The safetynet role seems particularly valid for simultaneous agroforestry systems, but under certain conditions may apply to sequential systems as well. Van Noordwijk (1989) used a simple leaching model (related to time-depth curves) to analyze under what leaching rates (and consequently for which combinations of net precipitation surplus and apparent nutrient adsorption constants) a deep rooted component can intercept nutrients leached beyond the reach of a previous, shallow rooted component (Fig. 7). A limited window of opportunities exists for such interception, but only when the rooting depth of the fallow vegetation substantially exceeds that of the crop. The chances for recovery of leached nutrients increase when K_a increases with depth, as may occur in soils with substantial nitrate adsorption capacity in deeper layers.

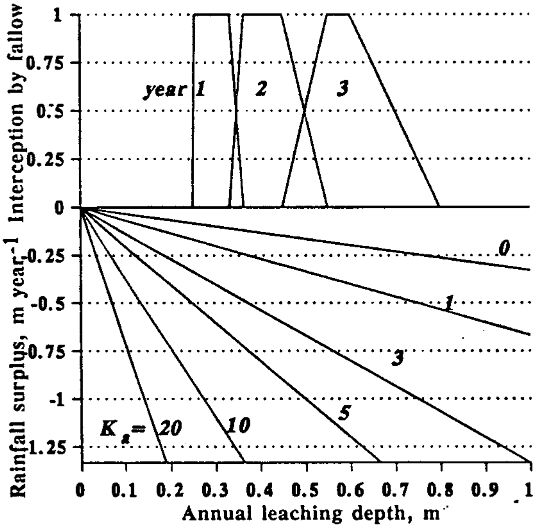

Fig. 7. Relationship between annual rainfall surplus (lower Y axis), annual leaching depth of nutrients (X axis, as determined by the apparent adsorption conctant K_a) and chances of interception (upper Y-axis) by a deep-rooted fallow following a shallow rooted crop (Van Noordwijk, 1989).

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5. Fertility improvement through tree litter and prunings (F)

The boundary between the direct fertility effect of prunings (F) and the long term soil fertility improvement (ΔL) discussed in the next section is not sharp. In experiments, however, F can be quantified directly in mulch transfer treatments, while ΔL needs long term experiments where trees are removed to test residual effects. Desirable tree characteristics for soil improvement and the scope for improvement by 'domestication' was discussed by Fernandes *et al.* (1993). Experiences with a number of trees for hedgerow intercropping on acid soils were given by Hairiah *et al.* (1992).

In quantifying the nutrient contribution of organic sources, the concept of 'fertilizer equivalent value' is a first point of reference. It relates the crop response to an organic source to the response to inorganic fertilizer (under standard application practices). If crop response (nutrient uptake) to fertilizer is approximately linear, the procedure is unambiguous. For example, data of Barreto (1993) show that the N content of a legume covercrop mulch (*Mucuna*) has 62% of the effect on crop as the N content of urea fertilizer. Van Noordwijk *et al.* (1995) found that urea fertilizer equivalents of various legume cover crops ranged from (8)-56-93%; the value of 8% was obtained for *Crotalaria juncea* which may have an allelopathic effect, especially on the young maize crop. Difficulties with this procedure arise where multiple nutrient deficiencies exist and the crops response to an organic input may be based on synergies of various nutrients rather than the single nutrient which is supposed to be the key variable. Research in temperate regions has often lead to the recognition of 'residual values' of organic sources, which indicate positive crop responses which can not be simulated by combinations of inorganic sources. The question whether this 'residual value' is mainly a matter of inadequate synchrony and synlocation in the fertilizer tests, or whether it is based on more fundamental differences between the two nutrient sources has never been fully resolved. On the relatively poor soils typical for the tropics this problem may seem to be a luxury problem, however, as we normally stay within the range of clear crop responses.

Much attention has been given to the 'synchrony hypothesis', in the context of managing N release patterns from organic sources (Swift *et al.*, 1994). Less attention has been given to nutrients other than N. Myers *et al.* (1994) compared synchrony of nutrient release by mineralization of organic inputs and nutrient demand by the crop between an intensively managed rubber plantation (5-year old) and in a mixed rainforest. In the rubber plantation clear pulses in litterfall were found, but nutrient release probably coincides with nutrient demand during the re-foliation stage. The more gradual nutrient release pattern in the mixed

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forest, due to more diverse litterfall patterns and litter compositions is in accordance with the more continuous nutrient demand.

The lignin/N ratio is used in models such as Century (Parton *et al.*, 1994) to predict N release patterns, with considerable success in a broad range of tropical situations. For a more detailed prediction, however, other litter quality parameters may have to be included. The content of polyphenolics can explain part of the variation in N mineralization from tree litter sources, in addition to C/N ratio and lignin content, but its importance decreases with higher leaching rates (Handayanto *et al.*, 1994).

Most attention has been given to N release patterns, partly because N is an important plant nutrient, but also because it is the most mobile and least buffered (compare figure 7). P release patterns can differ substantially from N release patterns, as P is stored in different cell components and may depend on phosphatase activity. For the cations, which are mostly in ionic form in the vacuoles, nutrient release patterns will simply depend on physical damage to the membranes and the cation exchange properties of the degrading cell wall complex.

We have to consider the spatial pattern of soil enrichment by litterfall. Litterfall data and nutrient contents of original forest trees maintained on bunds in rice fields in Northeast Thailand (Sae-Lee *et al.*, 1992; Vityakon, 1993) show that zones of enrichment and zones of depletion can be distinguished. In cropping patterns with fixed management regimes, such as in intensively managed oil palm plantations, specific areas are designated for organic inputs. Fairhurst (1994) gave data for a 10-year old oilpalm field in Sumatera and showed that significant differences in soil organic matter and most nutrients arise in that system, where fertilizer is added to clean-weeded circles around each tree and organic residues are accumulated in the frond stack. Figure 8 summarizes his results. Inputs are expressed per unit area, i.e. fertilizer inputs per unit area in the clean-weeded circle and organic inputs per unit area in the frond stack. The path area is taken as a point of reference, as no inputs occur here and probably little uptake by the tree.

Figure 9 shows similar patterns in cassava-based intercropping systems in Lampung, Sumatera. Cassava was planted in the same row position for 6 consecutive years. The cassava row had a lower C_{org} and available P content than the soil in between the rows, which had been intercropped with rice, maize or soybean. The Mg content of the cassava row had increased remarkably. Such patterns can be expected for any intercropping system and make sampling and nutrient balance calculations complex. They reflect on one hand un-even nutrient extraction patterns, even if the whole topsoil appears to be exploited by roots, and uneven litter deposition patterns. In the cassava based systems both the residue of the intercrop and the major part of the leaf litter fall of the cassava (Van Noordwijk and Purnomosidhi, 1992) occurred in the middle of the plot.

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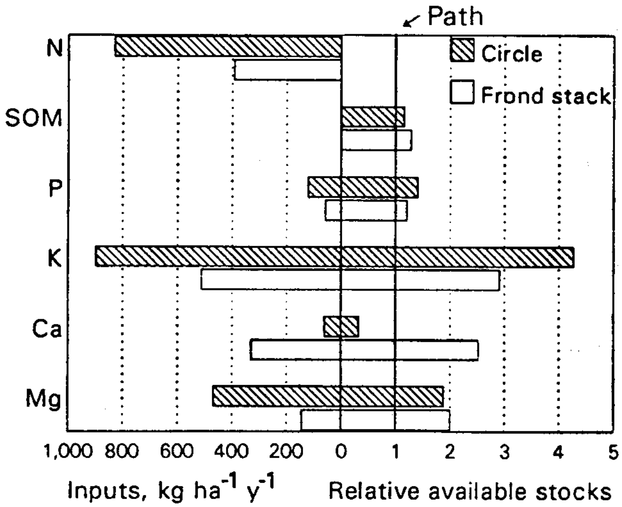

Fig. 8. Nutrient inputs (left) and available levels in the topsoil (right) in a 10-year old oilpalm field in Sumatera (Fairhurst, 1994); available levels for the weed-free tree circle and frond stack were scaled by the content of a path.

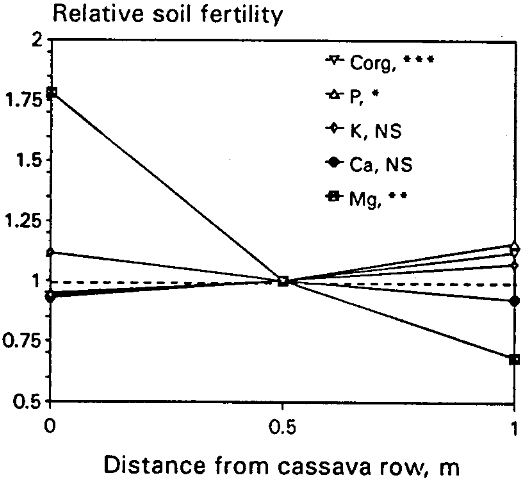

Fig. 9. Relative soil fertility as a function of distance to cassava rows after 6 years of planting at the same position in experiments in Lampung described by Sitompul *et al.* (1992).

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6. Soil fertility improvement in sequential agro-forestry systems (ΔL)

Fallow systems

If we try to avoid any interpretation, we can define a fallow as: land which has been cropped before, which is not currently cropped, but will be in future. One expects the crop yield in the first year of cropping after a fallow to be higher than in the last year before the fallow started. Normally, this is expressed as 'declining soil fertility' during cropping and 'restoration of soil fertility' during the fallow, but 'soil fertility' is an umbrella for a wide range of soil chemical, physical and biological aspects. If we want to extrapolate between soils and climatic zones, we should be sure of a site-specific diagnosis before we can hope to design relevant solutions.

Agroforestry research on fallows may have two objectives:

- to improve the fallow in its role towards the subsequent crop ("improved fallow"),
- to enrich the fallow and increase its direct use to the farmer, by yielding valuable products (firewood, grazing, opportunities for bee-keeping) ("enriched fallow"). Somewhere along the line, improved fallows can develop into full agroforestry systems and the perspective of subsequent cropping can become of secondary importance, as happens in the 'complex agroforests'.

Improvement and enrichment of fallows are not mutually exclusive and farmers may go for a combination. Yet, for purposes of analysis, we concentrate on the "improved fallow" here.

How can a fallow be improved?

The effect of improving soil fertility is normally associated with the duration of the fallow period. An 'improved fallow' is supposed to speed up the restoration process and have the same effect in a shorter period of time. Experiments usually compare the effect after an equal number of years, as this is easier to derive from existing designs, but a comparison of the time required to achieve a state where cropping becomes worthwhile may be more relevant to practical situations, where reduced length of fallows due to increased local population density is the cause of a breakdown of the system (not enough land for long fallows → cropping before soil fertility fully restored → lower yields → earlier switch to a new plot → even shorter fallows etc.). Normally the clearing of a natural fallow vegetation is followed by burning the slashed biomass. Burning slashed forest vegetation still appears to be the cheapest and most effective way to ensure crop nutrition. Not burning is not a productive alternative for slash-and-burn farmers (Van Reuler and Janssen, 1993).

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Table 1. Reasons for having a fallow and opportunities for improving it.

Constraint to continuous cropping	Major restoration process during fallow	Yard stick of success	Scope for improved fallow
A. N supply	Build up of (top) soil N mineralization potential, based on: - N_2 fixation, - atmospheric inputs - deep soil N sources - absence of losses/ exports	1. Pool size of 'intermediate' fraction SOM, 2. N mineralization rate of the soil	1. Producing more biomass which contributes to SOM (low to intermediate quality litter ?) 2. Increased mineralization rate
B. P supply	1. Transforming poorly available P forms into organic P 2. Uptake from deep layers ??	Pool size of organic P in the top soil	More effective P mining (or better use of strategic P inputs...) and transfer to readily available/organic P pool
C. Cation (K, Ca, Mg) supply	Relocation of cations in the profile	Concentration of cations in the top layer	Increased cation uptake from zones where they are available but not accessable to crops
D. Soil acidification (Al toxicity), obstructing root development and hence resource capture by crops	1. Accumulating other cations in top soil (~ C) 2. Producing organic acids which can (temporarily) reduce Al toxicity 3. Localized Al detoxification around 'dead tree root channels'	1. Relative Al saturation of top soil 2. Concentration of monomeric (toxic) Al in soil solution 3. Tree root distribution and root turnover	1. see C 2. Increased production of the right type of organic acids 3. Increased production of 'dead tree root channels'

Table 1. Continued.

Constraint to continuous cropping	Major restoration process during fallow	Yard stick of success	Scope for improved fallow
E. Soil physical degradation, obstructing root development and hence resource capture by crops	1. Increased water infiltration 2. Reduced bulk density 3. Improved soil aeration	Biological activity (earthworms etc.), presence of macropores	1. Feeding the worms in a better way 2. Increased production of 'dead tree root channels'
F. Presence of (parasitic) weeds	1. Decreased viability of rhizomes of perennial weeds 2. Decay of seed bank of annual weeds	1. Viability of weed rhizomes 2. Size of seed bank 3. Re-infestation in cropping period	1. Earlier formation of a closed shrub/tree canopy, shading out perennials 2. 'Fooling' of parasitic weed seeds ?
G. Presence of soil borne diseases	Reducing population of disease organisms and/or increase population of antagonists	Population size of disease organisms and antagonists	More effective 'fooling' of the disease organisms, or stimulation of the antagonists
H. Decreased presence of 'symbionts' such as VAM fungi	Build up of VAM population	Soil VAM infection potential or spore density	Increased VAM spore production of the right type

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Technical developments to deal with thick mulch layers and avoid fire risks are needed if atmospheric pollution by burning is considered unacceptable.

The burning process leads to the loss of large amounts of N (and possibly P, S and ash as well), and may induce transformations in the top layers of the soil, depending on the temperature of the burn (amount and moisture content of the slashed biomass). A major distinction should thus be made between those types of "improved fallow" which do and those which do not depend on burning upon reclamation. We can only avoid burning if we have techniques for planting crops in (thick) layers of mulch, if decomposition rates of the mulch are sufficiently fast (and immobilization effects are small) and if pest and disease problems are manageable without a burn.

Research on 'improved fallows' would be much easier if we know what the main function of the fallow is in each location, and if we can find yard sticks for measuring the effect of fallows, without a direct test of growing a crop.

A number of the effects of fallows, especially F, G and H can also be obtained by proper crop rotation systems, and research methods can be derived from/ shared with this field. Fallow based systems are normally 'sequential' agroforestry systems, where trees and crops are present at different times on the same soil. Tree - crop interactions are mediated through soil conditions in this case. In some spatially zoned (simultaneous) systems such as 'hedgerow inter-cropping' an attempt is made to integrate the fallow function into a permanent system; this may be successful where litter production is the main criterion (part of A, D & E). In its current form hedgerow intercropping systems suffer from too intense tree-crop competition or from a decline of the tree component due to too intensive pruning. Currently, interest is increasing in 'rotational alleycropping' systems, where a number of years of pruning the trees and growing food crops is alternated with a rest period in which the trees can grow. Such systems are similar to 'improved fallows' in that they are based on a more rapid establishment of a tree phase than would occur by natural succession. In fact, they draw on the best traditional knowledge of shifting cultivators who abandon their plots while the tree stumps are still alive.

New prospects for fractionating soil organic matter by a combination of size and physical density (degree of association with mineral particles) hold a promise that a sensitive 'yardstick' for the various functions of soil organic matter can be found (Meijboom *et al.*, 1995; Barrios *et al.*, 1994).

7. Competition for nutrients between trees and crops in simultaneous systems (C)

Direct evidence for belowground competition between trees and crops can be obtained by separating the roots, by trenching or other means. Coster (1933)

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showed a strong competition by established *Tectona* trees on neighbouring food crops or new seedlings. Tree root competition in hedgerow intercropping can be serious, as evident from positive crop response to root trenching (Fernandes *et al.*, 1993). A separation of competition for water and for the various nutrients needs further treaments to see whether negative effects disappear at higher input levels. On-going experiments in Lampung suggested a strong competitive effect in a relatively dry growing season and a small effect in a wet one, pointing to water as the major resource competed for. As root trenching may also affect the aboveground performance of the tree, positive crop responses may in part be due to reduced shading, rather than reduced belowground competition. A more direct measurement of nutrient resource sharing between trees and crops can be based on tracer experiments, e.g. based on ^{15}N (Van Lauwe *et al.*, 1994).

As direct measurements of competition are complicated, we need a simple indicator to deal with the large number of tree-soil-crop combinations in the real world. Such an indicator may be found in the tree root distribution as evident at the stem base ('Proximal roots', Figure 10; Van Noordwijk and Purnomosidhi, 1995).

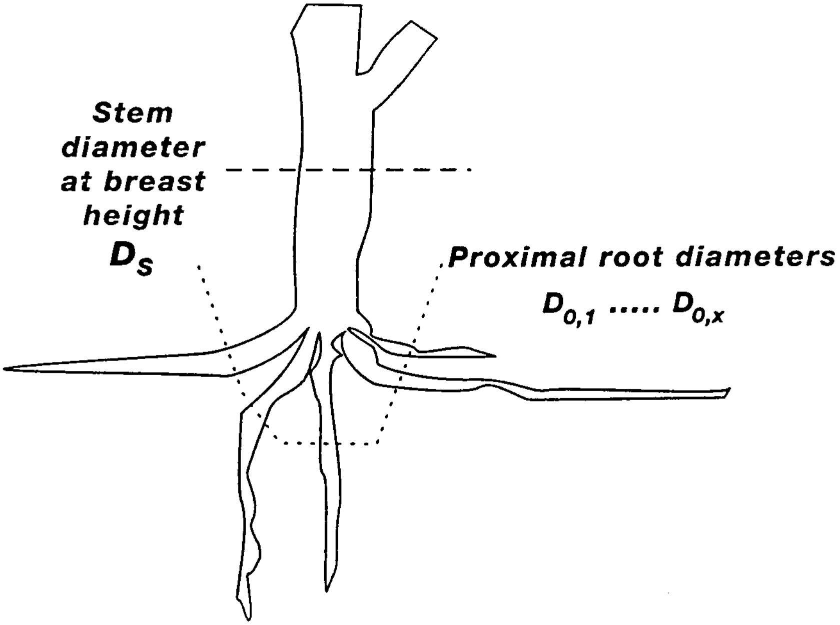

Fig. 10. Proximal tree root diameters can be easily measured and form a basis for a new 'index of tree root competitiveness'.

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Measurements of root parameters can be based either on measuring all roots belonging to a single plant, or on sampling a known volume of soil and extrapolation to the soil volume per plant. For annual crops, growing in a regular planting pattern, both procedures are possible. For forest trees in a regular spacing the second approach is normally used. For isolated trees both approaches are virtually impossible and an alternative estimation procedure is required. An analogy may be found in forest mensuration procedures, where aboveground tree biomass can be estimated with reasonable accuracy from measurements of stem diameter at a standardized height.

In a 'fractal' branching pattern, the same rules govern branching at each subsequent level. The initial size (diameter) and the essential branching rules thus contain the information required to construct the whole pattern. If root branching patterns have fractal characteristics, measurement of the proximal root diameter at the stem base and the branching rules as observed anywhere in the root system, would be enough to predict total root length, root diameter distribution and root length per unit dry weight (specific root length).

Table 2. Protocol for measuring proximal tree roots and index of root competitiveness.

1. Carefully excavate the first apart of the proximal roots at the stem base. For small tree a 0.3 m half sphere may be sufficient, for larger trees a 0.5-1 m half sphere will be needed. While excavating, all major roots should be left intact; destruction of most of the fine roots can not be avoided. Check for 'sinker' roots (vertically oriented roots starting from horizontal roots, often close to the tree stem).
2. Measure the root diameter of all proximal roots (i.e. roots originating from the stem base or as laterals from the top part of the tap root) and classify them by orientation (angle with a horizontal plane). Root diameter measurements should be made outside the range of obvious thickening close to the branching point or buttress roots (they normally taper off rapidly).
3. Measure stem diameter D_s (either as 'root collar' diameter or as stem diameter at breast height, depending on the size of the tree).
4. Calculate the sum of root diameter squares for roots with a horizontal (angle with horizontal plane less than 45°), ΣD_{hor}^2 and vertical orientation ΣD_{vert}^2.
5. A tentative *index of root competitiveness* is then calculated as $\Sigma D_{hor}^2/D_s^2$.

The average value of the proportionality factor (measured on branching points throughout the diameter range) and link length can be used in the equations for total length, surface area and volume given by Van Noordwijk *et* *al.* (1994a); if either of the regressions is has a significant slope, modified equations will have to be developed (e.g. on the basis of the numeric model given by Spek and Van Noordwijk, 1994). Further checks of the 'index of root competitiveness' are needed.

8. Sloping lands and erosion control

Erosion and sedimentation occur across a wide range of scales, but extrapolations from one scale to another are not as easy as is normally considered. 'Erosion control' can be based on two principles: a) prevent any soil movement, b) increase local deposition of soil material on the move. Hedgerows of trees planted along contour lines have been promoted for erosion control, with considerable success. Generally, the amount of sediment leaving the field is greatly reduced by such hedgerows, similar to effects of grass strips or natural vegetation. As a major source of nutrient export from the field is thus controlled, one may expect the overall 'nutrient use efficiency' to increase. Whether or not such improvement also leads to improved nutrient availability to the crops is questionable, however. Contour vegetation leads to terrace formation by soil redistribution and to considerable soil fertility gradients (Turkelboom *et al.*, 1993; ICRAF, 1994). The upper part of the terrace is depleted ('scoured'), while the terrace is build up from organic matter and nutrient rich topsoil. Soil fertility management can be based on a number of approaches:

- exploit the gradients by putting nutrient demanding (tree) crops in the terrace and good scavengers on scoured upper terrace,
- try to reduce the fertility gradients by corrective fertilizer application (organic an/or inorganic) on the upper terrace,
- try to reduce the terrace formation effect by controlling soil movement rather than increasing soil deposition; a nearly permanent soil cover by mulch may be needed to reduce the splash impact leading to soil movement. Trees with a slow litter decomposition rate will be superior in this respect. Grass strips can probably not fulfill this requirement.

As a first approach to modelling the crop effects, assume a parabolic distribution of relative crop yields, due to 'shade and mulch' type interactions between tree and crop, leading to increased yield in the middle of the alleys, compared to the no-tree control, and reduced yields close to the hedgerow. Soil fertility is assumed to be proportional to topsoil depth. If the distance X is scaled from 0 to 1 and the average yield is 1 (no net benefit or loss due to the hedgerows, this means that the yield Y can be described by:

$$Y = pX(1-X) + 1 - \frac{p}{6} \quad (12)$$

where the parameter *p* determines the shape of the curve.

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If the soil fertility of the topsoil, F, is redistributed, without any net losses or gains, we find:

$$F = q X + 1 - 0.5 q \qquad (13)$$

where the parameter *q* determines the gradient. By multiplying [12] and [13] we obtain a yield curve of the form:

$$Y = -pqx^3 + px^2(1.5q - 1) + x(p(1 - \frac{2q}{3}) + q) + 1 - \frac{p}{6} - \frac{q}{2} + \frac{pq}{12} \qquad (14)$$

This is a two-parameter cubic equation in X, which might be fitted to data sets of crop yields per row. Figure 11 gives examples for three values of q which may reflect three stages of terrace formation by soil redistribution. For the example p is 3 was used and q = 0 (situation a), 0.9 (situation b) and 1.8 (situation c), in equation [13]. In this multiplicative model, the effects of top-soil depth and tree-crop interaction are supposed to act independently on crop yield. In view of the shade and mulch model we would expect a less than proportional effect if soil fertility only affects the native soil N supply reflected in the N_{s0} parameter, but a more than proportional effect if it affects the maximum possible yield, Y_{max}, e.g. by increased water storage in the soil or improved non-N fertility factors. A linear response may thus be used as a first approximation.

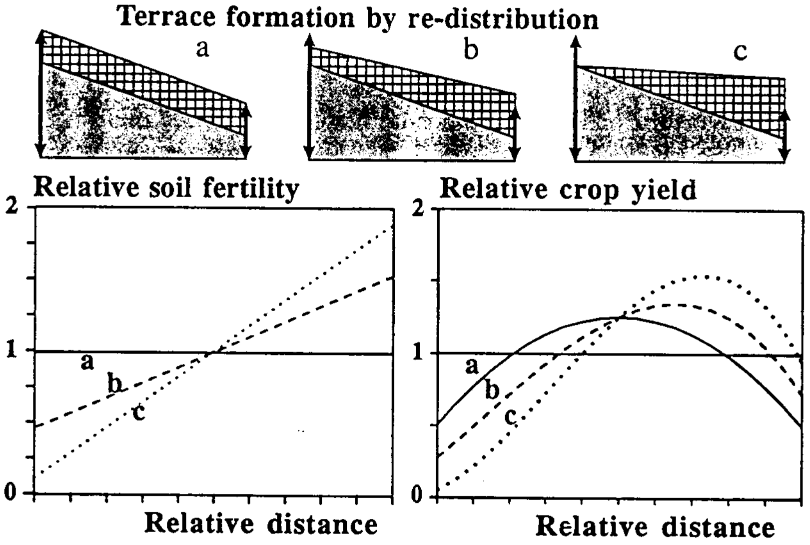

Fig. 11. Three stages in the process of terrace formation by soil redistribution and possible effects on crop yields.

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A consequence of the linear soil fertility gradient and the symmetric shade and mulch interaction curve is that the effect on average yield is neutral (as can be checked by integrating [14] over the interval [0-1]).

9. Concluding remarks

Research on nutrient use efficiency of agroforestry systems as presented here has to bridge a number of levels of complexity. Equal attention is needed for resource capture by the trees and processes which (finally) make it available to other (marketable) components of the system. Nutrient management is an integral part of the overall optimization of the agroforestry system. With increased availability of fertilizers and increased market integration, the 'service' roles of trees will probably decrease, while the direct market value becomes more prominent.

We believe that progress in agroforestry research can come from a combination of the following steps:

1. Inventory and classify the existing agroforestry systems and their *raison d'être* (farmer knowledge and values, soils, climate, market conditions and policy environment); diagnose the major constraints, management options and trade-offs, including risk management (Van Noordwijk *et al.*, 1994b).
2. Develop process-based models for the various types of interactions under a wide range of environmental conditions and estimate the relevant parameters in well controlled experiments.
3. Develop and test simple criteria/ indicators for judging interaction terms for any tree on any site, such as the index of tree root competitiveness; these criteria can be based on a combination of existing farmer knowledge, new observation skills and key parameters for the process-based models.
4. Use the model as well as the local indicators for optimizing management choices, including germplasm selection, for all relevant biophysical, socioeconomic and policy environments.

Agroforestry research in this sense has only just started and forms an exciting challenge.

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