A general tree-environment-crop interaction equation for predictive understanding of agroforestry systems

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Abstract

Agroforestry is a young science in need of theories and methods providing predictive understanding. The present study is an attempt to contribute to the development of a general agroforestry theory and accessory methods. A tree-environment-crop interaction equation is derived in which the overall tree effect on crop production is explained as a balance of (positive and negative) relative net tree effects on resource availability to the crop. In this balance, each relative net tree effect receives a weight that is equal to the degree of limitation of the resource in the specific environment. The equation thus makes explicit that the balance of available resources in the environment is a major factor determining the biophysical outcome of an agroforestry technology. The equation enables the formulation of two rules that can be viewed as the agroforestry counterparts of classic crop production laws. The agroforestry counterpart of the law of limiting factors states: the more a resource becomes available in the tree-crop environment, the smaller its share becomes in the overall tree-environment-crop interaction. The agroforestry counterpart of the law of the optimum states: the more other limiting resources become available in the tree-crop environment, the greater the share of a resource becomes in the overall tree-environment-crop interaction. These rules help with extrapolation, without requiring full quantification of the tree effect balance. They allow the development of a method for the analysis and synthesis of agroforestry experiments. The method is illustrated by analysing some published alley cropping experiments. This analysis indicates that for alley cropping systems: (1) the hypothesis that trees capture nutrients below the crop rooted zone resulting in a net benefit for the crop is probably true for nitrogen and not true for phosphorus, and that (2) competition for water by trees probably exceeds their water conservation effects. Suggestions for experimentation are given and the circumstances under which yield benefits of agroforestry systems can be expected are discussed. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Agroforestry; Trees; Crop production; Interaction equation; Methods

1. Introduction

“Agroforestry is a dynamic, ecologically based, natural resource management system that, through the integration of trees in farm- and rangeland, diversifies and sustains smallholder production for increased social, economic and environmental benefits” (Leakey, 1996). Although it was traditionally practised for centuries, only two decades ago it was brought into the forefront of agricultural research (Sanchez, 1995; see also Coe, 1997). Initially, agroforestry was promoted with great enthusiasm, but many innovations led to disappointments. This revealed the need of theories
that could provide a predictive understanding applicable to other situations. Agroforestry is not there yet (Sanchez, 1995). Without theories and accessory methods, the science remains on an empirical level: a collection of loose hypotheses, facts and technologies. On this level, each hypothesis has to be tested again and again in different environments. Each technology has to be developed by trial and error, and has to prove its usefulness time after time in diverse agro-ecosystems. A theory would make it possible to integrate knowledge gathered from different technologies and experiments in different agro-ecosystems. It would give directions for more efficient and effective experimentation; and it would provide predictive understanding, making extrapolation of research results to other types of environment possible. Recent efforts to come to predictive understanding are: dynamic modelling (Lawson et al., 1995), static modelling (Van Noordwijk, 1996), separation and quantification of the overall tree-crop interaction in fertility and competition effects (Ong, 1995, 1996), and analysis of tree-crop interactions in terms of resource capture and use (Cannell et al., 1996; Ong et al., 1996).

Cannell et al. (1996) have made clear that biophysical yield benefits of agroforestry (AF) systems are a good starting point for a more complete (biophysical, socio-economic and policy) evaluation of AF systems. They generalised the equation of Ong (1995) and formulated the hypothesis that biophysical yield advantages can only be expected if the trees can acquire resources that the crop would not otherwise acquire. This is a general statement and is in general probably true. Plants transform physical resources (inputs) to biomass (output), and an increased output requires the acquisition of additional inputs (see also Kass, 1996 point 4). Cannell et al. (1996) showed that most biophysical agroforestry hypotheses given by Sanchez (1995) can be reduced to this central statement, by applying the statement for environments where either water, or light or nutrients are limiting. Merits of the study of Cannell et al. (1996) are that it accentuates the crucial role of resource capture and that it reduces a variety of hypotheses, showing that their verification or falsification depends on the type of environment. However, their study is not specific concerning the interaction with the environment. Their symbols \( F' \) and \( C' \) denote a difference in crop yield in their Eq. (2), but denote resources in their Eqs. (3) and (4).

When the last two equations are substituted into the first, the resources are implicitly converted to crop yields. Herewith, the effect of the environment on this conversion is kept implicit too. Numerous alley cropping experiments all over the world have shown that the environment is a major factor determining the effect of AF technologies as appears from strongly positive to strongly negative effects of the alley cropping technology in different environments (see Section 4). The present study continues the analysis of tree-environment-crop interactions on the basis of physical resources, but aims at a more explicit role for environmental effects. It does not consider biotic relations such as allelopathic effects and effects on pests and diseases (see Anderson and Sinclair, 1993).

In line with the work of Ong (1995, 1996), the tree-environment-crop interaction is evaluated in terms of crop production. Possible extensions to include tree production and environmental changes in the evaluation are only mentioned. Crop production is viewed on a time scale of one season.

In this paper when reference is made to ‘a particular AF technology’ it denotes a certain AF technology (such as alley cropping, parkland, relay-intercropping, etc.) defined by: tree species and age, crop species including cultivar, a particular management (tree-crop arrangement in time and space, pruning, weeding and fertilisation regime, etc.), the effective soil depth and the slope. Where reference is made to ‘net tree effect on resource availability’ it denotes the net tree effect on the resource availability to the crop in the particular AF technology.

2. The nature of tree-environment-crop interactions

2.1. AF technologies as tree \(_\times_\) crop interactions

Although much agroforestry research directly aims to match AF technologies and environments, this section aims to find general characteristics of AF technologies that are as much as possible independent of the environment. The next Section 2.2 will describe the AF system as a technology \(_\times_\) environment interaction.

Trees may decrease the radiation available to the crop by intercepting part of it. The reduction depends on leaf area and extinction coefficients of the trees in
different layers of the canopy at different times (Ong et al., 1996).

Trees can increase the availability of water to the crop by improving soil physical properties, by reducing losses from run-off and by improving microclimate through reducing evaporative demand. Trees may decrease the available water to the crop by canopy interception and by use and depletion of water in the crop rooted zone (See Wallace, 1996).

The effect of trees on the transpiration (water capture) by crops does not only depend on the earlier-mentioned effects on water availability. It depends also on the limiting resources in the specific environment and on the tree effect on the availability of these limiting resources. If water is ample (i.e. other resources are limiting), both the sole crop and the crop in the AF system can transpire at their own maximum rates. These maxima are related to the leaf areas and thus by the crop’s growth. If the net tree effect on the availability of the limiting resources is negative, the leaf area of the crop in the AF system will be lower than that of the sole crop. Consequently, the overall tree effect on the crop’s transpiration is likely to be negative too, even if its effect on water availability is positive. The tree effect on the crop’s capture of water will only correlate (positively) with its effect on water availability in water limiting environments. The more water is limiting, the stronger will be this correlation.

Trees can increase the availability of nitrogen to the crop by reducing erosion and by root decay, litterfall and provision of mulch, whether in combination with N₂-fixation and deep capture (followed by recycling) by the trees or not. Trees decrease nitrogen availability to the crop by use and depletion of it in the crop rooted zone (See Nair, 1984).

In analogy with capture of water, the correlation between the tree effect on the crop’s capture of nitrogen with the earlier-mentioned effects on nitrogen availability is weak or zero if nitrogen is ample. It is only positive in nitrogen deficient soils. This correlation between the tree effect on capture and on availability will be stronger as nitrogen is more deficient. The same (except atmospheric fixation) can be said for other nutrients.

Net tree effects on availability of resources to the crop are determined by the particular AF technology. Net tree effects on captures of resources by the crop are determined by the particular AF technology and by the limiting resources of the specific environment. The last behaves as a disturbing factor if the objective is to find general characteristics of a particular AF technology. Hence, in aiming to characterise a particular AF technology, it is preferable to do this in terms of net tree effects on availability rather than in terms of net tree effects on capture of resources. The relative net tree effect on availability of a randomly taken resource \( A \) to the crop in the AF technology can be defined as

\[
T_A = \frac{A_{AF} - A_S}{A_S} \quad T_A > -1
\]

where \( T_A \) = the relative net tree effect on availability of resource \( A \) to the crop, \( A_{AF} \) = availability of resource \( A \) to the crop in the agroforestry system, and \( A_S \) = availability of resource \( A \) to the sole crop.

By taking the difference in availability relative to that for the sole crop, \( T_A \) is dimensionless and independent of the units used to measure availability.

The relative net tree effects on availability of each of the resources radiation (\( T_R \)), water (\( T_W \)), nitrogen (\( T_N \)), and other nutrients (\( T_F \)) are determined by the particular AF technology. They will be constant for a particular AF technology and independent of the environment if the absolute net tree effect on availability (\( A_{AF} - A_S \)) decreases proportionally with \( A_S \) in poorer environments and increases proportionally in richer environments. On the other extreme, not the relative, but the absolute net tree effect on availability may be constant over the whole range of environments. The absolute value of \( T_A \) will then increase in environments where the resource is more limiting and decrease when the resource becomes less limiting. Probably \( T \)-coefficients will behave somewhere between the two extremes, and closer to the first. This is a subject for further study. Nevertheless, in general, it is very unlikely that the environment influences the sign of the \( T \)-coefficients: i.e. that for a particular AF technology, in one environment addition outweighs subtraction of a certain resource, and that in another environment the reverse will be the case. Note that the effective soil depth and the slope have been defined to be part of the ‘particular’ AF technology. Knowledge of only the signs has already predictive value when AF technologies are transferred to other environments (see Section 3.1). \( T_R \) is zero in sequential AF technolo-
gies and negative in simultaneous AF technologies, \( T_W, T_N, \) and \( T_F \) can be negative, zero, or positive. The term \( T_F \) represents the combined net tree effect on all other resources (nutrients) not taken explicitly into account. If necessary, it can be split into more terms.

\( T_R, T_W, T_N, \) and \( T_F \) determine simultaneously the overall tree effect on crop production. The specific environment will determine how.

### 2.2. AF systems as technology \( \times \) environment interactions

This section describes the biophysical outcome of the AF system when a particular AF technology with particular \( T \)-coefficients is placed in a specific environment.

Let the crop production in a specific environment \((Y; \ e.g. \ kg/ha)\) be a function of the availability of the resources radiation \((R; \ e.g. \ MJ/m^2)\), water \((W; \ e.g. \ mm)\), nitrogen \((N; \ e.g. \ kg/ha)\) and other nutrients \((F; \ e.g. \ kg/ha)\):

\[
Y = f(R, W, N, F)
\]  

(2)

As emphasised by Cannell et al. (1996) and discussed in the introduction and in the former section, trees will not influence crops by modifying the production function (Eq. (2)), but mainly by their influence on resources which are available to the crop. Let \( n \) denote the tree density (number/ha) of a particular AF technology. Then according to the chain rule:

\[
\frac{dY}{dn} = \frac{\partial Y}{\partial R} \times \frac{dR}{dn} + \frac{\partial Y}{\partial W} \times \frac{dW}{dn} + \frac{\partial Y}{\partial N} \times \frac{dN}{dn} + \frac{\partial Y}{\partial F} \times \frac{dF}{dn}
\]

Multiplying both sides with \( dn \), and dividing both sides by \( Y \) gives:

\[
\frac{dY}{Y} = \frac{\partial Y}{\partial R} \times \frac{1}{Y} \times dR + \frac{\partial Y}{\partial W} \times \frac{1}{Y} \times dW + \frac{\partial Y}{\partial N} \times \frac{1}{Y} \times dN + \frac{\partial Y}{\partial F} \times \frac{1}{Y} \times dF
\]

\[
= \frac{\partial Y}{Y} \times \frac{R}{R} + \frac{\partial Y}{W} \times \frac{W}{W} + \frac{\partial Y}{N} \times \frac{N}{N} + \frac{\partial Y}{F} \times \frac{F}{F}
\]

So that by approximation:

\[
I = L_R \times T_R + L_W \times T_W + L_N \times T_N + L_F \times T_F \tag{3}
\]

where

\( I \)=the overall tree-environment-crop interaction on crop production; i.e. \( I = \Delta Y/Y = (Y_{AF} - Y_S)/Y_S \) with \( Y_{AF} \) is the crop production in the AF technology and \( Y_S \) is the crop production at a tree density of zero (i.e. production of the sole crop),

\( L_R, L_W, L_N, L_F = \)the environmental weight \((L_A = (\partial Y \times A)/(\partial A \times Y))\) for a relative change in availability of radiation, water, nitrogen, and other nutrients, respectively, and

\( T_R, T_W, T_N, T_F = \)the relative net tree effects on the availability to the crop \((T_A = \Delta A/A; \ see \ Eq. \ (1))\) of radiation, water, nitrogen, and other nutrients, respectively.

Eq. (3) explains the overall interaction \( I \) as a balance (weighted sum) of relative net tree effects on resource availabilities. These \( T \)-coefficients reflect the tree-crop or technology part of the overall interaction, and can be positive, zero, or negative (Section 2.1). They are weighted with positive environmental weights. These \( L \)-coefficients have been derived directly from the crop production function (Eq. (2)), and are thus crop-environment characteristics. A closer look at the \( L \)-coefficient of a random resource \( A \) shows:

\[
L_A = \frac{\partial Y}{\partial A} \times \frac{A}{Y}
\]

\[
= \frac{\partial Y}{A} \times \frac{A}{Y}/A
\]

Firstly, the \( L \)-coefficient equals a relative change in production \((\partial Y/Y)\), responding to and divided by a relative change in availability of resource \( A \) \((\partial A/A)\). The \( L \)-coefficient is thus dimensionless and independent of the units in which production and availability were measured. Secondly, the \( L \)-coefficient equals the slope of the response curve \((dY/dA; \ other \ availabilities \ constant)\) divided by the use efficiency \((Y/A)\) of the resource \( (see \ Fig. \ 1A)\). If a resource is non-limiting (on the plateau of the response curve), the slope equals zero, so that the minimum value of the \( L \)-coefficient equals zero. If the resource is the
only limiting resource, production is proportional to its availability. In this initial, proportional state of the response curve, the slope equals the use efficiency, so that the maximum value of the \( L \)-coefficient equals one. Between the initial, proportional state and the plateau, the slope reduces gradually to zero. The use efficiency will also decrease, but will never reach the value zero. Between the proportional state and the plateau, the \( L \)-coefficient is thus between one and zero (Fig. 1B).

Kho (2000) shows that the sum of the \( L \)-coefficients of all resources is constant for any reasonable production function (Eq. (2)) and is the most likely one:

\[
L_R + L_W + L_N + L_F = 1
\]  

Accordingly, if the \( L \)-coefficient of one resource increases, that of the others will decrease (see Fig. 2). The \( L \)-coefficients can be interpreted as the degree of limitation of the resources in the specific environment. Estimations of the \( L \)-coefficients can be derived indirectly from published agronomic experiments; or more directly by experiments in which reduction or addition of resources have been evaluated in terms of biomass production and capture of the resources (see Kho, 2000).

Eq. (3) thus states that if a resource is non-limiting \((L=0)\), a tree effect on that resource has not any effect on crop production; and that the more a resource is limiting \((0<L<1)\), the greater the tree effect on crop production via that resource.

In analogy with the equation by Ong (1995) Eq. (3) evaluates AF systems only, if crop yield is the sole economic component. If tree products are yielded, a similar equation (balance of crop effects) can be drawn up for the crop-environment-tree interaction on tree production. The \( T \)-coefficients are replaced by ‘\( C \)-coefficients’: relative net crop effects on availability of resources to the trees. They represent the crop-tree part of the overall interaction. The \( L \)-coefficients represent the environment-tree part.

Effects of the AF technology on the third component (the environment itself) can be evaluated by budgeting resources (Shepherd et al., 1996). Van Noordwijk (1996) shows how the three components crop production, tree production, and environmental changes can be evaluated jointly.
3. Methods for extrapolation, analysis and synthesis

3.1. Environmental agroforestry rules for extrapolation

The environment has a predictable effect on the $L$-coefficients. This allows the formulation of two rules that give predictive understanding of AF systems without complete quantification of Eq. (3).

Rule 1: The more a resource $A$ becomes available in the tree-crop environment (other factors equal), the smaller its limitation ($L_A$), and the smaller its share ($|L_AT_A|$) becomes in the overall tree-environment-crop interaction (Fig. 1). This rule can be viewed as the agroforestry counterpart of a generalisation of the law of limiting factors (Blackman, 1905; see also Kho, 2000).

The limitation of a resource does not only depend on its availability. A resource can be only limiting in relation to the availabilities of other resources. According to Eq. (4), a resource $B$ becomes relatively more limiting (increasing value for $L_B$) if other resources (e.g. $A$) become less limiting; i.e. if the availability of resource $A$ increases and raises the plateau of resource $B$ (Fig. 2; see also Kho, 2000). This leads to the second rule.

Rule 2: The more other limiting resources become available in the tree-crop environment, the greater the share of a resource becomes in the overall tree-environment-crop interaction. This rule can be viewed as the agroforestry counterpart of the law of the optimum (Liebscher, 1895; see also De Wit, 1992; Kho, 2000).

The directions of the two rules can be changed to situations with smaller availability and combined (Table 1). Table 1 shows the increase (+) and decrease (−) of an environmental weight and thus of the absolute value of a resource term ($|L_AT_A|$) in Eq. (3), when the availability of the resource itself or of another limiting resource changes. Note that the $T$-coefficients can be positive as well as negative. An increased weight of a negative tree effect will result in a lower (or more negative) overall interaction.

If for a particular AF system the signs (positive or negative) of the $T$-coefficients are known, one can deduce with Eq. (3) and Table 1 in which direction the overall interaction will change, when the AF technology would be transferred to another environment. Small tree effects that are negligible when the resource is ample may become important in the new environment. Attention should be paid to tree age, the effective soil depth and the slope of the surface, because they may fundamentally change the character of the AF technology. Young trees having a superficial and thus competitive rooting system will likely have lower (or more negative) $T_W$, $T_N$, and $T_F$ than older trees that may have a more developed canopy and thus a more negative $T_R$. A shallower soil may force tree roots to develop in the crop rooted zone, increasing belowground competition and decreasing (or making more negative) $T_W$, $T_N$, and $T_F$. A flat surface is not susceptible to run-off and water erosion, so that on a flat surface tree effects on these can only be marginal. The steeper the slope, the greater the hazard of soil and water loss and the greater the potential benefit by trees through reducing run-off and increasing run-on and sedimentation (Agus et al., 1998). A steeper slope may thus increase $T_W$, $T_N$, and $T_F$.

3.2. Inversion of the rules for analysis and synthesis

Positive or negative signs of the net tree effects on availability of the resources water, nitrogen, and other nutrients, can be found by analysing the direction of change of the overall interaction $I$ in different environments. Concerning radiation, its sign is negative in simultaneous AF technologies and zero in sequential AF technologies. To determine the other signs, both rules can be inverted delivering reversed rules.

If the availability of resource $A$ decreases, its $L$-coefficient increases (Fig. 1). A negative net tree effect on resource $A$ gets more weight which, according
to Eq. (3), results in a decreased overall interaction. A reversed rule derived from Rule 1 may thus be: if the overall interaction decreases with decreasing availability of resource A, this may be partly the result of a negative net tree effect on the availability of resource A.

If the availability of resource A decreases, the \( L \)-coefficient of other resources decreases (Fig. 2). A positive net tree effect on another resource (e.g. B) gets less weight which, according to Eq. (3), results in a decreased overall interaction. A reversed rule derived from Rule 2 may thus be: if the overall interaction decreases with decreasing availability of resource A, it may be partly because of a positive net tree effect on another resource.

By changing the directions of change (of the overall interaction and of the availability of resource A) and taking all combinations, a total of eight reversed rules can be derived from Rules 1 and 2. Figs. 3 and 4 show all possible reversed rules structured in two diagrams. One diagram (Fig. 3) starts with a positive overall interaction, and the other (Fig. 4) with a negative one. Although the second diagram is not fundamentally different from the first, its presentation facilitates the analysis of negative interactions. Each time, Rule 1 leads to the sign of \( T_A \), the net tree effect on the availability of the changed resource; and Rule 2 leads to the sign of the net tree effect on the availability of another resource (denoted with \( T_B \)). In principle, both rules may lead to true statements, because if the availability of one resource changes, the limitation (\(L\)-coefficient) of other resources changes too. However, if the overall interaction is positive (diagram in Fig. 3), the rule that leads to a positive \( T \)-coefficient is probably the most meaningful, because under the prevailing conditions this \( T \)-coefficient had a high environmental weight leading to the positive overall interaction. This net tree effect was probably responsible for the change in the overall interaction. If the overall interaction is negative (diagram in Fig. 4), the rule leading to a negative \( T \)-coefficient was probably responsible.

4. Analysis and synthesis of some alley cropping experiments

In the past 15 years, hundreds of alley cropping experiments were carried out all over the world in several climates and on several soils. The effect of the alley cropping technology varied from strongly positive to strongly negative. (Sanchez (1995), Table 1) gives a summary of some long-term alley cropping experiments considered to be reasonably devoid of interference between plots. Almost all experiments mentioned by Sanchez (1995) include the four
mulch-transfer treatments which are necessary to separate the overall interaction in a fertility (F), and a competition (C) effect in the equation by Ong (1995). After analysing the trials in terms of fertility and competition effects, Sanchez (1995) concluded that alley cropping is most likely to work where: (1) soils are fertile without major nutrient limitations, (2) rainfall is adequate during the cropping season, (3) land is sloping with erosion hazards, (4) there is an ample supply of labour, coupled with a scarce supply of land, and (5) land tenure is secure. The reasons why the fertility effects of alleys will most likely exceed the competition effects on especially fertile soils with adequate rainfall do not become clear. The hypothesis that (resource) constraints would ‘trigger’ competition is not confirmed by the data presented by Sanchez (1995). The fertility and competition effects vary greatly and there is not any systematic relation between the competition effect and the environment. Sanchez (1995) refers to other datasets and the impression remains that the first two points of his conclusion are more an empirical finding than a theoretical understanding.

Cannell et al. (1996) indicated that a substantial part of the fertility and competition terms can be based on the same resources, which are first obtained by the tree in competition with the crop and later recycled. The authors attempted to clean up both the F and the C terms from the overlap and introduced the concepts of $F_{\text{noncomp}}$ (resources acquired by the trees that the crop would not otherwise acquire) and $C_{\text{comp,nonrecycled}}$ (resources that the crop is deprived of which are used in tree growth and are not recycled). However, these concepts are difficult to quantify and to apply when analysing published experiments and to predict when and where alley cropping is most likely to work.

Although the method of Section 3 is developed for well-defined particular AF technologies, by applying it to some of the trials (Table 2) mentioned by Sanchez (1995) it may be possible to derive some generalisations about alley cropping.

The overall interaction was strongly negative ($-58\%$) in a fertile and N and P fertilised semi-arid Alfisol in India (Rao et al., 1991). An alley cropping experiment on a semi-arid moderately fertile soil in Machakos, Kenya (ICRAF, 1993) had an overall interaction of $-31\%$ in a season with low rainfall. The overall interaction $I$ increased (moved to zero) in these two experiments with decreasing availability of nutrients. According to the diagram in Fig. 4 (Rule 1) the net tree effect on nutrient availability is positive, and (Rule 2) the net tree effect on the availability of another resource than nutrients is negative. Because the soils were moderately fertile (low environmental weight for nutrient effects), and because the overall interaction was negative, Rule 2 was probably responsible for the increase of the overall interaction. The

![Fig. 4. Diagram to derive the sign of net tree effects, from a change of a negative overall interaction $I$ (other factors equal).](image)
high environmental weight for water effects (water was limiting in both environments) suggests that this other resource is water.

The overall interaction of the Machakos experiment was +11% in a season with high rainfall. The overall interaction increased with increasing water availability, and according to the diagram in Fig. 4 it can be concluded that (Rule 1) the net tree effect on water availability ($T_W$) is negative, and that (Rule 2) the net tree effect on the availability of another resource than water is positive. Similar reasons as above indicate Rule 1 (negative $T_W$) as responsible. But because the overall interaction became positive, Rule 2 cannot be excluded (the net tree effect on the availability of another resource than water is positive).

(ICRAF, 1995, Fig. 13; see also Van Noordwijk et al., 1998) shows grain yields of sole maize and of maize alley cropped with five different tree species in Lampung, Indonesia, in a wet and in a dry season. The overall interaction decreased (became more negative) with all five tree species, with decreasing water availability. So, these data confirm the negative value of $T_W$ and a positive net tree effect on the availability of another resource than water.

The environmental weight ($L_W$) for a negative tree effect on water availability will be one in extreme water limiting environments and near zero if water supply is ample. In dry areas, the negative tree effect on water availability (negative $T_W$) will thus fully count, exceeding possible positive net tree effects on availability of other resources (which will be low because of Rule 2). This analysis leads thus to the same conclusion as that of Sanchez (1995), namely that the alley cropping effect will probably be negative in semi-arid areas.

Analysis of the diagrams of experiments in the humid tropics, taking ‘soil fertility’ as a single resource, leads to contradictory results. The overall interaction increased from −30% in a strongly acid and infertile soil at Yurimaguas, Peru (Szott et al., 1991), to −3% in a fertile soil in Costa Rica (Kass, 1987). According to the diagram in Fig. 4 (Rule 1) the net tree effect on the availability of nutrients ($T_F$) should be negative, and (Rule 2) the net tree effect on the availability of another resource may be positive. The negative overall interaction and the negative net tree effects on the availability of other resources ($T_R$ and $T_W$) point to Rule 1 (negative $T_F$) as responsible.

The overall interaction was +32% in an acid soil from Lampung, Indonesia (Van Noordwijk et al., 1995). According to the diagram in Fig. 4 (Rule 1) the net tree effect on nutrient availability is positive, and (Rule 2) the net tree effect on the availability of another resource than nutrients is negative. Because the overall interaction became positive, Rule 1 cannot be excluded (positive $T_F$, which is contradictory to the earlier result).

Obviously ‘soil fertility’ cannot be viewed as one single resource. Trees in alley cropping systems have probably a negative net effect on the availability of

### Table 2

<table>
<thead>
<tr>
<th>Location [original source]</th>
<th>Rain (mm)</th>
<th>Soil</th>
<th>pH</th>
<th>$I$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Semiarid climate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyderabad, India [Rao et al., 1991]</td>
<td>550</td>
<td>Alfisol (N+P fertilisers)</td>
<td>6.0</td>
<td>−58</td>
</tr>
<tr>
<td>Machakos, Kenya (poor rains) [ICRAF, 1993]</td>
<td>230</td>
<td>Alfisol</td>
<td>5.6</td>
<td>−31</td>
</tr>
<tr>
<td>Machakos, Kenya (good rains) [ICRAF, 1993]</td>
<td>417</td>
<td>Alfisol</td>
<td>5.6</td>
<td>+11</td>
</tr>
<tr>
<td><strong>Humid climate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yurimaguas, Peru [Szott et al., 1991]</td>
<td>2200</td>
<td>Ultisol</td>
<td>4.2</td>
<td>−30</td>
</tr>
<tr>
<td>Turrialba, Costa Rica [Kass, 1987]</td>
<td>2650</td>
<td>Volcanic (Tropept)</td>
<td>4.6</td>
<td>−3</td>
</tr>
<tr>
<td>North Lampung, Indonesia [Van Noordwijk et al., 1995]</td>
<td>2700</td>
<td>Ultisol (P+K+Zn fertilisers)</td>
<td>4.7</td>
<td>+32</td>
</tr>
</tbody>
</table>

*a Adapted from Sanchez, 1995.*
some nutrients, and a positive net effect on the availability of other nutrients. The soils in Yurimaguas are strongly acid so that phosphorus and exchangeable bases (Ca, Mg, and K) are probably limiting. (Sanchez, 1987, Table 6) shows that in the top 5 cm of a soil in Yurimaguas, organic C content was 1%, available P was 8 ppm, and the Al saturation 66%. Beneath 5 cm, organic C content was 0.2–0.5% and the Al saturation 92–97%. In Lampung, organic C was slightly higher (1.5–2% in the top 15 cm; 0.5% in the subsoil); available P much higher (20 mg g⁻¹ in the top 15 cm; 5 mg g⁻¹ in the subsoil); and Al saturation much lower (20% in the top 15 cm; 60% in the subsoil). Moreover, all plots of the Lampung experiment received P, K, and Zn fertiliser (Van Noordwijk et al., 1995). So, the big difference between the Yurimaguas and the Lampung experiments is the availability of exchangeable bases and especially phosphorus. The overall interaction increased from −30% to +32% with increasing availability of phosphorus and exchangeable bases. According to the diagram of Fig. 4 (Rule 1) the net tree effect on these nutrients is negative (negative T_F), and (Rule 2) the net tree effect on another resource is positive (note that T_F now refers to phosphorus and exchangeable bases and not to ‘soil fertility’ in general). The negative T_F will get full weight if these nutrients are limiting (as in Yurimaguas) so that the alley cropping effect will thus probably be negative in phosphorus deficient (e.g. acid) soils.

There must still be a resource of which its availability is higher for the crop in the alley cropping system than for the sole crop. Otherwise a positive overall interaction would not be possible. The essence of an alley cropping system is that mulch is transferred to the crop. In a system without inorganic nitrogen fertiliser, organic material is the only source of nitrogen. Palm (1995) has shown that in general 4000 kg ha⁻¹ of tree prunings can easily meet crop N and Ca requirements, just the crop Mg demand, hardly the K demand and not the crop P demand. This suggests that the resource that is responsible for the positive overall interaction in an alley cropping system is nitrogen (positive value for T_N). The low organic C content indicates that available nitrogen in Yurimaguas may be absolutely low, but compared with available phosphorus and exchangeable bases it may be relatively abundant. L_N is then small compared with L_F, so that the negative net tree effect on phosphorus and bases outweighs the positive N effect. In other words, phosphorus and bases were so limiting that the crop could not respond to a positive N effect. In an environment where phosphorus and exchangeable bases are relatively less limiting (as in the P, K and Zn fertilised Lampung case), the reverse will be the case. The value of L_N here is high compared with L_F, so that the positive net tree effect on nitrogen availability outweighs the negative net tree effect on the availability of phosphorus and bases. The net tree effect on nitrogen availability (T_N) is thus probably positive. Agus et al. (1998) show maize and rice grain yields in contour hedgerow systems with and without N fertiliser. The overall interaction decreased with increasing nitrogen availability. These experiments thus confirm (Fig. 3) the positive value of T_N. The positive T_N will get more weight (higher L_N value) in N deficient soils, which is in agreement with results of Van Noordwijk (1996), who also predicted that opportunities for alley cropping increase, with decreasing N availability in the soil. Note that the positive T_N value explains the strongly negative overall interaction (−58%) in the Hyderabad experiment (Rao et al., 1991) which received nitrogen fertiliser. Because of the nitrogen fertiliser, the only positive net effect of the alleys got a small weight.

In the humid tropics, with overcast weather, the environmental weight for availability of radiation (L_R) may be greater than zero. The negative tree effect on the availability of radiation (T_R) can then be significantly important. It may (in combination with the negative effects on water and other nutrients) outweigh the positive N effect. In fact, the positive overall interaction of the Lampung case (Van Noordwijk et al., 1995) was obtained for only one single tree species (Peltophorum dasyrachis) which has a low shade/mulch ratio.

If land is sloping, the opportunities for water and soil conservation increase. The alley cropping technology may then fundamentally change (in positive direction) because T_w, T_N, and T_F might increase.

5. Experimentation

The equation of Ong (1995) separates the overall tree effect in positive (‘fertility’) and negative (‘competition’) effects. It suggests experimentation according to a 2^2 factorial design resulting in the four
mulch-transfer treatments as described and used by Sanchez (1995). The analysis in the former section did not make use of this separation, because the fertility and competition effects are only valid for a local situation and change in a different type of environment.

Eq. (3) separates the overall tree effect according to resource effects with an explicit role for the balance of available resources in the environment. It suggests other experiments. Comparing AF systems in different regions induces the problem that environmental effects may be confounded. This is solved by experimentation in which the researcher manipulates the environment so that environmental effects (i.e. resource availabilities) are independently changed. This can be done by using shade cloths and adding nitrogen and other inorganic fertilisers, in the AF system as well as in the sole crop in, for instance, a factorial design (Cochran and Cox, 1957). Repetition and randomisation will enable testing for significance of the change in the overall interaction responding to resource addition. If this experiment is repeated in another season (drier or wetter), the availability of water is changed which may give information about the sign of \( T_W \). A few of such experiments for well defined AF systems would lead quickly and economically to critical characteristics of the particular AF system (the signs of the \( T \)-coefficients).

If in those experiments nutrient uptakes of the sole crop and the crop in the AF system are measured, Eq. (3) can be quantified. Nutrient availability can be estimated by relating nutrient uptake to nutrient application, and extrapolation of the regression line until intersection with the horizontal at zero uptake (Dean, 1954; see also Kho, 2000). If this is done for the sole crop and for the crop in the AF system separately, the relative net tree effect on the nutrient in consideration (\( T \)-coefficient) can be calculated with Eq. (1).

6. Discussion and conclusions

A theory consisting of a general tree-environment-crop interaction equation (Section 2) and accessory methods (Section 3) has been developed. The theory helps to generate (Section 3.2) new hypotheses from existing data (the signs of the \( T \)-coefficients). These hypotheses are easily experimentally testable (Section 5). The generated hypotheses have direct practical value, because they give (Section 3.1) predictive understanding when extrapolating AF technologies to other environments.

The variation with the environment of the \( T \)-coefficients of particular AF technologies should be investigated further. If they vary, the rules and diagrams of Section 3 will most likely still be valid and even be strengthened, because the absolute values of the \( T \)-coefficients will then change in the same direction as the \( L \)-coefficients.

Analysis of some alley cropping experiments indicates that, in general, an alley cropping technology can be characterised by a positive value for \( T_N \) and negative values for \( T_R \), \( T_W \), and \( T_F \). Alley cropping is most likely to work in environments with a high environmental weight for the positive N effect, and low weights for the negative effects. This is the case on N deficient soils, but without major limitations of other nutrients and where rainfall is adequate during the cropping season. The analysis with Eq. (3), the two rules and the diagrams, leads thus to the same biophysical conclusion as that of Sanchez (1995), but with one big difference. Although Sanchez (1995) concludes that soils should be fertile without major nutrient limitations, this analysis indicates that soils should be fertile with the exception of nitrogen that should be deficient.

This analysis is not an extensive review, but merely an illustration of how the theory and methods can be used to explain crop response to tree effects in different environments. Experiments as described in Section 5 should give a confirmation. The analysis indicates that alley cropping is most likely to work on about 15% of the total land area of the tropics (see Kass, 1996; Sanchez, 1996). This suggests that alley cropping has on biophysical grounds still potential to increase crop yields and to generate social, economic and environmental benefits.

The analysis suggests that the net tree effect on the availability of nutrients other than nitrogen is in general negative (especially on that of phosphorus). In other words, subtraction outweighs addition of these nutrients in the crop rooted zone. So, the popular view that trees in alley cropping systems capture nutrients below the crop rooted zone, which results in a net benefit for the crop, should be rejected or be made more specific. However, the positive value for \( T_N \) implies that deep capture of nitrogen (the nutrient
which leaches most easily) resulting in a net benefit for the crop might still be possible, as well as might be N\textsubscript{2}-fixation. The work of Van Noordwijk et al. (1995) indicates that deep capture of nitrogen was indeed the case. The negative value for \textit{T}\textsubscript{w} implies that in general, competition for water outweigh water conservation effects in alley cropping systems.

Cannell et al. (1996) concluded that the best opportunities for complementarity exist if shortage of one particular resource is clearly limiting plant growth, but other resources are under-utilized and available. This was based on the notion that increased acquisition of the limiting resource will always be accompanied by increased use of the non-limiting resources. However, this implies that only one single resource can cause the yield benefit. This specific limiting resource must be found and acquired by the trees from a source that is not available to the crop. Eqs. (3) and (4) show that other resources found and acquired by the trees from sources not available to the crop can then not add to increased production. So, Cannell et al. (1996) propose a strategy aiming at increased acquirement of the single, very scarce resource with the great effect.

In environments where resources are more in balance, more resources may cause the yield benefit. Eq. (3) shows that if they are found, each of them will add to increased production proportional with the degree of limitation. The strategy here thus aims at increased acquirement of several, less scarce resources, each with a moderate effect.

Eqs. (3) and (4) show why AF technologies wherein trees have no direct value but only play a 'support' function may work in extensive systems in tropical regions and not in intensive systems in temperate regions. In these last environments radiation is the major limiting resource. Because \textit{T}\textsubscript{R} cannot be positive, but the other \textit{T}-coefficients can, opportunities for yield benefits by AF technologies exist on nutrient deficient soils with inadequate rainfall. The best opportunities are probably on nitrogen limiting soils (assuming that most AF technologies will have a positive \textit{T}\textsubscript{N}; i.e. increase the nitrogen availability to the crop; see Palm, 1995) and on sloping lands (high potential conservation benefits which may increase the \textit{T}-coefficients).

ICRAF (1997) reports that fresh leafy biomass (1.8 t dry weight ha\textsuperscript{-1}) of \textit{Tithonia diversifolia}, a common shrub in the field boundaries of eastern Africa, spread on the fields together with P fertilizer (either rock phosphate or triple superphosphate) may be a winning combination. The theory developed in this paper supports this indication, and suggests further that in general AF technologies with mineral phosphorus may be winning combinations. The \textit{T}-coefficient for phosphorus is most likely negative for alley cropping, but probably also for other (simultaneous) AF technologies. If phosphorus is limiting, its addition will according to Rule 1 neutralise the negative \textit{T}-coefficient for phosphorus and according to Rule 2 increase other tree effects. A positive nitrogen effect will thus be reinforced. According to the law of the optimum, the positive nitrogen effect will increase the use efficiency of phosphorus (compared with that for the sole crop). This will result in a positive interaction between the effects of AF technologies and phosphorus fertiliser. However, Eq. (3) indicates that this will be only the case under two conditions. Firstly, the environment should have a low \textit{L}\textsubscript{R} and/or the AF technology should have a \textit{T}\textsubscript{R} close to zero. Secondly, the environment should have a low \textit{L}\textsubscript{W} and/or the AF technology should have a positive \textit{T}\textsubscript{W}. Transfer of biomass implies a \textit{T}\textsubscript{R} of zero and because of the mulching effect a positive \textit{T}\textsubscript{W}, so that both conditions are fulfilled. The Lampung alley cropping case (Van Noordwijk et al., 1995) received phosphorus fertiliser. In this humid climate water was ample (i.e. low \textit{L}\textsubscript{W}) and a positive overall interaction was only found for \textit{Peltophorum dasyrachis} which has a dense canopy shape (i.e. a \textit{T}\textsubscript{R} close to zero). So, the two conditions were also fulfilled in this case. Because nitrogen and phosphorus are limiting in large parts of the tropics (which implies low values for \textit{L}\textsubscript{R} and \textit{L}\textsubscript{W}), the combination AF technology with mineral phosphorus is likely appropriate for large parts of the tropics.

Four other biophysical guidelines for design and development of AF technologies have been formulated earlier. Because they can be interpreted easily with the present developed theory they are given in the Appendix A.

Synthesis and extrapolation of experimental results, without considering the balance of available resources in the different environments, will lead to a large unexplained variation. This will be the case for all agricultural research, but certainly for an inherent multidisciplinary (‘holistic’) science as agroforestry. The paper has shown that in understanding AF systems, the balance of available resources in each specific environment is of crucial importance, because
it influences the crop’s response to tree effects on resource availability. The underestimation of its influence is probably a major cause of the disappointing results in the eighties when AF innovations were enthusiastically promoted in other areas.

Searching for the $T$-coefficients of AF technologies, testing their constancy and use of the presented methods may give predictive understanding.

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Appendix A. Biophysical guidelines for design and development of AF technologies

1. In nitrogen deficient soils, AF technologies with non-leguminous crops will perform better than AF technologies with leguminous crops. Nitrogen will be less limiting for leguminous crops because of $N_2$-fixation. These crops will probably have a lower $L_N$-coefficient. Assuming that most AF technologies have a positive net effect on the availability of nitrogen, this effect will count less for leguminous crops. However, the difference will become only manifest in nitrogen limiting soils, because if nitrogen is ample both $L_N$-coefficients will be zero.

2. In high potential environments (ample supply of water and nutrients) and in cloudy environments, simultaneous AF technologies with C4 crops will perform worse than simultaneous AF technologies with C3 crops. In these environments radiation is a limiting factor. At equal light intensity, C4 crops are later light saturated than C3 crops. The $L_R$-coefficient is thus higher for C4 crops. Consequently, the negative shading effect in simultaneous AF systems will count heavier for C4 crops than for C3 crops. However, the difference will become only manifest in light limiting environments, because if light is ample both $L_R$-coefficients will be zero.

3. Applied agroforestry research for improving a certain AF technology in a specific agro-ecosystem should be directed by the limiting resources of that agro-ecosystem. The quest to combinations of species that maximise resource use per unit land is based on the general truth that higher resource use leads to higher production. However, Eq. (3) makes clear that efforts to increase the capture of resources with low environmental weights will lead to disappointments.

4. When plant growth or crop yield are measured as a variable for evaluation, applied as well as process oriented research should be done in the real, on-farm environment. The on-station environment is probably different from the on-farm environment, having a different balance of available resources (i.e. $L$-coefficients) leading to a different balance of tree effects. The same applies to adding to all plots small doses of fertiliser (e.g. to encounter environmental variation). If farmers do not use fertiliser, extension of the results of such AF experiments may lead to disappointments.

References