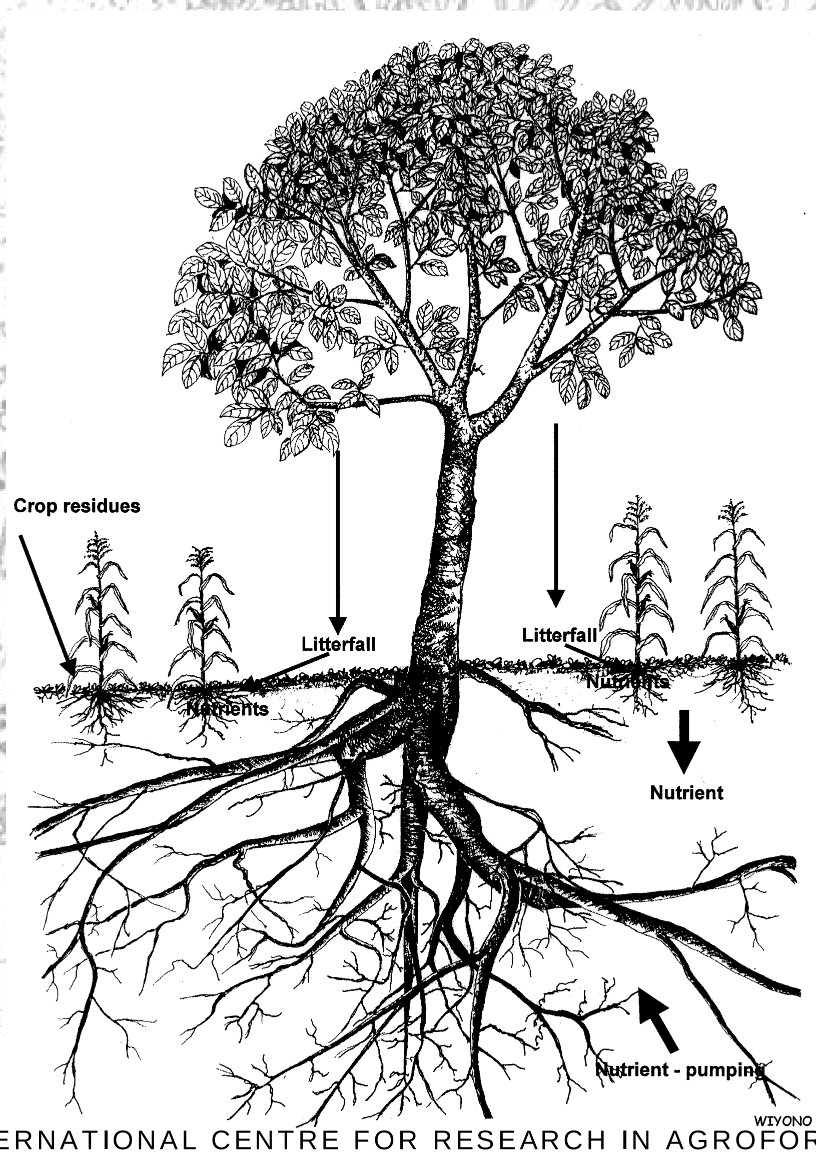
Lecture Note 2

Tree-Soil-Crop Interactions

Meine van Noordwijk and Kurniatun Hairiah



INTERNATIONAL CENTRE FOR RESEARCH IN AGROFORESTRY

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These lecture notes are mainly developed in support of the training-of-trainers course on *'Agroforestry for improved land use and livelihood systems in Southeast Asia'*, which took place in Chiang Mai from 8-20 March 1999, and its follow-up activities, both sponsored by the Netherlands' Government through DSO. However the materials are also meant to respond to the need for teaching materials formulated by universities and technical colleges in the region.

The development of these lecture notes was mainly supported by the Ministry of Foreign Affairs, the Netherlands Directorate General International Cooperation (DGIS) Cultural Cooperation, Education and Research Department Education and Developing Countries Division (DCO/OO). Other collaborators and donors were the University of Brawijaya (UNIBRAW) and the Flemish Office for Development Cooperation and Technical Assistance (VVOB). Their generous support is hereby acknowledged.

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April 2000

Bogor, Indonesia

Published in April 2000

Published by:
International Centre for Research in Agroforestry
Southeast Asian Regional Research Programme
PO Box 161, Bogor, Indonesia
Tel: +62 251 625415; fax: +62 251 625416; email: icraf-indonesia@cgiar.org
Web site: http://www.icraf.cgiar.org/sea

Cover illustration: Wiyono

Layout: T Atikah

Lecture note 2

TREE- SOIL- CROP INTERACTIONS

By Meine van Noordwijk and Kurniatun Hairiah

I. Objectives

- Discuss the various positive and negative tree-crop interactions illustrated with the example of a simultaneous agroforestry system
- Illustrate how these interactions can be quantified from a bio-physical point of view
- Demonstrate how these common principles can be applied in a wide array of situation-dependent agroforestry systems, rather than using blueprint models.

II. Lecture

5. 1. Background/General scheme

In agroforestry systems trees can share space and time (simultaneous systems), or crop and tree phases can be sequential (fallow systems). In simultaneous agroforestry systems, trees and food crops interact in many ways, leading to positive and negative impacts on the growth of both tree and crop (Figure 1).

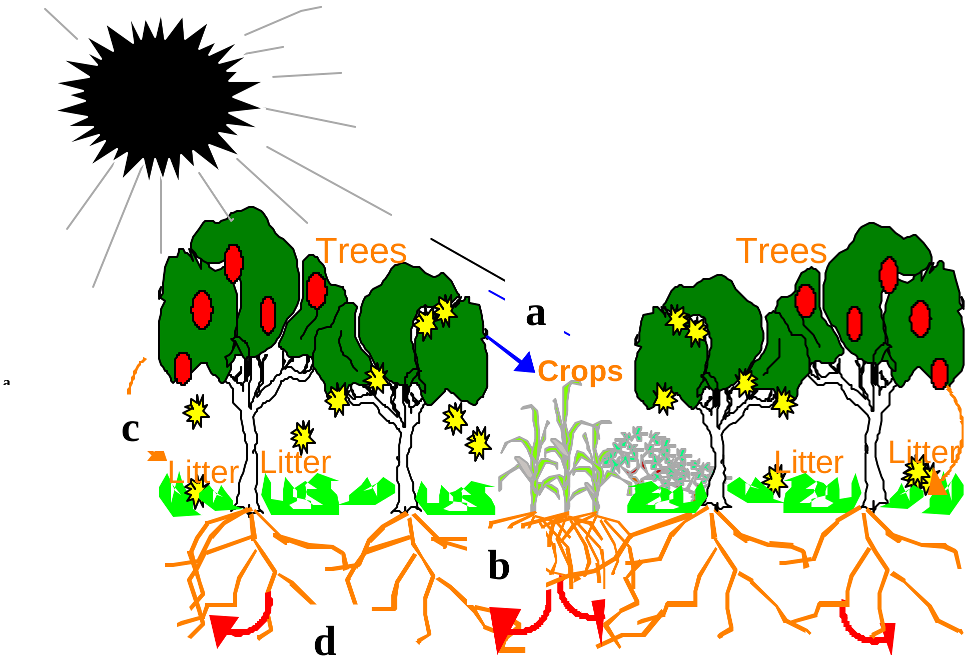


Figure 1. Interaction between trees and crops in a simultaneous agroforestry system. (a = shading; b= competition for water and nutrient; c = litter fall of trees increases C, N, P and other nutrients; d = deep rooted trees play a role as a 'safety-net' for leached nutrient in the deeper layer)

Discussion Question 1:

Consider three forms of simultaneous agroforestry systems relevant in your area:

- Can you recognise all interaction processes for all systems?
- Which interactions depend on climate, which on soil type and which on crop and tree type? What interactions can be influenced by management?
- What is the overall balance of positive and negative effects?

2. Tree-crop interactions

Interactions can be ***positive, neutral*** or ***negative***. Figure 2 shows schematically the relationships between two agroforestry components according to the type of interactions between them. When the interaction is ***positive***, there is complementarity between the components, while there is competition if interaction is ***negative***. This leads to subdivision of interactions as shown in Table 1. Existing agroforestry practices and technologies give examples of the different possibilities and are also shown in Table 1.

Fast growing plants need a lot of light, water and nutrients. The past focus on 'fast growing trees' for agroforestry has often underestimated competition effects.

Table 1. Analysis of interactions between two populations A and B (modified from Torquebiau, 1994). (0 : No significant interaction; + : Advantage for the population in question (growth, survival, reproduction etc.); - : disadvantage for the population in question)

Type of interaction	**Effect of the interaction on the population**		**Nature of the interaction**	**Agroforestry example**
	A	**B**		
Mutualism	+	+	Interaction favourable to the two populations	Mycorrhizae, Rhizobium - legume
Facilitation	+	0	Interaction favourable for A but not obligatory; B not affected	Windbreaks, shade trees Alley cropping (well managed)
Commensalism	+	0	Interaction obligatory for A; B not affected	Support trees for vines; Improved fallows
Neutralism	0	0	None of the populations affects the other in crop land	Scattered trees
Parasitism/predation	+	-	Interaction obligatory for A; B is inhibited	Pest and disease
Amensalism	-	0	A inhibited; B not affected	Allelopathy
Competition and interference	-	-	Each population is inhibited by the others use of (above- or below ground) growth resources	Alley cropping (poorly managed)

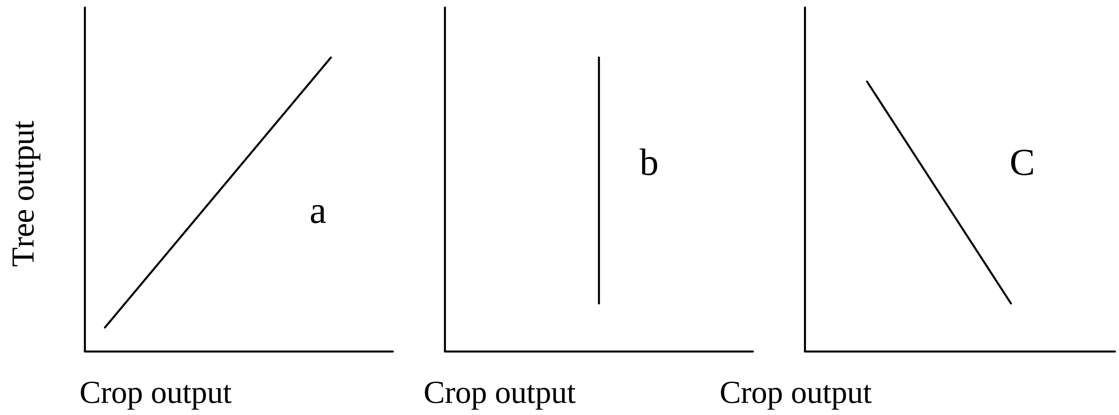


Figure 2. Complementary (a), supplementary (b), or competitive (c) interactions between agroforestry components (Torquebiau, 1994).

3. Tree-soil -crop interactions

A more elaborate list of **positive** and **negative** interactions:

Negative interaction (Interference)

a. ***Shading*** by the trees, reducing light intensity at the crop level
b. ***Root competition*** between tree and crop for water and/or nutrients in the topsoil. Hereby the tree root architecture is important. Shallow tree root systems are likely to compete more with the crop for scarce nutrients, while deep tree roots can act as a 'nutrient pump' or 'safety net' , where nutrients are so deep that they are out of reach for the crop roots
c. Trees and crops can be a ***host*** of each other's pests and diseases.

Positive interaction (Facilitation)

a. ***Nutrient recycling*** can be based on:
   - Nutrients taken up in the topsoil by tree roots in competition with crops,
   - Nutrients taken up while leaching down to a deeper layer with tree roots acting as a 'safety net'.
   - Nutrients taken up from weathered minerals in deeper layer, with deep tree roots acting as 'nutrient pump'.
b. **Litter** production. If litter is high quality (low C/N ratio, low lignin and polyphenolic content), it will decompose rapidly and make nutrients available to the crop and the trees.
c. **Mulch**: Litter of low quality (high C/N ratio, high lignin and polyphenolic content) decomposes slowly and is suitable as mulch. Mulch maintains soil moisture during the dry season. Especially on sandy soils, where water supply for the crops could be a problem, mulch is important.
d. ***Nitrogen supply*** by tree roots to crop roots, either due to root decay or root death following tree pruning or by direct transfer if nodulated roots are in close contact with crop roots,
e. Tree and crop effects ***reducing weeds*** (by shading in relevant parts of the year) and reducing dry-season fire risks.
f. Tree and crop effects ***reducing pest*** and disease pressure by facilitating biological control agents.

g. Tree effects on ***microclimate*** (reducing wind speed, increasing air humidity, providing partial shade)
h. Long term effects on reducing ***erosion***, maintaining soil organic matter content and soil structure.

4. How to quantify tree-crop interactions?

The success of any intercropping depends on the balance of ***positive*** and ***negative*** interactions between the components.

A simple equation is:

Equation 1:

$$Y_{system} = Y_{tree} + Y_{crop} = Y_{tree} + Y_{crop,0} + F - C$$

With Y_{system} = yield of tree + crop system
Y_{tree} = yield of tree products
Y_{crop} = yield of crop products
$Y_{crop,0}$ = crop yield in a monoculture on the same soil
F = Positive effects of trees on crop growth via soil fertility improvement
C = Negative effects via competition for light, water and nutrients.

The question whether or not agroforestry has any advantage over separate crop fields and woodlots, can now be rephrased as:

Positive interaction, if **F > C**

Negative interaction, if **F < C**

Question is now: How can we identify, analyse and synthesise those various tree-soil-crop interactions?

Research offers a way out. A three-step approach is presented in Table 2 (Van Noordwijk *et al.*, 1998). It links those overall terms to experimental treatments, process research and WaNuLCAS as a synthesis model.

Table 2. A direct experimental separation of the terms in the equation is combined with quantification of key processes and followed by model synthesis to explore management options and system-site matching.

Y_c =	Y_0 +	F_1 +	F_ω +	C_l +	C_{w+n} +	M
Crop yield in interaction	Crop yield in monoculture	Direct fertility effect	Long term fertility effect	Competition for light	Competition for water and nutrients	Micro-climate effects
1. Experimental method		Mulch transfer	Residual effect (tree removal vs. control)	Tree removal vs. control	Root barriers	
2. Process-level understanding		Litter quality, mineralisation rates	Functional soil organic matter fractions	Canopy shape, light profiles	Root architecture	
3. Synthesis model		W A N U L C A S				

It must be recognised that the relative importance of different terms of the equation depends on the agroforestry system, the environment and the management of the system. Simulation models are an important tool for predicting how these interactions depend on soil, climate, crop and tree architecture and physiology. These three steps are further explained in the next paragraphs on 'Process level understanding using experimental methods' and 'Synthesis model'.

5. Process level understanding using experimental methods

On-station field experiments are a way to test which processes are important under what conditions.

Discussion Question 2:

Looking at equation 1, how can the positive and negative interactions (processes) in the three agroforestry systems you discussed before be separated? Can you outline an experimental treatment, which allows you to measure F and or C separately?

How a scientist went about it, is explained in following case study.

Tree-crop interaction of a hedgerow intercropping system

An example of the approach in Table 1, tree-crop interactions was tested in a simple agroforestry system. It was a long-term (8 years) hedgerow intercropping experiment on an acid soil in North-Lampung, Sumatra, Indonesia with maize planted as a test crop.

Purpose of the experiment

- To quantify the effect of hedgerow trees on light interception
- To quantify root competition on water and nutrient uptake

- To quantify residual effects of hedgerow intercropping (after removing the hedgerow trees)
- To quantify the differences in interactions of six different common hedgerow tree species

Treatments:

Six tree species were planted as hedgerows in 1986: (a) *Peltophorum dasyrrachys*, (b) *Gliricidia sepium*, (c) alternating rows of *Peltophorum* and *Gliricidia*, (d) *Calliandra calothyrsus*, (e) *Leucaena leucocephala*, and (f) *Flemingia congesta*. The control treatment was 'planting no hedgerow trees'. Each plot in the control treatment was split into four subplots to test N-response:

- No fertiliser
- 45 kg ha^{-1}
- 90 kg ha^{-1}
- 135 kg ha^{-1}

How to set up experimental treatment to test tree-crop interactions?

From the above main treatment, following sub-treatments were set up to separate the positive and negative interactions between tree and crop.

Parameter	***Experimental treatment***
Shading	• Without canopy pruning • With canopy pruning
Competition of water and nutrient	• Without root barrier • With root barrier
Mulching	• Without mulch transfer • With mulch transfer
Long term residual effect	• Without tree removal • With removal of complete hedgerows
Total plot	8 sub plot per tree species

Results

This on-station trial showed that only the local tree *Peltophorum* gave a consistent beneficial effect on crop yields.

After 8 years the hedgerow trees were removed in part of the plots, and maize yields showed a strong positive response ('residual effect') based on soil fertility maintenance, relative to the continuously cropped control (Figure 3A). Maize yields (average of two seasons) in the plots that had grown *Calliandra* and *Leucaena* were significantly higher than those obtained with the highest N-fertiliser rate tested (135 kg ha^{-1}), showing a major below-ground residual effect of the N-fixing trees, which were just removed.

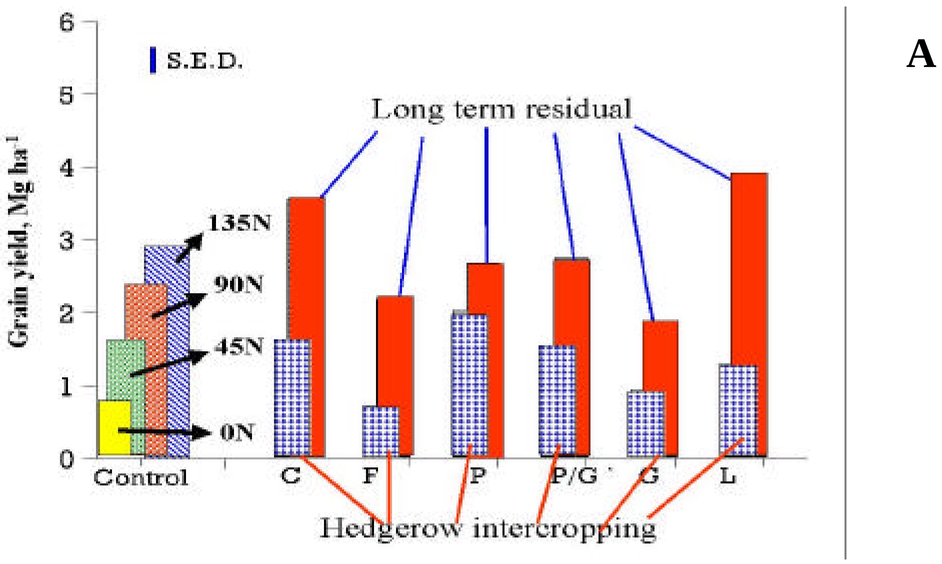
Under the normal hedgerow intercropping system, however, only *Peltophorum* gave maize yields higher than those obtained in the control plot with N-application of 90 kg ha^{-1}. The difference was largely due to aboveground interactions (shade), as the effects of fresh mulch application and below ground interaction (measured by the effects of root trenches) were small (Figure 3B). Further analyses on effects of soil fertility (*F*) and competition (*C*) on maize yield relative to control are summarised in Table 3. The relative success of the local tree ***Peltophorum*** in this experiment was not due to very pronounced positive effects (+58 %), but to **small negative** effects (-26 %). *Peltophorum* is less competitive than the others, partly because of a **deeper root system**, (which is why it was selected initially), but especially because of the **shape of its canopy** (concentrated near the tree trunk), which gives it a high mulch-to-shade ratio.

Table 3. Analyses of tree-crop interaction based on effects of soil fertility (*F*) and competition (*C*) on maize yield.

Species	Fertility effect, %	Competition effect, (%)	Interaction, %
Leucaena	152	-159	-7
Calliandra	120	-115	+5
Peltophorum	58	-26	+32
Flemingia	37	-89	-52
Gliricidia	19	-60	-41

A second adjacent experiment also contained mulch transfer treatments. Both single (90% of total pruning biomass was about 9 Mg ha^{-1}) and double mulch rates (18 Mg ha^{-1}) in the second season (which was much drier than normal) produced positive effects, clearly outyielding the N-response curve (Figure 4). The highest N-rate gave even a negative response to maize yield. As all treatments received a moderate basal P fertiliser dressing (since low P availability was the main limiting factor of crop growth), the mulch effect was largely attributed to positive effects of improved water status as a result of reduced evaporation from the soil. The double level (18 Mg ha^{-1}) of mulch application did not improve the grain yield of maize at normal level (9 Mg ha^{-1}). This information is very useful for low input agriculture systems, where the availability of organic matter in the field has become a bottleneck.

Overall the experiment shows the considerable positive soil fertility effects that can be obtained with tree mulches on these acid soils, but it also points at the strong competition that occurs in hedgerow intercropping.



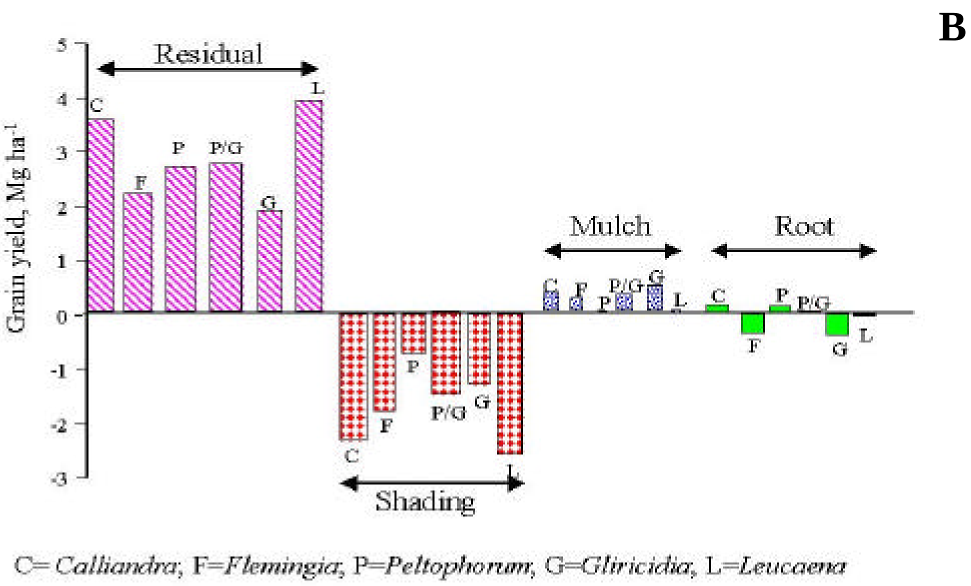


Figure 3. The positive and negative effects of tree hedgerow species in hedgerow intercropping systems based on two season measurements: Response of maize on a long term residual effect (A) and interaction of hedgerow trees and crops (B). (s.e.d. = Standard error deviation)

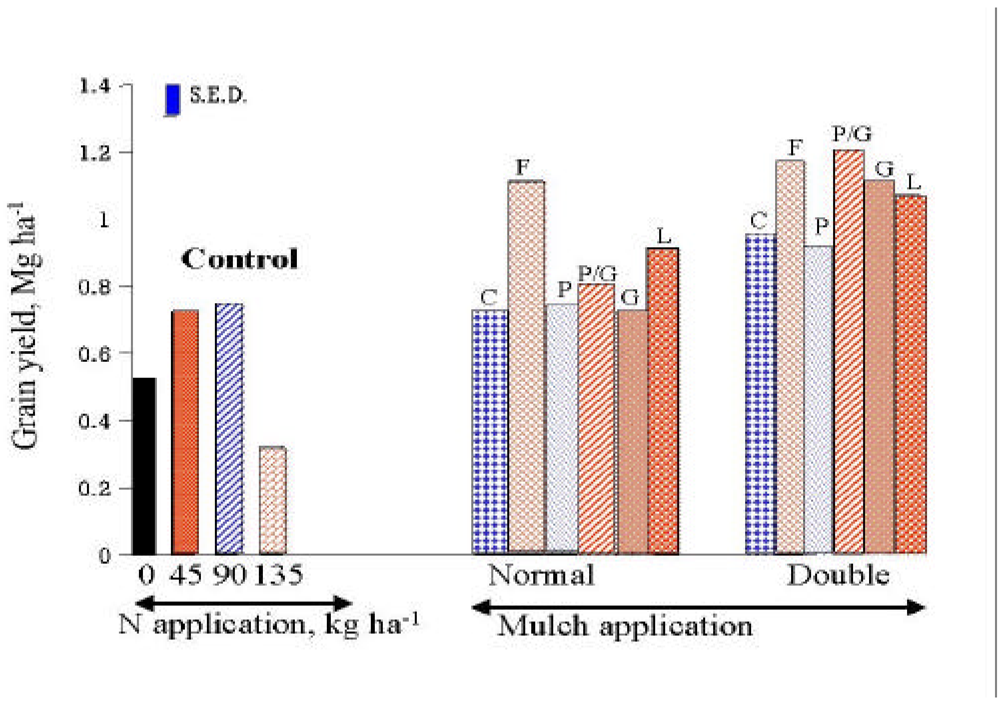


Figure 4. Maize response to mulch transfer in the second cropping season (dry season). Control refers to sole-crop response to Nitrogen fertiliser. (s.e.d. = Standard error deviation)

6. Synthesis model

Mulch + shade model

Fast growing trees produce a lot of mulch material, but also cast a lot of shade. Van Noordwijk (1996a) presented explicit algebraic solutions for an agroforestry model, which links both the *mulch production* and its ensuing soil fertility effect and the *shading* which is assumed to have a negative effect on crop yields to the biomass production of the tree. The model leads to a simple mulch/shade ratio as a basis for comparing tree species. The model also predicts that at low soil fertility, where the soil fertility improvement due to mulch can be pronounced, there is more chance that an agroforestry system improves crop yields than at higher fertility where the negative effects of shading will dominate.

The mulch/shade model, however, does not incorporate the dynamic interactions between *water availability, N dynamics, and crop and tree growth*. Incorporating these elements on the basis of a daily time step extends the model beyond what can be solved explicitly. It leads into the realm of dynamic simulation models, which keep track of resource stocks outside and inside the plants and use these to calculate daily resource flows and daily resource capture.

WaNulCas (Water Nutrient Light Capture) model.

The WaNuLCAS simulation model provides a synthesis of current understanding of the processes in ***water, nutrient*** and ***light capture*** in a range of agroforestry systems, as influenced by soil properties and climate. Agroforestry models have to include a two-plant interaction as illustrated in Figure 4, similar to intercropping and crop-weed models, but differ as one of the plants is a perennial species. The model makes use of the **STELLA II (r)**-modelling environment and represents a 4-layer soil profile with water and N balance. Water and nutrient uptake by crop and a tree is based on their root length densities and current demand. The model allows for the evaluation of different pruning regimes, hedgerow spacing, choice of species or provenance and fertiliser application rates. It includes various tree characteristics such as root distribution, canopy shape, litter quality, maximum growth rate and speed of recovery after pruning. The model also can be used for both simultaneous and sequential agroforestry systems and may help researchers understand the continuum of options from improved fallow relay planting of tree fallows to rotational and simultaneous forms of hedgerow intercropping. Details can be found on **http://www.icraf.cgiar.org/sea**

The tree-soil-crop interaction equation can be further analysed by:

- differentiating between ***short*** and ***long*** term fertility effects (F_1 and F_ω, respectively)
- separating the competition term in an ***above***- and a ***below ground*** component (C_l and C_{n+w}, respectively)

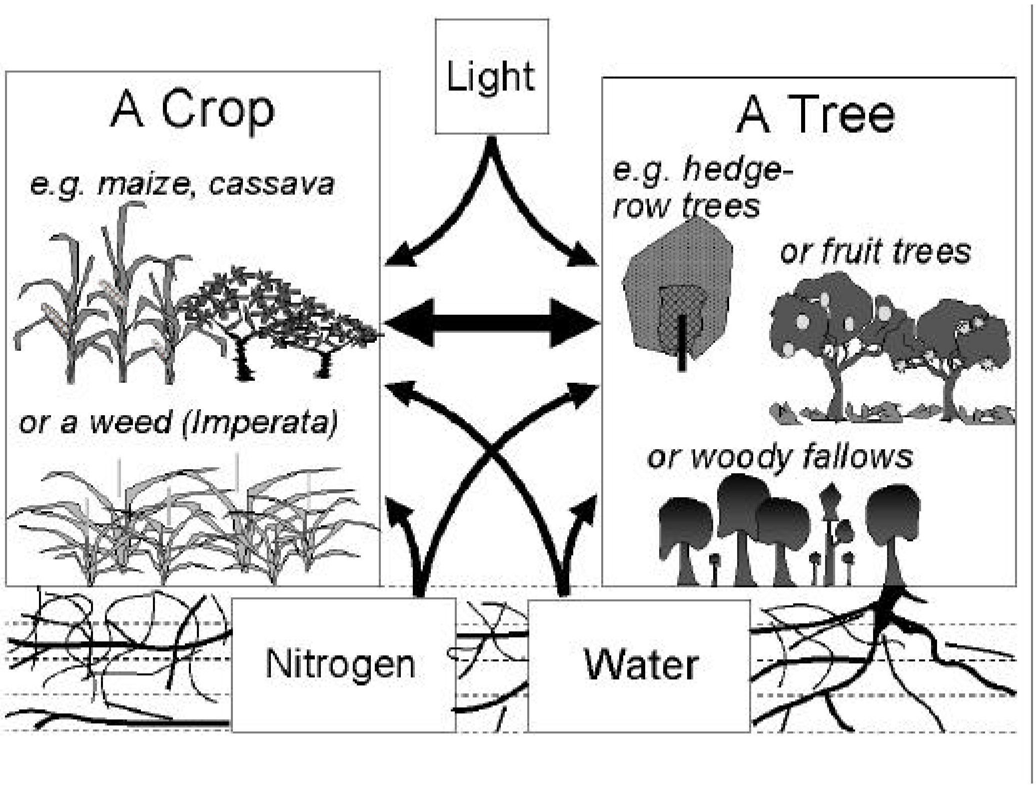


Figure 4. Components of the WaNuLCAS model

The total balance for below ground resources (water or nutrients) inputs into an agroforestry system is formulated in equation 2:

Equation 2

$$\Delta Stored = Input + \mathrm{Re}\,cycle - Upt_{crop} - Upt_{tree,comp} - Upt_{tree,noncomp} - Loss$$

The terms used in the above equation are presented in Table 2, where the term $Upt_{tree,noncompetitive}$ represents the 'safety net' function of tree roots for nutrients and water leaching and percolating below the zone of crop roots and/or outside of the crop growing season, as well as a nutrient pump role for resources stored in the subsoil for longer periods of time (Young, 1997).

Table 4. Representation of resource capture (equation 1) in a simple tree-crop agroforestry system. The crop roots are confined to the 'topsoil' and the tree roots explore the 'subsoil' as well; the subscripts 1, 2 and 3 refer to crop zones with increasing distance to the tree

Term in eq. 2	Water	Nitrogen	Light
Input	Rainfall, irrigation run-on-runoff	Fertiliser & organic import	Sum of daily radiation
Recycle	Hydraulic lift into crop root zone	Litterfall, tree pruning, crop residues	-
$Uptake_{Crop}$	ΣW_Uptakecrop	N_fix(Crop) + ΣN_Uptakecrop	ΣLightcap_crop
$Uptake_{Tree,Competitive}$	Σ_{top}W_Uptaketree	Σ_{top}N_Uptaketree	ΣLightcap_tree$_{1,2}$
$Uptake_{Tree,Noncomp}$	Σ_{sub}W_Uptaketree	N_fix(Tree) + Σ_{sub}N_Uptaketree	Lightcap_tree$_{3}$
Losses	ΣPercolation from lowest zone	ΣLeaching from lowest zone	1 - ΣLightcap
Δstorage	ΔWater content	Δ(Nmin & SOM)	-

7. Management options

To what extent can these research results now be translated into management recommendations? That is what ultimately matters for the farmer!

a. Fast growing trees usually have a broad distributed canopy; **pruning** can reduce the aboveground competition (shading!), but this is labour-intensive
b. **Frequency and height of** aboveground **pruning** affect depth distribution of tree root systems. More frequent and low level tree pruning stimulate superficial tree roots, increasing competition for water and nutrients.
c. **Fallowing** the land can be beneficial where residual effects of the trees benefit the crops in subsequent years.
d. **Choice of tree species** is crucial with regard to shading effects, root competition or production of useful products for the farmer. As trees generally have a long lifetime, a good choice is a far-reaching decision, which has effects on the longer term.
e. **Mulching** crops with prunings from the trees are a possible way to improve soil fertility. Decomposition of organic residues have a direct effect on crop growth, by mineralisation of N and other nutrients, and an indirect one, by build-up soil organic residues which may increase future efficiency of nutrient use. Rapidly decomposing organic residues of low C/N ratio contributes mainly by N-mineralisation and slowly decomposing organic residues contribute especially to build up of the soil organic matter pool. Slowly decomposed organic residues are also suitable for mulching. What quality criteria of organic residues were used? Organic residues have a low quality if they have a C/N ratio >25, a lignin content >20 % and a polyphenolic content >2%, usually found in thick and shiny leafs and woody biomass.

Summary

Agroforestry systems are only beneficiary - from a biophysical point of view -, if there is at least some complementarity in resource capture. Direct empirical approaches to quantify complementarity are possible for aboveground processes, but are more complex below ground.

Resources that are stored over a longer period of time make it more difficult to judge whether or not resources could have been used outside an agroforestry context. Models of tree-soil-crop interactions have to pay specific attention to the depth from which each component is capturing water and nutrients on a daily basis, in order to derive overall complementarity on a seasonal basis.

III. Reading Materials

Book chapters

Akyeampong E, Duguma B, Heineman AM, Kamara CS, Kiepe P, Kwesiga F, Ong CK, Otieno HJ, Rao MR, 1995. A synthesis of ICRAF's research on alley cropping. *In*: Alley farming research and development. AFNETA, Ibadan, Nigeria. p 40-51.

van Noordwijk M, Hairiah K, Lusiana B, Cadisch G. 1998. Tree-soil-crop interactions in sequential and simultaneous agroforestry systems. *In*: Bergstrom L, Kirchmann H, eds. Carbon and nutrient dynamics in natural and agricultural tropical ecosystems. CAB International, Wallingford, UK. p 173-191.

Textbook

Huxley P, 1999. Tropical Agroforestry. Blackwell Science, UK. p 370

Ong CK, Huxley P, 1996. Tree-crop interactions – A physiological approach. CAB International, Wallingford, UK. p 386

Vandermeer JH. 1989. The ecology of intercropping. Cambridge Univ. Press. Cambridge, UK.

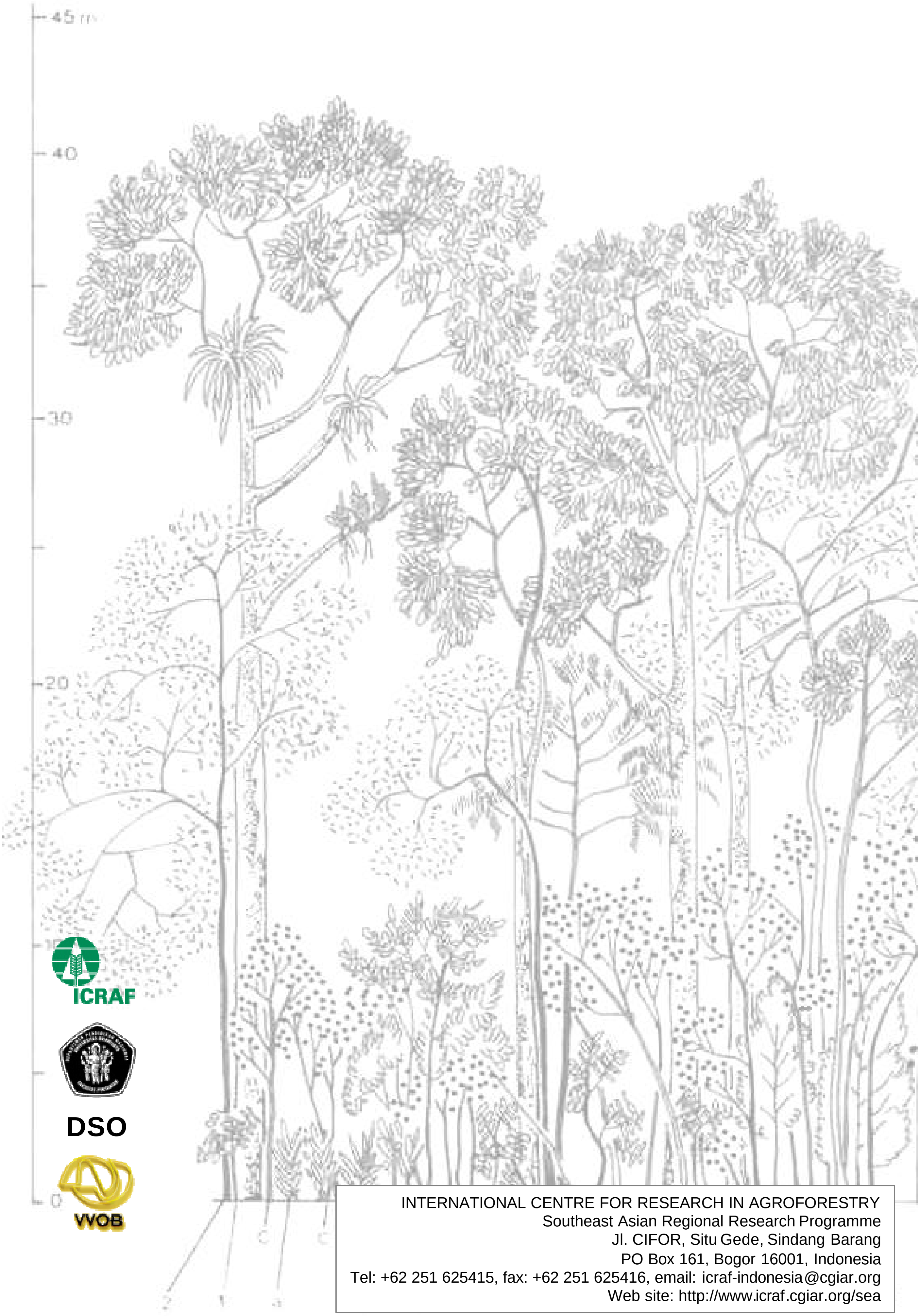
Training materials

Torquebiau E. 1994. Ecological interactions in agroforestry. Personal communication.

van Noordwijk M, Lusiana B. 2000. WANULCAS 2.0. Background on a model of water, nutrient and light capture in agroforestry systems. ICRAF SE. Asia, Bogor.

Web site

http://www.icraf.cgiar.org/sea



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