1 A Framework for Quantifying the Various Effects of Tree–Crop Interactions

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Introduction

> Agroforestry systems will be able to mimic or replicate many of the nutrient-cycling and favourable environmental influences found with forest ecosystems, while generating the exportable outputs achieved with agricultural systems.
>
> (Kidd and Pimentel, 1992)

Early assessments of the potential benefits of agroforestry at the farm level were based largely on the assumption that it is possible to extrapolate from existing information on forestry and agriculture (Huxley, 1983; Nair, 1993), and partly on observations of traditional agroforestry systems that showed increased growth of understorey vegetation (Ong and Leakey 1999; Kho *et al.*, 2001). Various negative effects have also been recognized, such as competition for moisture, excessive shading and allelopathy, although these have attracted much less attention from scientists. Most of the evidence of benefits and drawbacks of agroforestry continues to be qualitative or indirect, i.e. extrapolated from a wide range of systems, creating often unrealistic expectations of the benefits of agroforestry technologies (Garcia-Barrios and Ong, 2004). Fortunately, the volume of agroforestry research has grown rapidly since 1983, as various international and national institutes have become involved in both tropical and temperate regions (Sanchez, 1995; Rao *et al.*, 1998). With many field experiments in progress, the growing volume of evidence necessary to establish a scientific basis for the *quantitative* analysis of the various interactions that occur when trees and crops are grown together in a range of climatic and geographical regions is rapidly becoming available.

The past decade has experienced weather patterns and global temperatures outside the normal range, and the likelihood of climate change is now broadly accepted (Boko *et al.*, 2007). Large percentages of human populations in developing countries derive their livelihoods from agriculture and are particularly vulnerable to climate change. For example, the Intergovernmental Panel on Climate Change has presented evidence that climate is modifying the natural ecosystems and Chagga homegardens on Mount Kilimanjaro through complex interactions and feedbacks (Hemp, 2006; Boko *et al.*, 2007; see cover photograph). The traditional Chagga homegardens maintain a high biodiversity with over 500 vascular plant species and over 400 non-cultivated plants, and are typical of

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the multi-layered agroforestry systems throughout the humid tropics of South-east Asia, Africa and Latin America (Fig. 1.1). During the past few decades, many of these homegardens have been abandoned by smallholders, who have focused instead on growing new coffee varieties that are sun tolerant and do not require the shade provided by the traditional system. However, recent studies in Uganda show that intercropping banana and coffee is highly profitable for smallholders and can even enable them to cope with the effects of climate change (van Asten *et al.*, 2011). To feed everyone adequately, the world food supply will need to double over the next 30 years (Cleaver and Schreiber,

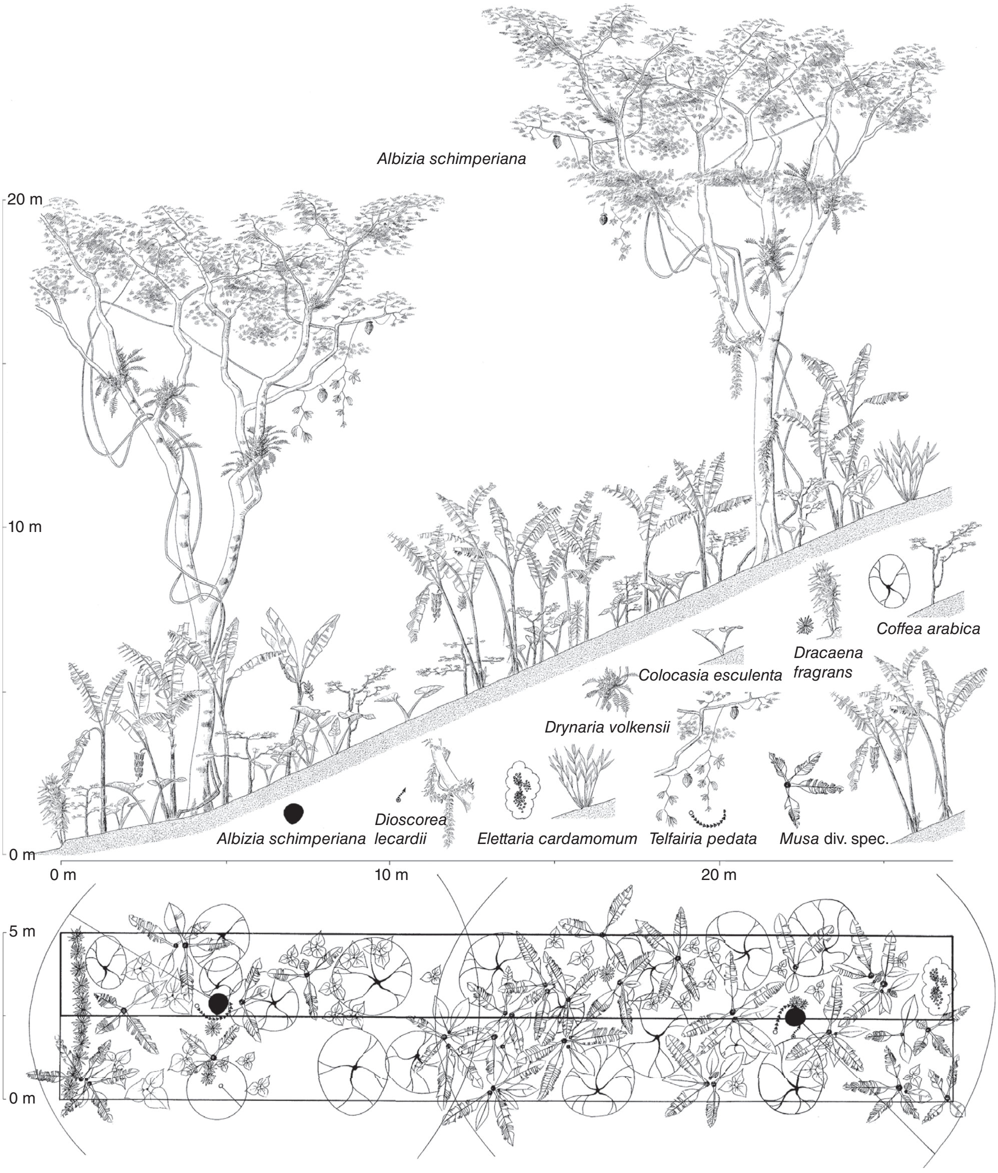


Fig. 1.1. Profile and ground plan of a typical Chagga homegarden at Old Moshi, Kilimanjaro, Tanzania. (Figure courtesy of Andreas Hemp, Institute of Plant Physiology, University of Bayreuth, Germany.)

1994). In many countries, there will be limited ability for new varieties and increased fertilizer use to increase yields (Huang *et al.*, 2002). Climate change will add additional stress to an already overtaxed system. For example, it is predicted that climate change will reduce the length of the growing season of rice (Aggrawal and Mall, 2002) and affect the incidence of pests and diseases, whose incidence is often still poorly understood. Agroforestry options may provide a means of diversifying production systems and increasing the resilience of smallholder farming systems to climate extremes (Lin, 2011; de Leeuw *et al.*, 2014). However, research into the contribution that agroforestry may be able to make in buffering against climate change and variability is not well advanced (Verchot *et al.*, 2007). Work on alternatives to slash-and-burn agriculture in the humid tropics has provided solid evidence of the potential of agroforestry systems in Sumatra and Cameroon (Gockowski *et al.*, 2001; Palm *et al.*, 2004). These systems can be promoted through the Clean Development Mechanism (CDM) to create synergies between mitigation and adaptation and to meet the requirements that CDM projects produce social as well as environmental benefits at the global level. Four new chapters in this second edition of this book explore how agroforestry systems may buffer against climate change by modifying microclimatic conditions (Chapter 5), mitigation of the impact of temperature extremes on important crops such as coffee and rice (Chapter 10), the beneficial effects of scattered trees in parklands (Chapter 11) and finally a synthesis of the prospects for crops for the future (Chapter 12).

A scientific framework for quantitative analysis of tree–crop interactions is needed for several reasons. First, it should provide reliable methodology to determine which benefits are likely to be realized for a given agroforestry technology in a defined situation. Secondly, it should enable researchers to evaluate the relative importance of each interaction in order to guide them more precisely in the choice of research priorities. This is no trivial matter, as agroforestry research requires long-term commitment of research resources, and it is not easy to separate the complex interacting factors involved (Anderson and Sinclair; 1993; Rao *et al.*, 1998; Garcia-Barrios and Ong, 2004). Thirdly, the advantages of agroforestry cannot be quantified simply in terms of productivity alone, because some of the benefits result from environmental improvements such as erosion control and increased soil organic matter content; these cannot be measured within only a few seasons. Finally, a quantitative approach is an important step in the quest for a fuller understanding of the complex mechanisms of tree–crop interactions, which should offer the scientific basis for designing yet more productive and sustainable agroforestry systems.

This chapter briefly describes the individual effects of tree–crop interactions and suggests how these may be quantified. Subsequent chapters examine how tree–crop interactions can be explained in terms of competition principles (Chapter 2) and a simple model of shading and water balance (Chapter 3). Later chapters explore the physiological and physical mechanisms involved in each interaction in detail.

Main Types of Tree–Crop Interactions

Before considering methods for quantifying the overall effects of tree–crop interactions, it is useful to list the biophysical benefits and consequences that are commonly attributed to agroforestry systems to determine whether the evidence for each interaction is based on direct or indirect observations. The relative importance of each effect will depend on both the type of agroforestry system and the location of the site. For example, the effects of any soil fertility enrichment by agroforestry will be less obvious if fertilizer input is high. For the purpose of this chapter, it is premature to include effects that have not yet been substantiated by field observations. For example, there is no quantitative experimental evidence concerning the effectiveness of agroforestry in controlling weeds or maintaining sustainability (Table 1.1), although there are good theoretical reasons to expect such benefits. Another unresolved issue

Table 1.1. Main effects of tree–crop interactions. + and **–** denote positive and negative effects; 0 indicates that no evidence is available. Key sources are cited.

	Evidence		
Effect	Direct	Indirect	Reference(s)
1. Increased productivity	+	+	Rao *et al*. (1998)
2. Improved soil fertility	+	+	Akinnifesi *et al*. (2007)
3. Nutrient cycling	+	+	Sileshi *et al*. (2008)
4. Soil conservation	+	+	Young (1997)
5. Improved microclimate	+	+	Brenner (1996)
6. Competition	–	–	Rao *et al*. (1998)
7. Allelopathy	0	–	Tian and Kang (1994)
8. Weed control	0	+	Sileshi and Mafongoya (2006)
9. Sustainability	0	+	Sanchez (1987); Young (1997)
10. Pests and diseases	0	–	Zhao (1991); Bos *et al*. (2007)

is the potential importance of allelopathy, which has been reported repeatedly for some tree species under laboratory conditions but is doubtful in field conditions for various reasons (see the critical review by Horsley, 1991).

There is ample evidence that overall biomass production in agroforestry systems is generally greater than in annual cropping systems, although not necessarily greater than in forestry or grassland systems. The basis for the potentially higher productivity may be due to increased capture of growth resources such as light, water and nutrients (Chapter 4, this volume), or improved soil fertility. Competition, a negative influence in this context, is often a significant factor in simultaneous agroforestry systems, even when there is evidence that the combined productivity by both components is increased. It is fair to conclude that only the top six effects shown in Table 1.1 have been substantiated by field observations. Certainly, there remains an urgent need for research to acquire more 'hard evidence' before the formidable task of translating the 'promise' of agroforestry into sustainable land use can be attempted.

Soil fertility improvements

Many of the frequently quoted examples of improvements in soil fertility are based on traditional agroforestry systems that have been established for many years. The potential for microsite enrichment by some trees is an extremely important aspect of agroforestry that has received considerable attention (Nair, 1984; Young, 1997). Surprisingly, most of these examples are based on widely scattered, slow-growing trees such as *Faidherbia albida* in arid or semi-arid environments in West Africa (Felker, 1978), *Prosopis cineraria* in Rajasthan, India (Singh and Lal, 1969) and *Pinus caribaea* in the savannah of Belize (Kellman, 1979). These authors concluded that accumulation of mineral nutrients is the result of a long-term process of capture of precipitation or nutrient-rich litter. This argument implies that the ability of trees to contribute directly to fertility enhancement is likely to be small at first as they are initially slow growing. Studies of recently planted (5–10 years old) *F. albida* stands in India and Africa confirm that microsite enrichment is a slow process.

In contrast to the slow enrichment of soil fertility in traditional agroforestry systems, alley cropping (also known as hedgerow intercropping or avenue cropping) using fast-growing, nitrogen-fixing trees such as *Leucaena leucocephala* and *Gliricidia sepium* in the humid tropics can significantly increase soil fertility within 2–3 years (Kang *et al.*, 1990). A major feature of the alley-cropping concept is the capacity of trees to produce large quantities of biomass for green manure and the need for regular pruning to prevent shading to reduce competition with associated crops. Alley cropping has been shown to be successful in relatively fertile soils, but attempts to extend this technology to infertile acidic soils of the humid tropics (Szott *et al.*, 1991; Matthews *et al.*, 1992) or the semi-arid tropics (Singh *et al.*, 1989; Rao *et al.*, 1998) have been disappointing. The main constraints are poor tree growth, aluminium toxicity, low nutrient reserves and excessive competition with crops (Kang, 1993). Considerable progress has been made in selecting acid-tolerant fast-growing tree species such as *Senna reticulata*, *Senna spectabilis*, *Inga edulis* and *Calliandra calothyrsus*, but economically viable techniques for reducing tree–crop competition are still lacking. So far, it appears that alley cropping was not sustainable on acidic, infertile soils without the addition of chemical fertilizers, chiefly due to the inherent soil infertility and insufficient recycling of nutrients from prunings, when carried out at Yurimaguas in Peru, Northern Zambia and Claveria in the Philippines (Maclean *et al.*, 1992; Matthews *et al.*, 1992; Szott and Kass, 1993, Sanchez, 1995).

Soil conservation

Contour hedgerows have consistently been shown to be highly effective in controlling soil erosion even within periods as short as 18 months (Lal, 1989; Maclean *et al.*, 1992). Woody hedgerows provide a semi-permeable barrier to surface movement of water, while mulch from the trees reduces the impact of raindrops on the soil and minimizes splash and sheet erosion (Young, 1997). Mulching also provides an effective means of reducing soil evaporation and other improvements in microclimate, although these effects are seldom measured in agroforestry systems. Current emphasis is on selection of tree species that provide effective physical barriers to erosion and produce mulch that offers a longer-lasting protective role (Kiepe and Rao, 1994). Relatively little information is available on the influence of trees on the physical properties of soils in terms of infiltration rate or bulk density and soil water storage capacity (Siriri *et al.*, 2006, 2012).

Microclimate improvements

The use of trees as shelterbelts in areas experiencing high winds or sand movement is a well-established example of microclimate improvement that enhances crop yields (Reifsnyder and Darnhofer, 1989). Of course, where environmental conditions are already favourable for crop growth, there is little advantage in reducing wind speed (Lott *et al.*, 2009) or moderating air temperature (Monteith *et al.*, 1991). Even when there is a clear advantage in reducing wind speed to protect young seedlings, negative effects may be induced due to competition for moisture between the roots of trees and crops during dry periods (Malik and Sharma, 1990). The greatest benefit of shelterbelts is observed when soil water supply is not limiting, especially where irrigation is possible (Brenner, 1996).

The evidence for the beneficial effects of shade trees depends on the nature of the understorey crops. The clearest effect is reported for crops that require shading for optimal growth, such as black pepper, turmeric and cacao (Nair, 1984). Analysis of *Paulownia* and tea-based agroforestry systems in subtropical China suggests that tea production improved slightly when shading was around 37%, but the overall economic benefit was largely due to the production of additional timber from *Paulownia* (Yu *et al.*, 1991). Details of shelterbelt effects on microclimate and crop responses have been described by Brenner (1996) (see also Chapter 5, this volume).

Competition

Although competition between trees and crops for the same limiting growth resources is most obvious when they are grown in close proximity, the extent of below-ground competition is often not apparent (Singh *et al.*, 1989). Assessment of the extent of competition is thus complicated by possible interference between neighbouring plots due to proliferation of tree roots into adjacent plots or the effect of shading, especially with tall trees (Huxley *et al.*, 1989; Rao *et al.*, 1998; Siriri *et al.*, 2012). Another complication is the choice of an appropriate control for both tree and crop species to provide a reliable basis to assess the impact of competition on crop yield (Ong, 1991). For example, many studies of alley cropping have used the yield of the alley crop where mulch is removed as the sole crop 'control'. This is clearly erroneous as the crop will still be influenced by the adjacent hedgerows (Gichuru and Kang, 1989). More rigorous experimental design and precautions are necessary to ensure that assessment of competition is free from interference by other treatments. These aspects are considered below.

A simple but effective method to determine competition is to measure tree and crop yields along transects across the tree–crop interface (Huxley, 1985). The use of transects is particularly useful in on-farm situations as it is difficult to obtain sole crop controls in scattered tree systems. However, to understand the mechanistic origin of competition, it is necessary to determine the soil and aerial environment within the transect. For example, studies of two tree species (*Vitellaria paradoxa*, *Parkia biglobosa*) scattered among three annual crops (cotton, sorghum and pearl millet) in south Mali, West Africa, showed that sorghum and pearl millet exhibited 50–60% yield reductions under the trees, despite a significant increase in soil fertility (Kater *et al.*, 1992). However, cotton yield was relatively unaffected by *V. paradoxa* (–8%) and *P. biglobosa* (–16%). Kater *et al.* (1992) concluded that the yield reduction resulted from plant mortality caused by fungal attack or shading, in agreement with Kessler (1992).

Quantifying Tree–Crop Yield Performance

Before quantifying the effects of tree–crop interactions, an appropriate measure is needed, which depends on the goal of the land-use system involved. For farmers, the primary goal is on short-term crop production, with more intangible goals such as food security and sustainability setting boundary conditions. Subsequent sections in this chapter and other chapters focus on the production aspect of tree–crop interactions.

When the products of each component species in mixed agroecosystems are equally important to farmers, either financially or in terms of biomass production, the land equivalent ratio (LER) provides a widely accepted index for evaluating the effectiveness of mixed cropping (Willey, 1979; Vandermeer, 1989). LER is the ratio of the area needed under sole cropping to the area under intercropping, at the same management level, that is required to provide an equivalent yield. It is the sum of the fractions of yields of the intercrops relative to their sole crop yields:

$$\text{LER} = \frac{X_\text{i}}{X_\text{s}} + \frac{Y_\text{i}}{Y_\text{s}} \qquad (1.1)$$

where X and Y are the yields of the component crops in either an intercrop (i) or a sole crop (s) system. When LER = 1, there is no advantage of intercropping over sole cropping, but when LER is >1, production in the intercrop is higher than in separate sole crops. The stand density in the sole crop influences the outcome, and the implicit assumption that the stand density in the sole crop is at its optimum is usually made.

In agroforestry systems, the yield of annual crops is generally more important to farmers than the yield of tree products as the trees usually have only a supportive function for associated crops, with possible tree products being regarded as extra benefits. The yield of sole trees is not known, and neither is productivity at the optimum tree density. In such cases, the production performance is better expressed by I, the difference in crop yield resulting from the presence of trees relative to the yield of the sole crop:

$$I = \frac{Y_\text{AF} - Y_\text{s}}{Y_\text{s}} \qquad (1.2)$$

where Y_AF and Y_s represent crop yields in the agroforestry system and sole crop, respectively. The minimum value of I is –1 (i.e. the trees suppress the crop completely and crop yields in the agroforestry system are zero) but when I is >0, the agroforestry system is more advantageous than the sole crop. In Eqn 1.2, I is defined as a fraction. If it is to be expressed as a percentage, it must be multiplied by 100.

Tree–crop interaction models

Models represent an idealized, simplified representation of reality. All models are, by definition, wrong, but some may be useful (Box and Draper, 1987), particularly where they provide predictive power with extensive scope and minimal complexity. Such models provide insight and direction to help understand and manage agroecosystems worldwide.

Concerning tree–crop interaction models, ‘scope’ first refers to the applicability of models to contrasting global agroecological zones. The corresponding goal is to understand and predict yield performance over a wide range of biophysical situations. Secondly, mostly within a specific agroecological zone, scope can refer to different management and technology options (e.g. the exact arrangement and placement of trees and crops). The corresponding goal is to optimize specific agroforestry technologies. Thirdly, scope may refer not only to yield performance but also to the growth processes leading to defined yields (i.e. dynamic models including a time dimension). The corresponding goal is to understand and optimize the underlying processes. Of course, increased complexity is needed with increased scope, but the art is to avoid excess model parameters that decrease predictive power and so reduce outputs to merely descriptive information. The ‘big picture’ must also be kept in mind to avoid becoming lost in detailed modelling subprocesses that contribute little to model performance and output.

Three approaches to tree–crop interaction models can be distinguished: (i) separating positive and negative effects; (ii) the resource balance approach; and (iii) modelling resource capture.

Separating positive and negative effects

Four decades ago, agroforestry was promoted with great enthusiasm but often led to disappointment. Apparently, besides the positive effects, there were definitely also negative effects of the trees on crop growth. This was formalized by Ong (1995) as:

$$I = F + C \qquad (1.3)$$

where I is the overall interaction, i.e. the percentage net increase in crop production attributable to the presence of trees; F is the fertility effect, i.e. the percentage production increase attributable to favourable effects of the trees on soil fertility and microclimate; and C is the competition effect, i.e. the percentage decrease in production attributable to competition by the trees for light, water and nutrients. The equation was quantified by field experiments with 2 × 2 factorial designs, with factors being defined as the presence or absence of trees and/or mulch. This separated the mulch (‘fertility’) effect from other tree (‘competition’) effects. Similarly, root competition effects were separated from other tree effects by treatments involving vertical polythene barriers or trenches (e.g. Corlett *et al.*, 1992). The experiments showed that: (i) competition from trees may be strong; (ii) rapid tree growth is associated with severe competition; and (iii) positive and negative effects are highly site specific and vary depending on environmental conditions. The predictive power of individual experiments was therefore limited to the same agroecological zone.

After a modification of Ong (1995), the equation evolved to the following (Rao *et al.*, 1998):

$$I = F + C + M + P + L + A \qquad (1.4)$$

where F refers to effects on chemical, physical and biological soil fertility, C to competition for light, water and nutrients, M to effects on microclimate, P to effects on pests, diseases and weeds, L to soil conservation and A to allelopathic effects. Equation 1.4 is comprehensive, incorporating all possible effects involved, but, as emphasized by the authors, many of the effects are interdependent and cannot be estimated experimentally independently of one another. Because of the overlap, the equation cannot provide insight into the relative importance of each term for specific systems.

Cannell *et al.* (1996) reinterpreted Ong’s equation in terms of resources (light, water and nutrients) and deduced that ‘The tree must acquire resources that the crop would not otherwise acquire.’ Because most biophysical agroforestry hypotheses mentioned by Sanchez (1995) can be reduced to this central tenet, Cannell *et al.* (1996) referred to this as the central agroforestry hypothesis. However, this insight is more a logical theorem than proof that the premise is true. Thus, a mixture of two species is likely to exploit a specific environment better than a single species if more resources are available to the mixture than to either species when grown alone. Cannell *et al.* (1996) did not explicitly consider either conversion from resource capture to crop yields or environmental influences on the efficiency of this conversion process.

The resource balance approach

Kho (2000b) attempted to make the relationships with resource supplies and environmental conditions more explicit, while simultaneously avoiding overlap of simple tree effects. He recognized that these (Eqn 1.4 and Fig. 1.2) influence crop production mainly by altering the balance of resource availability to crops, and that the balance of resource limitations in the environment of agroforestry systems has a major impact on the final outcome. If a resource is in ample supply, changes in its availability do not influence crop production greatly. However, if there is a shortage of a resource, even small changes in its availability can have a substantial impact on crop production. This idea was formalized by Kho (2000b) as:

$$I = L_R \times T_R + L_W \times T_W + L_N \times T_N + L_F \times T_F \qquad (1.5)$$

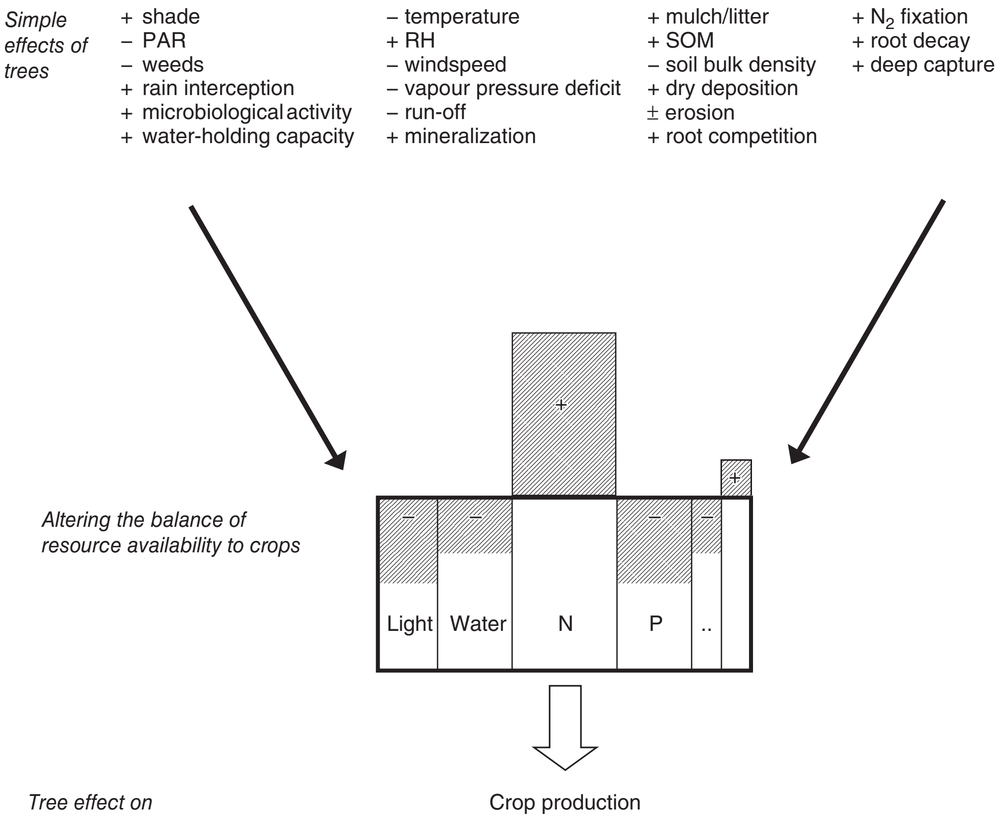


Fig. 1.2. Trees influence crop production by altering the balance of resource availabilities to the crop. The height of each shaded area relative to the height of the rectangle represents the relative net tree effect on availability of the resource (T_i; see text). The width of each shaded area relative to the total width represents the limitation of the resource in the tree–crop interface (L_i; see text). The sum of positive and negative shaded surfaces relative to the total surface of the rectangle represents the overall tree effect *I* expressed as a fraction of sole crop production. PAR, photosynthetically active radiation; RH, relative humidity; SOM, soil organic matter. (Adapted from Kho *et al.*, 2001.)

where I is the overall net effect of trees on crop production (Eqn 1.2); L_R, L_W, L_N and L_F are environmental factors indicating the limitations of the resources radiation, water, nitrogen and other nutrients, respectively; and T_R, T_W, T_N and T_F are factors indicating the relative net effects of trees on the availability to crops of radiation, water, nitrogen and other nutrients, respectively. This equation can easily be expanded by dividing the last term for 'other nutrients' into additional terms. The mathematical derivation of the equation is shown in Appendix 1.1. Effects of trees which operate outwith resource availability include pests, diseases and allelopathy.

The environment determines the limiting factors. The limitation L_i is the weight for the relative net effect of tree on the availability of resource i and is defined as the ratio between the slope of the production response curve at a certain resource level (determined by the environment) and the average use efficiency of that resource by the crop (Kho, 2000a):

$$L_i = \frac{\delta W/\delta A_i}{W/A_i} \tag{1.6}$$

where W represents crop production and A_i is the availability of resource i. L_i is dimensionless, independent of the units used for crop production and resource availability and is a metric between zero and one. If the resource is not limiting, the slope of the response curve equals zero and therefore limitation equals zero; if that resource is the only limiting resource, production is proportional to resource availability and the slope is equal to the corresponding use efficiency and the limitation is equal to one. Kho (2000a) showed that, if the proportional relationship of outputs to inputs (de Wit 1992) holds, the sum of all limitations should be:

$$L_R + L_W + L_N + L_F = 1.0 \tag{1.7}$$

The type of agroforestry system involved determines the technology parameters, with the result that the relative net effect of trees on the availability of a resource i to the crop is:

$$T_i = \frac{\Delta A_i}{A_i} = \frac{A_{i;AF} - A_{i;S}}{A_{i;S}} \tag{1.8}$$

where $A_{i;AF}$ represents the availability of resource i to the crop in the agroforestry system and $A_{i;S}$ is resource availability to the sole crop. The net effect of trees on the availability of radiation to the crop is negative in simultaneous agroforestry systems and zero in sequential agroforestry systems. For other resources, the net effect of trees can be positive or negative, although it is probably generally negative for water and positive for nitrogen; this question should be investigated further for different agroforestry technologies.

As Ong's (Eqn 1.3) and Kho's (Eqn 1.5) methods both lack a time dimension, delayed effects and long-term trends are not part of the models. The scope of these methods is thus limited to a particular agroforestry technology in a certain state (e.g. at equilibrium). In the first few years of an agroforestry system, T_N and T_F are likely to be lower (or more negative) than in mature systems because young trees have a superficial, and therefore less competitive rooting system, and nutrients in slowly decaying tree material are not yet available to crops. Competition for light is relatively low in newly established simultaneous agroforestry systems but increases progressively (T_R becoming more negative) as the system matures.

Two rules can be formulated to predict the performance of agroforestry systems and can be viewed as agroforestry counterparts of classic crop production principles:

Rule 1. The greater the availability of a specific resource within an agroforestry system, the smaller its relative importance in the overall interaction because the severity of the limitation decreases as availability increases.

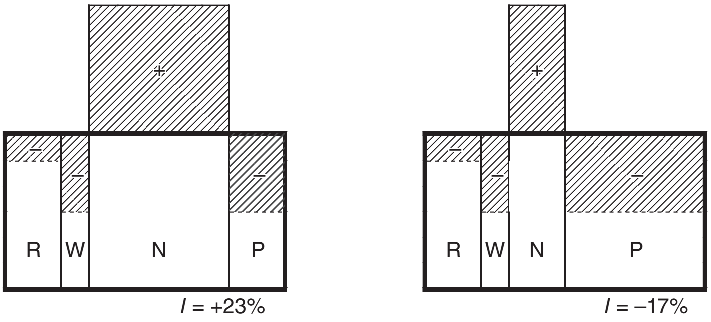
Rule 2. The greater the availability of other limiting resources within agroforestry systems, the greater the relative importance of individual resources in the overall interaction because the limitation increases as the constraints by other resources decrease (Eqn 1.7).

These rules are helpful when developing agroforestry technologies or extending them to other environments. For example, Kho (2000b) showed that the net effect of trees on the availability of resources such as light, water and phosphorus to crops in alley-cropping systems is most likely to be negative, while that for nitrogen is probably positive. In humid climates with nitrogen-deficient soils (Fig. 1.3a), the substantial limitation of nitrogen gives the positive nitrogen effect a high weight, leading to a positive overall interaction. Addition of nitrogen fertilizer (Rule 1) decreases the relative importance of the positive nitrogen effect, leading to a negative overall interaction (Fig. 1.3c). Under similar climatic conditions, but on acid soil, phosphorus is less available, and its reduced availability not only increases the negative phosphorus effect (Rule 1) but also decreases the positive nitrogen effect (Rule 2), leading to a negative overall effect (Fig. 1.3b). Addition of phosphorus fertilizer decreases the negative phosphorus effect (Rule 1) and increases the positive nitrogen effect (Rule 2), resulting in a positive overall effect (Fig. 1.3d). In general, management options such as phosphorus fertilization, water-conserving tillage and weeding are all appropriate for alley-cropping technology to decrease the negative net effect of trees (Rule 1). External inputs of organic or inorganic nitrogen will probably decrease the overall interaction.

The resource balance approach can thus be used easily in a qualitative way. For a particular agroforestry technology, key information is: (i) the sign of the net effect of trees for the resources water, nitrogen and phosphorus, i.e. is the availability of these resources to crops greater or less in the agroforestry system than in sole crops?; (ii) the constancy of this sign, i.e. is the sign of a net effect of trees on the availability of a specific resource independent of the availability of other resources?; and (iii) the extent of these

(a) N-deficient soil

(b) Acid soil



(c) N-deficient soil + N fertilizer

(d) Acid soil + P fertilizer

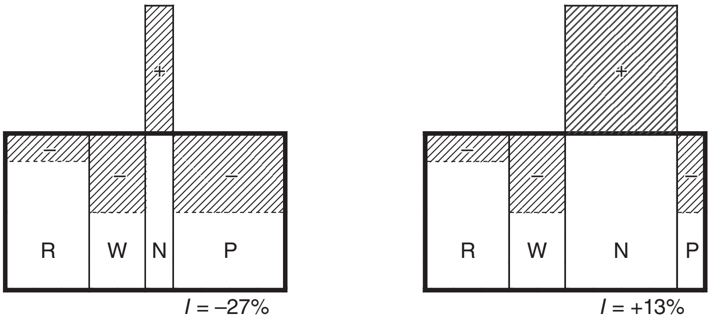


Fig. 1.3. Possible tree effect balances of an alley-cropping technology in a humid climate in nitrogen (N)-deficient soils (a), in acid (phosphorus (P)-deficient) soils (b), in N-deficient soils with N fertilizer (c) and in acid soils with P fertilizer (d). The relative net tree effects on the availability of each resource (T_i) remain equal; only the environment (i.e. resource limitations L_i) changes, explaining the different overall effects (I).

effects, i.e. quantification of Eqn 1.8. These features can all be obtained by factorial experiments that mimic different environments by manipulating resource availability. For example, to investigate the effect of nitrogen, the four treatments shown in Table 1.2 should be used.

For these treatments, the overall interaction without fertilizer is (Eqn 1.2): $I_0 = (A0 - S0)/S0$ and the interaction in a nitrogen-rich environment is $I_N = (AN - SN)/SN$. If the net effect on nitrogen availability to the crop is positive ($T_N > 0$), the difference between crop production in the agroforestry technology and the sole crop should be smaller with fertilizer (Rule 1) than without fertilizer (i.e. $AN - SN < A0 - S0$). If it is negative ($T_N < 0$), the reverse should be the case. In other words, the sign of T_N is estimated by the sign of the contrast $A0 - S0 - AN + SN$.

To investigate the nitrogen and phosphorus effects simultaneously, the eight treatments shown in Table 1.3 can be carried out. For each pair of fertilizer treatments, the overall interaction (Eqn 1.2) can be determined, e.g. for nitrogen-rich environments $I_{N0} = (AN0 - SN0)/SN0$, and for phosphorus-rich environments $I_{0P} = (A0P - S0P)/S0P$, etc. The sign of T_N is estimated by the sign of $A0 - S0 - AN + SN$ with and without phosphorus fertilizer. Thus, the sign of T_N is estimated by the sign of the contrast: $A00 - S00 - AN0 + SN0 + A0P - S0P - ANP + SNP$. Similarly, the sign of T_P is estimated by the sign of the contrast $A00 - S00 + AN0 - SN0 - A0P + S0P - ANP + SNP$. Statistical significance can be tested by analysis of variance (ANOVA). Treatments may be randomized as a split-plot design, with agroforestry technology/sole crops comprising the whole plots and the fertilizer treatments providing the split plots, and ANOVA carried out accordingly.

Table 1.2. A 2 × 2 design to investigate the net effect on nitrogen (N) availability.

Treatment	System	N addition
A0	Agroforestry technology	No N fertilizer
S0	Sole crop	No N fertilizer
AN	Agroforestry technology	N fertilizer
SN	Sole crop	N fertilizer

Kho (2000b) postulated that the sign of the net effect of trees on the availability of a specific resource is constant and does not depend on the level or availability of other resources. Thus, concerning the net effect of trees on nitrogen availability, the sign of $A00 - S00 - AN0 + SN0$ should be the same as the sign of $A0P - S0P - ANP + SNP$ and, regarding the net effect of trees on phosphorus availability, the sign of $A00 - S00 - A0P + S0P$ should be the same as the sign of $AN0 - SN0 - ANP + SNP$. These are interesting hypotheses that may verify or contradict the validity of the resource balance approach. Note that the availability of a resource may (and probably will) depend on the availability of other resources, e.g. phosphorus transport from soil to roots may be decreased by decreases in soil water content, although this is not key. Most important in the resource balance approach is that it is not the availability of a specific resource itself, but that the relative net effect of trees on the availability of specific resources to associated crops is independent of the availability of other resources.

The given contrasts do not provide estimates of the technology factors (Eqn 1.8), but give (and test) only the *sign* of these.

Table 1.3. A 2 × 2 × 2 design to investigate the net effect on nitrogen and phosphorus availability.

Treatment	System	N addition	P addition
A00	Agroforestry technology	No N fertilizer	No P fertilizer
S00	Sole crop	No N fertilizer	No P fertilizer
AN0	Agroforestry technology	N fertilizer	No P fertilizer
SN0	Sole crop	N fertilizer	No P fertilizer
A0P	Agroforestry technology	No N fertilizer	P fertilizer
S0P	Sole crop	No N fertilizer	P fertilizer
ANP	Agroforestry technology	N fertilizer	P fertilizer
SNP	Sole crop	N fertilizer	P fertilizer

However, data from the above experiments can be used to obtain quantitative estimates of L_i (Eqn 1.6), T_i (Eqn 1.8) and thus Eqn 1.5, but this requires more complicated analysis because, even when no fertilizer is applied, a background level of nitrogen and phosphorus is available that should be taken into account. Fortunately, the absolute availability of these background levels is not required and only relative changes are relevant (Kho, 2000a; Kho *et al.*, 2001).

If the experiment summarized in Table 1.3 was repeated in another season with different rainfall, and hence water availability, information about the sign of the net effect of trees on water availability (T_W) could also be obtained by applying Rule 1. If the difference (I) between agroforestry technology and sole crops increases, or becomes less negative, with increasing water availability (statistical significance may be tested using paired *t*-tests, for example), the net effect of trees on water availability (T_W) is negative. Figure 1.4 summarizes all possible outcomes and interpretations.

Experiments containing the treatments shown in Table 1.3 are relatively simple to perform and provide information on key features of agroforestry technologies. Biomass is more closely related to availability of resources than to the harvest of specific plant organs; to obtain a mechanistic understanding, it is better to evaluate these experiments using above-ground crop dry biomass production rather than the harvest of an economically valuable product.

Modelling resource capture

The resource balance approach recognizes that trees influence crop production by altering availability of resources to crops, but leaves an open question as to how this happens. Process-oriented research is needed to address this question. Principles of light, water and nutrient capture and use have been fruitfully applied for sole crops (Monteith *et al.*, 1994) and were later extended to intercrops, weeds and agroforestry (van Noordwijk *et al.*, 2004; Chapters 3 and 6, this volume). A third approach to provide insight into tree–crop interactions is to investigate and model the processes of resource capture and convert these to biomass production:

$$\mathrm{W} = \varepsilon_{\mathrm{conversion}} \times \mathrm{Capture} \tag{1.9}$$

where W represents dry biomass production (e.g. $\mathrm{g\,m^{-2}}$), $\varepsilon_{\mathrm{conversion}}$ is the conversion efficiency (e.g. $\mathrm{g\ dm^{-1}\ MJ^{-1}}$ for light, $\mathrm{g\ dm^{-1}\ mm^{-1}}$ for transpired water and $\mathrm{g\ dm^{-1}\ g^{-1}}$ absorbed for nutrients), and Capture represents the accumulated capture of specific resources (e.g. $\mathrm{MJ\ m^{-2}}$ for light, mm transpired for water and $\mathrm{g\ m^{-2}}$ uptake for nutrients). The assumption is made that a strict law of the minimum is applicable, that the resource under investigation is the only limiting resource and that all other resources are in ample supply. Then, biomass production is proportional to Capture with a constant proportionality factor $\varepsilon_{\mathrm{conversion}}$, as suggested by Eqn 1.9. If light is not limiting, additional interception will not increase growth if, for example, the stomata are closed; if water is not limiting, additional transpiration will not increase growth if, for example, shortage of nutrients prevents the formation of structural biomass. If a specific nutrient is not limiting, additional uptake will not increase biomass but will increase its concentration within the plant biomass. Thus, if a resource is not limiting, additional capture is the result of growth but does not lead to further increases in growth and yield. The fact that resource capture is both the result and determinant of growth shows that the relationship between biomass (W) and Capture of a single resource is a correlation and not a causal relation. From a methodological point of view, correlations are not a sound basis for making predictions, so Eqn 1.9 should be used with caution. If a strict law of the minimum is applicable, Eqn 1.9 can only be viewed as a causal relationship if the resource in consideration is the only limiting resource. However, Kho (2000a) showed that a strict law of the minimum is seldom the case and that it is better to think in terms of multiple limiting factors, each with their own degree of limitation.

This theoretical drawback is also supported by data. Azam-Ali *et al.* (1994) presented radiation conversion efficiencies for three C_4 species and nine C_3 species growing under apparently optimal conditions or under conditions of water and/or nutrient deficiency. Under optimal conditions, radiation conversion efficiency ranged from 1.2 g MJ^{-1} for barley (C_3) to 2.69 g MJ^{-1} for sorghum (C_4). However, within the same species, the conversion efficiency may range from 0.23 to 1.3 g MJ^{-1} in soybean and from 0.57 to 2.62 g MJ^{-1} in millet. Similarly, van Duivenbooden *et al.* (1996) reviewed hundreds of fertilizer experiments and reported nitrogen and phosphorus conversion efficiencies for five major cereals. The maximum phosphorus conversion efficiency ranged from 832 g dm^{-1} g^{-1} of phosphorus for wheat to 1418 g dm^{-1} g^{-1} of phosphorus for sorghum. Within the same species, phosphorus conversion efficiency ranged from 444 to 1389 g dm^{-1} g^{-1} of phosphorus for rice and from 557 to 418 g dm^{-1} g^{-1} of phosphorus for sorghum. These and other data sets clearly show that conversion efficiencies are determined more by environmental conditions than by species. Consequently, the scope of a model that uses empirical estimates of conversion efficiencies is limited to similar environmental conditions.

The variation of conversion efficiencies with environmental conditions is a pitfall for modelling the growth of sole crops, but this is even greater when modelling agroforestry systems. Because trees alter resource availability to crops, the limitations, and hence conversion efficiencies, for crops in agroforestry systems are likely to differ from sole crops. For example, on theoretical grounds, one can expect the radiation conversion efficiency to be greater if light is more limiting, as occurs under a tree canopy, than in the open.

Notwithstanding the limitations and pitfalls of modelling resource capture, process-based simulation models are important tools for understanding why, and to what extent, the availability of resources differs for crops grown in agroforestry systems compared with sole crops. They are also important for optimizing agroforestry technologies and evaluating different management options. To counter these pitfalls, models could be used with different conversion efficiencies as input to evaluate the sensitivity of the outcome to assumed efficiencies.

Lessons from Alley Cropping and Parkland

In past decades, hundreds of alley-cropping experiments have been carried out all over the world in different climates and on different soils. Sanchez (1995) reviewed some long-term alley-cropping experiments that included the four mulch transfer treatments that are necessary to separate fertility (F) from competition (C) effects using Ong's equation. The fertility effect ranged from +3 to +58%, the competition effect from −8 to −77% and the overall interaction from −58 to +32%. Sanchez (1995) concluded that alley cropping should work at sites where the supply of water and nutrients is likely to be sufficient. However, the reasons why the fertility effect would probably be lower than that of competition, especially on fertile soils with adequate rainfall, remain unclear. The fertility and competition effects vary greatly, and there was no systematic relationship with soil or climate.

Kho (2000b) reviewed the same alley-cropping experiments without separating F and C and found, on the basis of the resource balance approach, the two rules and Fig. 1.4, that the net effect of trees on water and phosphorus availability to the crop is most likely to be negative (negative T_W and T_P) and that the net effect on nitrogen availability to crops is most to be likely positive (positive T_N). Hence, alley cropping should work on sites where water and nutrient supplies are ample, with the exception of nitrogen, which should be deficient (Fig. 1.3). Many alley-cropping experiments (e.g. Sanchez (1995) and others) fit this framework well. Hundreds of alley-cropping experiments were necessary to come to this insight. In retrospect, one well-controlled multi-year experiment involving the treatments shown in Table 1.3 would have been sufficient to provide the same information. This is an important lesson from the alley-cropping experience.

The parkland system (scattered trees in cropland) is a well-known traditional agroforestry system in semi-arid regions. In the Sahelian region, parkland tree species include the shea butter tree or karité (*V. paradoxa*),

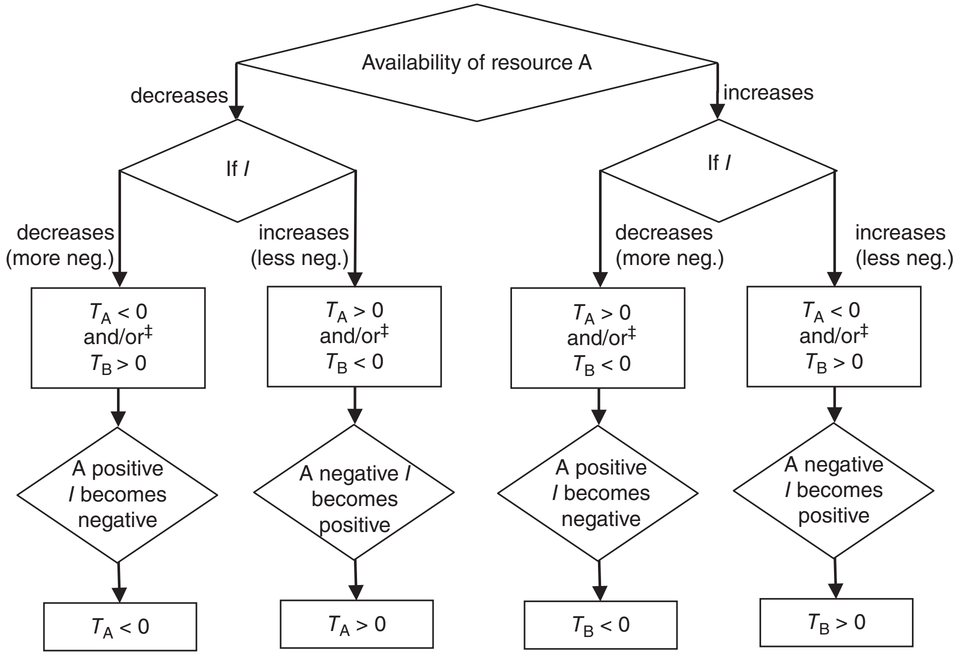


Fig. 1.4. Diagram to derive the sign of net tree effects on availability of a resource (other factors being equal). T_A refers to the net effects of trees on the changed resource and T_B to that of another limiting resource. ‡Both statements may be true. However, if *I* is negative, the statement with the negative *T* value is most meaningful; if *I* is positive, the one with the positive *T* value is most meaningful. If the overall interaction *I* changes sign, then certainty about one net effect of the trees is given. (Adapted from Kho, 2000b.)

néré (*P. biglobosa*) and *F. albida* (formerly *Acacia albida*). The latter is particularly notable because it has a reverse phenology and develops a green canopy during the 9-month dry season and sheds its leaves at the onset of the rainy season, thereby reducing direct competition for light, water and nutrients. Under the tree crown, crop growth is considerably better (the so-called '*albida* effect'; Vandenbeldt, 1992). This has been attributed to increased soil fertility, improved microclimate and soil physical properties and its reverse phenology (Depommier *et al.*, 1992; Kamara and Haque, 1992; Rhoades, 1995). Whether nutritional or physical effects dominate, the *albida* effect is likely to have important consequences for the management of these parklands. The higher soil fertility under the crown of trees could result directly from the presence of trees (Geiger *et al.*, 1992) or the lateral redistribution of resources by animals or roots. In both cases, the system as a whole would gain nothing from a higher tree density. However, if physical factors dominate the *albida* effect, the trees would increase the productivity of the system, suggesting that high tree densities would be beneficial.

Vandenbeldt and Williams (1992) reported that soil temperature was up to 10°C lower under the canopy of *F. albida* trees than in the open. In a separate experiment, they used vertical shade barriers to modify soil surface temperature by varying the period over which the soil was exposed to direct sunlight in plots located some distance from the tree to remove any confounding effects of differences in soil fertility. Pearl millet was sown in this range of environments in rows perpendicular to the barrier. Vandenbeldt and Williams (1992) found a clear negative linear relation between shoot dry weight 6 weeks after sowing and mean soil surface temperature. Because this relationship was consistent with the lower soil temperature and greater millet growth under the crowns of *F. albida* trees, they concluded that shade-induced reductions in soil temperature contributed to the improved growth of crops under the trees. They suggested that, without the companion effect of decreased temperature under *F. albida*, millet crops would be unable to exploit the greater fertility associated with this tree species; they proposed a greater use of soil shading to reduce soil temperature.

Kho *et al.* (2001) planted five replicates of the eight treatments shown in Table 1.3 together with two additional fertilizer treatments in which half the nitrogen dose and half the phosphorus dose used in the agroforestry systems and sole crop were applied. In total, there were 25 split plots containing pearl millet under the canopy of five *F. albida* trees and 25 split plots containing pearl millet in five open areas. At 25 days after sowing, mean biomass was greater under the *F. albida* canopy, although not significantly. Phosphorus fertilizer induced a highly significant effect, but the effect of nitrogen fertilizer was not significant. At harvest, the effects of nitrogen and phosphorus fertilizer were highly significant, as was the effect of *F. albida* trees and the negative interaction between the trees and applications of nitrogen fertilizer. Without fertilizer, dry matter production in millet grown under *F. albida* was 36% greater than in the open, but this difference disappeared with the high nitrogen fertilizer treatment, with and without phosphorus fertilizer. Following the high nitrogen fertilizer application, its limitation (L_N) decreased. As the *albida* effect disappeared entirely, the positive nitrogen effect (T_N) must have been the most important component of the effect of this tree species. Indeed, Kho *et al.* (2001) estimated that nitrogen availability accounted for approximately two-thirds of the *albida* effect (*c.*26% production gain arising from a 200% increase in nitrogen availability; $T_N = 2$) and that phosphorus accounted for one-third (*c.*13% production increase arising from a 29% increase in soil phosphorus availability; $T_P = 0.29$) (Fig. 1.5). The increase in phosphorus availability was relatively small, but because of the high limitation (0.46), it had a large impact. Rhoades (1995) also found that soil nitrogen availability was up to three times greater beneath *F. albida* canopies than in the open.

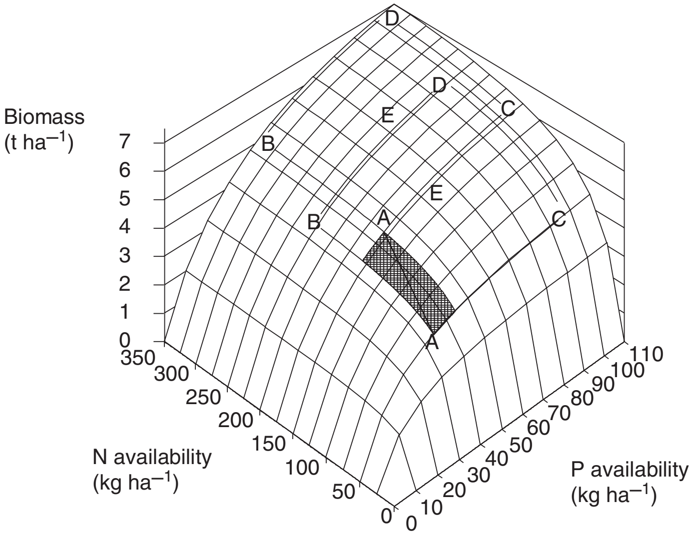


Fig. 1.5. Millet dry biomass in the open field at N'Dounga, Niger, as a function of nitrogen (N) and phosphorus (P) availability. The letters A–E denote the placement of the fertilizer treatments in the open (lower square) and under *Faidherbia albida* (upper square). A, control; B, 180 kg N ha^{-1}; C, 60 kg P ha^{-1}; D, 180 kg N ha^{-1} and 60 kg P ha^{-1}; E, 90 kg N ha^{-1} and 30 kg P ha^{-1}. The shaded area corresponds to the tree effect on N and P availability. (From Kho *et al.*, 2001.)

The conclusions of Kho *et al.* (2001) contradict those of Vandenbeldt and Williams (1992), as an unshaded millet crop grown in the open exploited the increased fertility provided by applied fertilizer without any accompanying effect of decreased temperature, whereas the experiment described by Vandenbeldt and Williams (1992) was terminated 6 weeks after sowing. Nitrogen is not limiting at the start of the growing season because net mineralization is strongly stimulated if this is preceded by a long, hot, dry season (Penning de Vries and Djitèye, 1982; Rhoades, 1995). At the start of the growing season, water and phosphorus were probably limiting. Vandenbeldt and Williams (1992) created the gradient in soil surface temperatures by varying the period over which the soil was exposed to direct sunlight with distance from a vertical barrier. The soil temperature gradient was thus confounded by a gradient in radiation, and probably also wind speed, and hence a gradient in evapotranspiration. If water availability for evaporation (i.e. loss of latent heat) is insufficient to balance incoming solar energy supply, soil surface temperature rises. The temperature gradient must therefore have been confounded by a gradient in soil water availability. This shows that the observed negative relationship between millet growth and soil surface temperature in the experiment reported by Vandenbeldt and Williams (1992) was in fact a correlation and not a causal relationship. Both variables were related to a third variable, soil water availability, which was at least partly the real causal variable. Two lessons can be learned. First, relationships between paired measured variables are correlations and not necessarily causal. Since R.A. Fisher developed systematic experimental design at Rothamsted Agricultural Research Station, Harpenden, UK, a century ago, we have learned that: (i) only by randomization of the different levels of the independent variable, can an empirically established relationship be accepted as causal; and (ii) it is hazardous to make predictions on the basis of correlations. Second, the balance of available resources should be taken into account constantly, not only when transferring an agroforestry technology to a different environment but also when extrapolating results from a subprocess (e.g. growth during crop establishment) to another, higher, level (e.g. growth over the whole season). Growth results from subprocesses can only be applied to other situations if the resource limitations are the same.

The net effects of *F. albida* are positive for nitrogen, phosphorus and, probably, water (positive T_N, T_F and T_W) and negative for radiation (negative T_R). Because of its reverse phenology, the reduction of radiation is relatively small (*c.*50%; Vandenbeldt and Williams, 1992), which, in highly nitrogen- and phosphorus-limiting environments is insufficient to increase the light limitation under the canopy significantly. In nitrogen- and phosphorus-limiting environments, such as the Sahelian and Sudanian zones in West Africa, the *albida* effect is then a nitrogen and phosphorus effect. For other parkland tree species without reverse phenology, such as karité and néré, the reduction in solar radiation received by understorey crops may be up to 80% (Kessler, 1992; Jonsson *et al.*, 1999), which would increase light limitation under the tree canopy and hence reduce the limitations of water, nitrogen and phosphorus (Eqn 1.7). For these trees, the negative effects of competition for light may nullify (millet: Jonsson *et al.*, 1999) or outweigh (sorghum: Kessler, 1992) the positive effect of increased fertility under the tree canopy. Kessler (1992) showed that pruning of tree branches can reduce competition for light and hence decrease crop yield losses.

Implications for Species Choice

Farmers' common sense tells them that mixtures of two or more species represent a good combination if each 'fits into' space not occupied by the others. This is, in principle, the same insight reported by Cannell *et al.* (1996) that trees must acquire resources that the crop would not otherwise use. This is a general paradigm for species choice.

In simultaneous agroforestry systems, competition for light may outweigh all positive effects. Tree species selected for use in such systems should ideally provide limited competition for light. Suitable species are characterized by a compact canopy shape and erect structure, as became clear from alley-cropping experiments (van Noordwijk *et al.*, 1995; Chapter 3, this volume) and parkland systems (Kessler, 1992). If trees have numerous vertical leaves, their extinction coefficient, and hence light interception, will be minimal (Chapter 4, this volume). Lower light interception by trees will reduce competition not only for light but also for water because transpiration is directly related to the quantity of radiation intercepted by their canopies (Chapter 6, this volume). C_4 crop species have a much higher photosynthetic light saturation level for incident solar radiation than C_3 crops and thus have a larger limitation (L_R) than C_3 crops. Hence, C_3 crops are more appropriate from a biophysical viewpoint in light-limiting environments.

A major factor determining direct and indirect competition for water and mobile nutrients such as nitrogen and potassium is the relative rooting depths of trees and crops (d_{crop}/d_{tree}). This ratio should be as low as possible, calling for shallow-rooted crops and deep-rooted trees. Although the desirability of such complementarity of rooting architecture is obvious, the reality of achieving this is not (Chapter 8, this volume). In nitrogen-limited environments, the best results (highest I) are expected from combinations of leguminous trees and non-leguminous crops. Leguminous crops have a lower limitation (L_R) and therefore profit less from the enhanced nitrogen supplies provided by leguminous trees than non-leguminous crops.

A major factor determining direct competition for water and poorly mobile nutrients such as phosphate is the root length density (cm of root length cm^{-3} of soil) of the trees relative to the crop in shared soil layers (van Noordwijk *et al.*, 2004; Chapter 8, this volume). Thus, trees with a low percentage of fine roots in the top soil horizons are preferable, especially in phosphate-limiting environments.

Conclusions

The above framework provides an overview of simple methods to examine tree–crop interactions at the farm level but does not address the complex mechanisms used by farmers to cope with stress and shocks resulting from drought and climatic extremes. Over the past three decades, resilience has emerged as an important framework for analysing the sustainability of socio-ecological systems (Folke, 2006). Resilience is considered the ability of a complex system to continue to perform its desired functions when it is under stress or external shock (Folke, 2006). For example, complex agroforestry systems have been considered by ecologists to be ‘structurally and functionally the closest mimics of forests yet attained’ (Ewell, 1999) and, because of their high species diversity and low export of nutrients, are regarded as the ‘epitome of sustainability’ throughout the tropics (Kumar and Nair, 2004). To understand how adaptation to increased climate variability might be accomplished, it is useful to examine how species and populations are coping with current climatic variation and extreme events.

Tree-based agroecosystems have obvious advantages in terms of maintaining production during unusually wet or dry years. First, the deep root systems of trees can exploit a larger soil volume for water and nutrients than crops, which will be beneficial during periods of drought. Second, increased soil porosity and infiltration rates and retention of water in the soil profile can reduce moisture stress during low-rainfall years. Third, new observations have confirmed that tree-based systems have lower soil evaporation rates than row crops and may even modify regional climates (Ong *et al.*, 2014). Agroforestry options may provide a means for diversifying production systems and increasing the resilience of smallholder farming systems (Chapter 12, this volume). The most dramatic examples are those described in sub-Saharan Africa, where use of fertilizers by smallholders to replenish their soils is often not economically feasible due to high prices and the risk of drought stress (Kater *et al.*, 1992; Ong and Leakey, 1999). The future is currently bleak, as several studies project that higher temperatures and lower rainfall in parts of Africa, combined with a doubling of the human population, will lead to a massive increase in food insecurity over the next two decades (Boko *et al.*, 2007). Restoring soil health is often regarded as the first entry point for increasing agricultural productivity because soil nutrient depletion is generally most extreme in areas occupied by smallholder farmers.

The greatest opportunity for simultaneous tropical dryland agroforestry systems appears to be exploitation of complementary interactions between trees and crops grown for their marketable products (Ong and Leakey, 1999; de Leeuw *et al.*, 2014). Although trees provide valuable ecosystem services, these are not usually the primary reason why farmers retain, manage or plant them. In some areas, trees are highly valued by farmers because economic yields from marketable tree products more than compensate for losses of crop yield. Thus, in semi-arid Kenya, farmers have developed intensive parkland systems using the fast-growing indigenous species *Melia volkensii* (Meliaceace), which is reputed to be highly compatible with crops and produces high-value timber within 5–10 years (Stewart and Bromley, 1994). To determine whether growing *M. volkensii* in cropland is cost-effective, Ong *et al.* (2002) compared the timber products gained with that of the crop value lost due to competition over an 11-year rotation in Kitui District, Kenya. Their estimates showed that, at the end of the rotation, the total income from trees exceeded that of accumulated crop yield losses resulting from competition by US$10 or 42% during average years, or US$22 or 180% with the assumption of 50% crop failure during drought years. de Leeuw *et al.* (2014) compiled numerous examples of the resilience provided by trees in the East Africa drylands.

Species with outstanding hydrological properties and excellent complementarity of water use are often neglected by farmers. Many native tree species are ideally suited for planting with annual crops but suffer from the low value of their produce and/or slow growth rates. An exceptional case of successful avoidance of competition in simultaneous agroforestry systems is the traditional use of *F. albida*, now a target species of the farmer-managed natural regeneration programme (FMNR) in the parklands of the Sahel in Africa. The high degree of complementarity results from its unusual reverse canopy phenology, as it is leafless during the cropping season and leafy during the dry season. Many authors have reported increased crop yields under *F. albida*, which have been attributed to improved availability of water and essential macronutrients, particularly nitrogen and phosphorus, although the relative importance of these factors varies seasonally and depends on soil water and nutrient status at specific sites (Rhoades, 1995; Kho *et al.*, 2001).

However, the ‘albida effect’ would require 20–40 years to develop in countries such as Ethiopia (Poschen, 1986), a timescale well beyond the planning horizon of most farmers. Of course, it would be ideal to match valuable trees with crops, as reductions in crop yields would be more than offset by valuable products from the trees. One example is the *M. volkensii*/millet system used in semi-arid Kenya (Ong and Leakey, 1999). A recent approach is to promote and assist FMNR of useful trees such as *F. albida* (Garrity *et al.*, 2010). FMNR began in Niger in the 1980s due to the failure of massive conventional reforestation projects in the Sahel. Analysis of satellite imagery has revealed that 4.8 m ha of *F. albida*-dominated farmlands have spread through the Maradi and Zinder regions through this practice (Reij *et al.*, 2009). Further research is needed to understand fully how FMNR promotes rapid tree growth in Niger.

A few decades ago agroforestry was promoted with great enthusiasm. Based on the analogy with natural tree–herb ecosystems that could exploit the environment much better than sole crops alone, the benefits of agroforestry were often presumed. Disappointments enforced a more scientific treatment of agroforestry, and since then, major improvements have been made. At the start, as a science, agroforestry was more descriptive and phenomenological. Many field experiments in a range of climatic and geographical regions provided a wealth of technologies, hypotheses and facts. Theoretical developments provided a framework for quantifying the various effects of tree–crop interactions, placing them in a wider perspective. These various effects and theories have been summarized briefly in this chapter. The scientific endeavours of the past decades make it increasingly possible to predict when, where, how and why agroforestry can realize its promise, and when, where, how and why it cannot.

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Appendix 1.1. Derivation of Kho's Equation (Eqn 1.5)

Within the temperature range at which a crop species can grow and reproduce (*c*.0–35°C for temperate species and 10–45°C for tropical species; Ong and Monteith, 1985), crop dry matter production (W) in specific environments is a function of resource availability:

$$W = f\,(A_1, A_2, \ldots, A_n) \qquad \text{(A1.1)}$$

where A_1 is the availability of resource 1 and n represents the quantity of all resources. Apart from allelopathy and effects on pests and diseases, trees will not influence crops by modifying the production function (Eqn A1.1), but by their influence on the availability of resources to the crop, z denotes tree density (number ha^{-1}) in a particular agroforestry technology. According to the chain rule:

$$\frac{dW}{dz} = \sum_{i=1}^{n} \frac{\delta W}{\delta A_\mathrm{i}} \times \frac{dA_\mathrm{i}}{dz} \qquad \text{(A1.2)}$$

Multiplying both sides of the equation by dz, and expressing the differentials relative to the sole crop value (i.e. dividing both sides by the production of the sole crop, W_s, and multiplying the right-hand side by $A_{\mathrm{i;S}}/A_{\mathrm{i;S}}$) gives:

$$\frac{dW}{W_\mathrm{S}} = \sum_{i=1}^{n} \frac{\delta W}{\delta A_\mathrm{i}} \frac{A_{\mathrm{i;S}}}{W_\mathrm{S}} \times \frac{dA_\mathrm{i}}{A_{\mathrm{i;S}}} \qquad \text{(A1.3)}$$

By approximating the differentials with differences, the tree–environment–crop interaction equation may be derived:

$$\frac{W_\mathrm{AF} - W_\mathrm{S}}{W_\mathrm{S}} = \sum_{i=1}^{n} \frac{\delta W}{\delta A_\mathrm{i}} \frac{A_{\mathrm{i;S}}}{W_\mathrm{S}} \times \frac{A_{\mathrm{i;AF}} - A_{\mathrm{i;S}}}{A_{\mathrm{i;S}}} \qquad \text{(A1.4)}$$

where W_AF is the production of the crop in the agroforestry system. Substituting Eqns 1.2, 1.6 and 1.8 yields the general version of the resource balance equation:

$$I = \sum_{i=1}^{n} L_\mathrm{i} \times T_\mathrm{i} \qquad \text{(A1.5)}$$

For the four main resources of radiation, water, nitrogen and 'other nutrients', this is Eqn 1.5.