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Abstract. Agroforestry research is being transformed from a collection of largely descriptive studies into more scientific approaches, based on process-oriented research. The development of agroforestry as a science should be based on four key features: *competition, complexity, profitability and sustainability.* Managing the *competition* between trees and crops for light, water and nutrients to the farmers' benefit is the biophysical determinant of successful agroforestry systems. Simultaneous agroforestry systems are more susceptible to competition than sequential ones. A tree–crop interaction equation helps quantify competition vs. complementary effects on fertility. Alley cropping, a simultaneous agroforestry system, has limited applicability because the competition factor usually exceeds the beneficial fertility effects. The *Faidherbia albida* parkland, another simultaneous system, is almost always beneficial since the reverse phenology of *F. albida* minimizes competition while enhancing the fertility effect. Sequential systems such as relay intercropping and improved fallows also minimize competition but the processes responsible for crop yield increases are largely unquantified. New methodologies for reliably measuring complex below-ground interactions are being developed.

Socioeconomic and ecological *complexity* are typical of agroforestry systems. Participatory, analytical and multidisciplinary characterization at different spatial scales is the required first step in effective agroforestry research. Diversity of products and services should be manipulated in a way that puts money in farmers' pockets. Domestication of indigenous trees with high-value products enhances *profitability*, particularly those that can be marketed as ingredients of several finished products. Policy research interventions are often necessary to help farmers during the initial years before trees become productive and exert their positive ecological functions. *Profitable* agroforestry systems are potentially *sustainable*, controlling erosion, enhancing biodiversity and conserving carbon, provided nutrient offtake is balanced by nutrient returns via litter and the strategic use of fertilizers, particularly phosphorus. A list of research gaps indicates where hard data are needed to provide a predictive understanding of the competition, complexity, profitability and sustainability aspects of agroforestry.

Introduction

Agroforestry is the traditional practice of growing trees on farms for the benefit of the farm family. It has been in use for at least 1300 years according to pollen records [Brookfield and Padoch, 1994], although tree domestication probably started much earlier [Simmonds, 1985]. Agroforestry was brought from the realm of indigenous knowledge into the forefront of agricultural research less than two decades ago, and was promoted widely as a sustainability-enhancing practice that combines the best attributes of forestry and agriculture [Bene et al., 1977; Steppler and Nair, 1987]. Growing trees along with crops and livestock was postulated to enhance crop yields, conserve soil and recycle nutrients while producing fuelwood, fodder, fruit and timber.

The potential of agroforestry was initially based on largely descriptive and anecdotal information, usually collected from high-potential environments [Nair, 1989]. Applied research was vigorously pursued with limited attention to the underlying biophysical or socioeconomic processes.

While such efforts raised awareness and helped institutionalize agroforestry in national programs throughout the world, the need for a critical, science-based approach gradually emerged. Many agroforestry innovations did not deliver what their promoters expected. The limited usefulness of alley cropping, perhaps the prototype agroforestry technology, contrasts sharply with the very high expectations of it during the 1980s. A recent review of process-oriented agroforestry research produced very little hard data [Anderson and Sinclair, 1993].

The transformation of a descriptive practice into a science happens when hypotheses are developed by systematic observation, description and interpretation. Such hypotheses, coupled with inductive reasoning and deductive experimentation, can lead to theories that provide a predictive understanding applicable to other situations. Hypotheses are continually challenged by testing, disproving and formulation of new ones, which often result in new ways of thinking, or paradigms. The fundamental sciences, mathematics, philosophy, physics and chemistry, developed in such a manner. Refinements, combinations and new ideas gave birth to other basic sciences such as biology, astronomy and psychology. Further combinations and developments produced botany, zoology, economics, ecology, statistics and other sciences. Applications to real-life situations resulted in new applied sciences in medicine, engineering and agriculture. Further specialization led to more focused applied sciences such as agricultural economics, plant genetics, plant physiology and soil science. These are all recognized as sciences because their key principles have been established through the methods previously described.

Agroforestry is not there yet. Its theoretical underpinnings are yet to be developed in a sufficiently rigorous manner to assure predictive understanding. At this point agroforestry is a field of study which involves the combined application of ecology, economics, anthropology, agronomy, forestry, soil science, animal science, tree genetics, biometrics and other applied sciences. Out of this cauldron a recognized science may emerge, and what an exciting one it may be, given its broad interdisciplinary nature.

The fundamentals of agroforestry are now being intensively investigated by many institutions throughout the world. Two key principles set agroforestry systems apart from agricultural or forestry systems: *competition* and *complexity*. They in turn determine two desirable properties: *profitability* and *sustainability*. The purpose of this paper is to outline these principles and properties as an approach to science-based agroforestry. All four combine biophysical and socioeconomic issues. This paper, however, is not a comprehensive review of the literature, so many of the references and examples used are the ones most accessible to the author. Comments on the drafts of this paper were received from 35 colleagues, many of whom provided new insights and valuable criticisms. Key substantive additions not supported by references are credited as personal communications in the text.

Competition

When plants grow in proximity to each other they interact in positive ways (complementarity) or in negative ways (competition). The biophysical bottom line of agroforestry is how to manage the interaction for light, water and nutrients between the tree component and the crop and/or livestock components for the benefit of the farmer. Much of the initial enthusiasm when agroforestry was brought into the research agenda was based on the assumption that when trees and crops are brought together they complement rather than compete with each other in their capture of growth resources.

The anecdotal evidence about the potential of agroforestry raised some suspicions in this author's mind when it was realized that most of the successful examples of agroforestry came from high-potential environments, where water or nutrients were not major limiting factors. A soil–agroforestry hypothesis was formulated out of this inquiry [Sanchez, 1987]. Anthony Young transformed it into ten hypotheses [Young, 1989b], and the number keeps growing [Van Noordwijk and Dommergues, 1990; Wilson, 1990; Ong et al., 1991a]. The current 17 biophysical hypotheses are listed in Appendix 1. Many of them remain to be tested or rejected in a sufficiently rigorous manner and under a wide enough range of conditions to be accepted as broadly applicable principles. All of them deal with competition or complementarity. Much of the work to test these hypotheses is recent (see references listed in Appendix 1), indicating the current impetus of process-oriented research. Science advances as much by disproving as by proving hypotheses. Many of the hypotheses shown in Appendix 1 are very general; they should be tested in specific agroforestry systems under specific biophysical and socioeconomic conditions, such as differing climate, soil, slope, cultural tradition and income levels.

Simultaneous vs. sequential agroforestry systems

The term agroforestry system is used when the tree and crop and/or animal components interact with each other and have discrete boundaries, separating the system from others on a farm. Although agroforestry systems have been classified in a myriad of different ways [Nair, 1989], there are only two functionally different types, simultaneous and sequential [ICRAF, 1994]. Simultaneous agroforestry is where the tree and the crop components grow at the same time and in close enough proximity for interactions to occur. Examples of this type are alley cropping (hedgerow intercropping), contour hedges, parklands, boundary plantings, homegardens and several silvopastoral systems.

In sequential agroforestry systems the maximum growth rates of the crop and the tree components occur at different times even though both components may have been planted at the same time and are in close proximity. Examples of this type are shifting cultivation, improved fallows, taungya, and some multistrata systems. Interactions between the crop and the tree components are minimized with time in sequential agroforestry.

Simultaneous agroforestry systems can be transformed into sequential agroforestry systems. This is the case when the trees in an alley-cropping system are allowed to grow into a fallow and cropping is discontinued. In the next cropping cycle the trees are severely pruned to minimize competition with crops, but they are allowed to grow when the crops are gone (B. Duguma, pers. comm.). Long-duration multistrata or complex agroforests start as sequential systems with crops and trees interacting, but develop into simultaneous systems when the various tree species fully develop.

The following section describes the biophysical interactions of some short-duration simultaneous and sequential agroforestry, focusing on the competition issue.

The alley-cropping experience

Alley cropping, also known as hedgerow intercropping and alley farming, is a simultaneous agroforestry system where trees, mainly leguminous, are grown in dense hedges between 'alleys' of specified width where short-cycle food crops are grown. The hedges are pruned periodically and the resulting mulch is placed on the alleys to provide nutrients and control weeds [Kang et al., 1981]. Interactions between the tree and the crop components are maximized by this spatial arrangement. Alley cropping should not be confused with contour hedges, another simultaneous system where the hedges are planted along contours on steep slopes but at variable widths and usually include grasses and trees that are not pruned.

The principles of plant interactions have been well studied in natural systems by plant ecologists [Harper, 1961] and in multiple-cropping systems by agronomists [Papendick et al., 1976; Willey, 1979]. For simultaneous agroforestry systems that have crop yields as the only product, Ong [in press] and Ong and Black [in press] proposed a tree–crop interaction equation for quantifying the crop and the tree component effects; it is modified as follows:

$$I = F - C \qquad (1)$$

where

I = overall interaction, as a percentage of sole-crop yields free from interference with trees,

F = the fertility effect, i.e., the percentage of crop-yield increase caused by soil fertility improvements (nutrient inputs from tree prunings plus microclimate modifications such as less soil evaporation, lower soil temperatures), and

C = the competition effect, i.e., the crop-yield decrease caused by competition with trees for light, water and nutrients.

A positive I value in this equation means net complementarity, the desired outcome of agroforestry. A negative I value means net competition to the detriment of crop yields. The I value is based on total area, including that occupied by trees. Since the trees are used only as a source of mulch in this system there is only one product: crop production. In agroforestry systems that also produce poles, fruits, firewood or fodder from the trees as well as crops, the equation has to be modified to take these tree products into account as is done in intercropping research [Andrews and Kassam, 1976; Willey, 1979; Anderson and Sinclair, 1993; Van Noordwijk, in press]. This equation is still at the developmental stage. Other factors such as allelopathy and positive or negative effects of pest activities could be specified, although they are included as yield effects. The final judgement is the economic value of all products versus the sole crop, and this is done by converting the biophysical yield data into monetary values. The equation differs from the classic intercropping ones of land equivalent ratios or relative yield totals [Andrews and Kassam, 1976] in that the complementary and competition effects are separated.

The measurement of the two parameters in Eq. (1) can be accomplished with four treatments in an alley-cropping experiment [Ong, in press].

Co = sole crop
Cm = sole crop + mulch from pruned trees
Ho = crop + tree with mulch removed
Hm = crop + tree with its mulch

F can be measured as $Cm - Co$, that is the effect of tree prunings due to their nutrient input upon decomposition plus microclimatic changes on the soil surface or weed suppression prior to decomposition. F is therefore the fertility effect in its broadest sense, involving both nutrient availability and soil physical changes due to litter or mulch inputs.

C can be measured as $Hm - Cm$, or $Ho - Co$, that is, the effect of trees on crop yields separate from the fertility effect. Therefore a second equation makes the determination of crop-yield effects operational [Ong, in press]:

$$I = (Cm - Co) - (Hm - Cm) \qquad (2)$$

Unfortunately, there are very few alley-cropping experiments that have these four treatments arranged in a proper experimental design that assures no interference between treatments [Ong, in press]. A bias in favor of a positive alley-cropping effect is introduced when plots are so small that the sole-crop treatment (*Co*) is invaded by tree roots from adjacent *Hm* or *Ho* plots. In such cases there is unintended competition for below-ground resources which depresses yields in the sole-crop treatment and allows the trees from adjacent plots to capture additional water and nutrients. A review by Coe [1994] on this topic describes these pitfalls. The methodological solution is to use large plots, on the order of 10 × 20 m, and root barriers or trenches down to 1 m depth. Unfortunately, solid root barriers can be effective for as little as one season; after that tree roots grow under the barriers and up into the control plots [Singh et al., 1989; Hauser, 1993].

Ong [1994, in press; Ong et al., in press], Reynolds [1994] and Woomer et al. [in press] have analyzed the available literature, comprising over 100 alley-cropping experimental data sets. A summary of some long-term experiments considered to be reasonably devoid of interference between plots is shown in Table 1. Trials ranging from semi-arid to humid climates, in widely different soils are interpreted according to Eq. (2).

The effect of alley cropping was strongly negative (–58%) in a fertile semi-arid Alfisol in India [Rao et al., 1991]. In this environment the fertility effect was moderate (+19%) but the competition effect for water was very strong (–77%). A similar effect was observed in another semi-arid site with moderately fertile Alfisols at Machakos, Kenya [ICRAF, 1993]. Competition for moisture was very marked in a season with low rainfall, but a positive alley-cropping effect of +11% was observed at the same site during a season with high rainfall. The magnitude of the competition effect decreased from –34% to –8% with increasing rainfall. The fertility effect also increased with higher rainfall, because more tree biomass was produced and returned to the soil as mulch. These and other data sets [Reynolds, 1994] indicate that the likelihood of drought stress results in a strong probability that the alley-cropping effect will be negative in semi-arid areas.

Examples from the subhumid tropics show intermediate effects of fertility and competition. At Chipata, Zambia, the negative alley-cropping effect shown in Table 1 is typical of many results in the area [Akyeampong et al., in press]. The original alley-cropping trial at Ibadan, Nigeria [Kang et al., 1981], showed a tremendous positive fertility effect (+58%). Unfortunately this trial did not have a sole-crop control, impeding the estimation of *I* and *C*. Estimates of sole-crop maize yields from adjacent areas at the IITA station, however, suggest a *C* effect of –54% and therefore an overall alley-cropping effect of +4% (calculated from IITA, 1988].

Finally, in the humid tropics, where moisture is not expected to be limiting but fertility may be, trials still show a major competition effect, presumably because of competition for light and nutrients. In a fertile soil of volcanic origin from Costa Rica the overall alley-cropping effect was close to neutral (–3% with *Erythrina poeppigiana* and +1% with *Gliricidia sepium*, Kass [1987]). In a strongly acid and infertile soil at Yurimaguas, Peru, the overall effect was strongly negative (–30%) and attributed to competition for nutri-

Table 1. Examples of alley cropping results interpreted in terms of the tree-crop interaction equation. Values for *I* (overall interaction], *F* (fertility effect] and *C* (competition effect] are expressed as percentages of sole-crop yields. Compiled from information by C. K. Ong and M. van Noordwijk.

Location (original source)	Climate	Soil	Tree	Crop	*I*	*F*	*C*
Hyderabad, India [Rao et al., 1991]	Semiarid 550 mm	Alfisol pH 6.0	*Leucaena leucocephala*	Millet Peanut	–58	+19	–77
Machakos, Kenya (poor rainy season) [ICRAF, 1993]	Semiarid 230 mm this crop	Alfisol pH 5.6	*Senna siamea*	Maize	–31	+3	–34
Machakos, Kenya (good rains) [ICRAF, 1993]	Semiarid 417 mm this crop	Alfisol pH 5.6	*Senna siamea*	Maize	+11	+19	–8
Chipata, Zambia [Akyempaong et al., in press]	Subhumid 760 mm	Alfisol pH 4.6	*Leucaena leucocephala*	Maize	–20	+36	–56
Ibadan, Nigeria [Kang et al., 1981, 1985]	Subhumid 1400 mm	Sandy Entisol pH 6.2	*Leucaena leucocephala*	Maize	+4	+58	–54
Yurimaguas, Peru [Szott et al., 1991]	Humid 2200 mm	Ultisol pH 4.2	*Inga edulis*	Rice	–30	+28	–58
Turrialba, Costa Rica [Kass, 1987]	Humid 2650 mm	Volcanic (Tropept) pH 4.6	*Erythrina poeppigiana* *Gliricidia sepium*	Maize	–3	+52	–55
North Lampung, Indonesia [Van Noordwijk et al., 1995]	Humid 2700 mm	Ultisol pH 4.7	*Peltophorum dasyrachis*	Maize	+32	+58	–26

ents [Szott et al., 1991]. One major exception to this trend is alley cropping with *Peltophorum dasyrachis* in an acid Ultisol from Lampung, Indonesia, with an *I* value of +32% [Van Noordwijk et al., 1992, 1995]. This non-legume species grows as very dense, low hedgerows, producing a large mulch-to-shade ratio. Its *F* value is not unusually large (+58%), but its *C* effect is unusually small (–26%).

Many factors affect alley-cropping performance: the choice of tree species and crop species, alley width, biomass production, number of crop cycles, time and frequency of prunings, tillage, fertilization and weed dynamics. These are well described [Kang et al., 1981, 1985, 1990; Yamoah et al., 1986; Szott et al., 1991; Fernandes et al., 1993; Kang, 1993, in press; Salazar et al., 1993; Juo et al., 1994; Wendt et al., 1994; Palm et al., 1995b] but the bottom line appears to be that alley cropping will only work in limited and very site specific circumstances.

There is now a predictive understanding as to where alley cropping should work: at sites where the supply of water and nutrients is likely to be ample; that is, on fertile soils with a reliable and adequate rainy season. Immediately one wonders whether alley cropping should be the system of choice under such favorable environments.

In addition, alley cropping has major soil conservation and socioeconomic implications. When used as contour hedges on sloping lands, alley-cropping systems clearly decrease runoff and erosion [Lal, 1989; Young, 1989a; ICRAF, 1994; Kiepe and Rao, 1994]. As mentioned earlier, contour hedges are different from alley cropping in that the width of the hedge is determined by the slope and not by a specified alley width; also, the hedges can contain both grasses and trees, which are frequently used for fodder instead of for mulch, and include freely growing trees for fruit or timber [Garrity and Mercado, 1994]. The soil conservation effects of contour hedges are discussed in a later section. It should be clear, however that alley cropping on slopes is an effective way to control erosion, as long as the hedges on the contour are sufficiently well developed to provide a continuous barrier. This effect may in some instances override competition considerations.

Socioeconomic studies in western Kenya indicate that alley cropping requires about an 18% increase in maize yields above those for sole cropping to cover additional labor costs during establishment [ICRAF, 1993]. Swinkels and Franzel [submitted] found that pruning the trees increases labor requirements by only 5%. But there are two critical constraints on pruning labor. First, pruning is required during the farmers' peak periods of labor use, and delaying pruning can greatly decrease crop yields, because of increased competition. Second, women consider pruning too tedious and expect males to do it, who would rather be doing something else. Studies in Nigeria indicate farmers are unwilling to plant many trees in hedgerows unless they have clear ownership of the land [Lawry et al., 1994]. Therefore, alley cropping is most likely to work where the following conditions apply.

- Soils are fertile without major nutrient limitations.
- Rainfall is adequate during the cropping season.
- Land is sloping with erosion hazards.
- There is an ample supply of labor, coupled with a scarce supply of land.
- Land tenure is secure.

It is unfortunate that over 15 years of research has been devoted to this agroforestry technology without fully taking into account the principles of competition. As one of the scientists who got excited about alley cropping in the early 1980s and initiated research in the Amazon, this author shares this responsibility with others. He was also one of the first to question its suitability for low fertility soils [Sanchez, 1987].

In retrospect, the principal strategic mistake was to equate alley cropping with intercropping of annual crops, where yield increases often occur when C3 and C4 crops with drastically different architectures are grown in rows [Papendick et al., 1976; Ong et al., 1991b]. But trees differ from short-cycle crops in two fundamental ways: they grow for several years and they also develop extensive root systems that capture nutrients and water at a time when crop root systems are beginning to develop. Both traits give trees a major competitive advantage. Short-cycle food crops are in a way analogous to uptight city dwellers who are always looking at their watches: crops must be planted, flower, set fruit and die on schedule. Trees are more akin to laid-back people: if there is a drought they can stop growing and shed a few leaves; there is plenty of time to recuperate and grow rapidly when conditions are favourable. Which strategy wins in the long run?

Alley cropping is like playing with fire, because it has strongly positive and strongly negative interactions and thus requires precise fine tuning in every situation, according to Van Noordwijk's [in press] shade and mulch model. Such factors as alley width, avoiding fast-growing trees because they are strongly competitive, and supplemental fertilizer applications are among the key fine tunings. As a system to be promoted widely to farmers, it probably requires too much management. The challenge is how to manage the intrinsic comparative advantages of trees for the benefit of the farmer. In most circumstances, alley cropping is not the way to do it.

Nevertheless, much has been learned from the alley-cropping experience. The original hypothesis about how trees can improve crop yields by enhancing soil fertility has been replaced with more focused hypotheses, as shown by the more recent ones listed in Appendix 1. Improving hypotheses is a way for science to progress. An immense amount of hard data have also been obtained about the tree–crop interface, plant litter quality, biological nitrogen fixation, pruning regrowth, and the adaptation of trees to adverse soil conditions.[1] Alley-cropping research also produced practical means to control erosion biologically. All these results are valuable for the understanding and improvement of other agroforestry or intercropped systems. Therefore, the general failure of this technology from the development perspective carries with it the benefit of new and valuable scientific insights in terms of concepts and methods.

The albida effect

After the negative experience with alley cropping, one may wonder if there are any simultaneous agroforestry systems that work. There is one that does so remarkably well: the *Faidherbia (Acacia) albida* parklands in the Sahel [Charreau and Vidal, 1965; Vandenbelt, 1992]. Millet and sorghum crops growing within a 5 to 10 m radius around mature *F. albida* trees yield two to three times more than adjacent crops growing in the open [Bonkoungou, 1992]. This may represent a positive *I* value of 100 to 150% in the tree–crop interaction equation, without including two other important benefits, providing fuelwood and dry-season fodder. The necessary studies with the four treatments previously mentioned, however, are yet to be done.

The Sahelian environment is characterized by a nine month dry season and a short, erratic rainy season coupled with sandy, infertile soils very deficient in phosphorus and nitrogen [Sivakumar et al., 1991]. *F. albida* trees exhibit a reverse phenology, developing a green canopy during the dry season and dropping leaves at the onset of the rainy season [Joly, 1992]. They tend to establish themselves on patches of soil that have a slightly higher clay content than surrounding areas, which is correlated with a higher content of organic matter and nutrients in this environment [Geiger et al., 1992]. Their presence also seems to be associated with old termite mounds in the subsoil, capturing the generally higher nutrient status of termite nests [Brouwer et al., 1993]. Tap roots reach down as much as 30 m, capturing soil moisture at such depths during the dry season [Alexandre and Ouedraogo, 1992; Deans et al., 1993]. Therefore, *F. albida* has a comparative advantage in capturing nutrients and water in an environment where both resources are limiting.

F. albida foliage is used as fodder for ruminant animals during the dry season. Pods are also good feed for ruminants and are commonly sold at local markets. Animals enjoy the shade, urinate and defecate more often under the *F. albida* trees. Birds congregate on tree branches, adding nutrient inputs to the soil under the tree canopy. *F. albida* may also fix nitrogen during the dry season with nodules located on roots several meters below the soil surface, near to the water table [Sprent et al., 1989; Dupuy and Dreyfus, 1992].

Leaves of this species have a nutritive value similar to other African browse legumes but with higher crude protein (20%) and lower contents of lignin and soluble polyphenolics than Australian acacias [Reed et al., 1992]. These investigators also showed that rams fed with *F. albida* grew at rates similar to rams fed with *Leucaena leucocephala*, *Sesbania sesban* and *Medicago sativa* hay. The relatively low lignin : nitrogen ratio (4 : 3) and the moderate soluble polyphenolics : nitrogen ratio (11 : 3), calculated from data of Reed et al. [1992], suggest a rapid rate of leaf litter decomposition at the onset of the rainy season. These processes result in the formation of 'islands of fertility' as the trees grow in size. There is huge genetic variability in this species but most trees grow slowly, such that it is estimated that the full effect takes more than 10 years to develop. Such islands of fertility, however, are considered to be indicators of an advanced stage in the process of desertification [Schlesinger et al., 1990].

When the rains start, decomposition of the litter and manure around the *F. albida* trees occurs rapidly, resulting in high mineralization rates. For example, alluvial soils in Malawi mineralized 125 kg N ha^{-1} in four months under trees in comparison with 47 kg N ha^{-1} in the open [ICRAF, 1993].

In addition, the microclimate under the defoliated trees also improves. Branches provide about 50% shade to the crops below the tree canopy, ameliorating excessively high soil temperatures that can kill germinating cereal seedlings, plus lowering leaf temperatures and transpiration rates during the hottest parts of the day, while allowing full solar radiation during the morning and afternoon [Vandenbelt and Williams, 1992]. Consequently, *F. albida* influences the crop microclimate positively.

Table 2 shows the different site properties of two *F. albida* parklands in Burkina Faso [Depommier et al., 1992]. One site is dominated by old trees. In both cases there are modest increases in soil organic matter, total nitrogen, available phosphorus and potassium. Sorghum yields under the canopy averaged 2.1 times higher than in the open.

There is little question about the positive tree–crop interaction in *F. albida*

Table 2. Site differences under the canopy and 15 m away from *Faidherbia albida* trees in two parklands in Burkina Faso. Adapted from Depommier et al. [1992].

Parameter	Park 3		Park 4	
Site characteristic				
Total area (ha)	0		2.2	
F. albida trees (ha^{-1})	7		19	
Average canopy size (m^2)	140		88	
Ground cover by *F. albida* (%)	9.8		16.5	
	Under	Away	Under	Away
Soil differences (0–20 cm)				
pH (water)	5.9	5.8	6.1	6.0
%SOM	2.7	2.4	1.6	1.6
%Total N	0.18	0.13	0.12	0.09
P (–g g^{-1})	14.0	10.6	8.3	6.1
Ca (cmol kg^{-1})	10.0	8.9	5.2	4.6
Mg (cmol kg^{-1})	3.9	3.9	2.3	2.3
K (cmol kg^{-1})	0.7	0.4	0.6	0.3
Grain yield				
Sorghum (t ha^{-1})	1.6	0.7	1.8	0.9

parklands, but it does not always happen [Brouwer et al., 1993]. The processes involved need to be fully quantified at well-characterized sites. How densely can the *F. albida* trees be planted and still provide the positive effects? How long does it take for the trees to start exerting such positive effects? Even more intriguing is the evidence of similar positive effects with two non-nitrogen-fixing tree species also present in the Sahelian parklands, karité or shea butter tree (*Vitellaria paradoxa*) and neré (*Parkia biglobosa*). Such tree effects on crop growth are not, according to visual observations, as spectacular as those of *F. albida*. Kessler [1992] suggests that the fertility effect of karité and neré is due to nutrient trapping instead of N-fixation. These two species do not exhibit reverse phenology; therefore, several processes are taking place and these need to be disaggregated and quantified.

Water, temperature and nutrient budgets, therefore, need to be assembled at several key sites and under the three tree species to ascertain how far the *F. albida* effect can be extrapolated and to what extent it can be manipulated. The time course of development of the crop effects also needs to be established. Observations, however, indicate that the effect diminishes and eventually disappears as the subhumid tropics are approached. Quantification is badly needed.

Other simultaneous systems

Tree–crop interactions in other simultaneous agroforestry systems are probably somewhere in between the generally negative scenario of alley cropping and the generally positive scenario of the *F. albida* parklands. Homegardens, boundary plantings, live fences, complex agroforests and silvopastoral systems should be characterized in terms of the tree–crop interaction equation, taking into account that the I parameter will be the sum of the different products out of those systems and not simply crop yields.

Minimizing competition is the paramount objective in simultaneous agroforestry systems. Perhaps the simplest way to achieve this is to choose tree species that compete less with crops for growth resources. One obvious example is the choice of *Grevillea robusta* vs. *Eucalyptus* spp. for boundary plantings in the East African highlands. *G. robusta* is known by farmers as ‘friend of the crop’, because it does not affect maize yields much, while *Eucalyptus* spp. in this ecosystem certainly do. *Eucalyptus* spp., as well as neem (*Azadirachta indica*) in the Sahel, can devastate cereal crops growing close to them when resources become scarce, because of their extensive root systems.

Silvopastoral systems are widespread simultaneous systems throughout the tropics [Budowski, 1993; Dzowela and Kwesiga, 1994; Singh et al., 1994]. The knowledge base about them, however, is essentially at the descriptive stage. Quantification of these important systems is badly needed as they are believed to be a key component of pasture recuperation in the humid tropics of Latin America [Serrão, 1993]. Trees in pastures often provide the major source of dry-season fodder in subhumid and semi-arid areas. Live fence posts are an important component of silvopastoral systems, providing fodder and decreasing the rates of deforestation caused by the need to replace rotten fence posts [Budowski, 1993]. Process-oriented research on silvopastoral systems is a high-priority research area.

Sequential systems: a different story

When the tree and the crop components of an agroforestry system grow at different times or at widely different rates, competition is decreased simply because the peak demands for growth resources occur at different times for each component. This may be achieved either by planting the components at different times or by planting them at the same time when one component grows rapidly while the other grows slowly. The first case is called relay intercropping in the agronomic literature [Andrews and Kassam, 1976]. The second case, perhaps the most common in sequential agroforestry systems, is usually called mixed intercropping. They are both classified as sequential agroforestry, for lack of a better term. Figure 1 shows this situation in a maize–*Cajanus cajan* system in Trinidad [Dalal, 1974]. Both species in this trial were planted at the same time but their initial growth rates were so different that their nutrient uptake patterns were really in sequence; when maize approached maximum nutrient uptake, *Cajanus cajan* initiated its period of fast growth, resulting in minimum competition for nutrient resources.

Shifting cultivation is also a sequential agroforestry system. After slashing and burning the forest, crops are planted between tree stumps, many of which resprout but are kept small by the farmer's machete. When farmers plant what they expect to be their last crop, they let the trees regrow as a secondary forest fallow for 10 to 20 years. There is little competition between crops and trees in traditional shifting cultivation. Trees in the fallows, because they are perennial and have extensive root systems, accumulate large quantities of nutrients in their biomass, which upon slashing and burning are transformed into ash, which acts as fertilizer for the next cropping cycle [Sanchez, 1976]. The demand for resources between the uptight city person (the crop) and the laid-back hillbilly (the trees) is nicely spaced in time. Unfortunately, traditional shifting cultivation is now almost an anthropological curiosity, having been replaced by various forms of slash-and-burn systems in disequilibrium, primarily because of shortening the fallow period as a consequence of pressures on the land [Bandy et al., 1993].

The tree–crop interaction equation should be modified for sequential agroforestry systems. Such an equation must include the variety of products obtained: grain crop yields, fuelwood, fruit, fodder and timber. Developing such an equation requires conceptual refinement to account for the recycling of nutrients and the fact that products are not harvested every year. Like the original one, this equation would be in biophysical terms and must be converted into monetary values as well. Two examples of sequential agroforestry

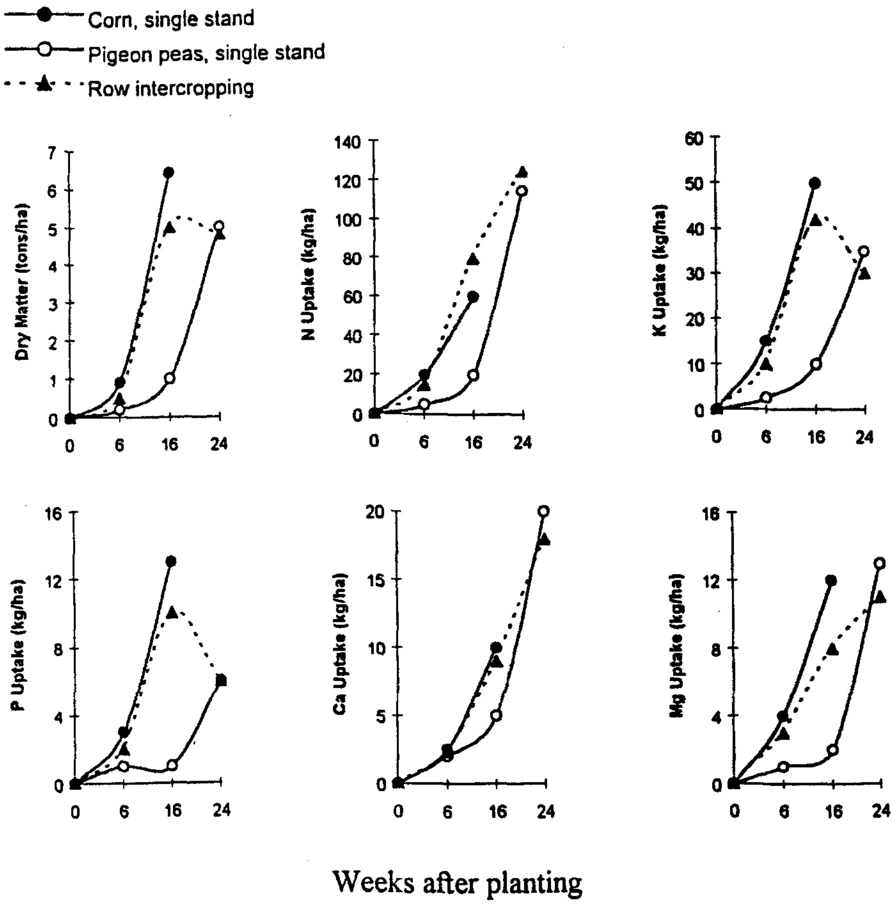

Fig. 1. Growth and nutrient uptake patterns of maize and pigeon peas (*Cajanus cajan*) in monoculture and row intercropping trial in Trinidad. *Source:* adapted from Dalal [1974].

systems merit attention because of their potential practicality: relay intercropping and improved fallows.

Relay intercropping in southern Africa

The vast subhumid plateau of southern Africa is a tropical savanna locally known as the 'miombo'. It is characterized by a rainy season four to six months long, followed by a long dry season, and by the dominance of trees of two leguminous genera, *Brachystegia* and *Julbernardia* [Huntley, 1982]. Average elevation is 1000 m and annual rainfall about 1000 mm; the soils, classified as Alfisols, Ultisols and Oxisols, are of moderate to low fertility. Typically, farmers grow maize during the rainy season and little is grown during the dry season. Maize responds strongly to nitrogen fertilizers, but most farmers have not been able to afford the recommended rates since the elimination of fertilizer subsidies. Frequent drought periods during the rainy season or delays in the start of the rains often decimate crop yields [ICRAF, 1993]. Diagnostic studies have indicated that low soil fertility, lack of fuelwood and lack of dry-season fodder are the main constraints perceived by farmers in the miombo [Dzowela and Kwesiga, 1994].

In densely populated areas of southern Malawi, farm size is extremely small, from 0.2 to 0.5 ha, precluding the possibility of fallow periods or cattle grazing. Nitrogen deficiency is the main fertility constraint. Given the doubtful on-farm results of alley cropping in this region, a sequential agroforestry alternative was sought to provide nitrogen inputs other than with fertilizers. *Sesbania sesban*, locally known as sesbania, grows fast and nodulates naturally in these soils. After considering the farmer labor calendar and in consultation with many farmers, the concept of relay intercropping maize with sesbania was developed.

Maize is planted in rows at normal spacing and population density, while sesbania seedlings are transplanted in rows at a rate of 7400 seedlings ha^{-1} shortly afterwards. Maize grows rapidly while sesbania establishes itself slowly, not competing much with the crop. After the first maize harvest, sesbania begins to grow rapidly and does so during much of the dry season when most fields are bare. To do this, sesbania taps water deep in the subsoil and fixes nitrogen, as evidenced by healthy nodules on its roots. *S. sesban* roots have reached a depth of 4 m in one year at Chipata, Zambia [Torquebiau and Kwesiga, submitted]. At Zomba, Malawi, sesbania trees accumulated about 1.7 t ha^{-1} of leaves, with very high nutrient concentrations (3.6% N and 0.37% P). Leaflets drop during the dry season, providing nutrient inputs in the order of 80 kg N ha^{-1} and 6 kg P ha^{-1} (J. A. Maghembe, unpub. data). Farmers then harvest about 1.7 t ha^{-1} of sesbania for fuelwood. At the onset of the next rainy season maize is planted and sesbania reseeds itself or is replanted, growing slowly and not competing much with the crop, because the crop for once has the competitive advantage. So far, this cycle has been repeated for five years.

The results of this system appear in Table 3, in which sesbania–maize intercropping is compared with sole maize to which no fertilizer is added and with sole maize to which fertilizer is added at the economically optimum rates of nitrogen and phosphorus [ICRAF, 1995]. There were no differences in maize yields during the first crop, because the trees were small and did not exert competitive or complementary effects. From the second year on, maize yields with sesbania intercropped were double those of the sole-crop maize, in both the presence and the absence of fertilizers. Drought was particularly acute in two years, 1992 and 1994, which resulted in widespread crop failures in southern Africa. Even in these years, maize yields doubled with sesbania intercropping in relation to the sole, unfertilized maize crop.

The positive effect of sesbania intercropping was also evident when the recommended fertilization was used. The five year average yields increased

Table 3. Performance of mixed intercropping system of maize and *Sesbania sesban* for five consecutive years (1989–1994) near Makoka, Zomba District, Malawi. The system is compared with sole maize with and without half the optimum fertilizer applications (28 kg N ha^{-1} and 5 kg P ha^{-1}). Maize grain yields and sesbania wood in tonnes ha^{-1}. Adapted from Maghembe, unpub.; ICRAF, 1993, pp 78–80; ICRAF, 1995.

Year	Seasonal rainfall (mm)	Sole maize no fert.	Sole maize + fert.	Maize + relay sesbania, no fert.	Maize + relay sesbania, no fert	SED	Wood[a]
1	1001	1.00	3.75	1.02	3.27*	0.40	2.08
2	1017	1.33	6.21	2.41*	6.13	0.60	0.05
3	551[b]	0.61	2.93	1.86**	3.54	0.39	2.24
4	962	1.02	4.79	2.33**	5.99*	0.51	3.01
5	522[b]	0.51	2.41	1.16*	3.29**	0.36	1.01
Mean	810	0.89	4.01	1.76	4.44		1.68

* Significant difference at 10%.

** Significant differences at 5%.

[a] Wood of *Sesbania sesban* relay-planted with unfertilized maize.

[b] Drought years (1992, 1994).

from 4.0 to 4.4 t ha^{-1} with sesbania intercropping plus fertilization. Fertilizing sole crops is still the most profitable option, but for those farmers who are unable to purchase chemical inputs, sesbania intercropping doubles yields during both good and bad years.

Fuelwood is another output of this system, which is currently valued at US$25 t^{-1} in Zomba District, Malawi. An average production of 1.7 t ha^{-1} yr^{-1} adds considerable value to sesbania intercropping.

The processes responsible for doubling maize yields in this sequential system have yet to be rigorously quantified. Nevertheless, on a yearly basis the I value of the tree–crop interaction equation must be over +100%, including the value of fuelwood. Growth and nutrient uptake curves of maize and sesbania need to be generated as well as quantification of the processes involved in nitrogen cycling.

Improved fallows in southern Africa

In less densely populated areas of the miombo woodlands, grass fallows of one to five years coexist with continuous maize cultivation, which no longer receives adequate fertilizers since the beginning of the structural adjustments. In a sense this is a form of shifting cultivation in tropical savannas. The strategy here was to use leguminous fallows to accumulate nitrogen in the biomass, smother weeds and improve soil physical properties [Kwesiga and Chisumpa, 1992]. Work done in Chipata, Zambia, demonstrated that two-year-old *S. sesban* fallows increased maize yields greatly compared with unfertilized maize [Kwesiga and Coe, 1994]. Results shown in Table 4 indicate that sesbania fallows doubled maize yields over a six year period, in comparison with continuous unfertilized maize production. This was accomplished in spite of two years without crop production while the sesbania was growing. Cost-benefit analysis also shows about twice the cumulative net benefit of the sesbania fallows over unfertilized maize (Table 4). This includes the value of sesbania wood. Sensitivity analysis indicates that two year fallows maintain their economic superiority over continuous, unfertilized maize under all realistic assumptions, including one or two drought years, fluctuations in maize and fuelwood prices, labor costs and discount rates [Place et al., 1994]. Therefore, this sequential system is also very promising; it is currently being tested extensively on-farm and is also being improved by farmers.

As in the case of relay intercropping, the processes responsible for such yield increases are yet to be quantified, but work has started on studies of litter decomposition, rooting depth, root productivity and changes in soil physical properties. Research is also in progress on alternative *Sesbania sesban* cultivars and on other species of *Sesbania*, cheaper establishment methods such as bare-root seedlings, and combining improved fallows with nitrogen fertilization to push yields to a higher plateau. Researchers are also examining farmer perceptions, local policies to protect the fallows from grazing and the overall adoption potential. A major constraint that remains to be resolved is

Table 4. Performance of two-year-old *Sesbania sesban* improved fallows in comparison with continuous maize production at Msekera, Chipata District, Zambia. *Sources*: Kwesiga and Coe [1994]; Place et al. [1994]; ICRAF [1995].

System	1988	1989	1990	1991	1992	1993	Sum of 6 yrs
Maize yield (t ha^{-1})							
Sesbania fallow	F	F	5.0	5.6	0.6	3.1	14.3
Continuous maize, no fert.	1.8	1.6	1.2	1.9	0.2	0.9	7.6
Continuous maize, 112 kg N ha^{-1} yr^{-1}	6.6	6.1	4.9	4.3	0.9	5.6	28.4
Net benefit US$ ha^{-1}							
Sesbania fallow[a]	−145	11	310	286	13	95	570
Continuous maize, no fert.	113	79	32	71	−10	7	289
Continuous maize, 112 kg N ha^{-1} yr^{-1}	460	343	200	134	−40	143	1240

[a] Includes wood production of 10 t ha^{-1} at harvest.

sesbania's susceptibility to root-knot nematodes (*Meloidogyne* sp.) as a host plant, which could harm sensitive crops like tobacco if they were planted in rotation. Screening for tolerance to nematode infestations is in progress in Malawi and Kenya.

Relay intercropping and improved fallows are promising alternatives for farmers in the miombo. The biophysical and socioeconomic processes involved must be fully quantified and understood before widespread adoption is promoted. These examples are described to emphasize the inherent advantage of sequential agroforestry systems over simultaneous ones in managing competition for the farmers' benefit. Such advantage, however, has not been satisfactorily quantified.

Complexity

Agroforestry research is full of complexity. The gist of the biophysical complexities has been described. In addition there are major socioeconomic and ecological complexities. Appendix 2 lists ten socioeconomic and ecological statements and hypotheses proposed by Izac [1994]; they will frame the discussions of the rest of this paper. When one adds to them the 17 biophysical hypotheses, complexity becomes obvious. The following section addresses some issues of socioeconomic, ecological and methodological complexity.

Socioeconomic complexity

The socioeconomic dimension of agroforestry is complex because of aspects related to temporal and spatial variability; scale factors; the multiplicity of products and services; the economic, social and ecological processes involved; the methods of characterization and diagnosis; and the diversity of institutions involved.

Agroforestry systems vary in space and time. Trees are seldom used uniformly across the farmer's land, and typically occupy discrete areas such as homegardens, contours, boundaries and fallow plots. Agroforestry frequently coexists with pure agricultural systems and pure forestry ones. Some sequential systems closely resemble agriculture in their early stages and forestry in their later stages.

The socioeconomic front is complex also because of the scale factor [Izac and Swift, 1994]. At one end is the farm household; at the other are the international pressures on national governments to 'internalize externalities' (assign monetary value to positive or negative consequences beyond the farm, such as siltation, loss of biodiversity and carbon sequestration). In between are two critical scales; one is the community or watershed scale with influences by local elders or their equivalents in the control of communal land. Community or watershed are seldom the same; one is a social demarcation while the other is geographical. The other critical scale is the national government where, for example, policies favoring timber exports may obliterate traditional community rights. The interactions between the different scales is indeed complex. Geographic information systems can help organize the data at the different spatial scales, aggregate or disaggregate them. This tool provides order to this difficult issue [Izac and Swift, 1994].

Another level of complexity is the multiplicity of products and services. Agroforestry systems not only produce food crops but also fruit, fodder, fuelwood, poles, timber and medicines; they also provide services: they conserve the soil and biodiversity and delineate boundaries. Most of the products have economic value, while most of the services have nonmonetary, environmental value.

Such systems, products and services are managed by different members of the household for their own purposes. The literature is full of descriptions of agroforestry systems at the household level [Nair, 1989], but rigorous analysis of the underlying socioeconomic processes involved is limited. Process-oriented research is not the monopoly of the biophysical sciences; it is equally important in the social sciences. The need to develop a predictive understanding on how farm households make decisions regarding land use is as essential as developing a predictive understanding of competition between tree and crop roots. In both cases there is a great deal of site specificity: cultural values, policies and income levels in one case; tree and crop species, climate and soil properties in the other. The general statements and hypotheses listed in Appendix 2 are primarily methodological; as the science evolves these hypotheses should become more process oriented.

Examples of socioeconomic processes are how households react to a diminishing resource base caused by nutrient depletion, how communities react to a different policy environment caused by increasing environmental consciousness by governments and how farmers intensify their land use in response to demographic pressure. Generalizations should be made about these processes to provide a predictive understanding beyond the specific cultural circumstances in which the data were obtained. This is what a science is all about.

The first step in agroforestry research, therefore, should be the characterization of the farmers' situations at a sufficiently detailed scale: watershed or regional. ICRAF pioneered the D&D (diagnosis and design) approach, which includes rapid rural appraisal and other methods. D&D is carried out by a team composed of at least an agronomist, a forester and a social scientist [Raintree, 1987; Avila and Minae, 1991]. Subsequent improvements added participatory approaches [Scherr, 1991], focus on gender issues [Kemerwa et al., 1994], and analytical (vs. descriptive) approaches based on quantitative and georeferenced data, combining both biophysical and socioeconomic parameters [Palm et al., 1995a].

Many of the diagnostic surveys are superficial in their analysis of constraints. It is not particularly useful to conclude that the main constraints facing farmers are low soil fertility, high soil erosion, lack of fodder, little fuelwood, unresponsive government policies, and limited access to credit and capital, because such conclusions apply to most tropical smallholder situations. Characterization and diagnosis should therefore be participatory, analytical and multidisciplinary. An example of this latter approach is the characterization methodology developed for the Alternatives to Slash-and-Burn Initiative [Palm et al., 1995a]. Such studies must be firmly based on relevant indigenous knowledge and also should be iterative. The latter is a characteristic of the social sciences that deals with the changing behavior of human beings (E. Zulberti, pers. comm.).

An operational dimension of additional complexity is the diversity of institutions involved in agroforestry research. Such institutions are attached to several public sectors such as agriculture, forestry, environment and soil conservation autofinance. Within a research institution or university, agroforestry cuts across many disciplinary or commodity-oriented departments. This is an integral part of natural resource management research.

Ecological complexity

Agroforestry systems exert two main ecological functions, productive and protective. The high total biomass of most agroforestry systems is responsible for the protective or buffering function [Kessler and Wiersum, 1993]. The scale and time factors of agroforestry add complexity from the ecological perspective [Fresco and Kroonenberg, 1992]. For example, the effects of a few trees on one farmer's field are different from those of thousands of trees on many farmer fields at the watershed scale. Ecological externalities such as stream sedimentation or, on the positive side, increases in plant species diversity, are seldom felt at the farm scale but they are certainly felt at higher spatial scales.

Ecological parameters interact with socioeconomic ones [Izac, 1994], building complexity upon complexity. This, however, is part of all natural resource management research, of which agroforestry is but one subject. Solid, scientifically sound approaches to natural resource management research are still in their infancy and must be fully developed.

In particular, next to nothing is known about the effects of different agroforestry systems, on the dynamics of pest–predator–disease interactions affecting food chains and life cycles that eventually determine sustainability and risk (R. Leakey, pers. comm.). The pantropical spread of the leucaena psyllid (*Heteropsylla cubana*) from its center of origin in the Caribbean to Hawaii in 1984, then to Asia and now in Africa since 1992 has caused major damage to *Leucaena leucocephala* [Vandenbeldt and Napompeth, 1992]. This, however, should not be viewed as an exceptional event. Exotic species leave their predators behind when they are moved away from their center of origin, but eventually predators catch up with them or new ones arise. Multipurpose tree species should not be expected to be pest or disease proof. Scientists should be prepared for such outbreaks by having a diverse genetic base available and they should alert the entomologists and plant pathologists associated with their research teams.

Methodological complexity

Methodological complexities are also part and parcel of agroforestry research. The challenge is to make research methods simple while remaining accurate and reproducible; experimental design and statistical analyses require extra care in agroforestry [Rao and Coe, 1992]. Oversimplification, however, has led to major shortcomings. One example is the inappropriate design of many alley-cropping trials, which has rendered them invalid as a result of root interference between plots [Coe, 1994]. There have been major methodological advances in measuring competition for light and water [Ong et al., in press]. Water-use measurement in agroforestry systems has been greatly simplified by straightforward methodologies that can follow water uptake of individual roots, branches and whole trees or crop plants [Ong et al., 1990; ICRAF, 1994].

The main methodological challenge is below ground, where straightforward ways to measure soil processes and root interactions are not well developed. Conventional soil fertility methods for assessing the availability of nitrogen and phosphorus are not sensitive enough to detect changes in low external input systems. New methods and approaches need to be developed [Sanchez, 1994a]. Relevant changes in soil organic matter content, for example, are seldom detected by conventional methods such as total soil carbon and total nitrogen determinations. Conventional phosphorus soil tests often fail to detect important changes in phosphorus availability. Recently, methods for evaluating soil biological processes have advanced much [Anderson and Ingram, 1993] but several parameters such as microbial biomass and labile organic phosphorus pools still lack replicability and threshold or critical levels. Simplifying root interactions is taking on a new dimension by the fractal branching approach proposed by Van Noordwijk et al. [1994] and Spek and Van Noordwijk [1994]. Methods for assessing the resilience and sustainability of agroforestry systems in economic, social and ecological terms remain to be developed.

Modelling in agroforestry is still in its infancy, in terms of both mechanistic and simulation models [Muetzelfeldt and Sinclair, 1993; Parton et al., 1994; Spek and Van Noordwijk, 1994; Ong et al., in press; Van Noordwijk, in press]. High priority should be given to developing robust models based on hard data, now that such data are becoming increasingly available.

Profitability

Agroforestry is also about putting money in farmers' pockets. This is in addition to the goals of providing food security, enhancing soil fertility, conserving soil and water, as well as increasing fodder and fuelwood production. Improved agroforestry systems should do all that, but to be sustainable, they must increase profitability in the medium term. Profitability is a necessary but not a sufficient condition of sustainability; in fact, many profitable systems are not sustainable in agronomic, social or ecological terms. Nevertheless, the most sustainable agroforestry systems are those that combine a high-value marketable product, such as coffee or cacao, with sound biophysical practices. The complex agroforests in Indonesia are perhaps the epitome of sustainability, with biodiversity levels approaching the original tropical rainforest they replaced after slash-and-burn [Michon and de Foresta, 1990; Michon et al., in press]. They provide farmers with a steady flow of income from jungle rubber, damar resins and fruits, all high-value–low-volume products that have assured markets and that are grown with little nutrient removal from the soil. Three research strategies to increase profitability in agroforestry are domestication, marketing and policy innovation.

Domestication

The first strategy is to introduce new products through the domestication of ‘Cinderella’ tropical tree species that have been largely overlooked by science [Leakey and Newton, 1994]. These include indigenous fruit trees and others that provide medicinal products and high-grade timber [Toledo, 1994]. Examples are the peach palm (*Bactris gasipaes*), indigenous to humid tropical Latin America, which produces food and animal feed from its fruits, ‘heart of palm’ from the apical meristem, medicines from its roots and wood for parquet floors [Clement, 1989; Szott et al., 1991; Mora Urpi et al., 1993; Villachica, 1994]. Other examples are camu-camu (*Myrciaria dubia*), a riverine Amazonian bush that produces berries with 40 times the vitamin C concentration of citrus [Peters and Vazquez, 1987; Peters, 1990; Ordoñez, 1994] and pygeum (*Prunus africana*), a tree from the African highlands whose bark produces an extract used as an ingredient in chemotherapy for prostate cancer [Cunningham and Mbenkum, 1993].

A wide variety of fruit trees are locally known but have limited international trade. They include the bush mango (*Irvingia gabonensis*) from the humid tropics of West Africa, which is traded regionally [Okafor, 1975]; cupuacú (*Theobroma grandiflora*) and arazá (*Eugenia stipitata*) from Amazonia [Clement and Villachica, 1994]; mahobohobo (*Uapaca kirkiana*), a source of wine in southern Africa [Maghembe et al., 1994], and karité (*Vitellaria paradoxa*), a Sahelian tree that produces oils used in the cosmetic industry [Bonkoungou, 1992].

Very little is known about how to convert most of these species into domesticated crops in agroforestry systems [Sinclair et al., 1994]. Research on reproductive biology and phenology is often in its infancy. Domestication in agroforestry consists of three stages [Leakey and Newton, 1994]. The first is the identification of potentially useful species through socioeconomic appraisal or ethnobotanical surveys [Franzel et al., 1995]. The second is the capture of germplasm by seed or vegetative propagation, followed by its conservation and selection, and the third is the incorporation into existing agroforestry systems. Instead of requiring many years as in traditional tree breeding, domestication can be done rapidly using the recently modified traditional horticultural techniques of vegetative propagation and clonal selection that maximize genetic diversity and minimize risk [Leakey, 1991; Leakey and Maghembe, 1995]. In the case of fruit trees, detailed physiological research is required to enable mature tissues to be easily propagated by cuttings [Leakey et al., 1994]. A list of species ICRAF is currently domesticating is shown in Appendix 3 as an example of the scope of such activities.

Domestication of indigenous fruit trees would in addition contribute to improved nutrition, particularly during the dry season when food supplies are limited and of low quality. Fruit of some of the species mentioned becomes available during the dry season (S. Minae, pers. comm.).

Marketing

Successful marketing of indigenous fruits and non-timber forest products is necessary for putting money in farmers' pockets [Toledo, 1994]. Market development of nontraditional products is best done by the private sector, but government policies can help remove key obstacles. An example is the relaxation of air freight regulations by the governments of Kenya and Zimbabwe, which opened European markets to horticultural products and flowers from these two countries [Tomich et al., 1994]. These issues were articulated at a recent workshop on the marketing of non-timber tree products (NTTPs), sponsored by the Alternatives to Slash-and-Burn Initiative (T. Tomich, pers. comm.). One conclusion was the need for policy-oriented research on the marketing of these products using existing methods rather than developing new methodologies. The research toolkits of agricultural economists and anthropologists are suitable for policy research on NTTP markets.

A second major conclusion was to focus on existing markets for NTTPs or on commodities for which NTTPs can be substituted. First, a demand must be created for new products, then the supply be created, not the other way around. The development of an international market for a totally new product, for example another kiwi fruit, is possible but risky. Perhaps the best approach is to expand on already existing national or regional markets, such as *Irvingia gabonensis* kernels in West Africa. Adoption is likely to be high when the products are already well known. It is easy, however, to saturate a local market by rapidly increasing production, causing prices to crash. Truly multipurpose trees also serve as a buffer against wide price fluctuations. *Bactris gasipaes* fruits can be used as animal feed when their price as food is low, or suckers can be allowed to grow from the base of the stem for heart-of-palm production. This is a major advantage over single-purpose trees like coffee.

Another approach is to focus on products that are ingredients of other products but not products themselves, for example, rubber or palm oil. The advantage is a wider market and less danger of market saturation. Environmentally friendly products can be successful, for example the 'green ivory' products of the tagua palm (*Phytelephas aequatorialis*) from the forests of Ecuador [Tangley, 1993]. Ingredients such as fruit concentrates or pulp and vitamin C are examples of this approach.

Regardless of approaches, research institutions should not undertake their own marketing initiatives to develop new NTTP markets. They should link with specialized NGOs and the private sector, who clearly have the comparative advantage, and back them up with policy research (T. Tomich, pers. comm.).

A way to promote long-term profitability is to ensure that processing or transformation facilities are located near the sources of production, so local communities benefit from the value added. This may be as rudimentary as simple drying and grinding facilities to transform products such as cassava roots, peach palm fruits and legume leaves into dried animal feed. The traditional on-farm coffee drying facilities of Colombia have been successfully adapted for such purposes in the Chapare region of the Bolivian Amazon. It does not make much sense to export water out of the humid tropics. Likewise pulp extraction of indigenous fruits and canning facilities for heart of palm exist in the Brazilian and Peruvian Amazon. Bark of the cinchona tree is no longer exported from Indonesia; a pharmaceutical facility at Bandung transforms it into quinine. These examples should gradually become the norm, as value-added products will strengthen rural communities.

Policy

Policy intervention is perhaps the most critical element for making agroforestry happen. Technology development is a necessary but not a sufficient condition for the widespread adoption of most agroforestry innovations. Policy research, therefore, is an essential component of science in agroforestry. Successful policy research in agroforestry must integrate two schools of thought, the traditional agricultural economics/agricultural anthropology approach with natural resource or environmental economics. When working in pure agriculture the author always enjoyed working with 'economists with chlorophyll', those who really understood farming. In agroforestry, they are much needed, but social scientists who are comfortable with the principles and jargon of soils, biodiversity and systems ecology are also necessary.

There are two broad kinds of policy research: policies to favor agroforestry's contribution to sustainable land use [Brooks et al., 1995], and those that aim to reverse existing perverse policies [Sanchez, 1994b]. Land and tree tenure, assistance to farmers during the time lag before trees become productive, and the valuation of environmental externalities are the three main policy research issues, each encompassing both kinds of policy research.

Tenure. Secure tenure, be it land tenure or tree tenure, is a prerequisite for planting trees and investing in agroforestry. Farmers are understandably reluctant to plant many trees if they are unsure about long-term access to their land. This is probably the first policy issue to consider [Gregersen et al., 1994]. There are often perverse policies related to land tenure; for example, no land titling without first deforesting the land; no rights to services when the land is classified as forest reserve even though farmers have used it for many generations [Sanchez, 1994b; Vosti and Witcover, in press]. Some common issues in Africa are the inability of women to plant trees, various disincentives of land fragmentation to tree planting and the conflicts between agroforestry plots and free cattle grazing [Place, 1994].

The time lag. One of the key policy issues is how to cope with the fact that economic returns from improved agroforestry systems are not likely to be realized during the first three to five years, before the trees become productive. What is the real discount rate farmers intuitively apply? Interventions to help farmers endure this difficult period before the trees exert their profitability and ecological functions is a major issue in agroforestry policy research. In some cases, farmers are perfectly willing to wait out this period, particularly when they have land tenure and fully value the importance of tree products or services. The challenge to policy research is to identify critical entry points and create appropriate incentives. One common constraint is access to planting materials. Incentives for tree nursery development by farmer groups with the use of the recommended germplasm is a high-priority policy research issue throughout the tropics. Recapitalization of soil fertility in nutrient-depleted lands is another.

Valuation of environmental externalities. Another major policy issue is how to reconcile the gap between the individual farmer's benefits and society's benefits arising out of agroforestry adoption, for example, improved water quality from erosion control. In such cases, society is likely to prefer more agroforestry than individual farmers may be willing to undertake. Policies can then be developed to provide additional incentives to farmers (F. Place, pers. comm.). The challenge to policy research is to identify the critical entry points, identify the benefits or costs external to the farm, assess their value and design mechanisms that create appropriate incentives for smallholders to incorporate environmental costs and benefits into their decisions (T. Tomich, pers. comm.). This challenge is not specific to agroforestry policy research; it applies to all natural resources research.

Sustainability

The concept of sustainability has profitability, productivity and environmental components, with a strong time dimension. Agroforestry systems that are profitable make farming systems more robust and less subject to perturbations. The diversity of outputs and the positive environmental attributes of trees on farms make them so. Although agroforestry interventions can make many agricultural systems more robust, the focus in this paper is on the less well-endowed areas where rainfall is erratic, the soil is not fertile, topography is difficult and farmers have limited land and capital resources. It is under such circumstances that agroforestry can show its mettle in terms of environmental sustainability, even with low use of external inputs. Sustainability can be described in terms of conserving the soil, enhancing biodiversity, conserving carbon in terrestrial ecosystems, and enhancing nutrient capture and retention.

Soil conservation

Keeping the soil resource in place is one of the major sustainability issues because it ensures site productivity and avoids negative downstream externalities such as siltation and eutrophication of surface waters and in some cases pollution of coastal marine resources. Several paradigm shifts are taking place in hillslope conservation management. Garrity and Van Noordwijk [1995] identified three: 1) the engineering approach has yielded to the biological approach; 2) the top-down watershed management approach is yielding to bottom-up approaches with a farmer or community focus; and 3) the pruned, leguminous alley-cropping concept of contour farming is diversifying toward a much wider array of contour hedgerow options.

Many agroforestry systems help keep the soil resource in place by biological instead of engineering means. Closely spaced trees on slopes reduce soil erosion by water through two main processes: first, as a physical barrier of stems, low branches, superficial roots and leaf litter against running surface water; second, as sites where water infiltrates faster because of generally better soil structure under trees than on adjacent land [ICRAF, 1994]. The scientifically acceptable evidence is overwhelming [Young, 1989a; Lal, 1989; Kiepe and Rao, 1994; ICRAF, 1994; Juo et al., 1994; and many others]. Trees, however, do not provide these functions until they are well established and have developed a litter layer [Sanchez et al., 1985]. Sequential agroforestry systems that include crops or ground cover while the trees are small can overcome this limitation.

Once established, most trees protect the soil constantly, provided they are healthy and the litter layer is not removed. Biomass transfer of tree leaf litter to cropped fields undermines this process [Nyathi and Campbell, 1993]. The perennial nature of tree root systems provides a dependable source of carbon substrate for micro-organisms in the rhizosphere; microbial mucilage binds soil particles into stable aggregates, which results in improved soil structure [Tisdall and Oades, 1982]. This important process takes place continually in agroforestry systems instead of temporarily, as in annual crop systems.

Some trees, however, exert a strong allelopathic effect on the underlying vegetation to the point that they actually promote erosion when their own litter layer is sparse. Black wattle (*Acacia mearnsii*) is one example; farmers in Tanzania regard it as an erosion-prone tree on slopes (K. Snyder, pers. comm.).

Trees also help control wind erosion by providing a physical barrier. Windy areas in many parts of the world have tree windbreaks. Two issues merit emphasis: one, the effect is not instantaneous; trees must develop first. Second, the key height against wind erosion is the first meter above the soil surface. Scientifically acceptable evidence about the effect of boundary plantings with trees in reducing wind erosion is available in the tropics [ICRISAT, 1990]. Windbreaks, however, can reduce crop production in adjacent areas when tree root systems extend into cropped fields. Very competitive trees such as neem (*Azadirachta indica*) and *Eucalyptus* spp. can decimate crop yields several meters away. Less competitive trees such as *Grevillea robusta* do not.

There is very clear evidence that contour hedges and alley cropping effectively control erosion as long as the hedges provide an effective barrier [Lal, 1989; Kiepe and Rao, 1994; Banda et al., 1994; ICRAF, 1994; Fujisaka et al., in press]. Erosion control can also be handled by other means, such as terraces, grass strips and ditches along the contour of slopes [Young, 1989a; Kiepe and Rao, 1994]. Contour hedges, often composed of fodder trees and grasses, also provide additional products such as fodder for farm animals, which is produced in areas that do not compete with crops. Fruit or timber trees grown as an upperstory in such contours also produce additional services and income [Garrity, 1993; Garrity and Mercado, 1994]. Contour hedges do require management although certainly less maintenance than earth terraces; the key is that they become a productive niche in the farm in addition to conserving the soil [Kiepe and Rao, 1994].

Controlling soil erosion biologically has an additional advantage: the slope between the hedges becomes less steep and even flat in some cases [Garrity, in press; Kiepe and Rao, 1994]. These 'biological terraces' are produced by taking advantage of the erosion process within the contour hedges, with the tree growth keeping up with the higher soil surface at the lower end, something nonbiological terraces cannot do. Scouring of the topsoil at the upper end of these terraces occurs, with detrimental effects on crop yields [Garrity, in press]. This is usually the result of hoeing downwards. Reversing uneven terrace productivity is a high-priority research issue in steeplands.

Soil conservation, although usually expressed in terms of physical sediment transport, has major fertility implications. For example, erosion and runoff accounts for about half of the negative nitrogen and phosphorus balance in typical Rwandan farms [Smaling, 1993]. This process, carried over decades of cultivation, is one of the main causes of the depletion of soil fertility in the uplands of Africa. Contour hedges can put a definite and lasting stop to that. Erosion control through agroforestry is a prerequisite to nutrient replenishment efforts. The use of phosphate rock as a capital investment in phosphorus-depleted soils of Africa [World Bank, 1994] must be accompanied by erosion control measures.

Enhancing biodiversity

Agroforestry systems are more diverse than crop or forest plantation monocultures. But the most important way agroforestry helps conserve plant and animal biodiversity lies in its preventive value, the savings in current biodiversity attained by reducing further clearing of tropical forests with the use of viable alternatives to slash-and-burn agriculture [Sanchez, 1994b; Schroeder, 1994; Vosti, 1995]. Farmers at the forest margins clear additional lands when their fields are no longer productive. One such alternative is the multistrata or complex agroforests where annual food crops are planted along with trees that eventually occupy different strata and produce high-value products such as fruits, resins, medicinals and high-grade timber. Food crops cover the ground quickly and grow until they are shaded out by the faster growing trees. There are many such multistrata systems throughout the humid tropics [Nair, 1989; Michon and de Foresta, 1990; Subler and Uhl, 1990; Sanchez, 1994b; Toledo, 1994]. For every hectare farmers put into such systems, several hectares of rainforest can be saved every year from the shifting cultivator's axe in the farmer's search for a livelihood. Precise estimates of these substitution values do not exist for agroforestry systems, although figures of 7.1 and 11.5 have been reported [Schroeder, 1993].

Agroforestry plays a major role in the reclamation of degraded and abandoned lands and is generally considered the most workable approach to mimic natural succession and increase biodiversity [Anderson, 1990]. Hard data on increasing biodiversity in degraded lands through agroforestry, however, are practically non-existent [Sanchez et al., 1994]. This is an important research imperative.

Agroforestry systems are more biodiverse above and below ground than monocultures, at least in the humid tropics. Plant diversity is in the order of 300 species per hectare in the mature complex rubber agroforests of Sumatra, Indonesia [E. Penot, pers. comm.). The level of plant biodiversity attained in such long-term agroforestry systems by far exceeds that of rubber plantations (5 species ha^{-1}) but is still less than that of adjacent undisturbed forests, with 420 plant species ha^{-1}. The richness of bird species in 50-year-old damar agroforests is 70% that of the original rainforest and almost all mammal species are present in the agroforest [Michon et al., in press]. This is possible because such agroforests, composed of hundreds of small plots managed by individual families, occupy contiguous areas of several thousand hectares in Sumatra. Tracks of the rare Sumatran rhino (*Dicerorhinus sumatrensis*) were recently discovered in one of these rubber agroforests, implying that they may provide a habitat similar to the natural rainforest [Sibuea, 1995]. Such high biodiversity levels, however, cannot be expected of shorter duration agroforestry systems, such as improved fallows or in less geographically extensive systems [Sinclair et al., 1994].

Below-ground biodiversity is higher in agroforestry systems than in crop monocultures, approximating the levels of the natural forest in the Amazon

[Lavelle and Pashanasi, 1989] as well as in Indonesia [Michon et al., in press]. Soil macrofauna and microflora are key regulators of the basic decomposition processes that provide nutrients to higher plants and animals, but methodological difficulties in their quantification remain. Microbial biomass is concentrated in the rhizosphere and in fertility 'hot spots', which soil analysis does not detect, but plant roots certainly do. It is difficult, however, to apply molecular biology methods to soil microbial biomass, because of the current inability of isolating DNA from soil organisms in sufficient quantity and purity [Coleman et al., 1994]. Overcoming these obstacles will enhance our understanding of microbial biomass diversity and its role in soil processes. While not as attractive as 'furry and feathered creatures', soil communities are a major and largely ignored component of biodiversity conservation and ecosystem functioning. Quantifying the effect of agroforestry interventions on below-ground biodiversity is a research imperative.

Maintaining carbon in the terrestrial ecosystem

Agroforestry systems play an important role in keeping carbon in the terrestrial ecosystem and out of the atmosphere. This is accomplished by preventing further deforestation and by accumulating biomass and soil carbon [Schroeder, 1994]. Few hard data, however, are available on the magnitude of these processes.

As in the case of biodiversity conservation, the main contribution of improved agroforestry systems to terrestrial carbon conservation comes from its preventive effect, that is, the area of natural forests that will not be cleared because farmers can make continuous use of already cleared land through improved agroforestry systems [Schroeder, 1993; Unruh et al., 1993; Sanchez, 1994b]. Recent estimates indicate that tropical deforestation contributes approximately 20% to global warming and that this percentage is expected to increase in the coming decades [Dale et al., 1993]. One hectare of humid tropical forests contains on average 160 t ha^{-1} of carbon in the above-ground biomass [Houghton et al., 1987]. When it is slashed and burned, most of the carbon is emitted to the atmosphere either immediately during the burn or gradually through the decomposition of unburned logs and branches. Keeping this carbon resource (some 96 billion tonnes in the remaining humid tropical forest biomass) in situ is of critical importance.

Complex agroforestry systems of long duration such as the jungle rubber and damar agroforests of Sumatra and multistrata systems throughout the humid tropics can sequester carbon in their tree biomass which remains sequestered for decades. Again, quantification is lacking.

Soil organic matter can act both as a source and a sink of carbon. Contrary to popular opinion, total soil organic matter contents are not uniformly low in the tropics [Sanchez and Buol, 1975]. Soils contain as much carbon as the above-ground vegetation in humid tropical forest ecosystems, an average of 145 t ha^{-1} of carbon [Sombroek et al., 1993]. Deforestation increases topsoil carbon emissions to the atmosphere because of higher soil temperature, which leads to accelerated organic matter decomposition [Swift et al., 1979].

Topsoil carbon decreases of 25 to 40% are commonly measured in the top 25 cm during the first two to three years after slash-and-burn following conversion to agriculture, pastures or tree plantations [Sanchez et al., 1983, 1985]. Afterwards soil carbon will either reach equilibrium, increase or decrease, depending on the quantity and quality of organic inputs, including crop residues and the decomposition rate of soil organic matter [Sanchez et al., 1989]. In the cases of continuous cropping and plantation forestry, evidence indicates real decreases in topsoil carbon [Sanchez et al., 1983, 1985]. In the case of improved pastures, however, increases have been recorded [Serrão and Toledo, 1990; Serrão, 1993]. Similar increases also happen in mature secondary forest fallows that approximate the biomass level of primary forests [Nye and Greenland, 1960]. There are, however, no hard data about topsoil carbon dynamics in agroforestry systems.

Subsoil carbon is a major pool in tropical soils because of the considerable depth of the dominant soils of the humid and subhumid tropics. Amounts of subsoil carbon in the soil layer at 25–200 cm depth are about twice as large as the amounts found in the top 25 cm of the dominant Oxisols and Ultisols of the Amazon. This is because the greater volume of the subsoil more than compensates for its lower carbon concentration [Sombroek et al., 1993]. Subsoil carbon contents generally do not decrease upon deforestation and can actually increase with new land-use systems that bring extensive root systems to depths that were previously essentially devoid of roots. This is the case with the introduction of aluminum-tolerant grasses in the Llanos Orientales of Colombia. Fisher et al. [1994] report that grass–legume pastures of *Andropogon gayanus–Stylosanthes capitata* and *Brachiaria humidicola–Arachis pintoy* sequestered an additional 34 t C ha^{-1} in the subsoil layer at 40–100 cm depth in 9 to 13 years of grazing. They attribute the additional carbon to root turnover of the grasses that developed deep root systems in these aluminum-toxic Oxisols.

Trees certainly develop deep root systems in semi-arid areas but not so much in the humid tropics, where water is more available and where nutrients are concentrated in the topsoil. Thus, trees may perform a carbon-sequestration function similar to that of the aluminum-tolerant tropical pastures. Root studies in Pucallpa, Peru, indicate that peach palm (*Bactris gasipaes*) has as extensive but deeper rooting pattern than the aluminum-tolerant grass *Brachiaria dictyioneura* [Riesco and Ara, 1994]. The deep-rooting pattern of leguminous fallows in southern Africa could also result in carbon sequestration. The accumulation of root dry matter in the top 100 cm of an Alfisol in Zimbabwe by two year *Sesbania sesban* and *Acacia angustissima* fallows was 3 and 6 t ha^{-1}, respectively [B. Dzowela, unpub. results]. Data should be gathered on this important topic in agroforestry systems, in both humid and drier areas.

Soil organic carbon consists of a series of functional pools or fractions that perform different functions [Parton et al., 1994]. The more active fractions are responsible for nutrient release processes while the slow and passive fractions are more responsible for soil structure development and maintenance. The decomposed products of the organic input are distributed in the different pools, depending on litter quality, soil texture and clay mineralogy. The effect of agroforestry systems on the distribution of newly fixed carbon into the different pools is just beginning to be studied [Barrios et al., in press]. For carbon sequestration, the aim is to increase the size of the slow and passive soil carbon pools, since most of the carbon added to the active pools will decompose in less than two years.

In most agroforestry systems, carbon sequestration should be considered a byproduct rather than the principal objective. The magnitude of carbon sequestration by agroforestry, however, is considered among the highest of land-use systems by climate change researchers. Unruh et al. [1993] performed complex calculations of agroforestry systems in Africa, their biomass accumulation and their potential distribution using GIS techniques. Their results suggest a huge amount of carbon can be sequestered, ranging from 8 to 54 Gt (billion tonnes) of C in a total of 1.55 billion hectares where agroforestry could potentially be practised. Above-ground biomass would sequester 3–15 t ha^{-1} of C, while soil and root biomass would sequester an additional 1.3–6.5 t ha^{-1} of carbon. Another estimate by Schroeder [1993, 1994] suggests above-ground accumulation rates of 9 t C ha^{-1} in five years for the semi-arid tropics, 21 t C ha^{-1} in eight years for the subhumid tropics and 50 t C ha^{-1} in five years for the humid tropics but gave no below-ground estimates. Above- and below-ground carbon sequestration values, therefore, need to be generated locally, taking into account the duration of each agroforestry system, and extrapolated geographically in a realistic fashion, based on actual rates of agroforestry adoption.

Enhancing nutrient capture and retention

Soil nutrients are considered among the least resilient components of sustainability [Fresco and Kroonenberg, 1992]. A fundamental principle of sustainability, therefore, is to return to the soil the nutrients removed from it through harvests, runoff, erosion, leaching, denitrification and other loss pathways [Sanchez, 1994a]. Nutrient budgets are a tool for determining whether there is an adequate balance or whether nutrients are being depleted. In natural rainforest ecosystems the nutrient balance is adequate, while in intensively fertilized cropping systems of the temperate region a large, positive balance results in nitrate and phosphorus pollution [Sanchez, 1994a]. In the small farms of Africa, the net balance of nitrogen, phosphorus and potassium is negative, which is responsible for the widespread nutrient depletion throughout tropical Africa [Smaling, 1993]. Can agroforestry help? Early results are encouraging, particularly for nitrogen.

Nitrogen. Trees can provide additional nitrogen inputs via two processes: biological nitrogen fixation (BNF) and deep nutrient capture. Although the magnitude of BNF is methodologically difficult to quantify, some studies give ample proof of it [Ladha et al., 1993]. Empirical evidence, such as presence of active nodules and nitrogen uptake of leguminous species of the Papilionaceae and Mimosaceae families, suggest that BNF can supply considerable nitrogen inputs to crops via litter, in soils sufficiently well supplied with phosphorus. This is a definite nutrient input.

Deep nutrient capture is the uptake of nutrients by tree roots at depths where crop roots are not active. It can be considered an additional nutrient input in agroforestry systems, because such nutrients are leached as far as the crop is concerned. They become an input upon being transferred to the soil via tree litter decomposition. Evidence of this process in *Faidherbia albida* parklands has been described in earlier sections of this paper. An exciting dimension has recently been discovered in western Kenya for subsoil nitrate in nitrogen-deficient Nitisols (red Alfisols and Oxisols with high iron content). Hartemink et al. [in press] detected nitrate levels in the order of 120 kg N ha^{-1} in the 50–200-cm layer. They also found that *Sesbania sesban* fallows depleted this pool, thus capturing a resource that was unavailable to maize. The source of this nitrate pool is believed to be the result of the mineralization of topsoil organic nitrogen, which is relatively high in these soils; subsequent nitrate leaching from topsoil layers, particularly at the start of the rainy season; and nitrate sorption by positively charged subsoil clay surfaces. What the trees have done in effect is to expand the volume of soil used by a considerable amount [Cahn et al., 1992].

Nitrogen-fixing trees may have been oversold in comparison with non-fixing trees, particularly those of the Caesalpiniaceae family [Garrity and Mercado, 1994]. There is ample evidence that non-fixing trees, including several species of *Cassia (Senna)*, accumulate as much or more nitrogen in their leaves than nitrogen-fixing legumes, presumably because of their greater root volume [Szott et al., 1991; Garrity and Mercado, 1994].

Can agroforestry, through BNF and deep nutrient capture, eliminate the need for application of nitrogen fertilizers to crops? The answer depends largely on crop yield-level expectation. A typical maize crop in smallholder African farms yields 1 t ha^{-1} of grain and requires a plant accumulation of about 40 kg N ha^{-1}. A crop of 4 t ha^{-1} requires 80 kg N ha^{-1}, and a crop of 7 t ha^{-1} requires 200 kg N ha^{-1} [Sanchez, 1976]. Topsoil nitrogen mineralization provides an average input of about 30 kg N ha^{-1}, which approximates to the needs of a maize crop of 1 t ha^{-1}. Nitrogen inputs from 4 t ha^{-1} of leguminous leaf mulch dry matter range from 60 to 150 kg N ha^{-1} [Palm 1995, this issue]. This mulch input rate is a realistic one and the one actually recorded in the *Sesbania seban* improved fallows in Chipata, Zambia, discussed previously, which added 128 kg N ha^{-1} to the maize crop, resulting in a 4 t ha^{-1} maize yield. The fertilizer recommendation in that area is 112 kg N ha^{-1} , about the same as the nitrogen added by the *S. sesban* fallow.

Since the recovery of leguminous leaf nitrogen incorporated into the soil is about the same as fertilizer N (about 20 to 50%, Palm [1995, this issue]), agroforestry can replace fertilizer nitrogen applications at the grain-yield level for maize of 4 t ha^{-1}. At high yield levels comparable to commercial farms in the industrialised world, say 7 t ha^{-1}, organic nitrogen inputs are likely to be insufficient and must be supplemented by inorganic fertilizers [Szott and Kass, 1993]. The interaction between organic and inorganic sources of nutrients is essentially a new subject of research in the tropics. Very little is known about it, because previous research has mainly compared one source against the other.

Organic inputs, however, have an important advantage over inorganic fertilizers in sustainability terms. Much of the remaining 50 to 80% of the applied organic nitrogen not utilized by crops is incorporated into active pools of soil organic matter, because these mulches also provide a carbon source needed as energy for microbial immobilization [Palm, 1995, this issue]. Readily available or soluble carbon is often low in nutrient-depleted soils, even though the total organic matter contents appear normal. Soil micro-organisms need a carbon substrate to form organic nitrogen. Inorganic fertilizers do not contain such carbon sources; therefore, most of the fertilizer nitrogen not used by crops is subject to leaching and denitrification losses, while much of the nitrogen released from organic inputs and not utilized by crops will be ‘saved’ as soil organic nitrogen.

The slow accumulation of soil organic nitrogen with agroforestry organic inputs is likely to make a difference in terms of long-term sustainability. This strategy is not new and has been used for centuries in temperate-region agriculture, with crop rotations and winter leguminous cover crops. What is new is the potential to do something similar in the tropics with low-input systems that fit with farmer perspectives. The potential for improved nitrogen management needs to be quantified in agroforestry systems by measuring processes such as mineralization, immobilization, denitrification, volatilization and leaching, along with changes in the soil organic nitrogen pools in systems combining organic and inorganic sources of nitrogen.

Phosphorus. Agroforestry, however, cannot supply most of the phosphorus inputs required by crops. Deep capture of phosphorus is likely to be negligible because of the very low concentration of available phosphorus in the subsoil. Improved fallows and other sequential systems do accumulate phosphorus in their biomass and return it to the soil via litter decomposition. But this is recycling and does not constitute an input from outside the system. This situation is compounded by the physiological fact that most of the phosphorus accumulated by cereal crops and grain legumes is in the grain and is thus removed from the soil at harvest. The proportion of phosphorus recycled back to the soil in basic grain crops, assuming complete crop residue return, is in the order of 38%. Comparable figures for other nutrient elements are 54% for nitrogen, 89% for potassium, 95% for calcium and 70% for magnesium

[Sanchez and Benites, 1987]. Therefore, phosphorus is often the key critical nutrient in agroforestry and other low external-input systems.

Leguminous mulches applied at a realistic rate of 4 t ha^{-1} provide 8 to 12 kg P ha^{-1}, about half the phosphorus requirements of a maize grain crop of 4 t ha^{-1}, which accumulates 18 kg P ha^{-1} [Palm et al., 1991; Palm, 1995, this issue]. Therefore, inorganic sources of phosphorus must be applied to agroforestry systems in soils depleted of this element. The strategy is to utilize at maximum all the available organic sources first, including manures, and supplement the difference with phosphorus fertilizers [Sanchez, 1994a]. Interactions between organic and inorganic sources of phosphorus also need to be quantified.

In soils with high phosphorus fixation capacity by iron and aluminium oxides (which can usually be identified as having red, clayey topsoils) a different strategy is possible. Large applications of indigenous rock phosphates may replenish the phosphorus supply of these soils, the phosphates being gradually released by desorption from the oxide clay surfaces to plants for the next five to ten years. This is being considered as a new approach, investing in natural resource capital [World Bank, 1994].

The soil conservation dimension of many agroforestry systems ensures that nutrient inputs added through biological nitrogen fixation, deep nutrient capture or phosphorus fertilizers are not lost by runoff and erosion. A phosphorus investment program that does not include contour hedges or other erosion control technologies is likely to do more harm than good.

Nutrient budgets. Individual nutrient budgets at the field scale are useful, but whole-farm nutrient budgets are better. Small farms in Kenya often mix crop with milk production in zero-grazing systems, with several nutrient compartments and flows between them. Examples are the cropped fields, patches of napier grass (*Pennisetum purpureum*), contour hedges, boundary plantings, the cattle enclosure (boma) and a compost pile where some crop residues and household waste are added. Shepherd et al. [in press] modelled nutrient budgets for conventional practices and improved agroforestry systems, which consisted of fodder legumes as contour hedges and under large trees along boundaries for livestock feed, and nitrogen and phosphorus fertilizers for the grain crops. The results, presented in Table 5, show the different compartments that were measured or estimated as an example of the type of data that should be collected. Agroforestry interventions decreased the net negative nitrogen balance from –76 to –45 kg N ha^{-1} a^{-1} but transformed a net negative phosphorus balance of –3.8 kg P into a positive 9.4 kg P ha^{-1} a^{-1}. Although the results are far from ideal, they suggest that agroforestry systems can improve nutrient balance.

One way to balance nutrient budgets is with fertilizer applications in agroforestry systems. Fertilizer response has been most commonly reported in alley-cropping systems and perennial shade systems [Szott and Kass, 1993]. Nutrient balances in alley cropping are usually negative, particularly with

Table 5. Annual soil N and P budgets for the field compartment in an existing farm system and an improved agroforestry system in Western Kenya. *Source:* Shepherd et al., in press.

Components	kg N ha^{-1} a^{-1}		kg	
	Existing	Improved	Existing	Improved
Rock weathering	–	–	0.1	0.1
Deep uptake	0	69	–	–
Biological fixation	6	69	–	–
Asymbiotic fixation	4	4	–	–
Atmospheric deposition	6	6	1.0	1.0
Fertilizer application	0	115	0	35.0
Sum inputs	16	263	1.1	36.1
Faeces deposited	3	0	0.5	0
Urine deposited	2	0	–	–
Manure from boma	3	31	0.4	6.7
Urine from boma pit	0	31	–	–
Compost	6	116	2.0	27.0
Sum transfers in	14	178	2.9	33.7
Denitrification	22	39	–	–
Volatilization	2	0	–	–
Leaching	39	69	–	–
Sum outputs	63	108	0	0
Tree leaf fed to animals	0	48	0	2.4
Fuelwood	0	4	0	0.3
Crop harvest, fodder	0	224	0	45.1
Crop harvest, grain	26	75	3.5	9.9
Crop residues, fodder	4	27	0.4	2.7
Crop residues, fuel	2	0	0.2	0
Erosion to hedgerow	11	0	3.7	0
Sum transfers out	43	378	7.8	60.4
Balance	–76	–45	–3.8	+9.4

phosphorus [Palm et al., 1991; Woomer et al., in press], so fertilizer responses are common. Intensive fertilization is the norm in the very successful multistrata systems practised by descendants of Japanese settlers in the Amazon of Brazil, commonly referred to as the paragon of sustainability in that region [Subler and Uhl, 1990].

Conclusions

Agroforestry is well on its way to becoming a specialized science at a level similar to that of crop science, but is perhaps more exciting because of its multidisciplinary mix. The advances in process-oriented research since the beginning of this decade are impressive, but there is still a long way to go. The major gaps are research dealing with complexity, profitability and sustainability (both biophysical and socioeconomic) and in the development of testable hypotheses in socioeconomic aspects. The following research needs were outlined in the four sections of this paper and are summarized below.

Competition

- The biophysical research hypotheses listed in Appendix 1 must be thoroughly tested in specific agroforestry systems under a representative range of biophysical and socioeconomic conditions.
- The tree–crop interaction equation needs further conceptual development, particularly in relation to sequential systems.
- Long-term trials with the four key treatments of this equation need to be conducted in agroforestry systems, including the *Faidherbia albida* parklands.
- Particular care needs to be given to experimental design in agroforestry to avoid root interference between experimental plots.
- Process-oriented research on silvopastoral systems remains a major gap in work among the types of agroforestry systems.
- The processes responsible for major crop-yield increases in promising sequential systems and their socioeconomic implications must be thoroughly understood and quantified before they are recommended for wide-scale adoption.

Complexity

- Process-oriented research on socioeconomic complexities should be strengthened, particularly research on how households or communities react to policy environments.
- Characterization and diagnosis studies should be *participatory, analytical and multidisciplinary*, with due attention to indigenous knowledge and gender issues.
- Geographic information systems help organize data at the different spatial scales needed in agroforestry research.
- Research on the dynamics of pest-predator-disease interactions needs to be systematically initiated.
- Reliable and straightforward ways for measuring soil processes and root interactions need further development.
- High priority should be given to developing robust agroforestry models based on hard data, now that such data are becoming increasingly available.

Profitability

- Domestication of tropical tree species that produce high-value products such as fruits, medicines and high-grade timber is a research approach that will increase money in farmers' pockets and in some cases improve human nutrition.
- Market development of new, non-timber forest products is best done by NGOs or the private sector.
- Policy research on market development should focus on existing markets, on ingredients rather than totally new products and on local transformations for value-added production.
- Policy research is an essential component of science in agroforestry and a prerequisite for adoption, in most circumstances. Priority research areas are land or tree tenure, assistance to farmers during the time-lag before trees become productive, and the valuation of environmental externalities.

Sustainability

- Soil conservation is undergoing several paradigm shifts that require modifications in the research agenda: the engineering approach has yielded to the biological approach; the top-down watershed approach is yielding to bottom-up farmer- or community-focused approach; and the alley-cropping concept of contour farming is diversifying into an array of contour hedge options.
- Estimates of substitution values of agroforestry in preventing additional deforestation need to be developed to assess positive externalities of biodiversity conservation and prevention of greenhouse gas emissions.
- Hard data need to be collected on the increases in plant and animal biodiversity upon reclaiming degraded lands through agroforestry.
- The effects of agroforestry interventions on below-ground biodiversity need to be quantified.
- Above- and below-ground carbon sequestration values need to be generated locally, taking into account the duration of each agroforestry system, and extrapolated geographically based on realistic rates of agroforestry adoption.
- Several agroforestry systems can meet the nitrogen requirements of moderate yields of grain crops. Quantification is needed on factors affecting components of the nitrogen cycle, including the magnitude of inputs from biological N fixation, deep nitrate capture, litter decomposition and the fate of nitrogen not taken up by the crop but used to build soil organic nitrogen capital.
- As agroforestry is unable to meet about half of the phosphorous requirements of such crops, research should focus of the interaction between

organic and inorganic phosphorus inputs, using rock phosphates as an investment in nutrient capital.

The alley-cropping experience has done considerable harm to the reputation of agroforestry research, but scientists have learned much from it in terms of research approaches and methodologies. Care must be taken not to oversell the new and exciting technologies currently being developed, and to ensure that the biophysical and socioeconomic processes involved are satisfactorily understood. It is hoped that as confidence increases with time, new, scientifically solid results will become the norm rather than the exception in agroforestry research.

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Note

1. Kang et al., 1981, 1985; Yamoah et al., 1986; Mulongoy and Van der Meersch, 1988; Lal, 1989; Atta-Krah, 1990; Kang et al., 1990; Lawson and Kang, 1990; Palm and Sanchez, 1990, 1991; Ong et al., 1991b; Szott et al., 1991; Hariah et al., 1992; Fernandes et al., 1993; Haggar et al., 1993; Hauser, 1993; Kang, 1993; Rao et al.,1993; Salazar et al., 1993; Jabbar et al., 1994; Juo et al., 1994; Kass et al., in press; Sanginga and Mulongoy, in press; Palm, 1995, this issue, and many others.

Appendix 1

Biophysical agroforestry hypotheses. Adapted from the following sources: Hypotheses 1–10 from Young [1989b]; 11 from Wilson [1990]; 12 from Van Noordwijk and Dommergues [1990]; 13–18 from Ong et al. [1995].

Hypothesis	Status and references
1. Agroforestry systems can control soil erosion.	1. Proven in contour hedgerows and multistrata systems [Roose, 1970; Lal, 1989; Young, 1989b; Alegre and Fernandes, 1991; Banda et al., 1994; ICRAF, 1994: 80–88; Juo et al., 1994]; Kiepe and Rao, 1994.

Appendix 1 (Continued)

Hypothesis	Status and references
2. Agroforestry systems can maintain soil organic matter (SOM] at levels satisfactory for soil fertility.	2. Not proven. Too simplistic, since there are no reliable SOM levels related to satisfactory soil fertility. SOM increases have been detected temporarily in sandy soils under alley cropping [Lal, 1989; Kang et al., 1990;] but not for other soils [Rao, in press]. Relevant proof should be in terms of functional SOM pools in relation to system nutrient uptake and overall productivity.
3. Agroforestry systems maintain more favorable soil physical properties than agricultural systems.	3. Partially proven, for soils under contour hedgerows in relation to adjacent cultivated fields [Van Noordwijk et al., 1992; ICRAF, 1994: 85–86].
4. Nitrogen-fixing trees can substantially augment nitrogen inputs in agroforestry systems.	4. Proven [Ladha et al., 1993]. Limited quantification of N-fixation by legume species and subsequent biomass N accumulation and return to the soil via litter.
5. Trees in agroforestry systems provide deep nutrient capture from subsoil layers that are inaccessible to crop roots.	5. Proven for deep nitrate capture in oxic subsoils with positive charge [Hartemink et al., in press; ICRAF, 1995]. Not yet proven widely and unlikely to be relevant in other infertile subsoils.
6. Agroforestry systems can lead to more closed nutrient cycling and to more efficient use of nutrients and less leaching losses.	6. Not quantitatively proven. Highly probable in many systems, but the data are not there.
7. The cycling of bases accumulated by trees in agroforestry systems and returned to the soil as litter can help reduce soil acidity.	7. Proven for litter high in calcium and magnesium in non-agroforestry systems [Sanchez et al., 1985]. Decomposition of leaf litter produces metabolic organic products that temporarily complex aluminum in the soil solution thus decreasing soil acidity, for short time periods [Davelouis et al., 1991; Wong et al., in press].
8. Agroforestry is a useful component of systems for the reclamation of degraded soils.	8. Too general, probably will be proven in many circumstances. Proven for saline and alkaline soils [Singh et al., 1994] Proven for nitrogen-depleted soils of Eastern Zambia with sesbania fallows [Kwesiga and Coe, 1994].
9. The role of tree roots is as important as that of above-ground biomass in soil fertility maintenance.	9. Not proven. An important research topic.
10. Shade from tree canopy improves soil biological activity and nitrogen mineralization.	10. Proven [Wilson, 1990; ICRAF, 1993: 58–60].

Appendix 1 (Continued)

Hypothesis	Status and references
11. Roots of N-fixing trees have more nodules when in close contact with roots of non N-fixing plants. This may lead to direct N transfer to the non-nodulating plant.	11. Not proven. Highly controversial.
12. Annual crops are unable to use all water stored in the soil.	12. Proven for shallow rooted crops [Ong et al., in press].
13. The combination of trees and crops greatly enhances rainfall water use.	13. Proven [ICRAF, 1994: 67–73; Ong et al., in press].
14. Because agroforestry systems use more water than annual cropping systems, they should increase primary productivity.	14. Being tested; depends on competition.
15. There is less competition between tree and crop species that develop canopies at different times.	15. Proven [Dalal, 1974].
16. Competition for water in agroforestry systems can be reduced by modifying the spatial arrangement of trees.	16. Proven [ICRAF, 1994: 67–73].

Appendix 2

Socioeconomic and ecological guiding principles and hypotheses in agroforestry research, developed by ICRAF Programme 1 staff. Adapted from Izac [1994], and A.-M. Izac, pers. comm.

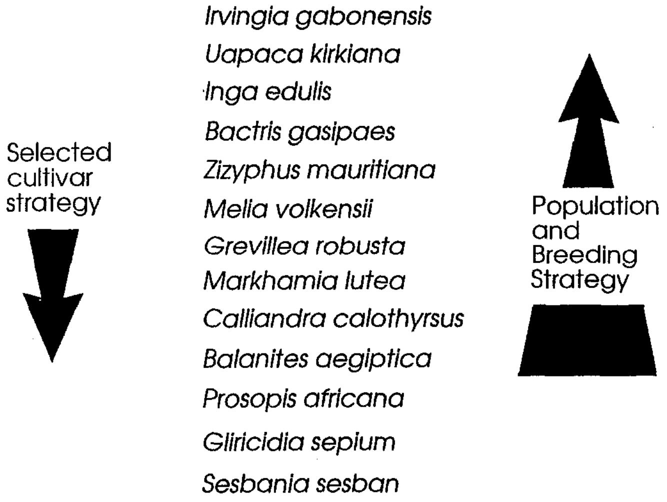
1. The identification of key driving socioeconomic and ecological processes within land-use typologies permits the spatial delineation of target and recommendation domains for agroforestry interventions.
2. Defining land use typologies across the landscape (based on parameters such as soils, climate, population density, level of market integration, policy level and the policy environment), is a prerequisite to the development and targeting of effective agroforestry interventions.
3. The adoptability of a new agroforestry practice is determined by five principal components: the farmers' natural resource base, their resource endowment, degree of market integration, cultural preferences and perceived benefits.
4. At the farming systems scale, agroforestry adoption has different impacts for different classes of farmers such as their gender.
5. Farmers are principally interested in the on-farm profitability and risk buffering capacity of agroforestry systems, while society is principally interested in the resilience, sustained productivity and biodiversity of these systems on the watershed and regional scales.

Appendix 2. (Continued).

6. Adoption of agroforestry practices usually necessitates policy changes that reconcile individual and social interests and benefits. The private benefits of agroforestry are restricted by policy and market constraints. Policy reform addressing such constraints will enhance the adoption of agroforestry.
7. Adoption of new agroforestry practices is principally a strategy for increased household welfare; adoption can be measured in terms of increased productivity, decreased risk and uncertainty, diversification of output, increased nutrient cycling efficiency, and securing land tenure.
8. Agroforestry interventions can lead to ecologically sustainable systems which at the same time are sufficiently productive and profitable to decrease rural poverty.
9. Policy interventions focusing on the maintenance of biodiversity at the landscape patch level can reduce pest outbreaks and enhance adoption of agroforestry.
10. The positive ecological and social impacts of agroforestry are superior in marginal soils, steep slopes, degraded lands, forests and desert margins compared to impacts on fertile lands.

Appendix 3

Summary of ICRAF's current domestication activities.



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