

Soil-plant interactions in agroforestry systems

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ABSTRACT

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Too often soils and their constraints are ignored when designing or evaluating agroforestry systems. This paper reviews the nature of soil constraints in the humid and semi-arid tropics and how these limitations affect plant/soil interactions related to nutrient additions, losses, and cycling via litter-soil organic matter (SOM) pathways in agroforestry systems. The ability of agroforestry systems to enhance nutrient availability on infertile soils is very limited compared to systems on fertile soils. On both, however, agroforestry systems can play an important role in reducing nutrient losses. Litter production and quantities of nutrients recycled in litter are greater on fertile than on infertile soils, however, management techniques for accelerating nutrient fluxes through pruning appear to hold promise for increasing plant productivity on the latter soils. Much more information is needed on the magnitude of and controls on below-ground litter production and how it can be managed. Litter decomposition and SOM dynamics in agroforestry systems might most easily be manipulated by managing woody vegetation to produce organic residues of a certain quality and to regulate soil temperature and moisture. More attention needs to be paid to specific SOM pools, their importance in nutrient supply and soil structure, how they are affected by soil properties, and how they can be managed.

INTRODUCTION

Agroforestry systems are expected to play a major role in tropical agricultural development in the coming years. These systems usually have low capital requirements, produce a range of economically useful goods, and may aid in maintaining soil nutrient levels, reducing erosion, and conserving water (Lundgren and Raintree, 1983; Nair, 1984). The latter 'service' roles of agroforestry are apt to be especially important in maintaining the productivity of land already in production as well as the approximately 200 million hectares of mostly marginal soils that will be brought into cultivation for the first time

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TABLE I

Soil characteristics and classification according to The Soil Taxonomy System and FAO¹

Soil Taxonomy	FAO	Description
Oxisols	Ferralsols and Plintisols	Deep, highly weathered, acid, low base status soils. Excellent structure and good drainage. No significant increases in clay with depth
Ultisols	Acrisols, Dystric, Nitisols and Alisols	Similar to Oxisols except for a clay increase with depth. Similar chemical limitations. Textures from sandy to clayey
Inceptisols	Various:	Young soils with A-B-C horizon development. Fertility highly variable
Aquepts	Gleysols	Poorly drained moderate to high fertility
Tropepts	Cambisols	Well-drained Inceptisols (Dystropepts = acid, infertile; Eutropepts = high base status)
Andisols	Andosols	Volcanic soils, moderate to high fertility, P fixation by allophane
Entisols	Various:	Young soils without A-B-C horizon development; generally high fertility except for sandy soils
Fluvents	Fluvisols	Alluvial soils usually of high fertility
Psamment	Arenosols and Regosols	Sandy, acid, infertile soils
Lithic groups	Leptosols	Shallow soils
Alfisols	Luvisols, Eutric, Nitisols, Planosols and Lixisols	Higher base status than Ultisols, but similar otherwise. Includes the more fertile tropical red soils. Dominant soil of west African subhumid tropics and savannas
Histosols	Histosols	Organic soils (> 20% organic matter). Peat soils
Spodosols	Podzols	Sandy surface horizon underlain with a horizon composed of organic and amorphous C, Fe, and Al compounds. Acid and infertile
Mollisols	Chernozems	Black fertile soils derived from calcareous materials
Vertisols	Vertisols	Dark heavy clay soils that shrink and crack when dry. Moderately high base status
Aridisols	Solonchak and Solonetz	Main limitation is moisture availability

¹Source: Sanchez et al. (1985), and Sanchez (1989).

in the remainder of this century (Dudal, 1980). In this fashion, agroforestry systems will play an important role in reducing deforestation and the negative consequences associated with forest conversion.

Hypotheses related to the soil-improving abilities of agroforestry systems have been formulated, favorable or contrary evidence reviewed, and common sources of conceptual errors identified (Nair, 1984; Sanchez, 1979, 1987; Sanchez et al., 1985; Huxley, 1986; Young, 1987, 1989; Szott et al., 1991). It is clear, though, that despite the rapid pace of agroforestry-related research during the last decade, scientific data required for the objective evaluation of most hypotheses are still lacking (Sanchez, 1987; Young, 1987, 1989). Moreover, there needs to be greater consideration of basic soil/plant interactions and processes which affect sustainability and performance of agroforestry systems and how these processes vary with soil type.

Given the recent nature of the above-mentioned reviews, it is not our intention to repeat them. Rather, we intend to identify some key soil/plant processes and how they are expected to vary with soil type. The Soil Taxonomy System (Soil Survey Staff, 1975) will serve as a basis of our discussion of soil properties since quantitative properties of soils are used as an objective basis for classification in this system (Table 1). Our emphasis will be on soils and agroforestry systems found on infertile soils of the humid tropics, but those in the subhumid and semi-arid tropics will also be considered.

SOILS DISTRIBUTION AND CONSTRAINTS

All eleven soil orders are found in the tropics (Table 2). In brief, acid infertile soils (Oxisols, Ultisols and Dystrypepts) dominate the humid tropics, with greater relative importance in Latin America (82%) than in Africa (56%) or Asia (38%). Conversely, humid tropical Asia has the largest proportion (33%) of soils of moderate to high fertility (Alfisols, Vertisols, Mollisols, Andisols, Eutropepts, and Fluvents) vs 12% and 7% for tropical Africa and America, respectively. Unlike Africa, however, most fertile soils in Asia are already under cultivation. Finally, 'problem' soils with severe management limitations (Spodosols, Lithosols, and Psammments) are least prevalent in Latin America (5%) and most widespread in Asia (22%), Sanchez (1989).

In the humid tropics, the main constraints to plant production are chemical in nature: low exchangeable base contents, low nutrient reserves, high aluminum toxicity, low phosphorus availability, and mild acidity (Table 3). All these constraints exist to varying degrees in Oxisols, Ultisols and Dystrypepts. Ultisols, however, are apt to have larger problems with aluminum toxicity as a result of their higher exchangeable aluminum contents, whereas levels of potassium, calcium, and magnesium are apt to be exceedingly low in Oxisols. Phosphorus fixation is high, hence phosphorus availability is low, on Oxisols and Andisols. Phosphorus and nitrogen availability are common

TABLE 2

Geographic distribution of soil orders in the tropics, based on the dominant soil in FAO maps at a scale of 1:5 million¹

Soils	Tropical America	Tropical Africa	Tropical Asia and Pacific	Total (million ha)
Oxisols	502 (332) ²	316 (179)	15 (14)	833 (525)
Ultisols	320 (213)	135 (69)	294 (131)	749 (413)
Entisols	124 (31)	282 (91)	168 (90)	574 (212)
Fluvents	(6)	(10)	(34)	(50)
Psamments	(6)	(67)	(17)	(90)
Lithic groups	(19)	(14)	(39)	(72)
Inceptisols	204 (61)	156 (75)	172 (90)	532 (226)
Aquepts	(42)	(55)	(23)	(120)
Tropepts	(17)	(19)	(58)	(94)
Andisols	31 (2)	1 (1)	11 (9)	43 (12)
Alfisols	183 (18)	198 (20)	180 (15)	559 (53)
Vertisols	20 (1)	46 (2)	97 (2)	163 (5)
Aridisols	30 (3)	1 (1)	56 (1)	87 (5)
Mollisols	65 -	0 -	9 (7)	74 (7)
Histosols	4 (4)	5 (4)	27 (23)	36 (31)
Spodosols	10 (10)	3 (3)	7 (6)	20 (19)
Total	1493 (673)	1143 (444)	810 (379)	3670 (1496)

¹Source: Sanchez and Salinas (1981), and Sanchez (1989).

²Numbers in parentheses are totals for the humid tropics.

problems in Vertisols. Sandy soils (Psamments and Spodosols) are especially low in nitrogen; phosphorus and bases may also be low.

Steep slopes and shallow soil depth are the chief physical constraints to plant production in the humid tropics. Some Oxisols have low water-holding capacity and some sandy Ultisols that have a sharp increase in clay with depth are particularly susceptible to erosion. Shrinking and swelling problems constrain production on Vertisols (Sanchez, 1989).

In the subhumid and semi-arid tropics, it is often assumed that moisture availability is the over-riding constraint to plant production, but low nutrient reserves, aluminum toxicity and soil acidity also limit plant productivity over large areas (Table 3). Many semi-arid systems are nitrogen or phosphorus limited as well (Felker et al., 1980; Penning de Vries et al., 1980; Lathwell and Grove, 1986; Tropsoils, 1987).

Differences in patterns of exchangeable aluminum among the major soil orders deserve further consideration since aluminum is toxic to plants and can severely restrict root growth and nutrient uptake. In Ultisols, aluminum saturation in the top 10 to 15 cm may be low but it can increase to over 90% with depth. In Inceptisols, aluminum contents vary, and may be greater, the same, or less than those found in Ultisols. Even where aluminum contents are

TABLE 3

Major soil constraints in the humid (H) and semi-arid (S) tropics¹

Soil constraint	Tropical America		Tropical Africa		Tropical Asia and Pacific		Total (million ha)	
	H	S	H	S	H	S	H	S
Low nutrient reserves	543	106	285	48	101	12	929	166
Al toxicity	490	84	226	37	92	10	808	132
Acid, not Al toxic	88	75	92	120	74	99	255	294
High P fixation	379	66	84	21	74	7	537	94
Poor drainage	90	39	59	49	42	10	191	98
Low ECEC	68	9	87	56	10	<1	165	66
Drought stress	-	270	-	404	-	294	-	968
Shrink-swell	11	12	2	42	3	45	17	99
Saline or sodic soils	8	8	4	10	5	14	17	32
Allophane	8	3	1	1	4	<1	13	4
Gravel	2	10	6	11	3	26	10	47
Slopes > 30%	145	45	22	40	73	62	241	147
Slopes 8-30%	290	108	142	110	59	109	491	327
Slopes 0-8%	263	148	260	254	91	123	714	525

¹Source: Sanchez (1989, and unpublished data).

high, however, the percentage aluminum saturation may be low because of the large quantity of exchangeable bases. In Spodosols, aluminum contents are very high in the top 5 cm, decline with depth, and then again increase in the spodic horizon. Finally, in Alfisols with near neutral pH, exchangeable aluminum and percent aluminum saturation may be very low. These large differences among soil orders in aluminum contents at different soil depths will differentially affect root distribution and will affect the magnitude and spatial extent of nutrient uptake, as well as nutrient retention by vegetation.

It should be noted that soil orders are rather broad classifications and that a significant range in chemical and physical properties exist among soils of a given order (Sanchez, 1989). Furthermore, large changes in soil chemical and physical properties can occur over relatively small distances, as commonly observed in associations of Oxisols and Ultisols with Dystropepts or Alfisols (Sanchez, 1976). Finally, a great deal of variability can exist in the field because of disturbance by animals or soil macrofauna, windthrown trees, patterns of forest felling and burning, and management practices.

As a response to high exchangeable soil aluminum contents some species accumulate aluminum while others exclude it (Webb, 1954; McCormick and Steiner, 1978; Haridasan, 1982). Chief adaptations to low nutrient availability include inherently low growth rates and nutrient requirements, the maintenance of a large root biomass, accumulation of tissue nutrient reserves dur-

ing times of high nutrient availability, reduction of nutrient losses from tissue via sclerophylly or retranslocation prior to litter fall, and rhizosphere processes that increase nutrient availability (Chapin, 1980; Vitousek, 1982; Clarkson, 1985; Chapin et al, 1986; Cuevas and Medina, 1986; Vitousek and Sanford, 1987). In many cases, the mechanisms underlying these tolerances are not known or require further study. These characteristics suggest that while selection and breeding have important roles in developing woody germplasm tolerant to soil acidity and low nutrient availability, such germplasm may have lower rates of growth and nutrient requirements than vegetation adapted to more fertile sites.

AGROFORESTRY SYSTEMS

Agroforestry systems can assume a wide variety of forms (Nair, 1984). Raintree and Warner (1985) classify the individual systems into two general categories: improved fallows and tree crop alternatives, each of which is subdivided into a few general agroforestry technologies. In the following discussion, we will relate our findings to variants of improved fallows, i.e. economically and biologically improved fallows (Raintree and Warner, 1985) and alley cropping (Kang et al., 1981, 1984, 1985). Among tree crop alternatives we discuss homegardens (Fernandes and Nair, 1987), and agrosilvopastoral systems (Felker, 1978; Mielie, 1986; Shankarnarayan et al., 1987). These systems are either more common or are more often suggested as options for increasing the productivity of traditional farming systems (Raintree and Warner, 1985; Raintree, 1987).

All of the above-mentioned systems are expected to increase biological and/or economic productivity and hence are likely to extract larger quantities of nutrients per unit time and/or area than the shifting cultivation systems they replace. As a result, nutrient inputs must be larger, losses lower, and/or recycling more rapid for such systems to be sustainable.

NUTRIENT INPUTS

Nutrients are made available to plants by: (1) weathering from primary and secondary soil minerals or changes from non- or slowly-available to readily-available forms, (2) atmospheric inputs (rain and dust), (3) fixation of nitrogen from the air, (4) mineralization of nutrients from organic forms, and (5) additions from sources external to the system. The qualitative ranking of these processes in the aforementioned agroforestry systems on fertile and infertile soils is shown in Table 4.

Nutrient weathering from primary and secondary minerals is controlled by soil type, inorganic chemical processes, temperature and rainfall, and hence will vary more with soil type than with agroforestry systems. Weathering in-

TABLE 4

Importance of nutrient sources in selected agroforestry systems on fertile and infertile soils. Rankings are qualitative and hypothetical

Agroforestry system	Mineral weathering		Atmospheric N ₂ fixation deposition				Mineralization from organic forms		External inputs	
	Fert.	Infert.	Fert.	Infert.	Fert.	Infert.	Fert.	Infert.	Fert.	Infert.
Economically enriched fallows	I ¹	N	I	I	?	?	I	I	N	N
Biologically enriched fallows	I	N	I	I	I	I	I	I	N	N
Alley cropping	I	N	N	N	I	I	I	I	I	I
Homegardens	I	N	I	I	?	?	I	I	I	I
Silvopastoral	I	N	I	I	I	I	I	I	I	I

¹I = important; N = not important; ? = uncertain.

Notes: Mineral weathering is of greater importance on fertile soils because of the large quantities of weatherable minerals present. Atmospheric deposition is important as a nutrient source in the majority of the systems because of accumulation in the long-term. Nutrient demand and removal in the alley cropping systems is higher and occurs over shorter time frames for deposition to have much importance. External inputs in the alley cropping systems take the form of chemical fertilizers; in the homegarden system, these inputs are household wastes, and in the silvopastoral system, manure.

put is unlikely to be of major importance in weathered or sandy soils (Oxisols, Ultisols, Psamment, Dystropepts, Spodosols), but may be significant in more fertile soils.

Atmospheric deposition of nutrients is usually small in magnitude, but may be important over long spans of time. Nutrient inputs in rainfall are little affected by soil type (Table 5), but this may not be true for dust. Average dust inputs in Niger, amounting to around 1500 kg ha⁻¹ yr⁻¹, were higher in total clay and fine silts, and contained 10 to 30 times higher levels of exchangeable calcium, magnesium, sodium and potassium than reference soils. Annual influxes of 2.7 kg calcium, 0.9 kg magnesium, and 1.2 kg potassium ha⁻¹ constituted a long-term chemical influx to these soils. Tree crowns act as dust traps; this may explain the observed higher clay content and hence higher organic matter levels beneath the canopies of trees such as *Acacia albida* (Sanchez, 1987). Such inputs are apt to be significant in silvopastoral systems, fallows, and other systems involving large tree canopies; alley cropping systems with reduced canopy areas are likely to benefit less.

The use of N-fixing woody perennials in agroforestry systems can increase nitrogen inputs (Dommergues, 1987) but the nitrogen contribution of legumes will vary greatly depending on soil, climate, species, and management (Table 6). As a result of methodological problems, reliable field estimates of nitrogen fixation from production systems found in humid and semi-arid areas are generally lacking (Sanginga et al., 1988).

TABLE 5

Atmospheric inputs of elements in the tropics¹

Site	Nutrient inputs (kg ha ⁻¹ yr ⁻¹)				
	N	P	K	Ca	Mg
Humid tropics					
Ghana	14	0.12	17.5	12.7	11.3
Cote D'Ivoire	21.2	2.3	5.5	30.0	7.0
Cameroun	12	1.7	12.0	3.8	1.5
Zaire	6.4		2.0	3.9	1.1
Costa Rica	5	0.2	2.5	1.4	1.0
Costa Rica	1.7 ^a	0.17 ^a	5.4	3.1	2.6
Panama		1.0	9.5	29.3	4.9
Puerto Rico	14			34.0	26.0
Venezuela – lowland ^b	21 ^a	25 ^a	24.0	28.0	3.0
– montane	9.9	1.1	2.6	5.6	5.2
Brazil	10	0.3		3.7	3.0
Brazil	6 ^a	0.16 ^a	3.4	– ^c	– ^c
Australia			4.0	2.0	2.5
Malaysia			12.5	14.0	3.0
Malaysia	13.5		6.4	4.2	0.7
Papua New Guinea – lowland			0.8	0.0	0.3
– montane	6.5	0.5	7.3	3.6	1.3
Semi-arid Tropics					
Niger ^d	ND ^e	ND	1.2	2.7	0.9

^aInorganic forms of the elements only.

^bWet and dry deposition together. Galloway et al. (1982) collected and analyzed 14 precipitation samples on the same site. Their volume-weighted concentrations times an annual precipitation of 3500 mm yields annual wet deposition rates of 2.4^a kg ha⁻¹ N, 0.65^a kg ha⁻¹ P, 1.1 kg ha⁻¹ K, 0.2 kg ha⁻¹ Ca, and 0.2 kg ha⁻¹ Mg.

^cBelow detection limits.

^dDust inputs. Average of three sites.

^eNo data.

Note: some of the studies report inorganic forms of N and P only, while others report total.

¹Source: Vitousek and Sanford (1987), and Tropsoils (1989).

In addition to the various constraints to N₂ fixation posed by the nature of the symbiotic association itself (Atkins, 1986), soil acidity and associated factors such as aluminum and manganese toxicity and phosphorus, calcium, and molybdenum deficiencies found in Oxisols, Ultisols, and some Inceptisols are likely to limit nitrogen fixation in these soils. Moisture stress will also reduce potential fixation, although the existence of available water and rhizobial populations deep in the soil profile may enable nodulation to occur during periods when surfaces of Aridisols or Entisols are dry (Jenkins et al., 1988).

Selection of host plants and symbiotic micro-organisms tolerant to soil

TABLE 6

Estimates of N₂ fixed by woody species suitable for agroforestry systems

Species	Estimate of N fixed (kg ha ⁻¹ yr ⁻¹)	Reference
(a) Legume species		
<i>Acacia mearnsii</i>	200	Orchard and Darby (1956)
<i>Erythrina poeppigiana</i>	60	Escalante et al. (1984)
<i>Gliricidia sepium</i>	13	Roskoski et al. (1982)
<i>Leucaena leucocephala</i>	100-500	Högberg and Kvarnström (1982). Sanginga et al. (1985)
<i>Inga jinicuil</i>	35-40	Roskoski (1981, 1982)
(b) Actinorhizal species		
<i>Casuarina equisetifolia</i>	58	Dommergues (1963)

acidity (Hutton, 1984; Halliday and Somasegaran, 1983) and/or deficiencies of nutrients such as phosphorus and calcium may help overcome soil constraints to nitrogen fixation. For example, in a field trial of 12 Central American provenances of *Gliricidia sepium* on an Ultisol (pH 4.5, aluminum saturation 65-85%) at Yurimaguas, Peru, large differences in growth rates and biomass production among provenances were noted, with production by a Guatemalan provenance exceeding that of local varieties (Fernandes, 1990). That identification of an optimum seed source is a major step in selection contributing to future success (Burley, 1987) is shown by the *Leucaena* breeding programs (Hutton, 1983; Brewbaker, 1983).

Well-developed mycorrhizal associations are also important for optimal nitrogen fixation and productivity in agroforestry systems, since increased phosphorus uptake by host plants via mycorrhizae has been shown to be associated with improved growth and nitrogen fixation in annual and tree legume species (Barea and Azcón-Aguilar, 1983; Huang et al., 1985). The high phosphorus requirement for nitrogen fixation and a minimum level of soil phosphorus for adequate mycorrhizal functioning suggests that nitrogen fixation is likely to be limited in some acid, infertile soils low in available phosphorus. However, some ectomycorrhizal species may be able to tolerate much lower levels of available soil phosphorus than endomycorrhizal species (Högberg, 1986) and allow their host to maintain high internal phosphorus concentrations. For example, *Cassia reticulata*, a non-nodulating legume used in alley cropping at Yurimaguas, has a higher foliar nitrogen content than other nodulated legumes such as *Inga edulis* and *Gliricidia sepium* (A. Salazar, unpublished data).

NUTRIENT OUTPUTS

Nutrients are lost from natural ecosystems by leaching, erosion, runoff, or gaseous exchange. In managed systems, nutrients are principally removed as

harvested products. The factors determining leaching, sediment, and runoff losses are complex and methodological difficulties in quantifying such fluxes, especially for leaching, result in a scarcity of reliable data. Limited data suggest, however, that leaching losses are apt to differ among soil type (Table 7).

Nutrient losses via erosion, runoff, or leaching are apt to be slight on soils in which infiltration is rapid and primarily through macropores (e.g., well-aggregated Oxisols) or on soils that have high moisture retention capacity (Andisols). Other things being equal, leaching losses of potassium, calcium and magnesium are generally larger on more fertile than infertile soils, but losses of nitrogen and phosphorus appear to be small regardless of soil type (Table 7).

It is expected that erosion and runoff in economically or biologically enriched fallows and homegardens would be similar to natural forest systems because of similar continuous soil cover and transpiration rates. Nutrient losses in alley cropping systems may be larger than in natural systems because of less extensive root systems and periods when the soil cover is reduced, but there are no data available to reject or support these hypotheses. Erosion losses in ploughed alley cropping systems on a sandy Entisol were low ($3 \text{ t ha}^{-1} \text{ yr}^{-1}$ or less) and were reduced compared to tilled, annual cropping systems, but were similar to no-till systems (Lal, 1987). Preliminary data from a replicated trial comparing erosion from bare plots, traditional cropping on con-

TABLE 7

Hydrologic losses of elements in moist tropical forest ecosystems. Most values represent inorganic forms of the element only¹

Site	Nutrients ($\text{kg ha}^{-1} \text{ yr}^{-1}$)				
	N	P	K	Ca	Mg
Moderately fertile:					
Costa Rica ^a	19.4	0	3.6	5.7	8.5
Panama ^b	-	0.7	9.3	163.0	44.0
Papua New Guinea-lowland ^b	-	-	15.0	25.0	51.0
Oxisols/Ultisols:					
Venezuela-lowland Oxisol	-	30.0	4.6	3.9	0.7
Brazil ^b	0.2	0.008	0.4	- ^c	- ^c
Brazil	-	0.4	12.7	16.7	8.1
Malaysia	-	-	11.3	2.1	1.5
Spodosols/Psamments:					
Venezuela	-	16.0	-	2.8	-
Montane forests:					
Venezuela	5.0	0.3	2.2	1.6	0.6

^aBudget over a 404-day period.

^bOutputs sampled in streamwater, otherwise using lysimeters.

^cNot detectable.

¹Source: Vitousek and Sanford (1987).

tours, an alley cropping system, and secondary forest on 20% slopes at Yuriaguas, show that rates of sediment erosion were 30 and 10 t ha⁻¹ yr⁻¹ in the bare and cropped contour plots, respectively, and less than 1 t ha⁻¹ yr⁻¹ in the alley cropping and secondary forest systems (J.C. Alegre, unpublished data). While tree-derived mulch, litter, or foliage can help reduce erosion and conserve soil moisture and some trees can help improve soil structure (Sanchez, 1987; Lal, 1984), it should also be recognized that these benefits depend on system management. The soil is especially vulnerable to erosion during tree establishment unless an annual crop or a cover of legumes or other vegetation is present to provide soil cover (Sanchez et al., 1985).

In semi-arid ecosystems, seasonal winds, high intensity rainfall, and soil surface crusting often combine to cause high rates of erosion. Crusting and erosion are apt to be problems in sandy Alfisols of the Sahel. Wind breaks are expected to reduce erosion and have been shown to increase crop yields in semi-arid zones (Tropsoils, 1989). On the other hand, such problems will be slight with well-aggregated Oxisols, Andisols, and Ultisols.

Gaseous losses of nutrients from managed or natural tropical ecosystems are poorly quantified. The presence of anaerobic conditions in soil or litter layers under high rainfall regimes suggests that denitrification may be an important process for nitrogen loss in Amazonia (Keller et al., 1983, 1986; Salati et al., 1982) and humid West Africa (Robertson and Rosswall, 1986), especially in agroforestry systems that maintain a thick, long-lasting mulch layer. Denitrification is apt to be more important in poorly drained soils (e.g., Aquepts, Aquents) but can also occur in aerobic soils (Robertson and Tiedje, 1987). Furthermore, NH₃ can be lost from plant leaves (Farquhar et al., 1979) and animal excreta (Woodmansee, 1978); the latter may be an important nitrogen-loss pathway in silvopastoral systems. In some agroforestry systems (e.g., improved fallows), the use of fire as a management tool results in the loss of nutrients in gases and in smoke particles. Nitrogen losses as a result of burning range from 10–40% of the quantity contained in above-ground vegetation and litter; losses in ash are much smaller and often follow the order nitrogen >> potassium > magnesium > calcium > phosphorus (Waring and Schlesinger, 1985). These losses are largely independent of soil type.

In summary, except for the nitrogen provided by nitrogen fixation, the potential for agroforestry systems to increase nutrient stocks on acid infertile soils appears to be limited. This may not be the case on more fertile soils in which nutrient release from weatherable minerals is larger and roots are able to exploit larger soil volumes. On both kinds of soils, tree cover and tree-derived litter play a valuable role in reducing nutrient losses via erosion and runoff. Native soil fertility and the quantities of nutrients lost through periodic harvests play a major role in determining agroforestry system sustainability.

It is significant that the systems often cited as examples of sustainable agro-

TABLE 8
Dry matter and nutrient inputs via litterfall/prunings in various production systems in the humid tropics

Systems	Dry matter (t ha ⁻¹ yr ⁻¹)	Nutrient inputs (kg ha ⁻¹ yr ⁻¹)					Source ¹
		N	P	K	Ca	Mg	
Fertile soils							
Rainforest	10.5	162	9	41	171	37	1
High-input cultivation*	9.3	139	15	98	52	23	2
Alley cropping							
<i>L. leucocephala</i> *	22.0	200-280					3 ^a
<i>Gliricidia sepium</i> *	11.0	171-205					3 ^a
<i>Sesbania</i> *	7.5	25-110					3 ^a
<i>L. leucocephala</i>	5-6.5	160	15	150	40	15	4 ^b
<i>Erythrina poeppigiana</i> *	9.6	278	24	216	120	52	5 ^c
<i>Gliricidia sepium</i> *	12.3	358	28	232	144	60	5 ^c
<i>L. leucocephala</i>	8.1	276	23	122	126	31	6 ^b
<i>Erythrina</i> spp.	8.1	198	25	147	111	26	6 ^b
Shade systems*							
Coffee/ <i>Erythrina</i>	17.2 (13.5)	366 (182)	30 (21)	264 (156)	243 (131)	48 (27)	7
Coffee/ <i>Erythrina</i> / <i>Cordia</i>	15.8 (9.1)	331 (75)	22 (8)	162 (45)	328 (46)	69 (12)	7
Coffee/ <i>Erythrina</i> pruned*	20.0 (12.2)	461 (286)	35 (24)	259 (184)	243 (121)	76 (43)	8 ^d
Coffee/ <i>Erythrina</i> non-pruned*	7.6 (2.0)	175 (55)	11 (4)	75 (14)	122 (40)	33 (9)	8 ^d
Cacao/ <i>Erythrina</i> *	6.5 (2.5)	116 (62)	6 (4)	40 (13)	116 (47)	41 (12)	8 ^d
Cacao/ <i>Cordia</i> *	5.8 (2.9)	95 (60)	11 (8)	57 (33)	108 (58)	43 (23)	8 ^d
Cacao/mixed shade	8.4	52	4	38	89	26	9
Cacao/ <i>Erythrina</i> *	6.0	81	14	17	142	42	10

Infertile soils							
Rainforest-Ox./Ult.	8.8	108	3	22	53	17	1
Spodosol	7.4	48	2	22	63	10	1
Savanna-Oxisol	3.5	25	5	31	10	11	2
Low input cultivation-Ultisol	6.0	77	12	188	27	12	2
Alley cropping-Paleudult							
<i>Inga edulis</i>	5.6	136	10	52	31	8	11 ^b
<i>Erythrina</i> spp.	1.9	34	4	19	8	4	11 ^b
<i>Inga edulis</i>	12.5						12 ^b
<i>Cassia reticulata</i>	6.5						13 ^b
<i>Gilricidia septum</i>	1.4						13 ^b
Shade systems							
<i>Erythrina</i> spp.-Dystropept	11.8-18.4	170-238	14-24	119-138	84-222	27-56	14 ^c

*Fertilized and limed; originally an acid, infertile soil.

* The numbers in parentheses represent litter production by *Erythrina*; the number to the left of the parentheses is total litter production.

^aBased on 2 m hedge spacing.

^bBased on 4 m hedge spacing.

^cBased on 6 m hedge spacing in 1st year, 3 m in other years. *Erythrina* spacing was 3 m × 6 m.

^dPlant densities: coffee (5000 ha⁻¹), *Erythrina* (555 ha⁻¹), *Cordia* (278 ha⁻¹).

^ePlant densities: coffee (4300 ha⁻¹), *Erythrina* (280 ha⁻¹).

^fSource: (1) Vitousek and Sanford (1987); (2) Sanchez et al. (1989); (3) Duguma et al. (1988); (4) Kang et al. (1984); (5) Kass et al. (1989); (6) A. Salazar (unpublished data); (7) Glover and Beer (1986); (8) Alpizar et al. (1983); (9) Boyer (1973); (10) FAO (1985); (11) Szoci (1987); (12) Palm (1988); (13) A. Salazar (unpublished data); (14) Russo and Budowski (1986).

forestry – homegardens and silvopastoral systems – are mainly found on base-rich Alfisols, Andisols, and Entisols (Sanchez, 1987), and that in both systems biological yields, and hence nutrient removals, tend to be low. In homegardens especially, attributes of the system which contribute to sustainability, such as nutrient recycling, investment in supportive, perennial structures, and a high proportion of photosynthate respired, “seem to have biological costs that are incompatible with high yields” (Ewel, 1986), even though the products obtained, like spices, may have high economic value.

The proposed abilities of agroforestry systems to maintain or improve soil chemical properties and organic matter and protect the soil surface are related to the processes of litter production, decomposition, and soil organic matter transformations.

LITTER PRODUCTION

Litter production is a major process by which carbon and nutrients are transferred from vegetation to soil. With regard to soil type, quantities of dry matter and nutrients recycled by above-ground litter in agroforestry systems show the same general tendency as in natural forests described by Vitousek (1984): litter production and the return of nitrogen, phosphorus, calcium and magnesium in litter are greater on more fertile soils (Table 8). Moreover, pruning of trees in the alley cropping and fruit/shade tree systems increases nutrient fluxes compared to natural forest, presumably because of the lack of retranslocation of nutrients from tissue prior to pruning. The addition of large quantities of nutrient-rich prunings also appears to stimulate plant and litter production by associated, but non-pruned plants (see comparison of pruned vs. non-pruned *Erythrina*/coffee system). It should be noted that the recycling data for the alley cropping systems do not include crop residues returned; these would, of course, increase the mass and nutrient totals for this system.

The importance of below-ground litter production in recycling of dry matter and nutrients in natural and agroforestry systems is virtually unknown. In natural tropical forest ecosystems, root biomass is larger on infertile than fertile soils (Table 9). Limited data suggest that root turnover is also larger and is responsible for large vegetation-to-soil nutrient fluxes in natural systems (Jordan and Escalante, 1980; Cuevas and Medina, 1988; Sanford, 1985). The magnitude of nutrient retranslocation from roots before death, however, is unknown. Agroforestry systems appear to have slightly larger fine root biomass than annual crops, but much less than tropical forests (Table 9). Lack of soil information, differences in methodology as well as problems with methodology (Singh et al., 1984; Martin, 1977; Milchunas et al., 1985), and the absence of data on root turnover or nutrient retranslocation do not allow

TABLE 9

Fine root biomass in managed and natural ecosystems in the humid and semi-arid tropics

System	Biomass (t ha ⁻¹)	Diameter limit (mm)	Depth of sample (cm)	Source ¹
Humid tropics				
Forest				
Fertile soils	4.99	<6	nl	1
Oxisol/Ultisol	14.57	<6	nl	1
Spodosol/Psamment	54.70	<6	nl	1
	15.91	<6	nl	
Agroforestry systems				
25 y-old Coffee/ <i>Erythrina</i> - Inceptisol	1.90	<5	25	2
5 y-old Coffee/ <i>Erythrina</i> - Inceptisol	2.6	<20	45	3
5 y-old Coffee/ <i>Cordia</i> - Inceptisol	4.5	<20	45	3
2.5 y-old Cacao/plantain/ <i>Cordia</i> - Inceptisol	1.87	<5	25	2
40 y-old Homegarden - Inceptisol	2.16	<5	25	2
1 y-old Mimic of succession - Inceptisol	1.48	<5	25	2
1 y-old Secondary forest - Inceptisol	1.16	<5	25	2
Annual crops				
Sweet potato - Inceptisol	0.41	<5	25	2
Corn - Inceptisol	1.03	<5	25	2
Upland rice - Ultisol	0.62	<2	30	4
Cowpea - Ultisol	1.03	<2	30	4
Corn - Ultisol*	0.97	<2	30	4
Soybean - Ultisol*	1.39	<2	30	4
Grassland/Savanna				
Grassland	1.7 - 8.7	nl	nl	5
Shrub savanna	13.7 -24.4	nl	nl	5
Tree savanna	39.7	nl	nl	5
Palm savanna	14 -28	nl	nl	6
Semi-arid tropics				
Tree stands				
2 y-old <i>Leucaena</i>	0.67- 0.74	<2	80	7
6 y-old <i>Leucaena</i>	1.28	<2	80	7
2 y-old <i>Cassia</i>	0.78	<2	80	7
2 y-old <i>Prosopis</i>	0.55	<2	80	7
<i>Acacia</i> woodland	11.5	nl	nl	8
Savanna/grassland				
Grassland	1.1 -20.7	nl	nl	5
Savanna	2.26	nl	nl	9
Annual crops				
Corn	0.30	<2	60	

nl: not listed.

*Fertilized.

¹Source: (1) Vitousek and Sanford (1987); (2) Ewel et al. (1982); (3) Alpizar et al. (1986); (4) TropSoils (1989); (5) Singh and Joshi (1979); (6) Jonsson et al. (1988); (7) Menaut and Cesar (1979); (8) Burrows (1976); (9) Rutherford (1978).

us to estimate root litter production for these systems or to relate root production and turnover to soil type.

Data on the effects of shoot pruning (e.g., in alley cropping and fruit/shade tree production systems) on root, nodule, and mycorrhizal dynamics and the type of roots most affected are generally lacking. In field and pot experiments with *Inga edulis*, we observed increased mortality of fine roots (<2 mm diameter) beginning three to four days after shoot pruning, but regrowth of fine roots commenced again from primary and secondary laterals eight to ten days after shoot pruning (Fernandes, 1990).

In agroforestry systems, the distribution of root litter depends on the type of vegetation and soil, vegetation age, and management practices. In soils with chemical barriers to root growth (Oxisols, and Ultisols), the majority of roots and, therefore, root litter production, are confined to the litter layer and topsoil (Lathwell and Grove, 1986). Hence, root litter deposition in the subsoil is very limited: In fallows enriched with acid-tolerant leguminous species on an Ultisol, fine root distributions are similar to those in natural secondary vegetation (Szott, 1987). In homegardens, roots are concentrated in the topsoil because of enrichment of this zone by litter inputs and household wastes (Ewel et al., 1982).

In alley cropping systems, it is often hypothesized that the hedges have deeper rooting patterns than those of associated annual crops. Limited evidence, however, suggests that rooting patterns in hedges and annual crops are similar and that depressions of crop yield close to the hedgerows are at least partly related to below-ground competition by the hedges (Szott, 1987; A. Salazar, unpublished; Jonsson et al., 1988).

LITTER QUALITY, DECOMPOSITION, AND NUTRIENT RELEASE

Litter quality determines, in part, rates of decomposition and release of nutrients from organic residues. By manipulating agroforestry components that produce organic residues of different qualities, it may be possible to affect the short- and long-term storage and mineralization of carbon and nutrients. In order to achieve this, reliable predictors or indices of quality are needed.

Work with tropical legumes has shown that indices of quality (e.g., C/N or lignin/nitrogen ratios) which work well in temperate zones (Melillo et al., 1982) may not be the best predictors of nitrogen mineralization from leguminous material in the tropics. Nitrogen release patterns may be more closely related to tissue polyphenolic contents than to lignin or nitrogen contents or lignin/nitrogen ratios (Vallis and Jones, 1973; Palm, 1988). Hence, use of leguminous material with low C/N or lignin/nitrogen ratios may not necessarily result in high rates of nitrogen release or increases in nitrogen availability.

Partly because of methodological problems, it is uncertain whether root and leaf litter differ in quality or whether root litter quality differs among vegetation types. In general, small diameter roots, such as those produced by food crops, would be expected to decompose and release nutrients rapidly, whereas decomposition and nutrient release from larger, more lignified root litter should be slower (Amato et al., 1987; Berg et al., 1987). Root litter from trees, however, may differ from that of annual crops in degree of homogeneity, proportion of fine roots, quantity of secondary or allelopathic compounds, nutrient concentrations, and the amounts of lignin and polyphenols present. Thus, conventional indices of quality may not be good predictors of tree root decomposition.

Generally, leaf litter quality is higher and rates of decomposition are more rapid on more fertile soils. Litter from Spodosols and Psamments is often low in nitrogen and that from Oxisols and Ultisols low in phosphorus (Vitousek and Sanford, 1987). Whether similar patterns hold for root litter is unknown.

Much has been said about the effect of litter quality on nitrogen release and availability, but little attention has been paid to phosphorus or other nutrients. Phosphorus, especially, may be more limiting to plant production on some tropical soils, but phosphorus availability and mineralization are difficult to measure (Walbridge and Vitousek, 1987). Palm (1988) has shown that patterns of loss of other nutrients besides nitrogen from legume residues can be affected by residue quality. Mineralization of phosphorus, potassium, calcium, and magnesium from pruned foliage of three woody legumes was more rapid from high quality *Erythrina* residues than from residues of *Inga edulis* or *Cajanus cajan*. Leaves of *Erythrina* lost approximately 40% of their initial phosphorus and calcium contents and 75% of their magnesium and potassium in 20 weeks. With leaves of *C. cajan* and *I. edulis*, however, there was little net loss of phosphorus, calcium, and magnesium during the first 8 to 12 weeks; by 32 weeks, phosphorus was reduced to approximately 40%, and calcium and magnesium to 50–80%, of their initial contents. Rates of potassium loss during the first 8 to 12 weeks were higher in *C. cajan* and in *I. edulis*, but by 32 weeks the percentage of initial potassium remaining in the material was similar (10%) for both species (Palm, 1988).

Apart from affecting nutrient availability, organic inputs can affect other parameters of soil fertility. Some organic inputs, when incorporated into the soil, temporarily reduce aluminum toxicity, presumably by complexation of aluminum in the soil solution by organic acids, polysaccharides and other initial decomposition products, and can increase plant productivity (Hargrove and Thomas, 1981; Davelouis, 1990). The effect may be temporary, since aluminum may be released again to the soil solution as these products undergo further decomposition. Little is known about the influence of organic input quality on this process. Readily decomposable inputs may be more effective than those which decompose slowly. This effect, although tempo-

rary, may be of significance when organic residues are added to acid soils in agroforestry systems.

SOIL ORGANIC MATTER

The transformation of organic inputs leads to the formation of soil organic matter (SOM) and the quantity and dynamics of SOM are affected by soil properties (Ladd et al., 1983; Amato et al., 1987). Soil moisture can affect rates of organic residue production as well as rates of SOM decomposition: both are apt to be greater with udic rather than ustic or aridic soil moisture regimes. Soils with higher clay contents favor the formation of aggregates in which SOM may be protected from microbial degradation; they are also cooler than sandier soils because they hold more water at a given tension and consequently have higher SOM contents (Lepsch et al., 1982; Ladd et al., 1983; Parton et al., 1987). In soils with variable charge minerals (Oxisols, Andisols, Ultisols), there may be greater affinity between SOM and mineral surfaces leading to lower SOM decomposition rates.

Soil organic matter has long been considered of paramount importance in maintaining soil fertility and structure, but cause-and-effect relationships are unclear (Goh, 1980; Swift, 1984; Sanchez and Miller, 1986). Perhaps the main reason for this is that the common measure of SOM, total carbon, yields little information on the types of SOM present or the transformations that occur.

As a result of the limited utility of total carbon as an indicator, recent conceptualizations of SOM focus on a series of pools whose turnover times differ because of differences in the chemical complexity of the material and its association with soil particles. These include an active pool, which appears to play a major role in determining nutrient availability and corresponds to microbial biomass and plant metabolic material; a slow pool which corresponds to inter-microaggregate material and is a major source of nutrients following soil disturbance; and a passive pool consisting of humified intra-microaggregate material which is largely inert as a nutrient source (Jenkinson and Rayner, 1977; Van Veen and Paul, 1981; Tisdall and Oades, 1982; Paul, 1984; Paul and Voroney, 1984; Elliot, 1986; Parton et al., 1987).

Pool types should receive more consideration when assessing the efficacy of agroforestry systems in maintaining soil organic matter. For example, it may be of little consequence that alley cropping systems maintain soil organic matter at 60% of that in natural systems, if most of that soil organic matter is passive and contributes little to nutrient supply.

A largely unexplored potential of agroforestry systems lies in how woody components might be chosen or managed to affect the size and rates of transformation of SOM pools in order to conserve soil fertility or increase system productivity. Although a number of factors determine SOM dynamics, pools might most easily be managed by manipulating the quantity and quality of

organic inputs and soil temperature. Low quality litter inputs may lead to more formation of stable forms of soil organic matter (slow and passive pools) than plant material of higher quality (DeHaan, 1976; Martin and Haider, 1980; Kelley and Stevenson, 1987; Parton et al., 1987; Palm, 1988); and lower soil temperatures should result in slower rates of soil organic matter decomposition. In tree-crop systems having lower nutrient demands than short-cycle crops, it may be better to use low quality, slowly decomposing organic materials which build up organic pools of nutrients and buffer long-term nutrient availability and release. On the other hand, in zonal agroforestry systems combining annual crops and trees (e.g., alley cropping), attempts should be made to synchronize nutrient release from organic residues and SOM with crop nutrient demand (Swift, 1984). This may entail the use of a mixture of rapidly decomposing material, to increase the active SOM pool and satisfy short-term nutrient requirements of the crops, and slowly decomposing material, to increase the inactive SOM pool and buffer nutrient release. In an alley cropping system, soil microbial nitrogen and crop yields increased with the quantity of organic residues applied and were larger with the use of high-quality rather than low-quality material (Palm, 1988). Recent data suggest that changes in soil microbial biomass and nitrogen are precursors to changes in SOM, nitrogen availability and crop productivity (Ayanaba et al., 1976; Carter and Rennie, 1982; Myrold, 1987; Janzen, 1987).

Little is known about the long-term effects of differences in organic input quality on SOM fractions and nutrient availability. It remains to be seen if these concepts can be applied to the management of agroforestry systems in the field.

CONCLUSIONS

The potential for agroforestry systems to contribute to sustainable economic production is often constrained by soil properties. In most cases, there is insufficient consideration of these constraints when making agroforestry recommendations. Successful agroforestry systems are nearly always practiced on inherently fertile soils.

Most agroforestry alternatives to shifting agriculture extract more nutrients than traditional systems, hence nutrient inputs or recycling must be larger or nutrient losses must be reduced if these systems are to be biologically sustainable.

On acid, infertile soils (Oxisols, Ultisols, Dystropepts, Psammets, and Spodosols) in both the humid and semi-arid tropics the potential for increasing nutrient inputs or reducing losses is limited by chemical barriers to root expansion (high aluminum saturation in the subsoil, low levels of calcium and phosphorus), lack of weatherable minerals, and nutritional constraints to N_2 fixation. Moreover, erosion hazard and poor physical properties exist

TABLE 10

Possible agroforestry interventions based on soil constraints

Soil types	Soil properties	Implications for agroforestry systems	AF-system components and interventions
Oxisols, Ultisols, Dystropepts	Low base status High Al saturation with depth Erosion risk on some Ultisols High P fixation Low CEC	Low nutrient availability and plant production Shallow roots because of Al saturation and nutrient deficiencies, hence more root competition between trees and annual crops Low N ₂ -fixation due to soil acidity and P deficiency Leaching risk due to low CEC	Maximize capture of atmospheric input Use acid-tolerant rhizobia/mycorrhiza Use adapted plant species Promote/maintain well-developed root systems Use mulch for soil protection to reduce erosion and runoff losses Minimize biomass removal Systems of improved fallow, rotational alley cropping, silvopastoral tree crop/cover crop grazing, homegardens, live fences
Spodosols, Psamments	Very sandy Low CEC and base status High Al saturation	High leaching likely Low N-fixation Shallow root systems Plant production low	Mulch or canopy for maximum soil protection Minimize biomass removal Aim for products of high value Best left alone
Alfisols, Mollisols, Fluvents	Fertile Few chemical constraints Erosion risks	Good root development with depth Potential for nutrient pumping from deeper, base-rich, soil layers Moderate to high N-fixing potential	High agroforestry potential and wide range of systems possible Special role for alley cropping where land scarce or sloping Homegardens
Andisols, Vertisols	Fertile P fixation in Andepts Shrinking and swelling of Vertisols	Potential for nutrient cycling from deeper soil layers	High agroforestry potential Homegardens Multi-strata shade trees/timber/fuel/fodder/coffee/cacao Silvo- and agrosilvopastoral systems for Vertisols with livestock on crop land in dry season
Aridisols	Moderate fertility Moisture stress Salinity Surface crusting	Deep roots hence good potential for nutrient pumping from deep unweathered soil High risk of wind and water erosion Salinity, high Al, or low N or P may limit plant growth in some instances	Agrosilvopastoral or managed fallows with high value gum/wax/oil species Multi-purpose shelterbelts/live fences to protect croplands and homesteads

on some Ultisols, Psamments, Spodosols, Lithic Entisols, and Plinthic Alfisols. As a result, plant growth, litter production, and nutrient recycling will usually be less than on more fertile sites. Agroforestry technologies on these soils may, therefore, generally resemble shifting cultivation fallows with relatively long fallow rotations and low yields. Systems may include economically and biologically enriched fallows and rotational, alley cropping systems. Some alternatives are shown in Table 10.

On more fertile soils, the scope of agroforestry is broader, but some constraints still exist. These include moisture stress throughout the semi-arid tropics; high phosphorus fixation in Andepts; erosion hazard in some Entisols and Alfisols, and shrinking and swelling in Vertisols. Some alternatives are shown in Table 10.

Litter production, decomposition, and soil organic matter dynamics are key processes affecting soil fertility and the sustainability of agroforestry systems based on no or limited use of purchased chemical inputs, but few data exist indicating the effects of organic input quantity, quality, timing, and placement on these processes. Knowledge of litter production and decomposition below-ground is especially lacking. Much work needs to be done on processes regulating nutrient release from litter and soil organic matter.

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