Reprinted from Gerald G. Marten (1986), Traditional Agriculture in Southeast Asia: A Human Ecology Perspective, Westview Press (Boulder, Colorado).

10
Soil Management in Traditional Agriculture

Gerald G. Marten
and Patma Vityakon

Perhaps no aspects of agroecosystem management are more important to long-term agroecosystem sustainability than those involving the soil. It is significant that traditional soil management does not depend on manufactured (i.e., inorganic) fertilizer inputs. It is also notable that traditional agriculture is practiced successfully on many kinds of land, including land that by virtue of steep slopes, poor soils, poor drainage, or unreliable water supply would otherwise be considered marginal for agriculture or simply unsuitable for it. Because a key feature of traditional agriculture is careful attunement of the cropping system (i.e., agroecosystem structure) to the agricultural capabilities of the site, a refined system of land suitability classification is essential. This chapter presents some examples of traditional systems of land classification and their relation to the kinds of traditional agroecosystems established on those lands. Nutrient cycling processes in agroecosystems and the "organic farming" methods that traditional farmers employ to maintain their soil fertility are then discussed. Finally, there is a review of the mechanisms by which traditional farmers' practices control soil loss due to erosion.

TRADITIONAL SYSTEMS OF AGRICULTURAL LAND CLASSIFICATION

Weinstock (1984) has reviewed the soil classification of some traditional agriculturalists in Southeast Asia. Malaysian farmers distinguish soil that is sweet, neutral, or sour to the taste—a reflection of soil pH. The same farmers use the *keduduk* bush *(Melastoma)* as an indicator of high levels of aluminum in the soil, the tree *pohon bakan (Hanguana)* as an indicator of acid soil with stagnant standing water, and *Imperata* grass, *keriang* berry bushes *(Ploiarium)*, and cashew trees as indicators of low soil fertility. Hanunoo swidden agriculturalists in the Philippines recognize the following criteria for soil quality: moisture content, sand content, rock content, general

Table 10.1. Traditional Sundanese Soil Classification in West Java

Criteria	Classes	Fertility Level
Color	*Tanah beureum* (red soil)	Low
	Tanah hideung (black soil)	High
	Tanah bodas (light soil)	Medium-high
Texture	*Tanah kasar* (coarse soil)	Low
	Tanah balus (fine soil)	High
Moisture content	*Tanah gersang* (dry soil)	Low
	Tanah gembur (wet soil)	High
Rock content	*Tanah berbatu* (gravel soil)	Low
	Tanah tak berbatu (nongravel soil)	Medium-high
Sand content	*Tanah keusik* (sandy soil)	Medium-high, but not good in water and nutrient holding capacity
Firmness (clay content)	*Tanah porang* (clayey soil)	High
	Tanah tidak liat (nonclayey soil)	Low-medium, depending upon other factors such as sand content, water/moisture content

Source: Linda Christanty and Johan Isakandar, personal communication.

texture (possibly reflecting clay content), firmness, crumb structure (particularly in the wet season), and color (Conklin 1975).

Java

Traditional soil classification in Java is generally based on color, texture, and soil water content. Sundanese farmers express soil texture in terms of rock content, sand content, and firmness (Table 10.1). Dark or black soil is considered to be more fertile than red soil, and light-colored soil is considered to have medium to high fertility. Soil color is important in annual-perennial rotation systems for indicating whether the land is ready for the field crop part of the cycle. If the soil in *talun* bamboo stands is dark, the farmers assume that the land is ready for cultivation. The dark soil color probably reflects an increase in soil organic matter during the bamboo phase of the cycle.

Moisture content can be used to determine the fertility level and the type of crops that are suitable for a particular soil. Soil with a low moisture content is considered to have low fertility and cannot be used to grow crops that have high nutrient requirements, while soil with a high moisture content is fertile and suitable for most crops. Farmers also use texture as a criterion for classification. A fine textured soil is considered more fertile than course soil. A sandy soil can be used for crops, but farmers do not consider it very good, since its water and nutrient-holding capacities are low. Degraded soils and soils with low moisture content are cultivated with trees such as *turi (Sesbania grandiflora)*, *petai cina (Leucaena leucocephala) Albizia*, or other leguminous trees that can restore fertility.

Thailand

Soil color and texture seem to be the two most important soil characteristics for traditional farmers in Thailand. As a rule, darker soils are considered more fertile than lighter-colored soils, presumably because of higher organic matter content. Farmers in Northeast Thailand use black organic soils from termite mounds and from under the canopies of large trees (where leaf litter has accumulated) to incorporate into the soil in their market gardens.

The degree of stickiness, which reflects clay content, is used to evaluate soil fertility in rice paddies. The more sticky the soil in the wet season, the more fertile it is considered to be. The stickiness of paddy soil probably indicates its capacity to hold water and impede drainage, essential conditions for lowland rice, rather than indicating soil fertility per se.

Saline soils are widespread in Northeast Thailand. Saline soil can be recognized by a white thin crust on the soil surface; taste is also used to recognize soil salinity.

Soil is a major consideration for the location of shifting-cultivation cropping systems in the uplands of Northeast Thailand. Fukui et al. (1983) classified the soils according to their physiographic positions and parent materials:

A—Soils found on terraces and derived from old alluvium.
L—Soils found on dissected erosion surfaces and derived from limestone.
M—Soils found on dissected erosion surfaces and derived from mixed basic sedimentary rocks.
I—Soils found on dissected erosion surfaces and derived from neutral to basic igneous rocks.

Group A soils are the only ones where maize is not a major crop. Group A soils are coarse in texture and highly permeable, so they are low in fertility and have low water-holding capacities. The absence of maize in areas where group A soils are dominant can be attributed to the low water-holding capacity of these soils since maize is vulnerable to drought.

Maize followed by mung bean is the basic cropping system in areas where soils belonging to group M predominate, whereas the basic cropping system is maize followed by sorghum in areas where soils of group L or I are found. The frequency of moisture stress diminishes from M to I and from I to L, and soil water-holding capacity appears to be the most decisive factor for the kind of crop to be planted after maize in the L, I, and M soil parent-material groups. In fact, water-holding capacity appears to override the impact of soil phosphorus. Mung beans are less tolerant of low levels of phosphorus than sorghum, yet mung beans are found on the group M soils, where there is less phosphorus than in group I and L soils.

These soil groups can be recognized by the color of their topsoils (i.e., A horizons). The topsoils are reddish in group M, black in group L, and brownish in group I. The color differences are common knowledge among farmers in the area who associate topsoil color with susceptibility to drought. Farmers say that maize begins to wilt on the reddish soil after there has been no rain for only one week, while maize does not wilt on the black soil until there has been no rain for several weeks.

There is a difference in the degree of crop diversity between group L (black) and group I (brown) soils. Fukui et al. (1983) suggest it is due to the farmers' perception that black soil is more drought resistant than brown soil. Maize gives high and reliable yields on black soils, and sorghum can be grown successfully after maize every year. The farmers consider maize-sorghum a reliable cropping system for black soils and see no need for crop diversification. In contrast, the brown soil is perceived to be more drought prone, so the best strategy is to diversify the crops, growing not only maize and sorghum but also less desirable crops that are more drought resistant (e.g., cassava).

Melanesia and New Guinea

In Melanesia, where yams and taro are the dietary staples, soils are evaluated particularly in terms of their potential for these crops. The Trobriand soil taxonomy has six categories (Malinowski 1935):

1. *Galaluwa*—black, heavy soil, dry and perhaps good for all cultivation.
2. *Butuma*—red, light soil found near coral ridges, unsuitable for taro but excellent for yams.
3. *Kwala*—black soil near wooded coral reefs, very fertile and good for all crops.
4. *Dumya*—greasy swamp soil, good for taro in the dry seasons, but never suitable for yams.
5. *Sawewo*—soil found in holes of the wooded coral reefs, suitable for large yams.
6. *Malala*—poor stony soil, unsuitable for taro, but good for hardy yams and *taytu*.

Among the Central Highlands people of New Guinea, specific garden types are closely associated with particular terrain units: mountain slopes, terrace sections, and steep-sided valleys separating mountain slopes. Garden types are also associated with soil characteristics (Table 10.2) and, to a lesser extent, microclimate (Waddell 1972). There are two major types of gardens: open fields and mixed gardens. Open fields are primarily sweet potato gardens with the sweet potatoes planted on large planoconvex mounds. Mixed gardens are established annually during the dry season by clearing off secondary growth and planting yams, sugarcane, or bananas. The effective life of a mixed garden is not more than fifteen months.

Table 10.2. Major Soil Types Identified by Farmers of the New Guinea Central Highlands

Soil Types, Local Names	Soil Characteristics
Pubuti	Chocolate-brown, finely structured, friable
Tugke	Firm greenish clay containing ocher-colored concretions
Aoai	Firm reddish-brown clay without concretions

Source: Waddell (1972).

Open fields are restricted to areas where *pubuti* is developed to a depth of at least 0.3 m as an upper horizon overlaying the clays. This soil is thought to be much more fertile than the others as it has a high organic matter content. This quality, which is called "grease" by the farmers, is used by them as a general indicator of soil fertility. They say that "grease" is a property the soil also acquires when dung or compost are mixed into it. *Pubuti* is relatively stable and easy to work, facilitating the preparation of mounds and continuous cultivation of open fields.

Mixed gardens are restricted to steep valley slopes, preferably those parts where some *pubuti* has developed. However, the universal practice of a long fallow after a single planting means *pubuti* is not absolutely essential. Yams and associated crops are planted directly in the mixed gardens where *pubuti* occurs, while sweet potatoes are planted on "poor" (stony or clayey) ground following initial clearing to break up the soil and enable *Casuarina* (a nitrogen-fixing tree) to root.

Farmers tend to avoid the grassy upper mountain slopes. This is because the soil (dark yellow or red clays) is poor, as indicated by a lack of "grease." Yields in this soil are low, and the necessary fallowing time is longer than on other terrain units. Farmers who must establish open fields on upper mountain slopes select shallow depressions where some *pubuti* has developed and the soil is less prone to drying out.

Central America

Carter's (1969) detailed description of Kekchi cultivation in Guatemala illustrates the highly sophisticated soil and land-use classification that is also commonplace in traditional Southeast Asian agriculture. The Kekchi practice *milpa* agriculture—mixed cropping based on maize, beans, and squash—as a form of shifting cultivation that employs a digging stick or hoe along with slash and burn. They have four criteria for soil quality: color, texture, drainage, and root content (Table 10.3).

Soils are described in such a way that drainage and root content overlap color and texture (e.g., muddy, white soil; black, root-bound soil; and stony, yellow soil). Judging soil qualities is considered important among the Kekchi because poor land selection and wasted labor are considered socially embarassing. The most desirable soil types seem to be those that are black, porous, soft, and well drained. The least desirable seem to be those that are red, hard, and poorly drained.

The Kekchi also use vegetation (Table 10.4) as an indicator of suitable agricultural sites. They consider land covered with high forest (mature forest) ideal for preparing wet *milpa* because it can be burned easily and provides the soil with readily available nutrients in the ash from cutting and burning the forest. When mature forest growth is not available for *milpa* preparation, preference is given to land covered by the tallest forest available. Next in preference is land covered by saplings, and finally land covered by low, ligneous growth. The Kekchi do not consider a herbaceous fallow conducive to successful *milpa*, and grasslands are looked upon as useless though redeemable by planting legumes, especially velvet bean.

Specific plants are also used by the Kekchi for the selection of *milpa* sites (Table 10.5). Plants indicative of good wet-season land are those with a relatively low tolerance for poor drainage conditions; plants indicative of dry-season land have a high tolerance for such conditions. Only one plant is considered promising for both types of cultivation, and this is *yaxte* (*Brunfelsia* sp.). For both dry- and wet-season *milpa*, land covered with soft-wooded timber is considered generally good, especially when the soil texture is loose and humid. This soft-wooded growth is exemplified by *hu (Virola quatemalensis)* and *puj (Ochroma lagopus)*. An abundance of any of three types of grass is thought to invalidate a piece of land as a *milpa* site: *pach aya (Paspalum conjugatum)*, *cak pach aya (Axonopus compressus)*, and *ac* (unidentified).

MIXED CROPPING AND THE SOIL

Some of the benefits from the mixed cropping common in traditional Southeast Asian agriculture derive from the fact that an interplanted mixture of crops can use soil water and nutrients more effectively than a single crop can. There is an abundance of experimental information to illuminate the nature and magnitude of these benefits.

Water limitation is the most serious environmental constraint in many parts of the tropics. Small-scale farmers on marginal lands may depend entirely on rainfall for their water, since irrigation may be too costly or unavailable (Andrews and Kassam 1976). Under these conditions one would expect any practice that buffers this reliance on rainfall to gain wide acceptance, and greater efficiency of water use appears to be a major reason that intercropping is so common among small farmers in the tropics (Miracle 1967, Francis et al. 1976, Ruthenberg 1976). Experimental intercrops of sorghum and pigeon pea in India demonstrated greater dry-matter yields than monocropping, apparently because water was used more efficiently (Willey 1979a, 1979b). In a study of sunflower-radish intercropping, two

Table 10.3. Soil Classification Categories Employed by the Kekchi

Kekchi Type	English Meaning and Land-Use Suitability
Soil color	
K'ek li ch'och'	Black soil, very good, most widely distributed of good soils
Mero k'ek li ch'och'	Brownish-black soil (half black), good for both wet- and dry-season *milpa*, widely distributed
Mero k'an li ch'och'	Brownish-yellow soil (half yellow), if soft (*k'un*) good for both wet- and dry-season *milpa*, limited distribution
K'an li ch'och'	Yellow soil, if soft (*k'un*) good for both wet- and dry-season *milpa*, often hard (*cau*), limited distribution
Sak li ch'och'	White soil, if soft (*k'un*) good for both wet- and dry-season *milpa*, if hard (*cau*) very poor for *milpa*, limited distribution
Mero cak li ch'och'	Reddish-brown soil (half red), fair for *milpa*, especially if soft (*k'un*), very widely distributed
Cak li ch'och'	Red soil, fair for *milpa*, especially if soft (*k'un*), very widely distributed
Tzakal cak li ch'och'	Very red soil, poor for *milpa*, fairly widely distributed
Soil texture	
K'un ru li ch'och'	Soft surfaced soil, good for both wet- and dry-season *milpa*, widely distributed
Samahi' ru li ch'och'	Sandy, silty loam, excellent for wet season *milpa* if well drained, good for dry season *milpa*, limited distribution
Mu' ru li ch'och'	Very soft-surfaced soil, top layer tends to be partially decayed organic material, best for dry-season *milpa* if it lies on low, flat land, less productive on wet-season *milpa*, limited distribution
Melb ru li ch'och'	Surface covered by pieces of hardened clay, good for both wet- and dry-season *milpa*, especially productive for beans, limited distribution
Pec ru li ch'och'	Stony-surfaced soil, usable for wet-season *milpa* if the stones are whitish or bluish and if covered with ligneous growth, stony soils which produce only sparse herbaceous growth or grasses are eliminated from consideration, common on hilly sites
Sactun ch'och'	Yellow and gray clays, usable for dry-season *milpa* if near water, rare

Table 10.3. *(continued)*

Kekchi Type	English Meaning and Land-Use Suitability
Seb ru li ch'och'	Yellow and red clay surface, excessively hard in dry season and sticky in wet season, poor for *milpa* if ground surface is *seb,* if *seb* lies under softer surface soils may produce good *milpa,* fairly common
Cuacab li ch'och'	Black and brownish-black clay, similar to *seb,* presenting many of the same problems, rare
Pok ch'och'	Partially decomposed limestone, used as a cleanser, poor for *milpa,* rare
Cau ru li ch'och'	Hard surfaced soil, poor for both wet- and dry-season *milpa,* fairly widely distributed
Drainage	
Chaki ch'och'	Dry soil, good for wet-season *milpa,* poor for dry-season *milpa*
Sulul li ch'och'	Muddy soil, if the condition temporary, soil may be usable for either wet- or dry-season *milpa,* inferior to soils having soft, granular surfaces, more usable for dry- than for wet-season *milpa*
Njore' li ch'och'	Cracked soil, cracks appear during dry season usually found on high ground or hillsides, usable only for wet-season *milpa*
Ha' ru li ch'och'	Soil covered by water, very poor for wet-season *milpa,* possibly good to excellent for dry-season *milpa,* commonly derived from clays (*seb*)
Sab ru li ch'och'	Perpetual swamp, useless for both dry- and wet-season *milpa*
Root content	
Tzatzalum	Root-bound soil, found almost exclusively in recently slashed and felled *milpas,* especially when they have been carved out of mature forest (*nink li q'uiche'*), generally poor first year but as the roots slowly rot away become good to excellent by the second year

Source: Carter (1969).

Table 10.4. Major Types of Vegetation Used as Indicators by the Kekchi

Kekchi Term	English Meaning
Rok cuaj	A field covered with small plants which appear in the first few months after harvest (literally, dried corn stalks)
Coc' pim	Low weeds
Pim ru	Thick, low weeds
Mas pim ru	Very thick brush
Ichaj ru	High grass (e.g., pasture grass)
Coc' che' ru	Sapling stage of secondary growth
Q'uis ru	Thorny vegetation
Ninki al c'al	High secondary growth
Mac'a' spimal	Higher secondary growth, characterized by sparse undergrowth
Nink li q'uiche'	Mature forest growth

Source: Carter (1969).

Table 10.5. Plant Indicators for Kekchi Site Selection

Wet-Season *Milpa*		Dry-Season *Milpa*	
Kekchi Type	Botanical Species	Kekchi Type	Botanical Species
Yaxte'	*Brunfelsia* sp.	*Quenk' caballo*	*Stizolobium* sp.
Tz'uyuy	*Cochlospermum* sp.	*Tz'imaj*	*Momordica charantia*
Tz'ukl	*Pithecolobium* sp.	*K'erk*	*Heliconia latispatha*
Hu	*Virola guatemalensis*	*Yaxte'*	*Brunfelsia* sp.
Cuachil	*Dialium guianense*	*Ak'l*	*Moraccae*
Muy	*Lucuma durdlandii*		
Pok	*Spondias purpurea*		
Chahib	*Trema* sp.		
Puj	*Ochroma lagopus*		
Yaxhab	Unidentified		
Kinam	*Vatairea lundellii*		

Source: Carter (1969).

crops extracted more water from the soil than either sole crop (Lakhani 1976).

The advantage gained in capturing water from the soil is analogous to the advantage of above-ground stratification in the canopy for capturing light: different crops have different vertical rooting patterns in the soil, so the soil is covered more thoroughly by the roots of a crop mixture. Theoretically, there is an "ideal" configuration of roots for exploiting water resources under any given conditions, where deeper-rooting species should have a competitive advantage in times of drought and shallow-rooting species should be able to take up small amounts of water quickly from infrequent and slight rains.

There has been much speculation concerning the mechanisms by which crop mixtures can more effectively use soil nutrients:

- Different plants use different quantities of different nutrients (Snaydon and Harris 1979);
- Different plants use nutrients in different forms (Snaydon and Harris 1979) or from different sources (Trenbath 1974);
- Different plants use nutrients at different times (Willey 1979a, 1979b, Baker 1974); or
- Different plants have different capacities for taking up and utilizing different nutrients (Olsen et al. 1981).

Any one of these mechanisms could give yield advantages, but the one that appears most significant is the difference in the timing of nutrient utilization (Willey 1979a, 1979b, Trenbath 1974, Kass 1978, Andrews and Kassam 1976). This effect has been shown both for crops differing in time periods to maturity and for similarly maturing crops planted at differing times (Willey 1979a, 1979b).

Differences in rooting patterns are also important for reducing nutrient competition between crops. Rooting patterns are influenced by soil mechanical properties (e.g., soil texture or soil compaction), soil nutrient status, and soil water status. For example, barley has a deeper rooting pattern on sandy soils than on clay soils (Newbould 1968). There are also more roots in those parts of the soil where nutrient concentrations are greater. Differences in rooting patterns occur not only because of inherent differences in the responses of crops to soil conditions, but also because of the mutual avoidance of different root systems (Raper and Barber 1970, Baldwin et al. 1972, Trenbath 1974). The root growth of one crop tends to avoid areas that have already had resources depleted by an associated crop.

The degree of root competition among crops can be assessed most reliably from the vertical distribution of small, metabolically active roots rather than the distribution of all roots. Two species of oats, *Avena fatua* and *Avena strigosa*, have been observed to exploit the soil profile differently, a behavior that increased the total yield of the mixture compared with the yields from pure stands (Ellern et al. 1970). Table 10.6 shows that *A. fatua* tends to have deeper roots than *A. strigosa*. Lawton et al. (1954) applied P^{32}-labeled phosphate beneath an alfalfa-brome grass mixture and noted that the grass roots were more effective in absorbing tracer from very shallow depths, while the legume roots were more effective at the 15–30-cm depth. Root competition for phosphorus was reduced by the fact that the two species were most active in phosphorus uptake at different depths in the soil profile. This is a striking contrast with browntop clover and white clover (Jackman and Mouat 1972a, 1972b), where the two species are in direct competition for phosphorus because they both obtain it from the same depth in the soil profile.

Table 10.6. Estimated Percentage of Total Root Weight at Each Depth of *Avena fatua* and *Avena strigosa* Grown in Mixture at Two Harvest Dates

	Harvest 1		Harvest 2	
Depth (cm)	*A. fatua*	*A. strigosa*	*A fatua*	*A. strigosa*
0–10	64.0	36.0	51.2	48.8
10–20	66.6	33.4	57.5	42.5
20–30	75.9	24.7	56.0	44.0
30–40	82.3	17.7	70.3	29.7

Source: Ellern et al. (1970).

A study of nine ecosystems in Central America (Ewel et al. 1982) provides an opportunity to correlate rooting patterns with ecosystem complexity (Table 10.7). All ecosystems lacking woody structure lacked deep roots. The root area index (RAI) (i.e., the root surface area) to a soil depth of 25 cm was greatest in wooded gardens and ecosystems where agricultural crops were planted to mimic secondary forest succession. The RAI was lowest in ecosystems of single crops such as maize or sweet potatoes. In all ecosystems, the roots, especially those in the smallest diameter class (0–1 mm), were most concentrated in the top 5 cm of the soil. In general, increased ecosystem diversity, even due to weeds, was associated with a greater root area. Older ecosystems, even those that were floristically simpler (e.g., shaded coffee), tended to have more root surface area and hence a greater nutrient and water uptake capacity.

Root exudates also may increase nutrient uptake and yields in mixed cropping. The effects of root exudates and secondary compounds have not been well documented (Putnam and Duke 1978), but a number of experiments point to the significance of positive chemical interactions among crop plants. Roy (1960) found growth stimulation in a mixture of two rice varieties that appeared to be caused by an agent carried between the crops in the irrigation water. Substances secreted from one plant can affect the absorption of nutrients by others (Lastavka 1970); for instance, phosphorous and potassium uptake by cereals improved in the presence of legumes (Tomashevskaya and

Table 10.7. Structure of Some Central American Ecosystems

Ecosystem	Description	Leaf Area Index[a]	Root Area Index[b] 0–5 cm	Root Area Index[b] 5–25 cm
Sweet potato	48 days old, 2000 m^2, unfertilized monoculture of *Ipomoea batatas,* nearly weed free	2.9	.20	.29
Young maize	2 months old, 0.12-ha test planting on site cultivated continuously, forest clearing 12–15 years ago, beans and maize had been planted in rotation each June and December, weeds controlled	1.0	.29	.22
Mature maize	3.5 months old, 0.5-ha planting by students using traditional farming methods, soil prepared 2 years earlier with machinery, left fallow since then, and vegetation cleared with machetes prior to planting	1.6	.52	.83
Shaded coffee	25 years old, 2-ha planting of *Coffea arabica* with overstory of *Erythrina poeppigiana*	4.0	.70	.95
Cacao-plantain-*Cordia*	2.5 years old, 450-m^2 experimental planting of *Thobroma cacao, Musa paradisiaca,* and *Cordia alliodora,* weeded first year manually and with herbicides	3.5	.97	.79
Gmelina	2.7 years old, 2-ha planting of *Gmelina arborea* (fast-growing pioneer tree native to India and Southeast Asia), planted in humid tropics for timber and paper pulp, first year part of the *Gmelina* interplanted with maize and another part with beans, only the maize *Gmelina* intercrop weeded, received insecticide and herbicide in first year	5.1	.46	.53
Secondary succession mimic	11 months old, 256-m^2 experimental plots with same location and history as secondary forest succession except species planted by investigators rather than introduced through natural dispersal and coppicing, contained about 40 species including economic and noneconomic species	4.2	.42	.75
Secondary forest succession	11 months old, natural regeneration and colonization of 256-m^2 plots cleared and burned in second-growth forest, contained more than 100 species of plants	5.1	.71	.55

Source: Ewel et al. (1982).

[a] Leaf Area Index = Total leaf area per unit area of ground.

[b] Root Area Index = Area of roots less than 5 mm diameter per unit area of ground surface. The Root Area Index is specified for two soil depth intervals (0–5 cm and 5–25 cm).

Lugovskaya 1970). Further research on such interactions has been reviewed by Loehwing (1937) and Rice (1974).

MAINTAINING SOIL FERTILITY

Soil fertility has a profound influence not only on yields but also on the kinds of crops that can be cultivated. For example, in Africa (Miracle 1967) bananas, plantains, and a variety of other high-value crops are usually interplanted on land where the forest has just been cleared. There is a large choice of crops immediately after clearing the forest because fertility is high, but after a few years of agricultural use, soil fertility often declines, and it is only practical to cultivate hardy crops such as cassava, soybean, peanuts, or sweet potatoes, usually in monoculture.

Mineral Nutrient Cycling

As discussed in Chapter 2, nutrient cycling is key to long-term soil fertility. In this section descriptions of nutrient cycling (see Figure 2.5) in Javanese agricultural systems illustrate the integration of traditional practices with modern agricultural technology such as chemical fertilizers.

Rice Fields. There are six major nutrient compartments in the rice field system: rice plants, soil, rice straw, weeds, water, and fish. Nitrogen and phosphorus from decomposing rice straw and from the soil can fertilize the water in the rice field, providing food for plankton. Fish consume the plankton as well as small insects in the water, and the fish in turn are eaten by birds or snakes in the rice field and are harvested by people for subsistence or commercial use. Part of the rice straw is used for animal feed, and part is put back in the field as a mulch or burned to use the ash as fertilizer. Farmers also apply chemical fertilizers and compost to their rice fields to increase yields. Other nutrient inputs can come from the atmosphere (rainwater), runoff, erosion from upper areas, and soil weathering. Nutrients leave the field in the harvest and through soil leaching.

Palawija. This system includes crops such as corn, soybeans, sweet potatoes, or vegetables on rice paddy land after the rice. The nutrient cycle in the *palawija* system is quite similar to that in the rice fields except it is simpler. Harvested products are sold or retained for household consumption, and the rest of the crop biomass is used for animal feed or mulch. Inputs in the form of fertilizer and compost are relatively high.

Homegardens. The nutrient cycle in homegardens is relatively complex because of the many kinds of plants and animals they contain. Homegardens require only small amounts of nutrient input because there is so much recycling within the system. Nutrients pass from the soil to trees and crops and return to the soil surface through foliar leaching or as litter. Litter decays quite rapidly, forming a mulch on top of the soil and protecting it from runoff and erosion. Fruits, leaves, and tubers from homegarden plants are consumed by humans and animals, and human and kitchen wastes are used to fertilize the fish ponds. Mud from the fish pond, animal waste, and

agricultural waste from other systems (e.g., rice straw, rice husks, maize stocks, and weeds) are mixed in a hole in the ground for composting, burned to form an ash fertilizer, or accumulated in animal pens until needed for fertilization. Chemical fertilizer is applied only to valuable species such as cloves and orange trees.

Kebun-Talun (Annual-Perennial Rotation System). The *kebun* (annual field crop) stage is characterized by intensive maintenance and high nutrient inputs. Harvested materials are used for subsistence, sale, and animal feed. The slash may be mulched in the field or composted in the homegarden. Legumes such as *kadoya (Dysoxylum amooroides)*, *dadap (Erythrina picta)*, *turi (Sesbania grandifora)*, and *johar (Cassia simea)* are grown as green manures and plowed into the soil. Legumes are particularly useful for this purpose because they fix nitrogen, have low carbon/nitrogen ratios (typically 13), and decompose rapidly (Webster and Wilson 1980). The production value of the *talun* (perennial tree) stage is not as high as the *kebun* stage, so nutrient inputs to the system are limited to natural sources such as rainwater and nitrogen fixation. Building materials (e.g., *Albizia* and bamboo) are clear-cut and removed from the field at the end of the *talun* stage. Because the total biomass of these materials can be high, their mineral nutrient content is correspondingly high, and mineral losses from the system during the *talun* stage may greatly exceed nutrient inputs. The slash from the clear-cut is burned and the ash used as fertilizer to initiate the *kebun* stage.

Organic Matter

Organic matter management includes mulching and the addition of compost and animal and green manures to the soil. Soil organic matter affects both physical and chemical properties of the soil and is particularly important for maintaining the cation exchange capacity (Lal 1975). The effect of mulching on soil physical properties includes (1) erosion control by reducing the impact of raindrops on the soil and reducing runoff because infiltration is maintained at a high level; (2) a reduction in soil temperature fluctuation; (3) improvements of the soil moisture regimes by decreasing losses due to surface runoff and evaporation; and (4) improvements in soil structure, porosity, and infiltration by protecting the soil from the impact of raindrops that can form an impermeable surface crust and by encouraging microflora and soil animals that help maintain soil structure (Lal 1975).

There is a serious hazard of progressive depletion of soil fertility and declining yields of major crops (e.g., cassava, kenaf, and rice) in Northeast Thailand due to the decrease in organic matter from soil erosion. The farmers deal with this by applying animal manure and rotating crops where the slash from each crop is plowed into the soil as green manure for the next crop. Typical cropping patterns are (1) cassava in rotation with cucumber or watermelon; (2) kenaf followed by peanut or watermelon; (3) cucumber, pumpkin, or sesame before rice, and (4) rice followed by peanuts. Moreover, rice straw is used as a mulch to decrease the rate of evaporation from the soil surface and to control weeds. Cassava, which is one of the most important economic crops in Northeast Thailand, is often grown as a monoculture, and weeds are left in the field so they act as a mulch and add to soil organic matter.

Farmers in Indonesia maintain soil fertility by using compost and green manure or by using rotation and mixed cropping systems to add organic matter to the soil. Compost is made from materials such as homegarden wastes, fish pond mud, leaf litter, rice straw, maize stalks, and rice husks. The green manure is usually legumes or rice straw. The rotational sequence is chosen so that residues from the harvest of the first crop can be used as a green manure for the second crop. For example, in the rotation of maize-beans-tobacco-*Acacia* in Central Java, after harvesting maize, the stalks are left to dry in the field without being cut and are used to support legume vines. Legumes are then harvested, and the maize stalks are cut and mixed with slash from the legumes and animal wastes to fertilize tobacco. The tobacco is intercropped with *Acacia*, which supplies nitrogen for the tobacco.

Corn research on tropical soils (Luvisols and Cambisols) in Nigeria, where environmental conditions are similar to many humid areas of Southeast Asia, has demonstrated the value of mulching. Corn mulched with rice straw and forest litter had yields 22–52 percent greater than unmulched corn (Lal 1974). Furthermore, mulched plants had higher growth rates and vigor and lacked the chlorosis and other nutritional deficiencies of unmulched plants. The increase in grain yield was due primarily to a decrease in soil temperature and partly to an increase in soil moisture. High earthworm activity along a mulched strip led to low bulk density and high permeability of the soil compared with soil in unmulched areas. The depth of root penetration was generally greater in mulched treatments, with a concentration of roots in the surface layer immediately beneath the mulch.

The Amazon Basin is an area similar to parts of Southeast Asia with poor soils. Because the traditional agriculture of the Amazon Basin, mainly shifting cultivation, is no longer feasible in some areas because of demographic pressures, new farming systems with improved soil management technology are needed to provide alternatives to shifting cultivation. Additions of organic matter as a source of plant nutrients and as a means of maintaining soil physical properties have been examined as a technology for continuous crop production in the Amazon (Wade and Sanchez 1983). Kudzu *(Pueraria phaseoloides)* or guinea grass *(Panicum maximum)* cuttings were used as mulch or incorporated as green manures under three fertilizer treatments in an Ultisol soil at Yurimaguas, Peru. Mulching with guinea grass decreased topsoil temperatures by 5°C prior to the establishment of a crop canopy, conserved soil moisture in the top 5 cm during dry weather, prevented surface crusting, and decreased weed growth. Incorporating kudzu at a rate of 8 tons of fresh material per ha per crop produced yields as high as in crops receiving complete inorganic fertilizer and liming treatment. The beneficial effects of kudzu as a green manure were associated with the

amounts of nitrogen, phosphorus, potassium, calcium, and magnesium released from the decomposing material, a decrease in aluminum saturation, and possibly enhanced nutrient accumulation due to less leaching and a lower soil density.

Lal (1975) discussed various ways to procure mulch, with their advantages and disadvantages as follows:

- *Transported mulch*—This is mulch obtained from a crop grown somewhere else either for the sole purpose of producing mulch or as a residue of a previous crop. Considerable time and labor are required, and often the material is not available when needed. The method is uneconomic except for high-value cash crops such as vegetables.
- *Live mulch*—This employs the principle of mixed cropping. A low-growing host crop, preferably a legume, is grown throughout the year. A small strip is then opened in which to plant a new crop. This method should work provided the host crop is not too aggressive at competing for light, moisture, and nutrients.
- *Using previous crop residues in situ*—Crop or weed residues on the soil surface offer maximum protection against runoff and soil erosion.
- *Tillage techniques*—Mulch-tillage employs minimum disturbance of soil through the use of live mulch and crop residues.

Mounding and Ridging

Mounding and ridging are practiced in market gardens in Southeast Asia to improve drainage or reduce soil moisture loss through runoff. Vegetables are planted on the mound or ridge, and if there is irrigation, it is brought in between the ridges, which act as water channels. Ridges are used in marsh areas to put the plants well above the water table (Jurion and Henry 1969). Mounds and ridges also can increase the amount of topsoil within the reach of crop roots and ease the harvesting of roots and tubers (Miracle 1967). Ridges may be employed where the topsoil is not sufficiently deep or fertile for demanding crops, with less demanding species being cultivated in the cleared furrows between ridges.

Mounding in New Guinea reduces the risk of crop damage and permits intensive use of the best soils for sweet potatoes. Waddell (1972) has explained the mounding technique as follows:

> The cultivation cycle is a continuous one in which, at the final harvest, the mound is broken up and the earth piled in a ridge at the perimeter. The weeds which have colonized it, together with the unwanted sweet potato vines, are thrown to the center and, over a period of about ten weeks, *S. palmaefolia* and sugar cane leaves may be introduced. A survey of the vegetable matter incorporated into ten mounds with dimensions averaging 3.1 m in diameter and 0.6 m high revealed a mean of 20.2 kg per mound, of which 63% were sweet potato vines, 20% a variety of ruderals and forbs, 10% leaves of *S. palmaefolia*, and 3% sugarcane leaves. The remaining 4% consisted of a banana leaf and a quantity of *Pyrethrum* plants reflecting the lack of any

> selectivity in mulching material. When the vegetable matter has started to decompose, the mound is closed, preferably on a dry day. The soil is shovelled from the rim to the center of the crater to cover the mulch and establish the general form of the mound; then, as the profile break between the top soil and low horizon is approached, the edge of the mound is delineated by horizontal movements with the spade. The mound is then smoothed into shape, large clods are broken up, any stone or exposed vegetable matter removed, and, finally, the surfaces compacted slightly.

Sweet potato gardens are primarily of the *modo* type, large planoconvex mounds averaging 3.8 m in diameter and 0.6 m in height. However, some are of the *yukusi* type, gardens of small mounds about 0.45 m in diameter and 0.23 m in height established prior to *modo*. *Yukusi* is used primarily when agriculture is new in the area and may occur on slopes up to 100 percent. It evolves to the *modo*, which is restricted almost entirely to terraced areas where the slope is less than 10 percent. *Yukusi* involves complete tillage of the soil without mulching. Soil that is freshly broken from a grass fallow is likely to contain very high percentages of raw organic matter, mostly in the form of roots. Further additions in the form of mulch would probably lead to immobilization of large quantities of nitrogen and phosphate by microorganisms, seriously affecting sweet potato production. *Yukusi* provides an appropriate means of cultivating sweet potatoes while the raw organic matter is being broken down to humus.

The mounding system in New Guinea is designed to permit continuously reliable harvests and cultivation of the soil despite serious environmental constraints (Waddell 1972). The main beneficial effect of the mounds at lower altitudes appears to be maintaining soil fertility through mulching, whereas at higher altitudes it appears to be a reduction in the likelihood of frost damage. People at higher altitudes say that sweet potatoes will develop only on mounds, because mounds are considered to be "hot," in the sense that they reduce frost hazards in comparison with undisturbed soil. A light frost can damage the sweet potato vine and retard growth, while a heavier frost or a series of frosts can damage the tuber, rendering it inedible. The shape of the mounds was demonstrated to have an important moderating effect on temperature inversions that occur close to the ground at night. Sweet potato vines are planted concentrically around the top of the mound to place them above the coldest air in the inversion. Frost-resistant introduced crops such as cabbage, corn, and Irish potato may be planted near the base of the mound where it is colder.

Temperatures immediately above and within the soil are influenced by other aspects of agricultural practice as well. For instance, the heat generated by decomposition of the mulch in the mound raises the soil temperature slightly (about 1.2°C). Moreover, tillage of the topsoil increases air spaces, reducing the soil's heat conductivity and increasing the amplitude of temperature fluctuations at the surface (Geiger 1965, Slatyer and McIlroy 1961). In the higher altitudes, where a short fallow rotation is practiced, the soil is only very roughly worked, in contrast to lower altitudes where the soil

is worked into the fine tilth characteristic of continuously cultivated mounds. This difference in the degree of tillage may result in the soil being relatively less aerated at higher altitudes, reducing the likelihood of a critical reduction in temperature at the soil surface.

Both *modo* and *yukusi* mounds have considerable decreases in soil moisture during the dry season compared with fallow ground, as a consequence of the mounding. There are also risks of low soil moisture associated with complete tillage in the dry season, but the improved drainage of the mounding appears to have a beneficial effect on soil moisture during the wet season, when saturation is a hazard.

Maintaining Soil Fertility in Rice Culture

Lowland rice culture is the most common form of traditional agriculture in Asia. One of the strengths of rice culture is its capacity to maintain reasonably high yields on a sustainable basis even when fertilizers are not employed. This contrasts with upland agriculture, where yields may be high at first but decline continuously in the absence of fertilizers. The difference can be attributed in large part to a natural supply of nitrogen to paddy fields due to nitrogen fixation by microorganisms (Yamaguchi 1976). For example, blue-green algae (*Anabaena azollae*) living in symbiosis with *Azolla*, a common aquatic plant in paddy fields throughout Asia, have been reported to fix as much as 1 kg of nitrogen per ha per day.

Rice farmers in developing countries now have accepted the use of chemical fertilizers to some extent, but they usually apply less than the "optimal" amount, possibly for good reason. For example, in Thailand, nitrogen-phosphorus-potassium basal fertilizer is commonly broadcasted before transplanting rice, but it appears that once fertilizer is used in large amounts, it has to be used continuously to maintain higher yields relative to those obtained from traditional rice culture without fertilizer. A major reason is that inorganic fertilizers can inhibit the growth of *Azolla* and decrease the nitrogen-fixing capacity of blue-green algae associated with *Azolla* (Yatazawa et al. 1980). Moreover, fertilizers can inhibit nitrogen fixation in other cropping systems. When nitrogen fertilizer is applied to soybeans or other legumes in amounts that exceed their growth requirements, biological nitrogen fixation and nodulation can be significantly reduced (Allos and Bartholomew 1959, Beard and Hoover 1971).

EROSION CONTROL

The Problem

Erosion is a particularly serious problem in the tropics for two reasons. The first reason is rainfall. Erosion occurs during heavy rains, which are commonplace in the tropics. The second reason is agriculture on sloping lands. When land has its natural vegetative cover removed for agriculture, the consequent erosion is much greater if the land is sloping. Small-scale agriculture in the tropics commonly occurs on land as steep as 25–50 percent slope because farmers can find no other land to make a living (Sheng 1982).

As a consequence, erosion rates in the tropics can be very high. The typical net loss of soil from large river basins in Asia, as estimated from suspended sediment loads in major rivers, is approximately 2 tons per hectare per year, equivalent to 0.4 mm of soil per year (El-Swaify et al. 1983). Soil can be eroded from some parts of a river basin and deposited in others. Erosion from agricultural fields on sloping lands is typically 10–50 tons per hectare per year, equivalent to 2–10 mm of soil per year (Dunne and Dietrich 1982).

It is well known that loss of topsoil from an agroecosystem leads to lower soil fertility and lower crop yields, and traditional agriculture features numerous techniques to keep erosion within acceptable bounds. However, as erosion control measures may demand substantial quantities of human labor, they may not be used if chemical fertilizers are available to stimulate crop yields. The difficulty is that once erosion has removed the topsoil, the quantities of fertilizers required for satisfactory yields can be so prohibitively expensive that the land is no longer suitable for agricultural use.

Although gully erosion is more conspicuous, sheet erosion causes soil losses on the largest scale. To understand how traditional agriculture protects the soil from sheet erosion, it is useful to keep in mind two key steps in the erosion process: (1) a falling raindrop breaking a tiny soil particle loose from the surrounding soil, and (2) lateral water movement (i.e., runoff) carrying that particle away. The magnitude of these two processes, and the consequent rate of erosion, depends upon rainfall, soil quality, vegetative cover, slope, and the extent of special conservation practices (Wischmeier 1975). All of these factors except rainfall can be manipulated through agroecosystem management to reduce erosion.

Soil Quality

Some aspects of soil quality (e.g., texture) affect the soil's erodibility but cannot be controlled by farm management. Soil organic matter can be managed and affects soil erodibility in several ways. Traditional agriculture often maintains a high soil humus content, and consequently good aggregate (i.e., crumb) structure, in the topsoil by applying animal or human manure, crop residues, kitchen wastes, or forest litter to the soil surface as a mulch or by incorporating them into the soil.

Little or no tillage is characteristic of much of the traditional agriculture in Southeast Asia. Experiments in West Africa indicate that zero or minimum tillage coupled with mulching effectively reduces soil loss on moderate slopes (Webster and Wilson 1980). Straw mulches are often 15 to 20 cm thick and constitute a dressing of not less than 6 tons per ha (King 1918). For example, a mulching rate of 4 to 6 tons per ha controlled soil erosion on slopes up to 15 percent even with open row crops such as maize (Lal 1976). Much higher quantities of manure and mulch are applied to upland annual crops on moderate slopes than to fields with gentler slopes or protection from tree cover (McCauley 1982).

A mulch protects the soil from the direct impact of raindrops, reduces the erosive capacity of runoff by impeding water movement, and acts as a filter that collects silt from the runoff before it gets into nearby streams. A strong crumb structure minimizes the chance that soil particles will be broken loose by raindrops and maintains a high soil permeability and infiltration capacity, minimizing the likelihood that runoff will be high enough to carry away any loosened soil particles. The fact that traditional fertilizers are organic is important, because application of chemical fertilizers to the exclusion of organic matter results in a weak crumb structure that leaves the soil vulnerable to erosion. A hard surface crust forms when the soil is dry, soil permeability is low, and runoff is high. A continuous supply of organic matter for incorporation into the soil is therefore a critical feature of erosion control in traditional agriculture. The total yield from traditional agriculture includes not only the consumable crop but also the residues that serve as organic fertilizers, preventing erosion and ensuring long-term agricultural sustainability.

Vegetative Cover

Vegetative cover protects the soil from falling raindrops. The protection is most effective if there is cover when heavy rains occur. It is also most effective if the cover is very close to the ground, since the impact of raindrops striking the ground is greater if the drops fall from higher leaves. Raindrops that fall from the leaves of tall trees have an impact virtually the same as raindrops that hit the ground directly during normal rainfall intensities. Monocultures of crops such as sweet potatoes can be effective in rapidly forming a protective cover, but a more complex mixture that includes perennials has the additional benefit of providing a crop cover throughout the year, along with a litter layer and root mass that effectively bind the surface soil (Ewel et al. 1982).

It is common for traditional agriculture in Southeast Asia to include a perennial or tree component. In addition to providing litter for use within the system itself or for removal to other agroecosystems, the dense foliar canopy of the trees can provide protection from torrential tropical rains (Bompard et al. 1980, McConnell and Dharmapala 1978). The litter serves to maintain a highly absorptive condition in the surface soil, and percolation of rainwater is aided by cracks and channels opened by living and dead roots (Webster and Wilson 1980). Inclusion of perennials in the traditional Indonesian *kebun-talun* system (described in Chapter 6) allows the cultivation of crops on slopes as steep as 100 percent while making terracing unnecessary as an erosion control measure (McCauley 1982). Many investigators have also considered the traditional multicanopied homegarden to be as effective as natural forests at preventing erosion (Terra 1954, Holdridge 1959, Kimber 1966, Igbozurike 1971, Wilken 1977, Sommers 1978, Stoler 1978, Anderson 1980, Gliessman and Amador 1980). Most of these small-holder, mixed-perennial cropping systems provide excellent soil conservation because of their reduced or zero tillage and the presence of a permanent plant cover

(Nair 1981, Conway 1974). The Raiapu of New Guinea have mixed gardens on slopes as steep as 100 percent, where twenty or more crops are planted in continuous succession and provide continuous cover (Waddell 1972).

In addition to providing ground cover through its aerial parts, a plant's subterranean part (i.e., its roots) helps to hold the soil. Bamboo is used in *talun-kebun* systems for protection against erosion because of its dense roots that bind the soil and prevent downslope soil movement. In Northeast Thailand, bamboo is used as a border for irrigation ponds to protect them from silting in.

Shifting Cultivation

Shifting cultivation is a form of traditional agriculture that often has been associated with high levels of erosion. For example, in Northern Thailand clean cultivation of steep slopes after forest removal can lead to tremendous erosion (Sheng 1982). Up-and-down planting following the burn, a traditional practice in some areas of the tropics, appears to cause concentrated runoff and accelerated erosion. Erosion plots in Taiwan, El Salvador, and Jamaica have shown that these kinds of traditional tillage methods on steep slopes can result in sediment losses of 100–200 tons of soil per ha per year (Sheng and Michaelson 1973, Hsu et al. 1977, Sheng 1982).

There are, however, many cases in which shifting cultivation with an 8- to 10-year forest fallow cycle does not cause serious soil erosion (Kalpage 1976, Lal 1982, Sanchez 1976). As most swiddens are zero tillage systems, traditional slash-burn clearing often has been observed to have less erosion than clearing by mechanical methods (Sanchez 1979, Seubert et al. 1977). Runoff in forest areas may decrease after burning because of increased permeability of the soil (Suarez de Castro 1957). The soil in traditional shifting agriculture is usually devoid of vegetative cover for only a few weeks, when abundant debris from tree trunks, branches, pieces of charcoal, and ash are capable of protecting most soils from erosion (Sanchez 1976). Large trees are often left standing in swiddens after burning, reducing erosion potential because of their root systems and continued litter production (Nwoboshi 1981, Eckholm 1976). Woody vegetative regrowth provides cover, and the living root systems of coppiced plants help to bind the topsoil.

Landscape Modification

There are many kinds of constructions and landscape modifications that reduce erosion hazards. Some reduce the gradient and length of a slope while others act as silt storage pits or drainage channels. In Southeast Asia large-scale landscape modifications constructed centuries ago still function effectively to prevent erosion. The terraced mountainsides of Java, Bali, and Luzon are examples of this and have been crucial to the sustainability of agricultural activities in steep mountain areas (Duckham and Masefield 1969). Traditional upland agriculture in Java employs a patchwork of cropping systems such that soil eroded from one field is recaptured by fields immediately downhill (El-Swaify et al. 1983).

Traditional lock-and-spill runoff storage ditches are dug fairly deeply with the contour and bermed downslope, giving the water an opportunity to infiltrate the soil and evaporate rather than running off and causing erosion. Berms between rice fields in Thailand are notched, serving to regulate water levels in the paddies. When water reaches the height of the notch it drains downslope and does not totally inundate the crop or destroy the bunds themselves. Traditional farmers sometimes build bermed drainage channels aligned up and down the slope. The area in between contains small ridges that wind irregularly down the hillside, so runoff water is confined laterally by the bunds and proceeds relatively slowly downhill behind the barriers made by the ridges across the slope (El-Swaify et al. 1983). Drainage channels used in the Central Highlands of New Guinea drain particularly wet areas and prevent runoff that can cause erosion (Waddell 1972). Silt pits, often associated with terraced or contoured fields, minimize the amount of runoff and reduce its velocity downslope, collecting silt lost from the slope above, which is then later returned to the fields and incorporated to the soil.

ACKNOWLEDGMENTS

Linda Christanty and Johan Iskandar contributed observations from Java, and Anan Polthanee and Katin Srimongkol contributed their observations from Thailand. Andrew Mittelman assembled much of the information on traditional erosion control practices.

REFERENCES

Allos, H.F., and W.F. Bartholomew. 1959. Replacement of symbiotic fixation by available nitrogen. *Soil Science* 87:61–66.

Anderson, J.N. 1980. Traditional home gardens in Southeast Asia: A prolegomenon for second generation research. In *Tropical Ecology and Development*, ed. J.I. Furtado, pp. 441–46. Kuala Lumpur, Malaysia: The Society of Tropical Ecology.

Andrews, D.J., and A.H. Kassam. 1976. The importance of multiple cropping in increasing world food supplies. In *Multiple Cropping*, eds. R.I. Papendick, P.A. Sanchez, and G.B. Triplett, pp. 1–10. Special Publication 27, American Society of Agronomy, Madison, Wisconsin.

Baker, E.F.I. 1974. Research on mixed cropping with cereals in Nigerian farming systems: A system for improvement. In *International Workshop of Farming Systems*, pp. 287–301. International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, India.

Baldwin, J.P., P.B. Tinker, and P.H. Nye. 1972. Uptake of solutes by multiple root systems from soil. II. The theoretical effects of rooting density and pattern on uptake of nutrients from soil. *Plant and Soil* 36:693–708.

Beard, B.H., and R.M. Hoover. 1971. Effect of nitrogen nodulation and yield of irrigated soybeans. *Agronomy Journal* 63:815–16.

Bompard, J., C. Ducatillion, P. Hecktsweiler, and G. Michon. 1980. A traditional agricultural system: Village-forest-gardens in West Java. Academie de Montpellier, University of des Sciences et Techniques du Languedoc, France.

Carter, W.E. 1969. New lands and old traditions. Kekchi cultivators in the Guatemalan lowlands. *Latin American Monographs.* Gainesville: University of Florida Press.

Conklin, H.C. 1975. *Hanunoo Agriculture.* Northfield, Conn.: Elliot Books.

Conway, G.R. 1974. Aftermath of the green revolution. In *Nature in the Round,* ed. C. Nigel, pp. 226–35. New York, N.Y.: Viking Press.

Duckham, A.N., and G.B. Masefield. 1969. *Farming Systems of the World.* New York, N.Y.: Praeger Publishers.

Dunne, T., and W. Dietrich. 1982. Sediment sources in tropical drainage basins. In *Soil Erosion and Conservation in the Tropics,* pp. 41–55. ASA Special Publication 43, American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin.

Eckholm, E.P. 1976. *Losing Ground: Environmental Stress and World Food Prospects.* New York, N.Y.: W.W. Norton and Company.

Ellern, S.J., J.L. Harper, and G.R. Sagar. 1970. A comparative study of the distribution of the roots *Avena fatua* and *Avena strigosa* in mixed stands using ^{14}C-labelling technique. *Journal of Ecology* 58:865–68.

El-Swaify, S.A., E.W. Dangler, and C.L. Armstrong. 1983. Soil erosion by water in the tropics. College of Tropical Agriculture and Human Resources, University of Hawaii Research Extension Series 024, Honolulu.

Ewel, J., S. Gliessman, M. Amador A., F. Berish, C. Bermudez, R. Brown, A. Martinez, R. Miranda, and N. Price. 1982. Leaf area, light transmission, roots and leaf damage in nine tropical plant communities. *Agro-Ecosystems* 7:305–26.

Francis, C.A, C.A. Flor, and S.R. Temple. 1976. Adapting varieties for intercropping systems in the tropics. In *Multiple Cropping,* eds. R.I. Papendick, P.A. Sanchez, and G.B. Triplett, pp. 235–54. Special Publication 27, American Society of Agronomy, Madison, Wisconsin.

Fukui, H., V. Kongkajandr, and A. Klungboonkrong. 1983. Present situation of upland farming in Thailand. In *Shifting Cultivation: An Experiment at Nam Phrom, Northeast Thailand, and Its Implications for Upland Farming in the Monsoon Tropics,* eds. K. Kyuma and C. Pairintra, pp. 168–84. Soil Science Department, Kyoto University, Kyoto, Japan, and Khon Kaen University, Khon Kaen, Thailand.

Geiger, R. 1965. *The Climate Near the Ground.* Cambridge, Mass.: Harvard University Press.

Gliessman, S.R., and M. Amador A. 1980. Ecological aspects of production in traditional agroecosystems in the humid lowland tropics of Mexico. In *Tropical Ecology and Development,* ed. J.I. Furtado, pp. 601–4. Kuala Lumpur, Malaysia: The Society of Tropical Ecology.

Holdridge, L.R. 1959. Ecological indications of the need for a new approach to tropical land use. *Economic Botany* 13:271–80.

Hsu, S.C., T.V. Li, and C.S. Su. 1977. Experiment on soil conservation practices for upland crops on slopeland (1st report). *Journal of Chinese Soil and Water Conservation* 8:91–104.

Igbozurike, M.U. 1971. Ecological balance in tropical agriculture. *Geographical Review* 61:519–29.

Jackman, R.H., and M.C.H. Mouat. 1972a. Competition between grass and clover for phosphate. I. Effect of browntop on white clover growth and N fixation. *New Zealand Journal of Agricultural Research* 15:653–66.

Jackman, R.H., and M.C.H. Mouat. 1972b. Competition between grass and clover for phosphate. II. Effect of root activity, efficiency of response to phosphate and soil moisture. *New Zealand Journal of Agricultural Research* 15:667–75.

Jurion, F., and J. Herry. 1969. Can primitive farming be modernized? Pub. de l'institut national pour l'etude agronomique du Congo (INEAC). Translated from the French by Agra Europe, Hors Serie 1969.

Kalpage, F.S.C.P. 1976. *Tropical Soils: Classification, Fertility and Management.* London: Macmillan Press Ltd.

Kass, D.C.L. 1978. Polyculture cropping systems: Review and analysis. *Cornell International Agriculture Bulletin* No. 32, Ithaca, New York.

Kimber, C. 1966. Dooryard gardens of Martinique. *Yearbook Association of Pacific Coast Geographers* 28:97–118.

King, R.H. 1918. *Farmers of Forty Centuries.* New York: Harcourt, Brace and Company.

Lakhani, D.A. 1976. A crop physiological study of mixtures of sunflower and fodder radish. Ph.D. thesis, Reading University, England.

Lal, R. 1974. Soil temperature, soil moisture and maize yield from mulched and unmulched tropical soils. *Plant and Soil* 40:129–43.

Lal, R. 1975. Role of mulching techniques in tropical soil and water management. International Institute for Tropical Agriculture Technical Bulletin No. 1, Ibadan, Nigeria.

Lal, R. 1976. Soil erosion on an Alfisol in Western Nigeria. *Geoderma* 16:363–431.

Lal, R. 1982. Effective conservation farming systems for the humid tropics. In *Soil Erosion and Conservation in the Tropics,* pp. 57–76. ASA Special Publication 43, American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin.

Lastavka, Z. 1970. Allelopathy and the process of ion absorption and accumulation. In *Biological and Physiological Bases for Plant Interactions in Phytocenosis,* ed. A.M. Grodzinsky, pp. 37–40. Kiev: Naukova Dumka (in Russian with English summary).

Lawton, K., M.B. Tesar, and B. Kawin. 1954. Effect of rate and placement of superphosphate on the yield and phosphate absorption of legume hay. *Soil Science Society of America Proceedings* 18:428–32.

Loehwing, W.F. 1937. Root interactions of plants. *Botanical Review* 3:195–239.

Malinowski, B. 1935. *Coral Gardens and Their Magic.* London: Allan and Unwin.

McCauley, D.S. 1982. Soil erosion and land-use patterns among upland farmers in the Cimanuk watershed of West Java, Indonesia. East-West Center Environment and Policy Institute Working Paper, Honolulu.

McConnell, D.J., and K.A.E. Dharmapala. 1978. The forest-garden farms. FAO Agricultural Diversification Project, Peradeniya, Sri Lanka.

Miracle, M.P. 1967. *Agriculture in the Congo Basin.* Madison: University of Wisconsin Press.

Nair, P.K.R. 1981. Plant associations and agroforestry land use practices with coconuts and other tropical plantation crops. Paper presented at Consultative Meeting on

Plant Research and Agroforestry, 8–15 April, International Council for Research on Agroforestry, Nairobi, Kenya.
Newbould, P. 1968. The absorption of nutrients by plants from different zones in the soil. In *Ecological Aspects of the Mineral Nutrition of Plants*, ed. I.H. Rorison, pp. 177–90. Oxford, England: Blackwell Scientific Publications.
Nwoboshi, L.C. 1981. Soil productivity aspects of agri-silviculture in the West African rain forest zone. *Agro-Ecosystems* 7:263–70.
Olsen, R.A., R.B. Clark, and J.H. Bennett. 1981. The enhancement of soil fertility by plant roots. *American Scientist* 69:378–84.
Putnam, A.R., and W.B. Duke. 1978. Allelopathy in agroecosytems. *Annual Review of Phytopathology* 16:431–51.
Raper, C.D., and S.A. Barber. 1970. Rooting systems of soybeans. *Agronomy Journal* 67:581–84.
Rice, E.L. 1974. *Allelopathy*. New York, N.Y.: Academic Press.
Roy, S.K. 1960. Interaction between rice varieties. *Journal of Genetics* 57:137–52.
Ruthenberg, H. 1980. *Farming Systems in the Tropics*. Oxford: Clarendon Press.
Sanchez, P.A. 1976. *Properties of Soils in the Tropics*. New York, N.Y.: John Wiley and Sons.
Sanchez, P.A. 1979. Soil fertility and conservation considerations for agroforestry systems in the humid tropics of Latin America. In *Soil Research in Agroforestry*, eds. H.O. Mongi and P.A. Huxley, pp. 79–124. Nairobi, Kenya: International Council for Research in Agroforestry.
Seubert, C.E., P.A. Sanchez, and C. Valverde. 1977. Effects of land clearing methods on soil properties and crop performance in an Ultisol of the Amazon jungle of Peru. *Tropical Agriculture* (Trin) 54:307–21.
Sheng, T.C. 1982. Erosion problems associated with cultivation in humid tropical hilly regions. In *Soil Erosion and Conservation in the Tropics*, pp. 27–39. ASA Special Publication 43, American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin.
Sheng, T.C., and T. Michaelson. 1973. Run off and soil loss studies in yellow yams. UNDP/FAO Jamaica 505 Project Working Document, Kingston, Jamaica.
Slatyer, R.O., and I.C. McIlroy. 1961. Practical microclimatology, with special reference to the water factor in soil-plant atmosphere relationships. Commonwealth Scientific and Industrial Research Organization, Canberra, Melbourne.
Snaydon, R.W., and P.M. Harris. 1979. Interactions belowground—The use of nutrients and water. In *International Workshop on Intercropping*, pp. 188–201. Hyderabad, India: International Crops Research Institute for the Semi-Arid Tropics.
Sommers, P. 1978. Traditional home gardens of selected Philippine households and their potential for improving human nutrition. M.S. thesis, University of the Philippines, Los Banos.
Stoler, A. 1978. How do your gardens grow? A study of garden use and household economy in rural Java. In *Agricultural and Rural Development in Indonesia*, ed. G.E. Hansen, pp. 242–54. Boulder, Colo.: Westview Press.
Suarez de Castro, F. 1957. Las quemas como practica agricola y sus efectos. *Federacion Nacional de Cafeteleros de Colombia*. Technical Bulletin No. 15.
Terra, G.J.A. 1954. Mixed-garden horticulture in Java. *Malayan Journal of Tropical Geography* 3:33–43.

Tomashevskaya, E.G., and E. Lugovskaya. 1970. Mutual influence of plants on their assimilation of nutrient elements in mixed cultures of legumes and cereals in connection with different conditions of nutrition. *Lastavka* 1:82–88.
Trenbath, B.R. 1974. Biomass productivity of mixtures. *Advances in Agronomy* 26:177–210.
Waddell, E. 1972. *The Mound Builders: Agricultural Practices, Environment, and Society in the Central Highlands of New Guinea*. Seattle: University of Washington Press.
Wade, M.K., and P.A. Sanchez. 1983. Mulching and green manure applications for continuous crop production in the Amazon Basin. *Agronomy Journal* 75:39–45.
Webster, C.C., and P.N. Wilson. 1980. *Agriculture in the Tropics*. London: Longman.
Weinstock, J. 1984. Getting the right feel for soil. *The Ecologist* 14:146–49.
Wilken, G.C. 1977. Integrating forest and small-scale farm systems in Middle America. *Agro-Ecosystems* 3:291–302.
Willey, R.W. 1979a. Intercropping: Its importance and research needs. I. Competition and yield advantages. *Field Crop Abstracts* 32(1):1–10.
Willey, R.W. 1979b. Intercropping: Its importance and research needs. II. Agronomy and research approaches. *Field Crop Abstracts* 32(2):73–85.
Wischmeier, W.H. 1975. The universal soil loss equation. In *Control of Water Pollution from Cropland. Vol. I, A Manual for Guideline Development*, ed. B.A. Steward, pp. 16–25. Washington, D.C.: Agricultural Research Service, U.S. Department of Agriculture.
Yamaguchi, Y. 1976. Nitrogen fixation in paddy soils in relation to their fertility. In *The Fertility of Paddy Soils and Fertilizer Applications for Rice*. Food and Fertilizer Technology Center for the Asian and Pacific Region, Taipei, Taiwan.
Yatazawa, M., N. Tomomatsu, and N. Hosoda. 1980. Nitrogen fixation in *Azolla-Anabaena* symbiosis as affected by mineral nutrient status. *Soil Science and Plant Nutrition* 26:415–26.