6 Sustainability of Tropical Land Use Systems After Forest Conversion

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Farmer decision making involves the weighing of many options, including those off farm and off site, and includes the possibility of migrating elsewhere. Of particular interest to natural resource management research is the balance between decisions for activities in the rural landscape that invest, plant, care, and conserve and those that exploit, harvest, and market the resources. When exploitation and harvesting dominate, the resources are likely to degrade, but the returns to labor and short-term profitability may be high. When conservation, planting and other types of investment dominate, the resources may recover from past exploitation but may not meet current livelihood demands. Finding a balance between these aspects within the landscape depends very much on the interactions between actors and stakeholders. Sustainability issues will play a role in farmers' decisions only if they are made aware of the problems and have other options.

Where a secure system of land tenure exists, the precept that "a man should always aim to hand over his farm to his son in at least as good a condition as he inherited it from his father" (Russell 1977) has been a major factor in promoting sustainable land management. Although the details may vary in different parts of the world (daughters may inherit farms, from either their mother or their father), the message remains clear: We have borrowed the resources from future generations and are supposed to return them intact.

There are many definitions of sustainability (table 6.1). Shifting cultivation systems can be sustainable if the fallow length is sufficient to undo the loss of productivity that occurs during a cropping period. If one looks at the cropping period in isolation the system appears to degrade, but when crop-

Table 6.1 Definitions of Sustainable Agricultural Systems

Definitions	**Source**
The successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources.	FAO (1989)
A system that maintains an acceptable and increasing level of productivity that satisfies prevailing needs and is continuously adapted to meet the future needs for increasing the carrying capacity of the resource base and other worthwhile human needs.	Okigbo (1991)
A system in which the farmer continuously increases productivity at levels that are economically viable, ecologically sound, and culturally acceptable through the efficient management of resources and orchestration of inputs in numbers, quantities, qualities, sequences, and timing, with minimum damage to the environment and human life.	Okigbo (1991)
A system that involves the management and conservation of the natural resource base and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development conserves land, water, plant, and animal genetic resources and is economically viable and socially acceptable.	FAO (1991)
A cropping system is not sustainable unless the annual output shows a nondeclining trend and is resistant, in terms of yield stability, to normal fluctuations of stress and disturbance.	Spencer and Swift (1992)
A sustainable land management system is one that does not degrade the soil or significantly contaminate the environment while providing necessary support to human life.	Greenland (1994)

Source: Greenland (1994).

ping and fallow periods are combined the basic resources are maintained from one cycle to the next and allow continued exploitation. This example may illustrate some of the considerations necessary for an assessment of sustainability:

- Sustainability of a larger system (crop and fallow) may be maintained even if a subsystem (the cropping period) is nonsustainable.
- Sustainability of a human livelihood system can be maintained even if specific activities are not sustainable as long as a sufficient array of options is maintained.

Whenever a specific form of land use runs into problems with one of the resources on which it depends, there may be alternative solutions that maintain the overall functioning of the system. These solutions may be more costly, but the fact that they exist means that sustainability assessments really depend on the boundary conditions that we set for such potential adaptations.

In general, however, it is easier to define what is nonsustainable than it is to say what is sustainable. Any system that does not maintain all essential parts of the resource base is nonsustainable, so finding one violation of the resource conservation rule is enough to characterize the system as a whole as nonsustainable. We can confirm that a system is sustainable only if we know the fate of all parts of the resource base and the degree to which they are essential; this is not a trivial task by any means. Sustainability at any level of complexity (from sustainability of cropping systems to that of human livelihoods) can be based on the sustainability of its components, possible adaptations, or the adaptive response of the key actors at each level in finding and fitting in new components (figure 6.1).

Sustainable livelihood options do not necessitate sustainable cropping systems or crops if there are enough potential alternatives. Existing sustainability indicators

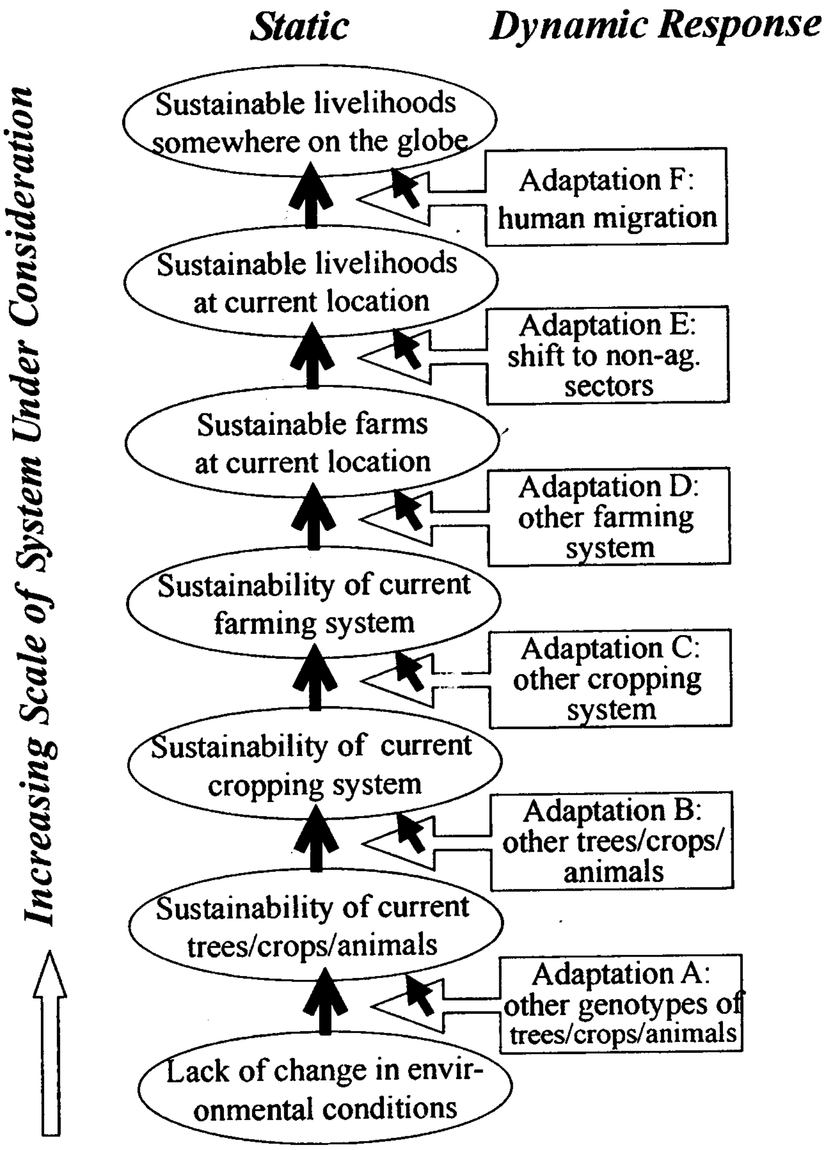

Figure 6.1 At any single level in the hierarchy from abiotic resources to global livelihoods, sustainability can be defined either as the persistence of the underlying level (the resource base) or as the availability of options (allowing the manager to be resourceful or agile in making adaptations).

appear to focus on persistence, ignoring adaptation and change. Yet options for change are not the same everywhere, so they should be taken into account as well.

If we combine a persistence view of sustainability with the options for dynamic change (figure 6.1), we see that sustainability at one scale does not extend to the scales above or below. Changes in the resource base and options for future change can affect sustainability at higher levels in the hierarchy, even if persistence criteria for the current system are met. Conversely, lack of sustainability at any level can be compensated for to achieve sustainability at a higher level in the hierarchy if options for adaptation are maintained. Therefore we have to be explicit in the system boundaries before we can measure, quantify, or assess sustainability.

In the context of our integrated assessment of land use options for the humid tropics, we will discuss the following:

- Assessments of sustainability of land use practices at plot level
- Assessments of sustainable agricultural livelihood systems at landscape scale

ASSESSMENTS OF SUSTAINABILITY OF LAND USE PRACTICES AT PLOT LEVEL

Sustainability of a range of land use systems that follow forest conversion can be assessed if we first specify the threats to persistence (figure 6.2). Four ways by which continued farming degrades its own resource base to a level that impairs future productive use of the land are as follows:

A. Not maintaining soil of sufficient structure
B. Not balancing the budget of nutrient exports and imports
C. Letting pest, weed, and disease problems reach unmanageable proportions
D. Not maintaining essential soil biota, such as mycorrhizal fungi and *Rhizobium*

Any of these problems can become such a constraint to continued farming that land may have to be abandoned, at least temporarily. Therefore the most serious category of problems determines the overall sustainability.

Other threats to continued farming that may dominate discussions of agricultural sustainability, especially in developed countries, are threats to water quality and quantity (E), air quality (F), and biodiversity (G) (figure 6.2). If there are serious negative effects on these factors, then outside stakeholders may take measures to stop the land use practice in its current form. Another threat is producing products of insufficient quality to meet consumers' expectations (H).

Categories A to D are essentially agronomic in nature; categories E to H depend on the perceptions and responses of consumers and other outside stakeholders, so

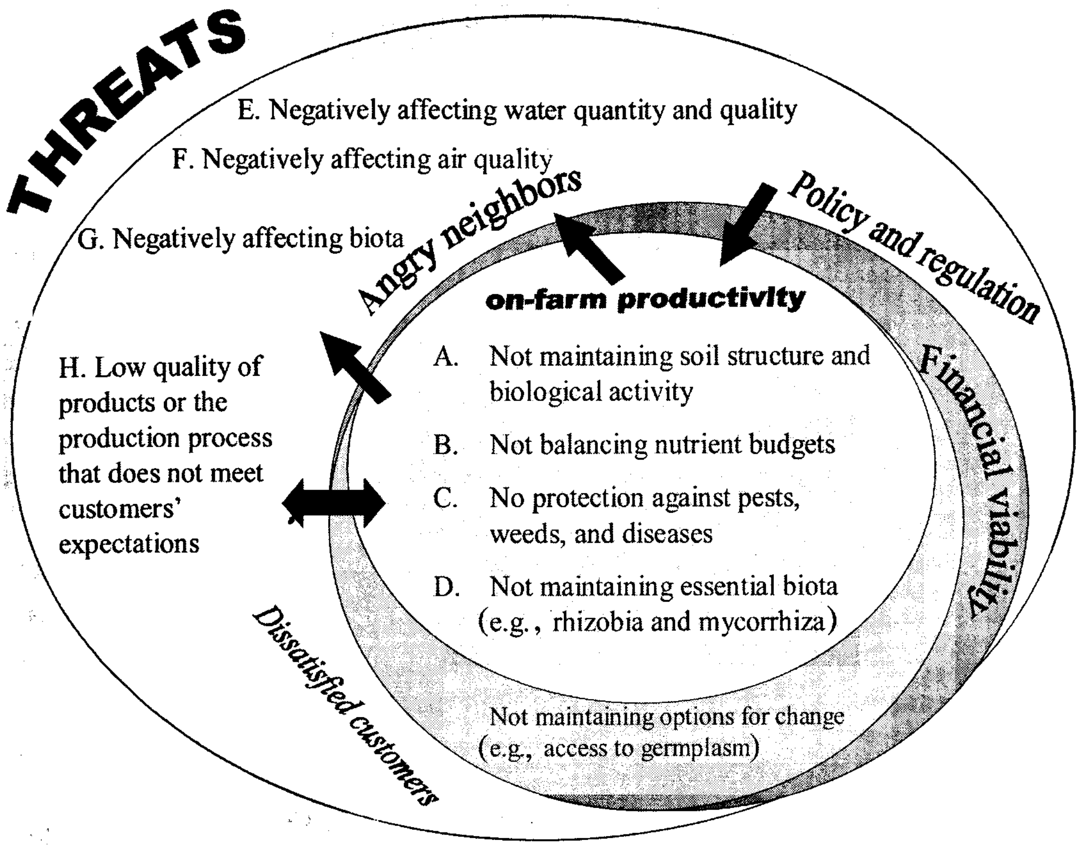

Figure 6.2 Threats to agricultural sustainability: The inner circle is essentially agronomic and the outer circle is more focused on environment and market issues (van Noordwijk and Cadisch 2002).

they necessitate very different methods of investigation. They affect farming through government or local regulations and financial incentives. Other threats to continued farming are based on the lack of financial viability of a farm, changes in prices for the products, and a lack of options for change.

For each category of threats, numerous indicators can be developed at two levels:

- Easily observable phenomena that can be used in rapid qualitative assessments
- Real measurable parameters for which standardized protocols and interpretation schemes (which include specific threshold values) can be made

Qualitative field-level indicators may be sufficient for monitoring on-site changes by (forest) farmers or other land users. To them, the presence of a surface litter layer and clear forest streams may be enough to indicate that the system they work with is sustainable. Yet such simple indicators are not sufficient for legally binding commitments. The latter require rigorous, quantifiable indicators, but even with such procedures, the interpretation of data may not be unequivocal because absolute reference values are lacking for many of the parameters. For example, a debate on how often landslides occur in "natural forest" landscapes can cast doubt on any data on sediment loads of rivers after forest conversion.

No agricultural land use can consistently yield harvests of produce without management efforts being invested in maintaining the system. Therefore, all judgments of sustainability must be made in the context of a specified management regime and farmer efforts to overcome obstacles. For each indicator a tentative threshold has to be identified, which allows a final judgment to be expressed, for example, in terms of three categories:

0: No major problems beyond the range that normal farm management can address.
–0.5: Additional effort will be needed to address these issues, which may affect the profitability of the land use system but may otherwise be within the range of farmers' management options.
–1: Problems may be beyond farmers' ability to resolve.

In the Alternatives to Slash-and-Burn (ASB) project, a set of criteria and indicators was developed that can be measured easily, often using data already collected as part of the integrated survey of biodiversity, carbon stocks, and greenhouse gas emissions. Details of the various criteria that were used are presented in the following sections. After that, the values and results obtained in the assessments in Indonesia, Cameroon, and Brazil are discussed.

Criteria for evaluating the impacts of land use on former forest soils (table 6.2) can be grouped by soil function, focusing on the sustainability of land use practices and on externalities or effects on environmental functions of forest soils. However, the measurables for these various functions show a high degree of overlap. Many of them are linked with the maintenance of surface mulch and soil organic matter.

CRITERION A: SOIL STRUCTURE AND BIOLOGICAL ACTIVITY

The following indicators can be used.

A1: Soil Compaction

Soil compaction is measured from soil bulk density (dry weight per unit volume, g/cm^3) in the topsoil relative to that of a forest soil of the same texture. Isolated, individual measurements of soil bulk densities are difficult to interpret because soils of differing texture have different inherent bulk densities such that values that are high and unsustainable for one soil type may not be for another. By using a "pedotransfer" function we can estimate the normal bulk density (BD_{ref}) of a soil of the same texture, and we can use the ratio BD/BD_{ref} as an indicator of change from the reference situation. Values above 1 indicate compaction, values below 1 a structure that is better than average (in the reference set). Wösten et al. (1995, 1998) derived such a pedotransfer function for a large set of soils from the temperate region that are under agricultural use:

Table 6.2 Criteria and Indicators for Evaluating Sustainability of Plot-Level Land Use on Previous Forest Soils in the ASB Project

Criteria	Indicators (qualitative)	Measurable Parameters (quantitative)
I. Maintain on-site productivity		
A. Maintain soil as a matrix of reasonable structure, allowing root growth and buffering water between supply (as precipitation) and demand (for transpiration)	Erosion: absence of gullies, presence of riparian filter strips and other sedimentation zones, soil cover by surface litter or understory vegetation Compaction: use of penetrometer Soil structure: spade test, root pattern Soil cover and absence of gullies as indicators of infiltration; absence of surface sealing and crusting	Net soil loss = internal soil loss – internal sedimentation. Percentage soil cover, integrated over the year (or over annual rainfall). Bulk density of topsoil. Soil macroporosity and H_2O infiltration rates. Water infiltration vs. runoff. Soil water retention. Effective rooting depth.
B. Maintain the nutrient balance: buffer nutrients between supply from inside and outside the system and demands for uptake	Annual exports of phosphorus and cations as fraction of total and available stock Annual exports of nitrogen minus inputs from biological N_2 fixation as fraction of total nitrogen content of the soil Financial value of net nutrient exports as fraction of potential replacement costs in fertilizer	Changes in stocks of plant available nutrients. Changes in mineralization potential or size of organic matter pools. Carbon saturation deficit. Limiting-nutrient trials.
C. Keep pest, weed, and disease problems within a manageable range	Absence of major diseases and weeds	Rate of increase of pest incidence. Change in composition and quantity of weed flora.
D. Maintain essential soil biota, such as mycorrhizal fungi and *Rhizobium,* and ecosystem engineers	Sporocarps (mushrooms) for ectomycorrhizal species Signs of ecosystem engineers among the soil fauna: earthworms, termites	Spore counts for vesicular arbuscular mycorrhiza. Mycorrhizal infection and nodulation in roots in the field and in trap crops in the lab. For details see chapter 5.
II. Externalities: Don't make the neighbors angry		
E. Provide a regular supply of high-quality water	Stream flow response time after rain storms; downstream areas free of floods and droughts Turbidity of streams	Stream flow amounts and variability. Sediment load of streams. Absence of agrochemicals in water.

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Table 6.2 (Continued)

Criteria	Indicators (qualitative)	Measurable Parameters (quantitative)
II. Externalities: Don't make the neighbors angry		
F. Air filter: mitigate net emission of greenhouse gases	Above-ground carbon stocks in biomass and necromass	Soil carbon stocks relative to soil carbon saturation deficit. Net emissions of NO_2 and CH_4.
G. Maintain biodiversity reservoirs: allow recolonization of depleted neighboring landscape units and germplasm collection for ex situ exploitation	Diversity of above-ground vegetation, based on diversity of plant functional attributes	Diversity of plant species. Diversity of soil biota in selected indicator groups.
III. Keep the consumers happy		
H. Maintain a product quality that consumers want to buy	Actual consumer response	Criteria based on the consumer's perception of quality. These may involve positive attributes (e.g., taste, nutritional value), lack of negative attributes (e.g., no chemical residues or genetically modified components), or lack of production process (social and environmental concerns).

For soils with Clay% + Silt% < 50 percent the following equation is used:

$$BD_{ref} = 1/[-1.984 + 0.01841 \times OM + 0.032 + 0.00003576 \times (Clay\% + Silt\%)^2 + 67.5/MPS + 0.424 \times \ln(MPS)],$$

where OM is the soil organic matter content ($= 1.7 \times C_{org}$) and MPS is the mean particle size of the sand fraction, with a default value of 290 μm.

For soils with Clay% + Silt% > 50 percent the following equation is used:

$$BD_{ref} + 1/[0.603 + 0.003975 \times Clay\% + 0.00207 \times OM^2 + 0.01781 \times \ln(OM)].$$

Although these equations were based on agricultural soils in temperate regions, they have been used here to approximate bulk density values for soils from differing land uses and with differing texture. This pedotransfer refers to soil under normal agricultural use rather than under forest, so we expect BD/BD_{ref} values to be below 1 for forest conditions.

A2: Soil Carbon Saturation

Soil organic matter is considered to be a key characteristic in judging the sustainability of land use systems. Yet total soil organic matter content is not a very sensitive indicator because it changes slowly under different management regimes and often has a high spatial variability linked to variability in soil texture, pH, and elevation.

Current methods for inventory of soil organic matter are based on an estimate of the soil carbon stored under natural vegetation and relative changes caused by aspects of human land use, including soil tillage, drainage, and a reduction in organic inputs compared against the natural vegetation. The difference between current and potential carbon storage can then be expressed as a carbon saturation deficit (van Noordwijk et al. 1997, 1998). We can now calculate a carbon saturation deficit on the basis of the difference between the actual soil carbon content and amount that would be expected for a forest soil with a long history of large litter inputs for the same type of soil.

$$C_{satDeficit} = (C_{ref} - C_{org})/C_{ref} = 1 - C_{org}/C_{ref},$$

where C_{org}/C_{ref} = soil organic carbon content relative to that for forest soils of the same texture and pH, and C_{ref} = a reference soil carbon level representative of forest soil.

More details on the basis for the equations and values for the carbon saturation deficit can be found in chapter 2. If the value of the C_{org}/C_{ref} ratio is 1, this means the soil is similar to that of a forest and basically carbon saturated, and values less than 1 indicate a carbon deficit relative to the forest soil.

A3: Active Soil Carbon

Microbial biomass forms only 1 to 4 percent of the total carbon content of a soil, but it is the most active fraction because nearly all transformations in the soil depend on microbial activity. Numerous indicators have been identified for comparing the size of this microbial pool or some other fraction or activity of the labile soil carbon in different land use types in a given area relative to the natural forest on an equivalent soil type.

- Microbial biomass is generally estimated by comparing the amount of carbon or nitrogen that is released into the soil after a chloroform fumigation that (supposedly) kills all microbes. It is measured through incubation or extraction methods. Microbial biomass estimates derived in this way often correlate well with soil nitrogen mineralization rates and crop yields and therefore are an indication of soil microbial activity and fertility. Soil microbiologists generally prefer other methods that target specific groups of soil microbes or have a stricter separation of live and dead fractions of the biomass, but for a first assessment the overall microbial biomass measurement still has value.

- Soil respiration or nitrogen mineralization (during lab incubation) can be used as an indication of the biological activity of the soil.
- Dry weight of the light fraction of soil organic matter represents recent inputs of organic matter as food for soil biota. This fraction can be obtained using a separation technique based on liquids of different densities, called the size–density fractionation procedure (Sitompul et al. 2000).
- It is becoming apparent that individual measures of microbial biomass or light fraction may not reflect the active or labile fraction of soil organic matter (SOM) because both fractions contain labile carbon. Chemical oxidation approaches such as that described by Blair et al. (1997) may be a more integrative measure of labile soil carbon.

The use of these parameters is valid when they are judged against the values obtained for natural forest sites. Yet there are still no critical values below which one can say the system is no longer sustainable.

A4: Soil Exposure

Soil exposure (SE) to the direct impact of raindrops and the sun, if frequent or for long periods of time, can lead to deterioration of soil structure. Therefore, a soil cover such as a surface litter layer or green leaves of plants growing close to the ground can protect the soil. Tree canopies alone do not count, however, because the energy of the splash impact of drips from the leaves can exceed that of rainfall.

Several indicators were developed to reflect both the percentage of time that a soil is exposed and the length of the cycle. The soil cover index integrates the information of both soil exposure and open time into one indicator. The indicators include the following:

> Soil exposure = 100 × number of months of low (less than 75 percent) soil cover/length of system cycle in months, that is, proportion of the length of the whole cycle that the soil has a low cover
>
> Time between clearing events, that is, the frequency of the removal of a protective canopy cover = total length of system cycle (in years)
>
> Soil cover index = length of system cycle in months – soil exposure time in months

CRITERION B: NUTRIENT BALANCE

Three indicators were developed to judge whether the nutrient balance is (or could potentially be) maintained in a cropping system.

B1: Net Nutrient Export

Net nutrient export (NNE) can be calculated as the total nutrients contained in all harvested products (which are removed from a field) minus the amount of nutrients added in the form of fertilizer inputs for nitrogen, phosphorus, and potassium, in kilograms per hectare per year. The value does not include the nutrients that are recycled in the system such as litterfall or prunings, crop residues, or manures. High net exports indicate the likelihood of depletion of the resource base; high net surpluses, on the other hand, may indicate excessive fertilizer use and risks of pollution of ground and surface water. Nutrient imports can also include dinitrogen (N_2) fixation from legumes in the system.

B2: Nutrient Depletion Time Range

Nutrient depletion time range (NDTR) represents the theoretical length of time (number of years) it would take for nutrient stocks to be depleted to zero (if current trends are extrapolated linearly). In any system, if nutrient stocks in soil and vegetation are large relative to net nutrient exports, nutrient offtake can be part of a wise natural resource management strategy. If exports are large relative to stocks, however, one can expect that yields will decline in the near future unless nutrient inputs are increased.

Two types of estimates were used for nutrient stocks in the system:

- The directly available nutrient pool in the soil
- The total nutrient content of soil plus vegetation (including less accessible pools in the soil)

Neither estimate is directly satisfactory, however, because measures of the available nutrient pool include arbitrary fractions and there is wide variation between plants in ability to access nonavailable nutrient sources. Because nutrient stocks depend on the soil type and vegetation cover, one cannot directly assign an NDTR value to a land use system. As an example from the peneplain of Sumatra, the inherently more fertile soils closer to rivers with a higher clay and silt content will have larger nutrient stocks than the sandier soils of the rest of the lowland peneplain. Thus, figures obtained may be accurate only within an order of magnitude.

B3: The Relative Nutrient Replacement Value

The relative nutrient replacement value (RNRV) relates the export of nutrients in harvested products to the costs of putting them back into the agroecosystem in the form of chemical fertilizer. This assessment is based on the harvested products rather than the full production system.

CRITERION C: CROP PROTECTION FROM WEEDS, PESTS, AND DISEASES

For criterion C, two indicators have been proposed, both based on expert opinion rather than direct measurements:

C1: Potential for Weed Problems

Weed problems become a major constraint in the system unless addressed by additional labor or technical input.

C2: Potential for Pest or Disease Problems

Pest or disease problems become a major constraint in the system unless addressed by additional labor or technical input.

CRITERION D: MAINTENANCE OF ESSENTIAL SOIL BIOTA

The relationship of different groups of soil biota to certain soil and ecosystem functions is discussed in chapter 5. Certain functional groups such as macrofauna (ants, termites, earthworms), nematodes, and plant microsymbionts have been identified as key to the maintenance of certain soil and ecosystem processes, but no critical values have been set.

CASE STUDIES: RESULTS FROM ASB INDONESIA (SUMATRA), CAMEROON, AND BRAZIL

CRITERION A: SOIL STRUCTURE AND BIOLOGICAL ACTIVITY

Data collected from the Lampung and Jambi benchmark sites in Indonesia (table 6.3) show that there is a clear difference in mean bulk density between undisturbed forests and land under a cassava–*Imperata* cycle, with intermediate degrees of compaction under agroforests and other tree-based production systems. Serious localized soil compaction was clear in logged-over forest where tracks and logging ramps were compacted beyond easy recovery. It is easy to compact a soil, but in systems without soil tillage it can take a long time before the soil recovers. Soil compaction can affect water infiltration, root growth, and greenhouse gas emissions but probably stayed below critical levels in all cases observed.

Table 6.3 Measured Soil Fertility Indicators for the Integrated Biodiversity Survey in Lampung and Jambi, ASB Benchmark Area (September – November 1996)

	BD/BD_{ref}, 2–7 cm	C_{org}/C_{ref}, 0–5 cm	Light Organic Matter, 0–5 cm (g/kg)	Bacterial Population/ C_{org}	Bacterial Population/ (C_{ref}/C_{org})	Soil Respiration (mg CO_2/ kg/d)
Forest	0.85	0.91	3.22	13.5	37	12.9
Relative to Forest						
Agroforest	0.99	0.75	0.77	1.48	1.43	0.91
Regrowing trees	1.21	0.73	0.81	1.78	1.69	0.84
Cassava	1.14	0.52	0.35	1.56	1.51	0.59
Imperata	1.26	0.66	0.58	1.59	1.62	0.80

Soil samples were taken at the surface layer (0 – 5 cm only), except for bulk density (BD), at 2–7 cm. See text for indicator descriptions.

The carbon saturation (C_{org}/C_{ref}) data show that no land use systems fully maintain the soil organic matter levels in the topsoil of a natural forest, as is shown by the values of C_{org}/C_{ref} of less than 1.0. Declines greater than 25 percent were found only for the cassava–*Imperata* land use type, with the greatest reductions of almost 50 percent measured in cassava fields. The low current value of carbon saturation may have resulted partly from reclamation history and current land use (bulldozer land clearing can remove part of the topsoil to outside the field boundaries). The frequent fires and soil tillage, together with low organic inputs through cassava litterfall (0.6 Mg/ha/yr compared with 12 Mg/ha/yr in secondary forest), are the likely causes.

These same land uses, except for cassava, had a high respiration rate, but when estimates of total microbial population size are scaled by soil organic matter content or carbon saturation, the active fraction of the total soil organic matter pool in forests appears to have been lowest. On the basis of this evidence and other data in the soil biodiversity survey (see chapter 5, this volume) we conclude that there is no lack of active soil biota in any of the land uses for the basic functions of nutrient cycling and decomposition, and *Imperata* grasslands are not depleted ecosystems from a soil biological perspective, even though their soil organic capital has been reduced.

The indicator of soil cover (A4) requires inferences over the lifespan of the system rather than point measurements. Figure 6.3 shows that the nature of soil cover can shift from dead wood and leaf litter in forests to covers dominated by green biomass in a *Chromolaena* fallow. Bare soil is rarely exposed in the landscapes of the peneplains. In all land use systems with a slash-and-burn land-clearing event, soil may be exposed for about 6 months per cycle (or 2 percent of the time for a rubber system with a 25-year cycle). The only land use system in which soil exposure may be an issue is the cassava–*Imperata* cycle, where soil may be exposed during the first 3 months of a cassava crop and for about 1 month per year in all cases when the *Imperata* fallow is burned. Com-

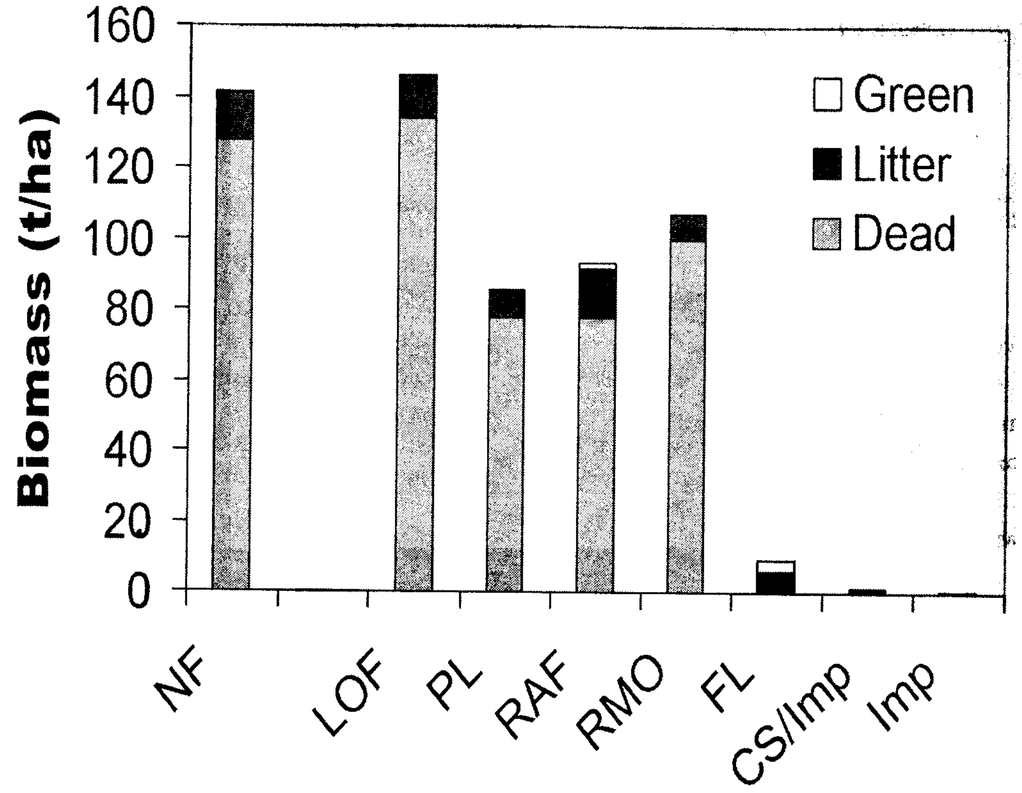

Figure 6.3 Soil cover in different land use types in Jambi. CS/Imp, cassava–*Imperata;* FL, *Chromolaena* fallow; Imp, *Imperata;* LOF, logged-over forest; NF, natural forest; PL, timber plantation (Paraserianthes); RAF, rubber agroforest; RMO, rubber monoculture.

bined, this may lead to about 10 percent of the time with incomplete soil cover, when the soil is vulnerable to the direct impact of rain and sun.

In the case of Cameroon (table 6.4), the systems have the soil exposed from 7 (long fallow) to 20 percent (short fallow) of the cycle, with intermediate values for the other systems. However, these values do not adequately reflect the fact that these exposure events occur much less often in some of the systems, resulting in soil cover indexes six and two times higher than those of the short and long fallow systems, respectively. Therefore the combined soil cover index probably is much more useful when such different systems are compared.

To summarize all the soil measurements, sustainability ratings were assigned to the different land use types on the basis of criterion A (maintenance of soil structure and biological activity) (table 6.5). The measurements were translated into a qualitative value within the range of 0 to –1, where –1 = problems beyond those that farmers can solve, 0 = no major problems, and –0.5 = problems within the range of farmer management. For numerous land use systems the overall rating is thus –0.5. Only the cassava–*Imperata* system has questionable sustainability according to several criteria.

Table 6.4 Soil Exposure, Time Between Clearing Events, and Soil Cover Index in Different Land Use Systems in the Cameroon Benchmark Area

Land Use Systems	Soil Exposure (% of cycle length)	Time Between Clearing Events (yr)	Soil Cover Index (mo)
SF: food intercrop	19.4	6	58
LF: food intercrop	7.3	16	178
SF: intensive cocoa with or without fruit	11.1	30	320
FOR: extensive cocoa with or without fruit	10.8	30	321
SF: oil palm	16.7	30	300
FOR: oil palm	17.5	30	297
Community-based forest management	0.0	100	360

SF, short fallow; LF, long fallow; FOR, derived from forest.
Source: Kotto-Same et al. (2000).

Table 6.5 Overall Assessment of Severity of Sustainability Problems of Various Land Use Systems for the Peneplain of Sumatra

Land Use System	A1	A2	A3	A4	B1	B2	B3	C1	C2	Overall	Main Issues
Natural forest	0	0	0	0	0	0	0	0	0	0	
Community-based forest management	0	0	0	0	0	0	0	0	0	0	
Commercial logging	–0.5	0	0	0	0	0	0	0	0	–0.5	C
Rubber agroforests	0	0	0	0	0	0	0	0	0	–0.5	
Rubber agroforests with selected planting material	0	0	0	0	–0.5	–0.5	0	0	–0.5	–0.5	C, K, W, P
Rubber monoculture	0	0	0	0	0	0	0	–0.5	–0.5	–0.5	W, P
Oil palm monoculture	0	0	0	0	0	0	–0.5	0	0	–0.5	Fert
Upland rice–bush fallow rotation	0	0	0	0	0	–0.5	–0.5	0	–0.5	–0.5	Fert, P
Cassava–*Imperata* rotation	–0.5	–0.5	0	–0.5	–0.5	–0.5	–1	–0.5	0	–1	C, Fert, W

C, soil compaction; K, potassium balance; W, weeds; P, pests and diseases; Fert, price of fertilizer.
0, no problem; –0.5, problem that probably can be overcome by the farmer, –1, problem probably out of reach of farmers' solutions.

CRITERION B: NUTRIENT BALANCE (INDONESIA)

At yield levels of 15, 2, 10, and 0.7 Mg/ha/yr for cassava, upland rice, oil palm, and rubber, respectively, the expected annual nutrient removals with harvested products can be derived from table 6.6 to be highest for cassava (40 kg N/ha/yr, 5 kg P/ha/yr, 60 kg K/ha/yr), followed by oil palm (30 kg N/ha/yr, 5 kg P/ha/yr, 40 kg K/ha/yr), and lowest for rubber (4 kg N/ha/yr, 1 kg P/ha/yr and 3 kg K/ha/yr).

Many farmers in the benchmark area appear to use no fertilizer at all in the cassava–*Imperata* cycle. For such no-input versions the nutrient balance is clearly negative. A clear tradeoff may exist for this land use type between sustainability and profitability.

The nutrient depletion estimates showed that the nutrient for which the most rapid depletion may occur is potassium. If only the directly available pool is considered, depletion within a 25-year time frame may occur for the rubber systems and

Table 6.6 Relative Nutrient Replacement Value for Main Products of Various Land Use Systems

A.

	Nutrient Removal (g/kg product)			Nutrient Replacement Value (Rp/kg) (*a*)	Farmgate Value of Product (Rp/kg) (*b*)	Relative Nutrient Replacement Value (*a*/*b*)
	N	P	K			
NTFPs, rotan	2	0.20	1	10	20,000	<0.001
NTFPs, petai and jengkol	5	0.50	5	24	500	0.05
NTFPs, durian	3	0.30	6	28	1,000	0.03
NTFPs, others						<0.001
Timber	2.5	0.25	1.5	13	108	0.12
Rubber (latex)	6.3	1.20	4.4	42	2,000	0.02
Oil palm (bunches)	2.9	0.55	3.9	25	60	0.41
Rice	11.8	2.90	2.7	70	400	0.17
Cassava	2.8	0.36	3.9	22	50	0.44

B. Data Needed for Calculating Nutrient Replacement Values

	N	P	K
Replacement price per nutrient exported, Rp/g $[x/(y \times z \times 1000)]$ (*a*)	2.3	12.0	2.9
Fertilizer price, Rp/kg (*x*)	260	480	400
Proportion of nutrient in fertilizer (*y*)	0.45	0.2	0.46
Nutrient recovery[a] by crops or products (above) (*z*)	0.25	0.2	0.3

Rupiah prices before July 1997, US $1 = 2300 Rp.

NTFPs, nontimber forest products.

[a] See text.

Source: Modified and extended from van Noordwijk et al. (1997a).

shifting cultivation as well as cassava production. If total stocks are considered (at least part of "nonavailable" potassium can be accessed by plants), the time frame to depletion becomes several decades at least. For nitrogen, no problems are to be expected for the land uses described here according to this calculation. However, these calculations are based on total soil nitrogen, and only 2 to 4 percent of that is mineralized and therefore available in any year. Also, the calculations do not include nutrient losses other than in harvested products, and substantial nitrogen losses, up to 80 percent of the nitrogen in the vegetation, occur during slash-and-burn clearing of forest lands and by leaching during subsequent periods of low nitrogen demand by the vegetation relative to the nitrogen supply from mineralization. A more refined estimate would have to include the full spectrum of processes incorporated in the Century model (Palm et al. 2002) and goes beyond the current sustainability assessment.

In the calculations for relative nutrient replacement values in table 6.6, the amounts of fertilizer needed to replace the nutrients exported in the harvested products are corrected for (long-term) nutrient recovery. It was assumed that only 25 percent of nitrogen, 20 percent of phosphorus, and 30 percent of potassium fertilizers that were applied were actually recovered (taken up) by the products or crops. Thus, for every gram of nitrogen exported in a harvested product, 4 g of nitrogen had been applied in the form of nitrogenous fertilizer. The N_2-fixing trees petai (*Parkia speciosa*) and jengkol (*Pithecellobium jiringa*) included in the nontimber forest products (NTFPS) scenario were assumed to derive two-thirds of their nitrogen from the atmosphere. The nutrient replacement value (*a* in table 6.6A) is calculated as the weight of each nutrient removed, multiplied by the replacement cost per nutrient (in table 6.6B), then totaled for nitrogen, phosphorus, and potassium (neglecting other nutrients).

Most relative nutrient replacement (RNRV) values are below 10 percent, and this indicates that nutrient replenishment would be within reach of farmers if, when, and where actual nutrient responses of the crop make fertilizer use necessary. For rice, the value is around 15 percent, and this indicates a range in which details of fertilizer use (and the various assumptions on efficiency made here) will be important for farmers' decisions on fertilizer use.

For oil palm and cassava the RNRV values are around 45 percent, indicating that fertilizer costs would be a major part of the farm budget if farmers had to balance the nutrient budgets. The high RNRV values for both products are caused by their low price (at the farmgate) per kilogram of product. For oil palm, marketing of fruits instead of bunches could reduce the nutrient exports and hence the RNRV. For cassava only a shift in farmgate prices of the product or of fertilizers could make fertilizer use more attractive.

To summarize all measurements, sustainability ratings were assigned to the different land use types on the basis of criterion B, maintaining nutrient balance (table 6.5). Only the cassava–*Imperata* rotation appears to be unsustainable in all the nutrient indexes and cannot be solved in most cases because of the current costs of fertilizers. Therefore it will be interesting to observe the economic and environmental trajectory of this land use system.

CRITERION C: CROP PROTECTION FROM WEEDS, PESTS, AND DISEASES (INDONESIA)

Weed problems are related mostly to *Imperata* (table 6.7), which is hard to control without herbicides that are often too expensive for smallholder food production or plowing (van Noordwijk et al. 1996a). In rubber-based agroforestry systems, damage by pigs and monkeys in newly planted fields can be a serious obstacle when clonal planting material is used because it is more expensive than the traditional planting stocks (Williams et al. 2001), whereas in the existing system, substantial tree losses are tolerated by planting low-cost seedlings at high densities. The natural secondary forest regrowth in rubber agroforests is probably less problematic as a "weed" than the grass or fern vegetation that develops under attempts at weed control.

SYNTHESIS OF SUSTAINABILITY INDICATORS FOR SUMATRA

When all indicators are combined (table 6.5) we conclude that

- Most land use systems considered have one or more aspects that need attention, but most of these stay within the range of problems that are solvable at farm level.
- The cassava–*Imperata* cycle has numerous problems associated with it, and one of these (maintaining a nutrient balance) is so serious that it probably cannot be resolved at the farm level within the current constraints.

AN OVERALL ASSESSMENT FOR CAMEROON

The overall assessment of agronomic sustainability for Cameroon is based on the information presented in table 6.8.

Soil Structure

A significant decline in soil structure over time is observed in intensively managed, short fallow, annual food crop systems. This decline is related to the frequent disturbance of the fallow vegetation, which is reflected in the longer soil exposure and soil cover index in this system (table 6.4). Fire used for getting rid of the slashed vegetation and the soil tillage accompanying planting operations may also contribute to this decline. With shortening fallows, the fallow vegetation itself shifts to thickets often dominated by *Chromolaena* or grasses. Alternative planted fallow systems that fix nitrogen and contribute to the stabilization of the soil organic matter pool may

Table 6.7 Cross-Site Comparison of Assessments of Agronomic Sustainability

	Soil Structure			**Nutrient Balance**		
	Brazil	**Cameroon**	**Indonesia**	**Brazil**	**Cameroon**	**Indonesi**
Forest extraction	0	0	–0.5	0	0	0
Multistrata agroforestry systems	0–0.5	0–0.5	0	–0.5–1	–0.5–1	–0.5
Simple tree crop systems	–0.5	0–1	0	–0.5	–0.5	0–0.5
Crop–fallow systems	0–0.5	–0.5–1	0	0–0.5	0–1	0
Continuous annual cropping systems	—	—	–0.5	—	—	–0.5
Pastures	0–1	—	—	–0.5	—	—

Table 6.8 Overall Sustainability Assessment of Soil Structure, Nutrient Balance, and Crop Protection Status in Different Land Use Systems in the Cameroon Benchmark Area

Land Use Systems	Soil Structure	Nutrient Balance	Crop Protection
SF: food intercrop	–1	–1	–1
LF: food intercrop	–0.5	0	0
SF: intensive cocoa with fruit	0	–1	–1
SF: intensive cocoa without fruit	0	–1	–1
FOR: extensive cocoa with fruit	–0.5	–0.5	–1
FOR: extensive cocoa without fruit	–0.5	–0.5	–1
SF: oil palm	0	–0.5	–0.5
FOR: oil palm	–1	–0.5	–0.5
Community-based forest	0	0	0

SF, short fallow, LF, long fallow, FOR, derived from forest.
Scores: 0, no problem; –0.5, problem that probably can be overcome by the farmer; –1, problem probably out of reach of farmers' solutions.
Source: Kotto-Same et al. (2000).

reduce this potential problem. Converting the short fallow land into a perennial crop system would also help to protect the soil better than annual cropping systems because of their reduced disturbance and exposure. In contrast, a deterioration of soil structure is expected when perennial crop systems are planted into fields newly cleared from forest. This is associated with the initial exposure of the soil and the regular traffic associated with the management of the systems. However, there is greater concern about soil compaction in oil palm systems than in cocoa systems because of the slower canopy closure at establishment in the former and the more regular traffic needed for harvesting bunches.

Nutrient Balance

The systems that cause most concern in terms of overexploitation of nutrients are the intensive perennial cocoa and oil palm systems. The potassium lost in the oil palm systems is compensated for by fertilizer use; however, no fertilizer is applied in the intensive cocoa system. The extensive cocoa system is of somewhat less concern because the yield levels are significantly lower. Fertilizer use can alleviate most of these concerns, and farmers are willing to use them if the institutional and financial environments are conducive. Although the nutrient exports from the short fallow and food crop system are moderate, we must assume that the nutrient stocks are already low in a system where the fallow period is only 4 years. Given that short fallows often are planted to subsistence crops with little cash return, the probability of farmers using external inputs is very low. Only the association of higher-value annual food and horticultural crops, such as tomato, with these systems would enable the use of fertilizers. Nitrogen could be supplied by the planting of N_2-fixing fallow species. Finally, no nutrient problems are expected in the long fallow and community forest systems.

Crop Protection

Major weed, pest, and disease complexes can develop in recurrent short fallow systems. The lack of longer fallows that allow trees to shade out the arable weeds, including *Chromolaena,* result in greater weed pressure and the emergence of weeds that are more difficult to manage manually (e.g., *Sida* spp. and grasses). Intensive weed management associated with a prior high-value crop (e.g., tomato) may reduce the weed pressure in subsequent subsistence food crops. Short fallows also allow volunteer crops to survive during the fallow phase, facilitating carry-over of pests and diseases into the next cropping period (e.g., the African root and tuber scale in cassava). Breeding crops for resistance associated with appropriate integrated pest management practices can reduce crop loss. The cocoa systems also face a major challenge in terms of pest and disease problems. If not treated, black pod disease can reduce yields up to 80 percent, and mirids can kill trees. Managing these entails a concerted control effort at the farm and community levels, with significant inputs of pesticides, unless integrated tree management options are further developed and adopted. Weeds are a threat only during the establishment of all perennial systems.

Overall Agronomic Sustainability

The most sustainable systems appear to be the long fallow and the community forest systems. The next sustainable is the establishment of oil palm systems on land previously under short fallows. All other systems have important agronomic constraints associated with them or lead to possible deterioration of the resource base. As indicated earlier, there are potential solutions, but the financial and institutional environment must be conducive.

COMPARISON OF SUSTAINABILITY INDEXES ACROSS LAND USE SYSTEM TYPES AND BENCHMARK SITES

Table 6.7 provides an overview of the assessment of three components of agronomic sustainability—soil structure, nutrient balance, and crop protection—for the Indonesia, Cameroon, and Brazil benchmark sites. If commercial logging is excluded, all sites reported that forest extraction was the most sustainable system. The main issues of concern in multistrata agroforests relate to crop protection problems, such as pod rot in cocoa in Cameroon, and potentially negative nutrient balances depending on the specific systems assessed. The nutrient balance problem is greatest in the Brazilian multistrata agroforestry systems based on fruits, which have a net negative nitrogen balance of –109 kg N/ha/yr, whereas the values for the complex rubber agroforests in Indonesia are generally low (e.g., –5 kg/ha/yr) because they are based on latex harvest. Simple tree crop systems often are linked with problems of soil structure, besides crop protection concerns. However, these plantation systems often receive fertilizers and therefore exhibit less negative nutrient balances. Crop–fallow systems vary greatly in their effect on agronomic sustainability. The long fallow systems with low cropping intensity in Indonesia and Cameroon (traditional slash-and-burn shifting agriculture systems) are sustainable, but unimproved short fallow systems with intensified cropping, as in Cameroon, can have a detrimental effect on soil structure, nutrient balance, and crop health. Planted fallow systems with herbaceous and tree legumes can improve soil structural and nitrogen balance concerns. Continuous annual cropping, as with cassava in Indonesia, is problematic at all levels. Pastures, particularly with improved management practices, tend to have a medium level of impact on the natural resource base, although impacts on global environmental issues (biodiversity and greenhouse gas emissions) may be large (see chapter 4, this volume; Palm et al. 2004).

SUSTAINABILITY ASSESSMENTS OF AGRICULTURAL LIVELIHOOD SYSTEMS AT THE LANDSCAPE SCALE

Farmer Perceptions of Sustainability

As part of the characterization process at the ASB sites, farmers were asked for their views on the threats and constraints to various land use options. This is essentially an assessment at farm level and includes elements other than the plot-level sustainability discussed so far. Several problems in four types of cropping systems (sawah–lowland rice, upland food crops, sugar cane, and tree crop–based systems) that were identified by farmers in North Lampung are presented in figure 6.4.

Four common problems were reported for all the systems: soil fertility, drought, fire, and the weed *Imperata cylindrica*. The upland food crop system was perceived to have the greatest amount of problems of the four cropping systems.

Maintaining Options for Land Use Change

The final criterion for sustainability is the possibility of continuing to farm on a given piece of land, keeping all threats at manageable levels. However, continued farming may depend on the ability to change and develop a farm in new directions. Whereas certain land use practices, such as cultivation of very efficient nutrient scavengers such as cassava, may meet the criterion of persistence for a period of, say, 20 years, this

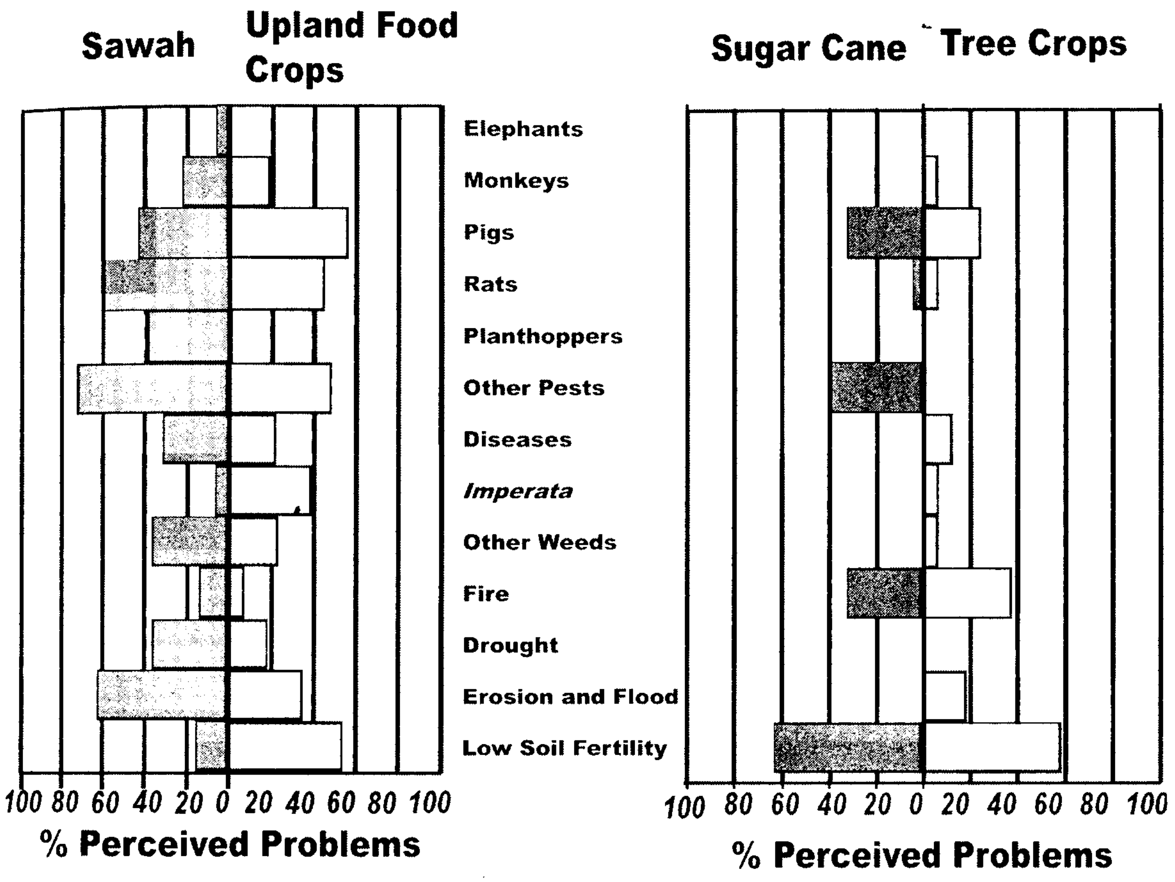

Figure 6.4 Problems identified by farmers in the ASB North Lampung benchmark area (van Noordwijk et al. 1996b).

practice is likely to reduce the number of future options because the soil depletion it induces will necessitate substantial reinvestment in soil nutrient stocks before other crops can be grown. The criteria used in the previous sections apply to the field-level land uses per se, because they are measurable, whereas a full land use transition matrix can be assessed only by other means. Such adaptive capacity research has to specify the range of options available and the way these options themselves change in time and differ between stakeholders. It is unlikely that land uses will remain unchanged over more than one (or a few) human generations, so it may be interesting to evaluate which options are kept open with a given land use system (table 6.9).

Natural forest can be used as the starting point for all land use types, but in a strict sense it can originate only from forests; community-managed forests, some logging techniques, and extensive rubber agroforests can lead to a return of a vegetation close to that of natural forests. At the other end of the spectrum, the cassava–*Imperata* cycle can be started after any land use system but forms a dead end because it cannot maintain its own productivity, and substantial efforts and expense for nutrient replenishment and *Imperata* control (Friday et al. 1999) are needed to return to other more profitable and sustainable land use types. The various tree crop systems appear to be freely convertible into each other, but extensive rubber agroforests change in character once the seedbank of original natural vegetation is depleted and the site is far from the natural vegetation, thus decreasing the possibility of seed dispersal. Table 6.9 strengthens the conclusion that the cassava–*Imperata* system is the most problematic of the land use systems considered here.

The resource base for adaptive capacity (resilience) can be viewed in light of the five types of capital described in Carney (1998): natural resource, human, social, physical, and financial capital. Adaptation of agroecosystems can be based on two mechanisms, one internal and one external to the current system. Agroecosystems, especially those rich in natural resource capital (agrodiversity and biological resources), can adapt by increasing the use of currently underexploited local resources or on the basis of new technology and resources (new crops, new cultivars, new management practices, new external inputs), depending on their financial, human and social capital. An indication of the types of capital needed for the various adaptive capacity aspects is given in figure 6.5. Agricultural research has supported a drive toward the simplification of agroecosystems. This drive results at least in part from the fact that research is less effective in dealing with more complex systems even if they would be superior (Vandermeer et al. 1998). Access to the fruits of this increasingly commercialized research depends on financial and social capital and is less likely in the less endowed parts of the world.

Adaptive capacity based on resources in the current landscape becomes more likely with an increasing choice of new components and resources in more complex agroecosystems, although we are not yet able to quantify how much complexity is needed for how much resilience (Vandermeer et al. 1998).

CONCLUSION

Our search for indicators and thresholds of agronomic sustainability has yielded numerous yardsticks that can be used to assess land use options at plot level. Production of bulk products of low value per unit biomass (such as the cassava in our example) is likely to cause nutrient depletion of the soil because the nutrient replacement costs by fertilizer use probably will exceed the value of the products. Systems relying on products with a high value per unit biomass, such as many tree products, are likely to be more sustainable because farmers will be (financially) able to maintain the nutrient balance. Systems with low soil exposure times, such as long fallow and perennial tree crops, reduce chances of soil compaction and the subsequent erosion and runoff problems that compromise sustainability.

For the broader issue of farming sustainability, however, we do not yet have a satisfactory set of indicators. Options for future change should be an essential part of the assessment, as should the interactions of farms with feedback loops through society, the economy, and government policies, which may have overriding influences on sustainable land use.

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