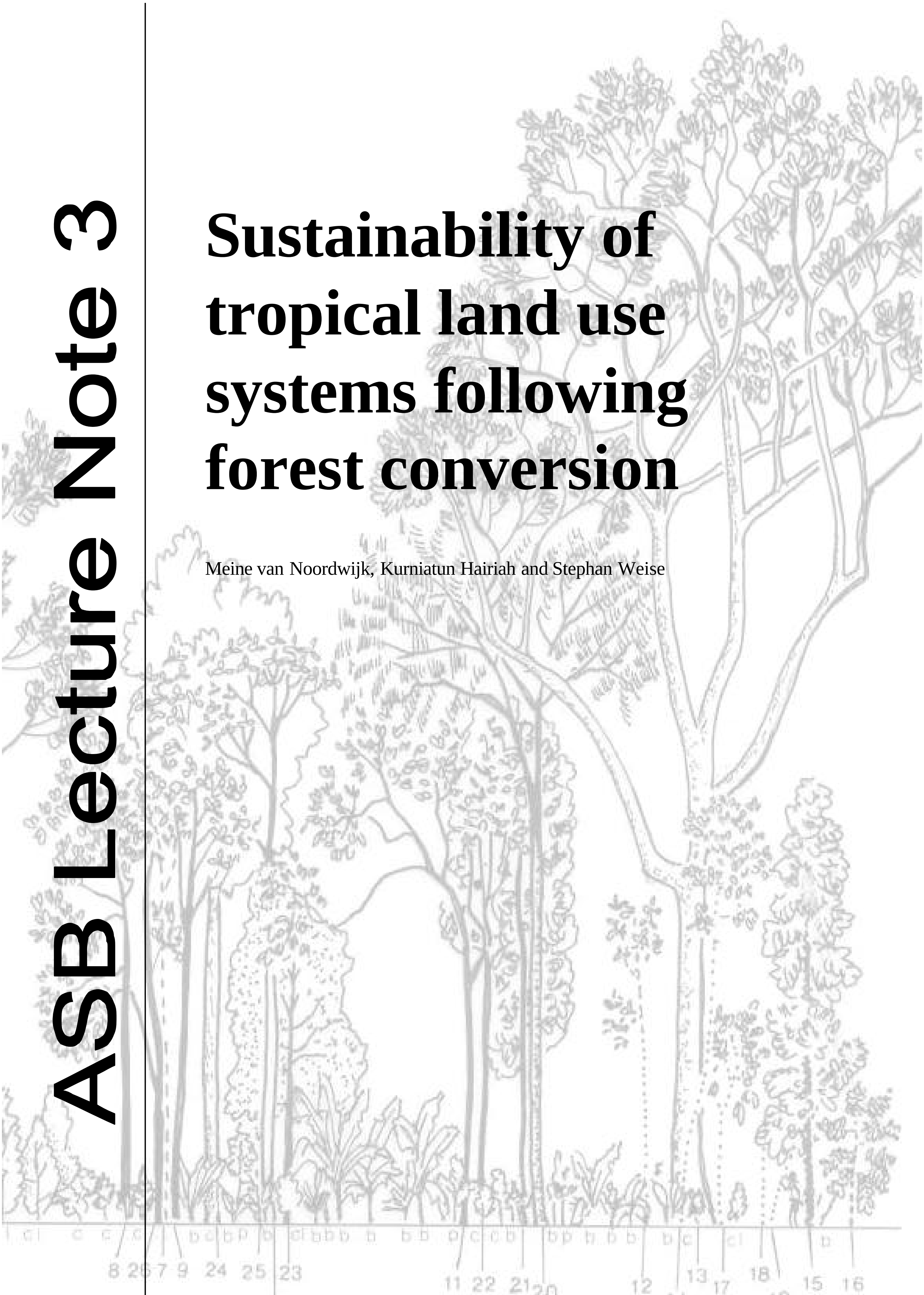
ASB Lecture Note 3

Sustainability of tropical land use systems following forest conversion

Meine van Noordwijk, Kurniatun Hairiah and Stephan Weise



INTERNATIONAL CENTRE FOR RESEARCH IN AGROFORESTRY

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Towards integrated natural resource management in forest margins of the humid tropics: local action and global concerns

Meine van Noordwijk, Sandy Williams and Bruno Verbist (Editors)

> Humanity stands at a defining moment in history. We are confronted with a perpetuation of disparities between and within nations, a worsening of poverty, hunger, ill health and illiteracy, and the continuing deterioration of the ecosystems on which we depend for our well-being. However, integration of environment and development concerns and greater attention to them will lead to the fulfilment of basic needs, improved living standards for all, better protected and managed ecosystems and a safer, more prosperous future. No nation can achieve this on its own; but together we can - in a global partnership for sustainable development. (Preamble to the United Nations' Agenda21 on Sustainable Development; http://www.un.org/esa/sustdev/agenda21chapter1.htm).

Background to this series of lecture notes

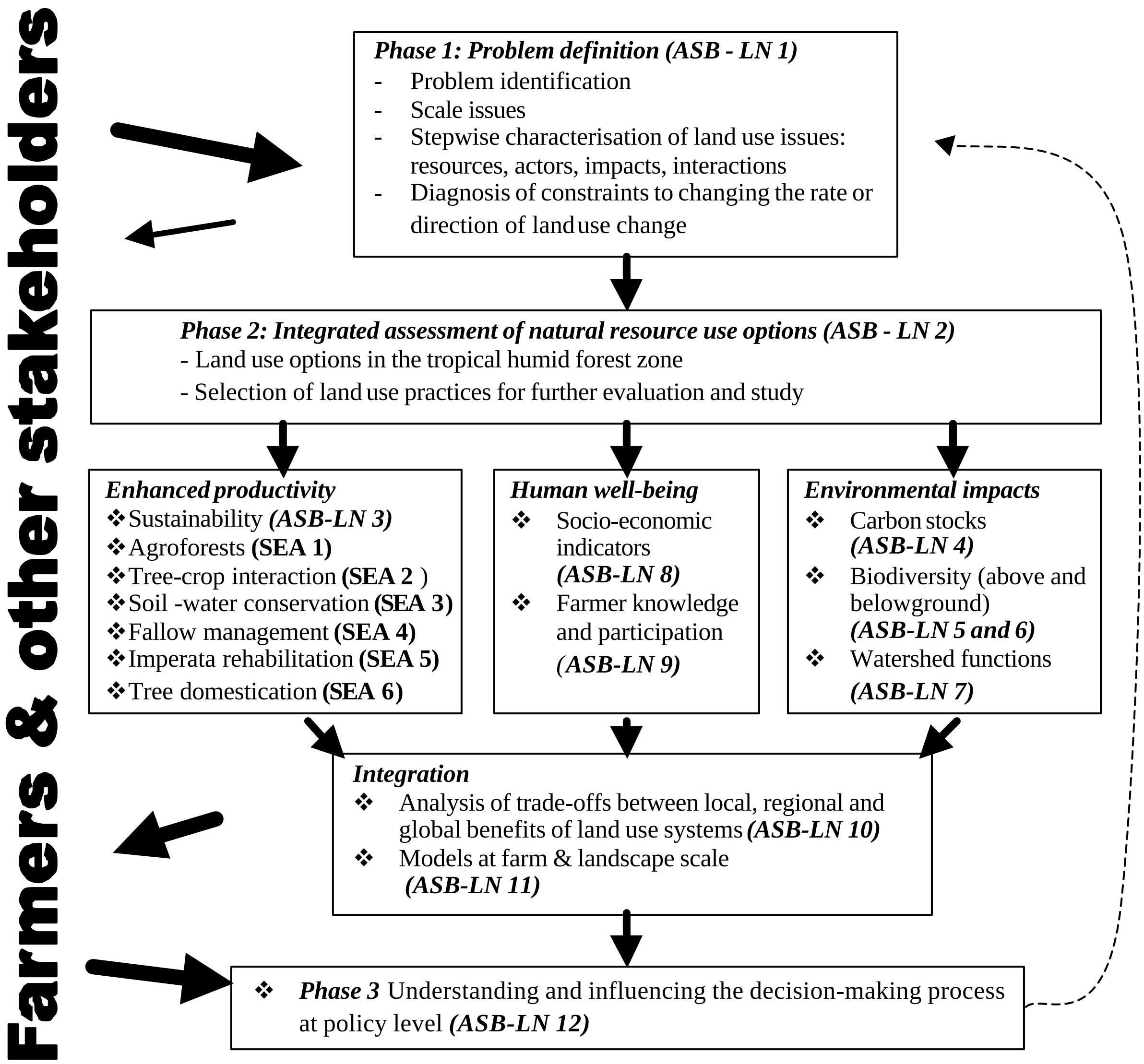
Much of the international debate on natural resource management in the humid tropics revolves around forests, deforestation or forest conversion, the consequences it has and the way the process of change can be managed. These issues involve many actors and aspects, and thus can benefit from many disciplinary perspectives. Yet, no single discipline can provide all the insights necessary to fully understand the problem as a first step towards finding solutions that can work in the real world. Professional and academic education is still largely based on disciplines – and a solid background in the intellectual capital accumulated in any of the disciplines is of great value. If one wants to make a real contribution to natural resource management issues, however, one should at least have some basic understanding of the contributions other disciplines can make as well. Increasingly, universities are recognising the need for the next generation of scientists and policymakers to be prepared for interdisciplinary approaches. Thus, this series of lecture notes on integrated natural resource management in the humid tropics was developed.

The lecture notes were developed on the basis of the experiences of the Alternatives to Slash and Burn (ASB) consortium. This consortium was set up to gain a better understanding of the current land use decisions that lead to ***rapid*** conversion of tropical forests, shifting the forest margin, and of the ***slow*** process of rehabilitation and development of sustainable land use practices on lands deforested in the past. The consortium aims to relate local activities as they currently exist to the global concerns that they raise, and to explore ways by which these global concerns can be more effectively reflected in attempts to modify local activities that stabilise forest margins.

The Rio de Janeiro Environment Conference of 1992 identified deforestation, desertification, ozone depletion, atmospheric CO_2 emissions and biodiversity as the major global environmental issues of concern. In response to these concerns, the ASB consortium was formed as a system-wide initiative of the Consultative Group on International Agricultural Research (CGIAR), involving national and international research institutes. ASB's objectives are the development of improved land-use systems and policy recommendations capable of alleviating the pressures on forest resources that are associated with slash-and-burn agricultural techniques. Research has been mainly concentrated on the western Amazon (Brazil and Peru), the humid dipterocarp forests of Sumatra in Indonesia, the drier dipterocarp forests of northern Thailand in mainland

Southeast Asia, the formerly forested island of Mindanao (the Philippines) and the Atlantic Congolese forests of southern Cameroon.

The general structure of this series is



This latest series of ASB Lecture Notes (**ASB-LN 1 to 12**) enlarges the scope and embeddes the earlier developed ICRAF-SEA lecture notes (**SEA 1-6**) in a larger framework. These lecture notes are already accessible on the website of ICRAF in Southeast Asia: http://www.icraf.cgiar.org/sea

In this series of lecture notes we want to help young researchers and students, via the lecturers and professors that facilitate their education and training, to grasp natural resource management issues as complex as that of land use change in the margins of tropical forests. We believe that the issues, approaches, concepts and methods of the ASB program will be relevant to a wider audience. We have tried to repackage our research results in the form of these lecture notes, including non-ASB material where we thought this might be relevant. The series of lecture notes can be used as a basis for a full course, but the various parts can also 'stand alone' in the context of more specialised courses.

Acknowledgements

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ASB-consortium members

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Lecture Note 3

SUSTAINABILITY OF TROPICAL LAND USE SYSTEMS FOLLOWING FOREST CONVERSION

By Meine van Noordwijk, Kurniatun Hairiah and Stephan Weise

Contents

I. Objectives

- To introduce and discuss the concept of sustainability and maintenance of adaptive options
- To provide a set of indicators that can be used to assess the sustainability of land use alternatives and give examples on how these indicators can be used

II. Lecture

1. Introduction

1.1 The balance between exploitation and maintenance

Farmer decision-making involves the weighing up of many options, which may be available, including those off-farm and off-site, and including 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 labour 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. Non-sustainability will only play a role in farmers' decisions if they are (made) aware of the problems, and if they 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.

1.2 Sustainability concepts in a systems hierarchy

Many enjoyable or profitable things cannot be sustained on a long-term basis. This doesn't really matter, as long as we can find other things to replace them that are equally good. The problem is that we have only one world at our disposal, so the number of 'other things' is limited when it comes to land use – we cannot let this planet go to waste and move on to the next one, as a large scale form of 'shifting cultivation'.

Shifting cultivation systems can be sustainable (in the sense of maintaining productive potential) if the fallow length is sufficient to undo the loss of productivity that occurs during a cropping period. When we look at the cropping period as such, we see that the system degrades, but when we look at the combination of cropping and fallow period, we can conclude that from one cycle to the next the basic resources are maintained that allow continued exploitation. This example may illustrate some of the considerations necessary for an assessment of 'sustainability':

- sustainability of a larger system (crop + fallow) may be maintained even if a sub-system (the cropping period) is non-sustainable,
- 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.

Many definitions have been developed for sustainability (Table 1), which indicates that there are several different conceptions of what constitutes sustainability.

Table 1. Definitions of sustainable agricultural systems (Greenland, 1994).

No.	Definitions	Sources
1	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
2 a	A system, which 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
2 b	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 danger to human life	Okigbo, 1991
3	A system which 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
4	A cropping system is not sustainable unless the annual output shows a non-declining trend and is resistant, in terms of yield stability, to normal fluctuations of stress and disturbance	Spencer and Swift, 1992
5	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

In general, however, it is easier to define what is ***non-sustainable*** than it is to say what is ***sustainable***.

Any system that does not maintain ***all*** *essential parts of the resource base is* ***non-sustainable****; so, finding one violation of the resource conservation rule is enough to characterise the system as a whole as non-sustainable.*

We can only confirm that a system is ‘sustainable’ 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. 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.

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, or on possible adaptations, or the 'agility' of the key actors at each level in finding and fitting in new components (Figure 1).

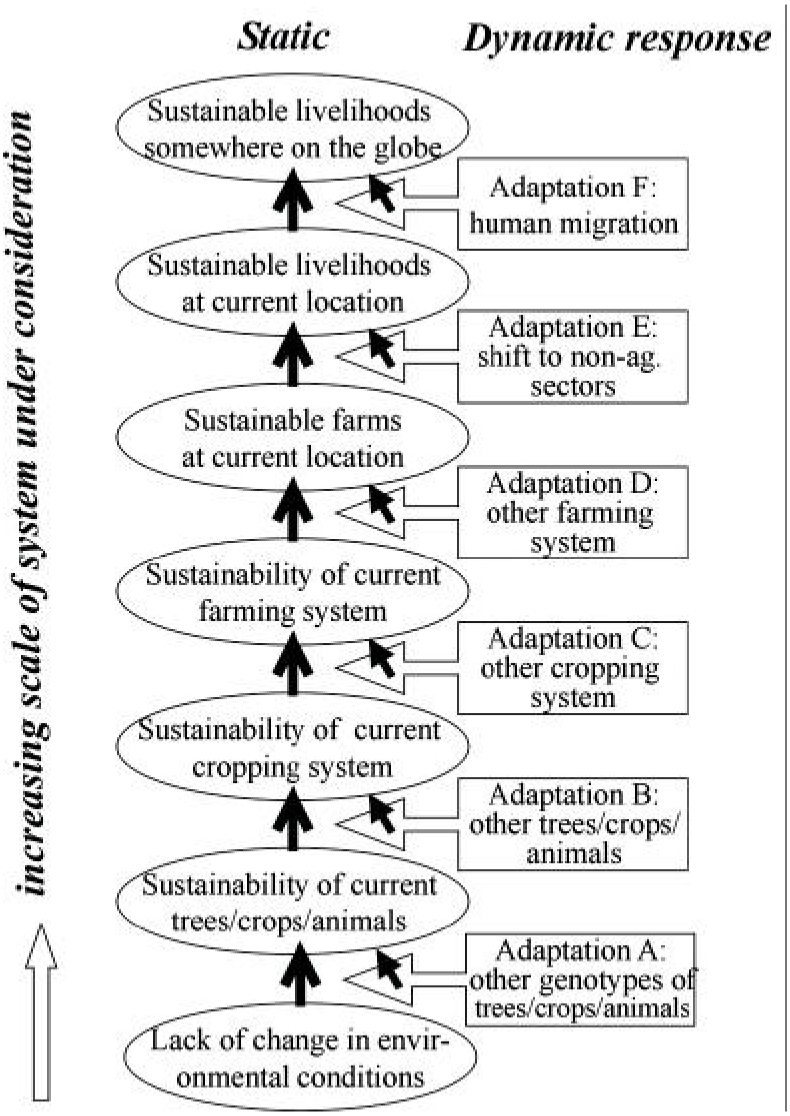

Figure 1. At any single level in the hierarchy from abiotic resources to global livelihoods, sustainability can be defined either as the persistence of the underlying level (the 'resource base') or as the availability of options (allowing the manager to be 'resourceful' or 'agile' in making adaptations).

Sustainable livelihood options do not require sustainable cropping systems or crops, provided that there are enough potential alternatives. Existing sustainability indicators appear to focus on the 'persistence' issue, 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 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. We thus 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:

- assessments of sustainability of land use practices at plot level,
- assessments of sustainable, agricultural livelihood systems at landscape scale.

Suggested exercise:
1. Formulate potential '**threats**' that could affect sustainability at each of the 7 levels of Figure 1.
2. Can you translate these 'threats' into criteria? Are these criteria measurable? Can you identify thresholds?

2. Assessments of sustainability of land use practices at plot level

Sustainability of a range of land use systems, which can follow forest conversion can be assessed if we first specify the threats to persistence (Figure 2).

Four ways by which continued farming degrades its own resource base to a level that impairs future productive use of the land are:

A. Not maintaining soil of sufficient structure and biological activity,
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 categories can become such a constraint to continued farming that land may have to be (temporarily) abandoned. Therefore the most serious category of problems determines the overall sustainability.

Other threats to continued farming that may dominate discussions on agricultural sustainability, especially in developed countries, are E, F, and G (Figure 2). Thus, if there are very serious negative effects on water (E), on the atmosphere (F), or on the soil or biotic (G) qualities of the environment, then outside stakeholders may take measures to stop the land use practice (in its current form). Another threat is H: not producing products of a quality that meets consumers' expectations.

Categories A to D are essentially agronomic in nature, categories E to H depend on the perceptions and response of consumers and other outside stakeholders, so they require very different methods of investigation. They have an impact on farming via government or local regulations and financial incentives.

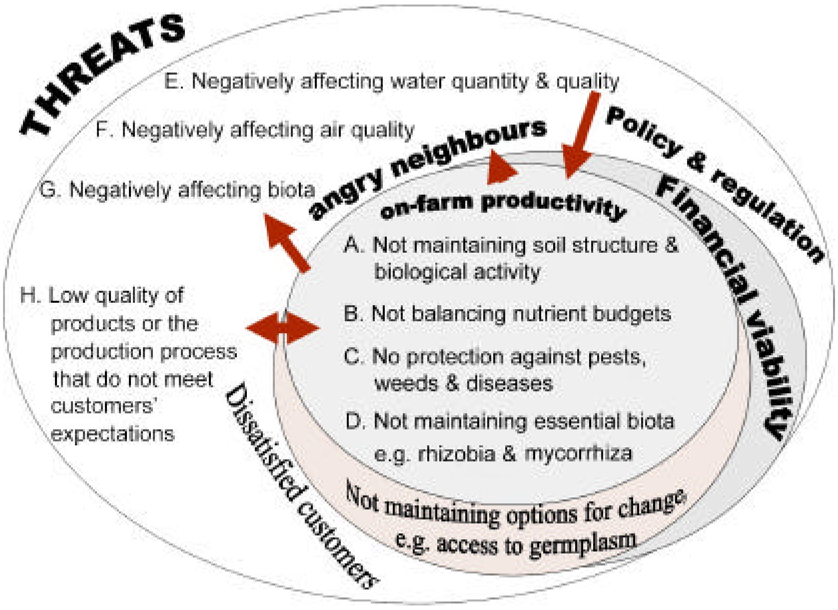

Figure 2. Threats to agricultural sustainability: the inner circle is essentially agronomic and the outer circle is more focused on environment and market issues.

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 (see below).

2.1 Criteria, indicators and thresholds: the theory

For each category of threats, a number of 'indicators' can be developed at two levels:

- easily observable phenomena which can be used in rapid assessments, but which are 'quick and dirty', and
- real measurable parameters, for which standardised 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 evaluate the system they work with as sustainable. Yet, such simple indicators are not sufficient for legally-binding commitments, which may stand up in a court of law. The latter require rigorous laboratory procedures, and descriptions of these are outside of the scope of this lecture note. Even with such procedures, the interpretation of data may not be unequivocal, as 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 maintenance of the system. Therefore, all judgements of sustainability have to 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 judgement' to be expressed, for example in terms of three categories:

-1 (RED)	= Problems may be beyond the means of farmers to resolve
-0.5 (AMBER)	= Additional effort will be needed to address these issues, which may affect the profitability of the land use system, but which may otherwise be within the range of farmers' management options
0 (GREEN)	= No major problems beyond the range that normal farm management can deal with.

Criteria for evaluating the impacts of land use on (former) forest soils (Table 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. The 'measurables' for these various functions, however, show a considerable degree of overlap. Many of them are linked with the maintenance of surface mulch and soil organic matter.

The background to sustainability assessments in the ASB project in Indonesia is given in Box 1. Details of the various criteria that were used are presented in the following sections. After that, in Section 3, the values and results obtained in the assessments in Indonesia and Cameroon are discussed.

Box 1. Sustainability assessments in the ASB project

Within the Alternatives to Slash and Burn (ASB) project, a set of criteria and indicators was developed that can be measured relatively easily, often using data already collected as part of the integrated survey of biodiversity, C stocks and greenhouse gas emissions (see lecture notes 4 and 5). In Indonesia these measurements were made for specific land cover types (the 'FARCI' (or 'ICRAF') series: *forest* (**F**); *mature agroforest* (**A**); *young tree-based systems* (**R**(egrowth)); *long-term cassava cropping* (**C**) and *temporarily abandoned* Imperata *grassland* (**I**)), in the Jambi as well as Lampung benchmark area. For each of these systems, a sequence of land cover types was considered that represents the land use system over its life cycle (see lecture note 2). For example, agroforests as a land use have an early phase in which they look like a crop field, as well as a mature phase in which they look like a forest. All measurements were made in the benchmark areas described in lecture note 2, and they thus contain the confounding effects of land use history and current management practices typical for the various actors. For example, continued production of food crops (cassava) is restricted to former transmigration settlements that were cleared from previous forest cover by bulldozer. Current levels of soil compaction may date back to this event regardless of the current land use, but this still forms part of a broader 'syndrome' of land use decisions.

We will focus here on issues A, B and C (Table 2), as other aspects are dealt with in more detail in other lecture notes

Table 2. Criteria and indicators for evaluating sustainability of plot-level land use on (previous) forest soils in the Alternatives to Slash-and-Burn project.

Criteria	**Indicators (qualitative)**	**Measurable parameters (quantitative)**
I. Maintain on-site productivity		
A. Maintaining 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 understorey vegetation	• Net soil loss = internal soil loss – internal sedimentation • Percentage soil cover, integrated over the year (or over annual rainfall)
	Compaction: use of penetrometer	Bulk density of topsoil
	Soil structure: 'spade test', root pattern	Soil macroporosity and H_2O infiltration rates
	Soil cover and absence of gullies as indicators of infiltration; absence of surface sealing and crusting	• Water infiltration versus run-off, • Soil water retention, • Effective rooting depth
B. Maintaining the nutrient balance: buffering nutrients between supply from inside and outside the system and demands for uptake	Annual **exports** of P and cations as fraction of total and 'available' stock, 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 • C-saturation deficit • Limiting-nutrient trials
C. Keeping 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. Maintaining essential soil biota, such as mycorrhizal fungi and *Rhizobium*	Sporocarps (mushrooms) for ectomycorrhizal species	Spore counts for V.A. mycorrhiza
	Signs of 'ecosystem engineers' among the soil fauna: earthworms, termites	Mycorrhizal infection and nodulation in roots in the field and in 'trap crops' in the lab ➔ ***See Below-ground biodiversity lecture note***

II. Don’t make the neighbours angry:		
E. Providing a regular supply of high quality water	Stream flow response-time after rain storms ; downstream areas free of floods and droughts	● Stream flow amounts and variability ➔ ***See Watershed function lecture note***
	Turbidity of streams	● Sediment load of streams
		● Absence of agro-chemicals in water
F. Air filter: mitigating net emission of greenhouse gases	Aboveground C stocks in biomass and necromass,	● Soil C stocks relative to soil C saturation deficit, ➔ ***See C-stock lecture note***
		● Net emissions of NO_2 and CH_4
G. Maintenance of biodiversity reservoirs: allowing recolonization of depleted neighbouring landscape units, and germplasm collection for *ex-situ* exploitation	Diversity of aboveground vegetation, based on diversity of 'plant functional attributes'	● Diversity of plant species ➔ ***See Biodiversity lecture note*** ● 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 etc.), lack of negative attributes of the product (e.g. no chemical residues or genetically-modified components) or of the production process (social and environmental concerns underlying consumer boycotts)

2.2 Criterion A: Soil structure and biological activity

The following indicators can be used:

A1. **Soil compaction** as evident 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 densities as such are difficult to interpret.

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 as it changes relatively 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 C stored under natural vegetation and the relative changes due to 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 C storage can then be expressed as a *C- 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 C content and the 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,

$\mathbf{C_{org}/C_{ref}}$ = soil organic carbon content relative to that for forest soils of the same texture and pH,

$\mathbf{C_{ref}}$ = a reference soil C level representative of forest soil.

C_{ref} is estimated using an equation derived from regression analysis of a large (forest) soil data set for Sumatra, and takes into account the inherent differences in organic carbon due to soil texture and pH:

$$Cref = (Z_s/12.5)^{-0.58} \exp(1.333 + 0.00994*Clay\% + 0.00699*Silt\% - 0.156*pH\text{-}KCl)$$

Where Z_s = soil sampling depth, cm

An alternative method for calculating C_{ref} is shown in Box 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/or is a "fertile soil"; values towards 0 mean "infertile soil".

Box 2. Example: Estimating Cref using the CENTURY Model

The C-storage potential of soils under forest can be estimated with suitable simulation models such as the CENTURY model (see also lecture note 4). The results are presented in Figure 3, and this figure can be used as a tool to predict the Cref for humid tropical forests for a range of soil textures. For other conditions, new runs of the model will be needed.

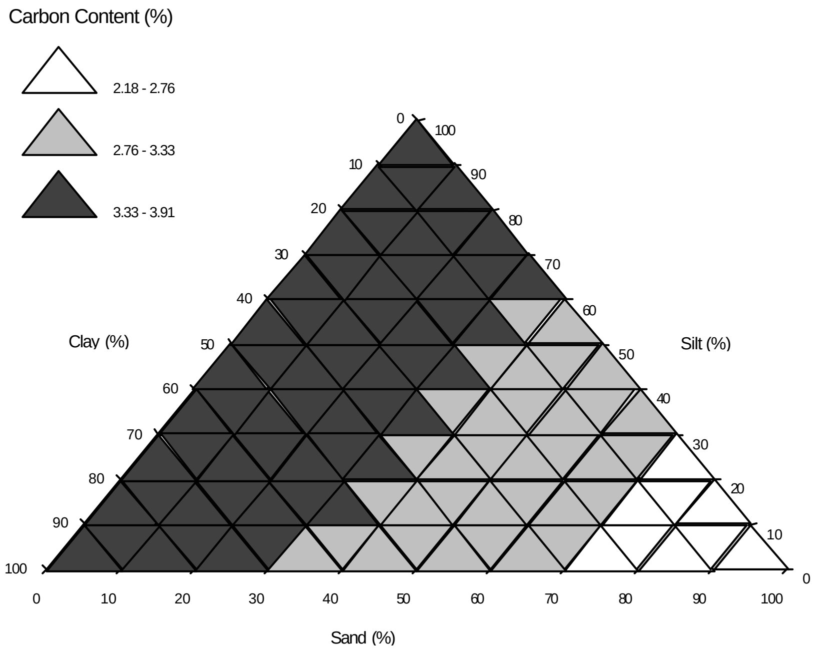

Figure 3. The potential for soil-C storage under forest in relation to soil texture, generated by the CENTURY model.

A3. **Active Soil Carbon** (ASC):

Microbial biomass forms only a few percent of the total C content of a soil, but it is the most active fraction, as nearly all transformations in the soil depend on microbial activity. A number of indicators have been identified for comparing the size of this microbial pool in different land use types in a given area, relative to the natural forest there:

- Dry weight of the 'light' fraction of soil organic matter; this fraction represents the most recent inputs of organic matter (the 'food' for soil microbes), and so indicates the amount of substrate available for transformation by microbes. This fraction can be obtained using a separation technique based on liquids of different densities, called the LUDOX size-density fractionation procedure (Sitompul *et al.*, 2000),
- Mineral N (NH_4^+ and NO_3^-) content of the topsoil during measurements; this indicates the result of microbial activity (e.g. nitrification), it is a measure of how much of the soil organic matter has been broken down (at least in the absence of fertilizer use);
- Counts of the total number of bacterial populations ('colonies'), expressed relative to the soil C content and also to the C saturation deficit (which should correct for

variation due to soil pH and texture)- this gives an indication of the population size;

- Soil respiration (during lab incubation) as an indication of the biological activity of the soil.

The use of these parameters is valid when they are judged against the values obtained for natural forest sites.

A4. **Soil Exposure** (SE):

Exposure of the soil to the direct impact of raindrops and the sun, if frequent and/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 do not count, however, as the energy of the splash impact of drips from the leaves can even exceed that of rainfall!).

Several indicators were developed (below), and values of these for different land use types in Cameroon are presented in Table 3:

- Soil Exposure = 100 x number of months of 'low' (< 75%) soil cover / length of system cycle in months
- (i.e. proportion of the length of the whole cycle that the soil has a 'low' cover)
- Time between clearing events (i.e. 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

The soil cover index integrates the information of both soil exposure and open time into one indicator.

Table 3. Soil exposure, time between clearing events, and soil cover index in different land use systems in the Cameroon benchmark area (see text).

Land Use Systems*	Soil Exposure (% of cycle length)	Time between clearing events	Soil Cover Index (months)
SF – Food intercrop	19.4	6	58
LF – Food intercrop	7.3	16	178
SF – Intensive Cocoa with fruit	11.1	30	320
SF – Intensive Cocoa without fruit	11.1	30	320
FOR – Extensive Cocoa with fruit	10.8	30	321
FOR – Extensive Cocoa 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: Ericksen, 2000.

2.3 Criterion B: Nutrient balance

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

1. Net Nutrient Export (NNE)
2. Nutrient Depletion Time Range (NDTR)
3. The Relative Nutrient Replacement Value (RNRV)

B1. **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 fertiliser inputs for N, P, and K, in kg ha^{-1} $year^{-1}$. 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 N fixation from legumes in the system (although these were not used in the land uses considered in the ASB project).

B2. **Nutrient Depletion Time Range (NDTR).** This indicator 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 off-take 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:

a) the **directly-available** nutrient pool
b) the **total** nutrient content of soil *plus* vegetation (including less-accessible pools in the soil).

Neither is directly satisfactory, however, as measures of the available nutrient pool necessarily use rather arbitrary fractions and there is considerable variation between plants in effectiveness of accessing 'non-available' nutrient sources. As nutrient stocks depend on the soil and vegetation cover, one cannot directly assign an NDTR value to a land use system in the peneplains of Sumatra; the soils closer to rivers with a higher clay and silt content will have larger stocks than the sandier soils of the rest of the lowland peneplain. Thus, figures obtained may only be accurate within an order of magnitude.

B3. The **Relative Nutrient Replacement Value (RNRV)** relates the export of nutrients in harvested products to the costs of putting them back into the agro-ecosystem in the form of chemical fertiliser. This assessment is based on the harvested products rather than the full production system.

2.4 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 becoming a major constraint in the system, unless addressed by additional labour and/or technical input

C2. **Potential for Pest or Disease Problems**

Pest or disease problems becoming a major constraint in the system, unless addressed by additional labour and/or technical input.

D. **Maintenance of essential soil biota**

This aspect is discussed in the belowground biodiversity lecture note (No. 6).

3. Case studies: results from ASB Indonesia (Sumatra) and Cameroon

3.1 Criterion A: Soil structure and biological activity (Indonesia)

Data collected from Lampung and Jambi benchmark sites (Table 4) 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 localised 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 have an impact on water infiltration, root growth and greenhouse gas emissions, but probably stayed below critical levels in all cases observed. This measurement can be 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, -0.5 = problems within the range of farmer management. For a number of land use systems the overall rating is thus -0.5 (see Table 5).

Table 4. Measured soil fertility indicators for the integrated biodiversity survey in Lampung and Jambi, ASB benchmark area (September – November 1996). 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.

	BD 2-7 cm, g/cm^3	Corg/ Cref 0-5 cm	'Light' org. matter 0-5 cm, g/kg	NH_4^+ mg/kg	NO_3^- mg/kg	Bacterial popula-tion / C-org	Bacterial. popula-tion / (Cref/ Corg)	Soil respiration mg CO_2, kg day^{-1}
Forest	1.04	0.91	3.22	29	18	13.5	37	12.9
Relative to forest:								
Agroforest	*1.05*	*0.75*	*0.77*	*0.79*	*0.72*	*1.48*	*1.43*	*0.91*
Regrowing trees	*1.22*	*0.73*	*0.81*	*0.33*	*0.44*	*1.78*	*1.69*	*0.84*
Cassava	*1.21*	*0.52*	*0.35*	*0.47*	*0.56*	*1.56*	*1.51*	*0.59*
Imperata	*1.29*	*0.66*	*0.58*	*0.52*	*0.33*	*1.59*	*1.62*	*0.80*

The carbon saturation (*Corg/Cref*) 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 *Corg/Cref* of < 1.0. Serious declines were only found for the cassava/*Imperata* land use type, with the lowest values measured in cassava fields. Reductions of soil organic matter content to this range is evidence of substantial depletion of organic nutrient stocks in the soil and may affect soil physical properties as well as nutrient buffering against leaching. As with soil compaction, problems can be created much faster than they can be solved.

Thus, for the A2 (soil carbon saturation) indicator, only the cassava/*Imperata* cycle gets a warning flag (-0.5 score in Table 5). As mentioned before for soil compaction, the low current value of C saturation may have been partly due to reclamation history as well as current land use (bulldozer land clearing can remove part of the topsoil to outside the field boundaries). The frequent fires, low organic inputs through cassava litterfall (0.6 t $ha^{-1}yr^{-1}$ compared to 120.6 t $ha^{-1}yr^{-1}$ in secondary forest) and frequent soil tillage can account for the low values found.

The various indicators of soil biological activity in Table 4 may give a partially conflicting signal: the mineral N supply at the time of measurement was higher in the forest and mature agroforests than in other land uses, indicating that N supply from mineralisation may have exceeded current N demand from the vegetation around the time of measurement (end of dry season); these same land uses had a relatively high respiration rate, but when estimates of total microbial population size are scaled by soil organic matter content or by C 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) we conclude that there is no lack of active soil biota in any of the land uses, 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 4 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% of the time for a rubber system with a 25 year cycle). The only land use system where soil exposure may be an issue is the cassava/*Imperata* cycle where soil is exposed during the first 3 months of a cassava crop (unless heavily weed-infested or intercropped with crops such as rice, which is not possible at reduced soil fertility), and for about 1 month per year in all cases when the *Imperata* fallow is burned. Combined, this may lead to about 10% of the time with incomplete soil cover, when the soil is vulnerable to the direct impact of rain and sun.

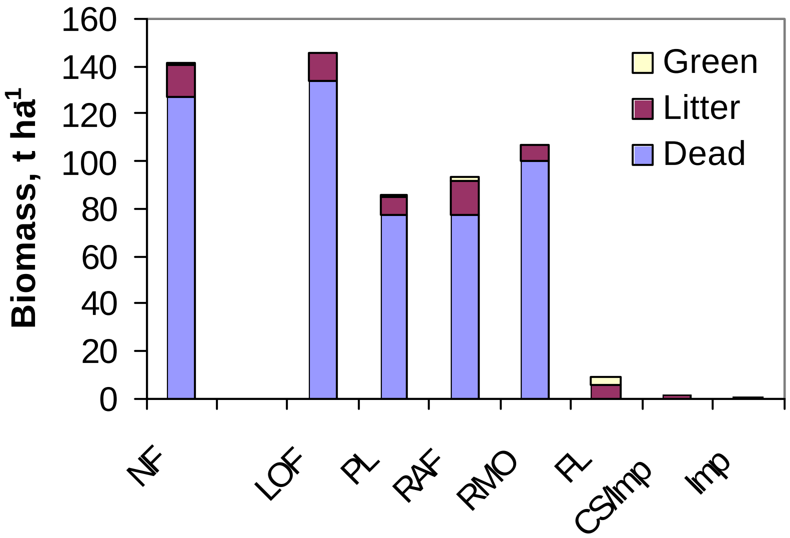

Figure 4. Soil cover in different land use types in Jambi (NF= Natural forest; LOF = Logged-over forest; PL = Timber plantation (*Paraserianthes*); RAF = Rubber agroforest; RMO = Rubber monoculture; FL = *Chromolaena* fallow; CS/Imp = Cassava/*Imperata;* Imp = *Imperata*).

To summarise all 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 5).

Table 5. Sustainability rating of land use systems for Criterion A (maintenance of soil structure and biological activity); 0 = no problem, -0.5 = problem that probably can be overcome by the farmer, -1 = problem probably out of reach for farmers' solutions

Land use system	A1 Compaction	A2 Carbon saturation	A3 Active soil C_{org}	A4 Soil exposure	Overall rating A	Comments on main issues which need attention
Natural forest	0	0	0	0	0	-
Community-based forest management	0	0	0	0	0	-
Commercial logging	-0.5	0	0	0	-0.5	Soil compaction in ramps and trails
Rubber agroforests with (traditional seedlings)	-0.5	0	0	0	-0.5	Soil compaction?
Rubber agroforests with clonal planting material	-0.5	0	0	0	-0.5	Soil compaction?
Rubber monoculture	-0.5	0	0	0	-0.5	Soil compaction?
Oil palm monoculture	-0.5	0	0	0	-0.5	Soil compaction?
Upland rice/ bush fallow rotation	0	0	0	0	0	-
Cassava/*Imperata* rotation	-0.5	-0.5	0	-0.5	-0.5	Soil compaction, low Corg, lack of soil cover

3.2 Criterion B: Nutrient balance (Indonesia)

Nutrient balance calculations for different land-cover types were based on the technical specifications used for the profitability assessments in the other lecture notes. Full details can be found in Tomich *et al.* (1998). For the cassava/*Imperata* cycle, a moderate use of fertiliser was assumed, below replacement level, but at least mitigating nutrient depletion. Many farmers in the benchmark area appear to use no fertiliser at all in this system, however. For such no-input versions the nutrient balance is clearly negative. A clear trade-off may exist for this land use type between <u>sustainability</u> and <u>profitability</u>.

Nutrient depletion time range (NDTR): the estimates showed that the nutrient where the most rapid depletion may occur is potassium (K). If only the directly-available pool is considered, depletion within a 25-year time frame may occur for the rubber systems and shifting cultivation as well as cassava production. If total stocks are considered (at least part of non 'available' K can be accessed by plants), the time frame to depletion becomes several decades at least. For N, no problems are to be expected for the land uses described here according to this calculation. However, our calculations do not include nutrient losses other than in harvested products and substantial N losses will occur during slash-and-burn clearing of forest lands, as well as by leaching during subsequent periods of low N demand by the vegetation relative to the N supply from mineralisation. A more refined estimate would have to include the full spectrum of processes incorporated in the Century model (Palm *et al.*, 1998) and goes beyond the current sustainability assessment.

In the calculations for Table 6, the amounts of fertiliser required to replace the nutrients exported in the harvested products are corrected for (long term) nutrient recovery. It was assumed that only 25% of N, 20% of P, and 30% of K fertilizers that were applied were actually recovered (taken up) by the products/crops. Thus, for every gram of N exported in a harvested product, four grams of N had been applied in the form of nitrogenous fertilizer. The N-fixing trees ‘petai’ (*Parkia speciosa)* and ‘jengkol’ (*Pithecellobium jiringa*) included in the *Non timber forest products* (NTFP) scenario were assumed to derive two thirds of their N from the atmosphere.

Table 6. Relative nutrient replacement value for main products of various land use systems (Rupiah prices before July 1997, 1 US $= 2300 Rp); modified and extended from Van Noordwijk *et al.* (1997).

	Nutrient removal, g/kg product			Nutrient replacement value, Rp/kg (see below)	Farmgate value of product, Rp/kg	Relative nutrient replacement value (RNRV)
	N	P	K	***(a)***	***(b)***	***(a/b)***
NTFP - rotan	2	0.20	1	10	20000	< 0.001
NTFP - petai/jengkol	5	0.50	5	24	500	0.05
NTFP - durian	3	0.30	6	28	1000	0.03
NTFP - others						< 0.001
Timber	2.5	0.25	1.5	13	108	0.12
Rubber (latex)	6.3	1.20	4.4	42	2000	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

The nutrient replacement value, ***(a)*** above, is calculated as the weight of each nutrient removed, multiplied by the replacement cost per nutrient (in bold, below), then totalled for N, P and K (neglecting other nutrients).

	N	P	K
REPLACEMENT PRICE PER NUTRIENT EXPORTED, RP/G	2.3	12.0	2.9
[A/(B*C*1000)]			
Fertilizer price, Rp/kg (A)	260	480	400
Proportion of nutrient in fertilizer (B)	0.45	0.2	0.46
Nutrient recovery[1] by the crops/products (above) (C)	0.25	0.2	0.3

[1] see text

Most relative nutrient replacement (RNRV) values are below 10% 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%, and this indicates a range where 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%, indicating that fertilizer costs would be a major part of the farm budget if farmers would have to balance the nutrient budgets. The high RNRV values for both products are caused by their low price (at the farmgate) per kg product. For oil palm, marketing of fruits instead of bunches could considerably reduce the nutrient exports and, hence, the RNRV. For cassava only a shift in farmgate prices of the product and/or of fertilizers could make fertilizer use more attractive.

To summarise all measurements, sustainability ratings were assigned to the different land use types on the basis of Criterion B (maintaining nutrient balance) (Box 4).

Table 7. Indicators of current and potential nutrient balance; NDTR = nutrient depletion time range; RNRV = relative nutrient replacement value; 0 = no problem, -0.5 = problem that probably can be overcome by the farmer, -1 = problem probably out of reach for farmers' solutions

Land use system	B1 Net export	B2 NDTR	B3 RNRV	Overall Rating B	Comments on main issue
Natural forest	0	0	0	0	
Community-based forest management	0	0	0	0	
Commercial logging	0	0	0	0	
Rubber agroforests	0	0	0	0	
Rubber agroforests with selected planting material	-0.5	-0.5	0	-0.5	Output increased at low input?; K supply needs attention
Rubber monoculture	0	0	0	0	
Oil palm monoculture	0	0	-0.5	-0.5	Assumed fertilizer rates may be too high; RNRV rating supposes fruits sold rather than bunches
Upland rice/ bush fallow rotation	0	-0.5	-0.5	-0.5	Fertilizer use required for intensification
Cassava/*Imperata* rotation	-0.5	-0.5	-1	-1	Nutrient balance can not be attained at current prices; K in short supply?

3.3 Criterion C: Crop protection from weeds, pests and diseases (Indonesia)

Weed problems are mostly related to *Imperata*, which is hard to control without herbicides (which are often too expensive for smallholder food production) or ploughing (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 (more expensive) planting material is used (Williams *et al.*, in press), whereas in the existing system, substantial tree losses are tolerated by planting low-cost seedlings at high densities (see Table 8). The natural secondary forest regrowth in rubber agroforests is probably less problematic as a 'weed' than the grass or fern vegetation which develops under attempts at 'weed control'.

3.4 Synthesis of sustainability indicators for Sumatra

When all indicators are combined (Table 9) we conclude that:

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

Table 8. Indicators of problems with crop protection from weeds, pests and diseases; 0 = no problem, -0.5 = problem that probably can be overcome by the farmer, -1 = problem probably out of reach for farmers' solutions

Land use system	C1 Weeds	C2. Pests & diseases	Comments on main issue
Natural forest	0	0	no problems
Community-based forest management	0	0	
Commercial logging	0	0	
Rubber agroforests	0	0	
Rubber agroforests with selected planting material	0	-0.5	pigs & monkeys at replanting; fungal diseases when sensitive clones are used
Rubber monoculture	-0.5	-0.5	fungal diseases, pigs and monkeys at replanting; ferns as ground cover may be problematic
Oil palm monoculture	0	0	
Upland rice/ bush fallow rotation	0	-0.5	vertebrate and insect pests are a constraint
Cassava/*Imperata* rotation	-0.5	0	*Imperata* fallows are a weed problem unless farmers have draught power available

Table 9. Overall assessment of severity of sustainability problems of various land use systems for the peneplain of Sumatra (synthesis of Tables 5, 7 and 8): 0 = no problem, -0.5 = problem that probably can be overcome by the farmer, -1 = problem probably out of reach of farmers' solutions.

Land use system	A1	A2	A3	A4	B1	B2	B3	C1	C2	Over -all	Main issues[1]
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	-0.5	0	0	0	0	0	0	0	0	-0.5	C
Rubber agroforests with selected planting material	-0.5	0	0	0	-0.5	-0.5	0	0	-0.5	-0.5	C, K, W, P
Rubber monoculture	-0.5	0	0	0	0	0	0	-0.5	-0.5	-0.5	C,W,P
Oil palm monoculture	-0.5	0	0	0	0	0	-0.5	0	0	-0.5	C, 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

[1] C = soil compaction; K = potassium balance; Fert = price of fertilizer, W = weeds; P = pests and diseases

3.5 An overall assessment for Cameroon

The overall assessment of agronomic sustainability is based on the information presented in Table 10.

Table 10. 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

Note: Scores: 0 = no problem, -0.5 = problem that probably can be overcome by the farmer, -1 = problem probably out of reach of farmers' solutions. SF = short fallow, LF = long fallow, FOR = derived from forest. Source: Ericksen, 2000.

A. Soil Structure: We expect a significant decline in soil structure over time in intensively managed, short fallow, annual food crop systems. Alternative biomass-management practices associated with planted fallows may reduce this potential problem. A deterioration of soil structure is also expected when perennial crop systems are planted into fields newly-cleared from forest. In contrast, perennial crops planted into short fallow land would help to protect the soil better than annual cropping systems. 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 required for harvesting bunches.

B. Nutrient Balance: The systems that cause most concern in terms of over-exploitation of nutrients are the *intensive* perennial crop systems, i.e. cocoa and oil palm. 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, since 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/food crop system are moderate, we must assume that the nutrient stocks are already low in a system where land is only left fallow for 4 years before the above-ground biomass is burned and cleared. Given that short fallows are often 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 (e.g. tomato) with these systems would enable the use of fertilizers. Nitrogen could be supplied by the planting of nitrogen-fixing fallow species. Finally, we do not expect any nutrient problems in the long fallow and community forest systems.

C. Crop Protection: We expect that major weed, pest and disease complexes will develop in recurrent short fallow systems. The latter can probably only be addressed through crop breeding. Intensive weed management associated with a prior high value crop (e.g. tomato) may reduce the weed pressure in subsequent subsistence food crops. The cocoa systems also face a major challenge in terms of pest and disease problems that would require a concerted control effort at the community level with major inputs of pesticides. Weeds are a threat in 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 above, there are potential solutions, but the financial and institutional environment has to be conducive.

4. Sustainability assessments of agricultural livelihood systems at the landscape scale

4.1. Farmer perceptions of sustainability

As part of the characterisation process (see lecture note 1), 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, sugarcane and tree crops based systems) which were identified by farmers in North Lampung are presented in Figure 5.

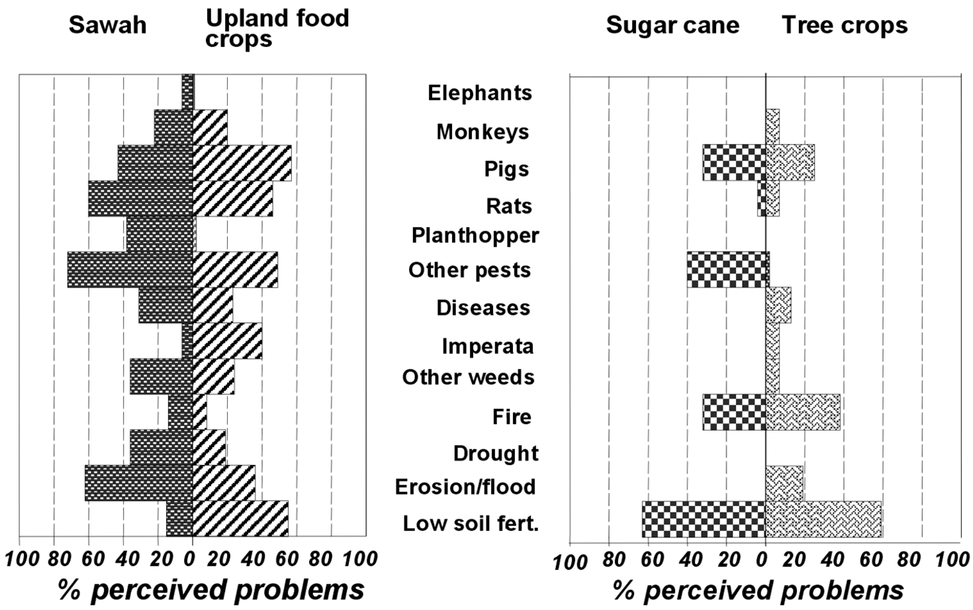

Figure 5. Problems identified by farmers in the ASB North Lampung benchmark area (Van Noordwijk *et al.*, 1996b).

There were four main problems observed for all systems: soil fertility, drought, fire and the weed *Imperata cylindrica.* The upland food crops system was perceived to have the greatest amount of problems, in comparison with the other three systems.

4.2 Maintaining options for land use change

When we introduced the plot-level indicators a certain vagueness in the sustainability concept was mentioned: the final criterion is the possibility to continue farming on a given piece of land, keeping all threats at manageable levels. Continued farming, however, 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 practice is likely to **reduce the number of future options**, because the soil depletion it induces will require substantial re-investment in soil nutrient stocks before other crops can be grown. The current criteria (those discussed above) refer to the field-level land uses per se, as these are measurable, while a full land use transition matrix can only be assessed by other means.

Research on adaptive capacity has to differ in character from that on sustainability. The latter has specific land use practices as its target; for these, experiments can be done and models can be made of their longer term behaviour. Adaptive capacity research has to specify the range of options available, as well as the way these options themselves change in time and differ between stakeholders.

Sustainability as defined above indicates the degree of reproducibility of a land use system: does it maintain the conditions required for its own continuation? In the real world, however, it is unlikely that land uses will remain unchanged over more than one (or a few) human generations, and it may thus be interesting to evaluate which options are kept open with a given land use system (Table 11).

Natural forest can be used as the starting point for all land use types, but in a strict sense can only originate 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', as it can not maintain its own productivity and it takes substantial efforts and expense (nutrient replenishment and *Imperata* control; Friday *et al.*, 1999) 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 will change in character once the seedbank of original natural vegetation is depleted and the site is out of reach of seed dispersal. Table 11 strengthens the conclusion that the cassava/*Imperata* system is the most problematic of the land use systems considered here.

Table 11. Land use transformations that are feasible in a 20-50 year period; crosses indicate where transitions from one land use system to another are possible. See text for discussion of '?' cases.

Land use system	1	2	3	4	5	6	7	8	9	Comment
1. Natural forest	X	X	X	X	X	X	X	X	X	Universal starting point
2. Community-based forest management	?	X	X	X	X	X	X	X	X	
3. Commercial logging	?	X	X	X	X	X	X	X	X	
4. Rubber agroforests	?	X	?	X	X	X	X	X	X	
5. Rubber agroforests with clonal planting material		?	?	X	X	X	X	X	X	
6. Rubber monoculture					X	X	X	X	X	
7. Oil palm monoculture					X	X	X	X	X	
8. Upland rice/ bush fallow rotation		X		X	X	X	X	X	X	
9. Cassava/*Imperata* rotation					?	?	?		?	Self incompatible, a 'dead end'

4.3 Maintaining adaptive capacity (resilience)

The resource base for adaptive capacity (resilience) can be viewed in the light of the five types of capital recognised in recent natural resource management literature (Pretty, 1999): natural resource, human, social, physical and financial capital, with partial but incomplete options for exchange between capital types (Figure 6).

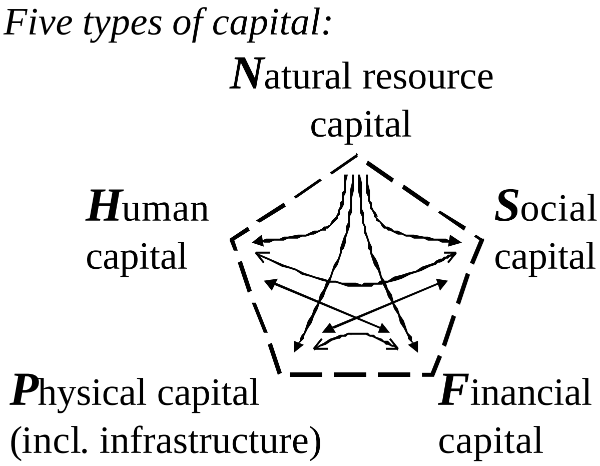

Figure 6. Five types of capital involved in development pathways (Pretty, 1999).

Adaptation of agro-ecosystems can essentially be based on two mechanisms, one internal and one external to the current system. Agro-ecosystems, especially those rich in agrodiversity and biological resources (Natural resource capital), can adapt (depending on their Human and Social capital) by increasing the use of currently under-exploited local resources, or on the basis of (locally or globally) 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 required for the various adaptive capacity aspects is given in Figure 7.

The likelihood of the externally based response (Figure 7: A, B, C) is greater in the simple agro-ecosystems of the more developed parts of the world, with effective 'technology delivery systems'. Research and knowledge delivery systems are expensive, so they depend on rigorous priority-setting mechanisms identifying the few components with the greatest potential market value.

Agricultural research has, by and large, supported a drive towards the simplification of agro-ecosystems. This drive is at least in part due to the fact that research is less effective in dealing with more complex systems even if these would be superior (Vandermeer *et al.*, 1998). Access to the fruits of this increasingly commercialised 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 agro-ecosystems, although we are not yet able to quantify how much complexity is required for how much resilience (Vandermeer *et al.*, 1998).

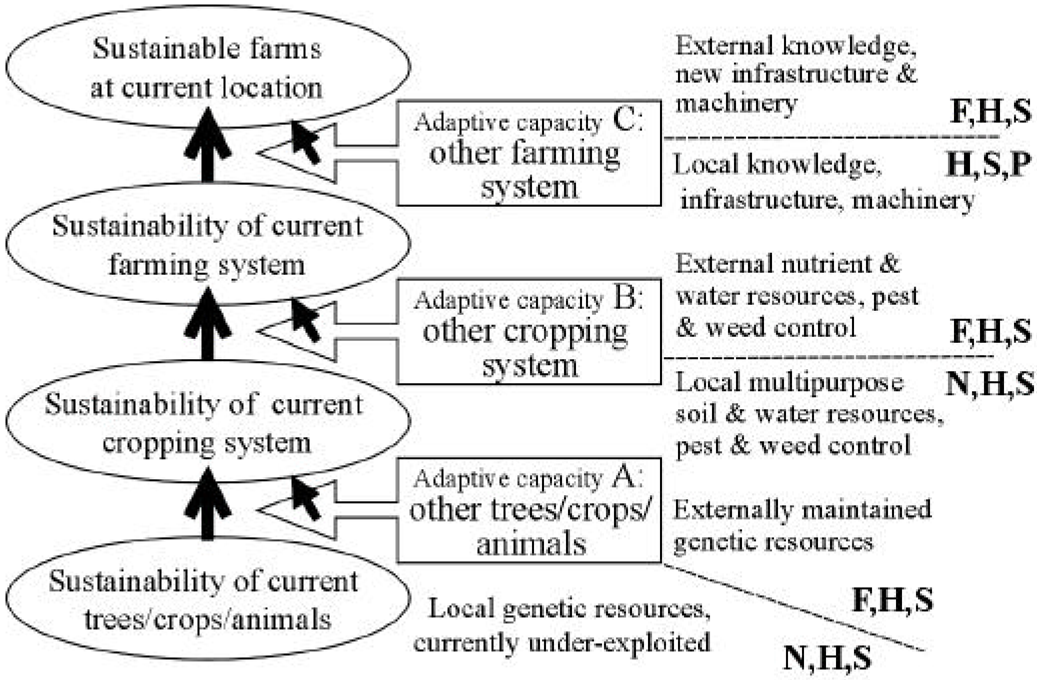

Figure 7. Resource base for local and externally acquired new components that can be incorporated into farming systems during an adaptation process (N, H, S, P and F refer to the five types of capital distinguished in Figure 6).

A hypothesis regarding the combined effect of these types of adaptation is that there is a middle range of agro-ecosystems where vulnerability is highest: they have little resilience based on local resources, and are not effectively reached by technologies (Figure 8A). In the absence of data, there is considerable uncertainty over the shape of the overall response (Figure 8B).

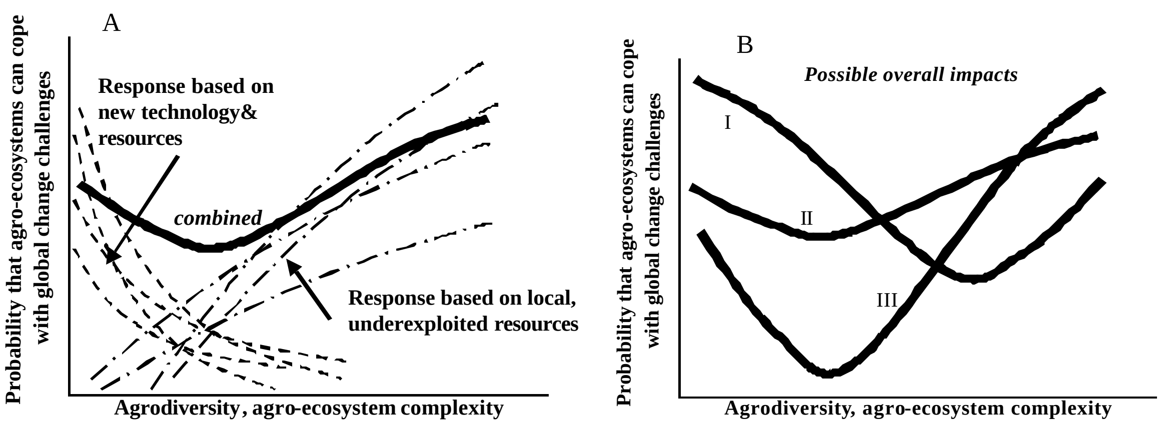

Figure 8A. Hypothesis that the probability that agro-ecosystems will be able to cope with the challenges of global change depends on the agrodiversity and complexity of current agro-ecosystems, based on resilience and technology-based adaptation. B. It is likely that systems of intermediate complexity will be the most vulnerable, but there is much uncertainty about the shape of the curve, as shown by lines I, II and III.

4.4 The 'segregate-integrate' debate: sustainability aspects

The 'segregate-integrate' debate was introduced in lecture note 1: to attain the twin goals of productivity (food, timber, other products/raw materials etc.) and maintenance of environmental services (watershed functions, C stocks, biodiversity, etc.) what is the best spatial arrangement of land uses in the landscape? Would a fully segregated landscape, where natural undisturbed forests are kept separate from lands where intensive high-input agriculture is practised, be most efficient at achieving the two goals? Or would a fully integrated landscape, composed entirely of a mosaic of crops, trees and small forest patches be best?

We can now summarise the consequences of segregated or integrated land-use options for the sustainability debate (Table 12). The types of threats to sustainability differ between the two extremes: the main threat to sustainability of a segregated solution is the divergence of interests between the 'conservation' and the 'development' side of the coin, and the challenge this puts on maintaining a status-quo for the boundary between the forest and intensive agricultural land. In 'integrated' options such as agroforestry systems, competition between the components forms a threat to be controlled, but the wide array of options maintains considerable scope for continued adaptation of the farming system.

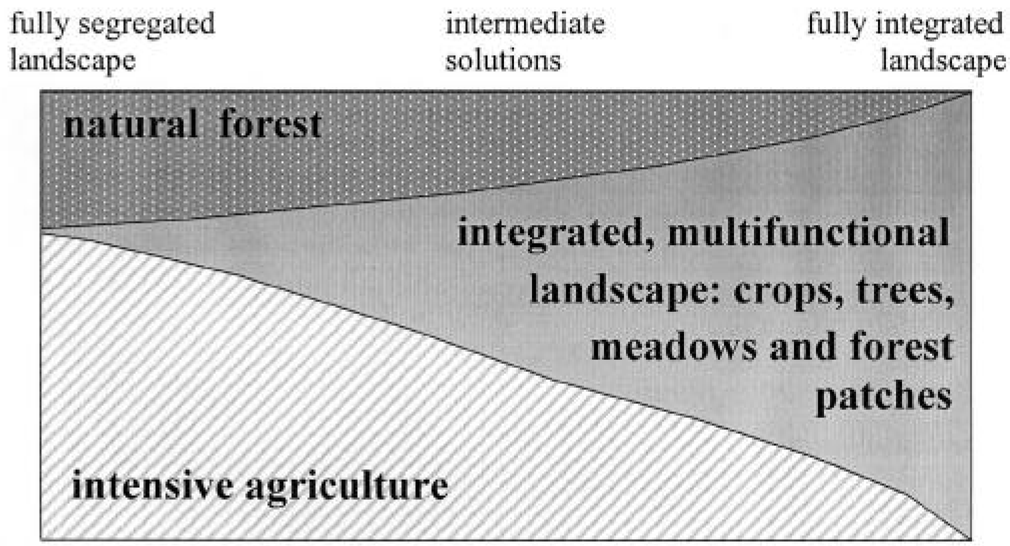

Figure 9. Segregated and integrated landscapes.

Table 12. Summarising sustainability concerns in segregated or integrated landscapes (see lecture note 1)

Segregated - Agriculture	Segregated - Natural forest	Segregated landscape with combined Ag + Forest	Integrated - Agroforestry mosaic
Highest internal risks for low value, bulk production	Main threats from outside: continued conversion into agriculture and degradation by logging	The forest boundary is likely to be under continuous threat	Competition between components is a major 'threat', but the fact there are multiple components also provides opportunities for adaptive response (refer back to Figure 1)

5. In conclusion

Our search for indicators and thresholds of agronomic sustainability has yielded a number of yardsticks that can indeed be used to assess land use options at plot level. For the broader issue of sustainability of farming, however, we do not yet have a satisfactory set of indicators. Options for future change have to be an essential part of the assessment, and the interactions of farms with feedback loops through society, the economy and government policies bring us way outside the scope of the current study.

Non-sustainability is always easier to assert than sustainability. Production of bulk products of low value per unit biomass (as the cassava in our example) is likely to cause nutrient depletion of the soil, as the nutrient replacement costs by fertilizer use will likely 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, as farmers will be (financially) able to maintain the nutrient balance. Other sustainability issues are closely linked with environmental impacts of farming via C stocks, above- and below-ground biodiversity and watershed functions, and will be discussed further in the relevant lecture notes (4, 5 & 6, and 7 respectively).

III. Reading Materials

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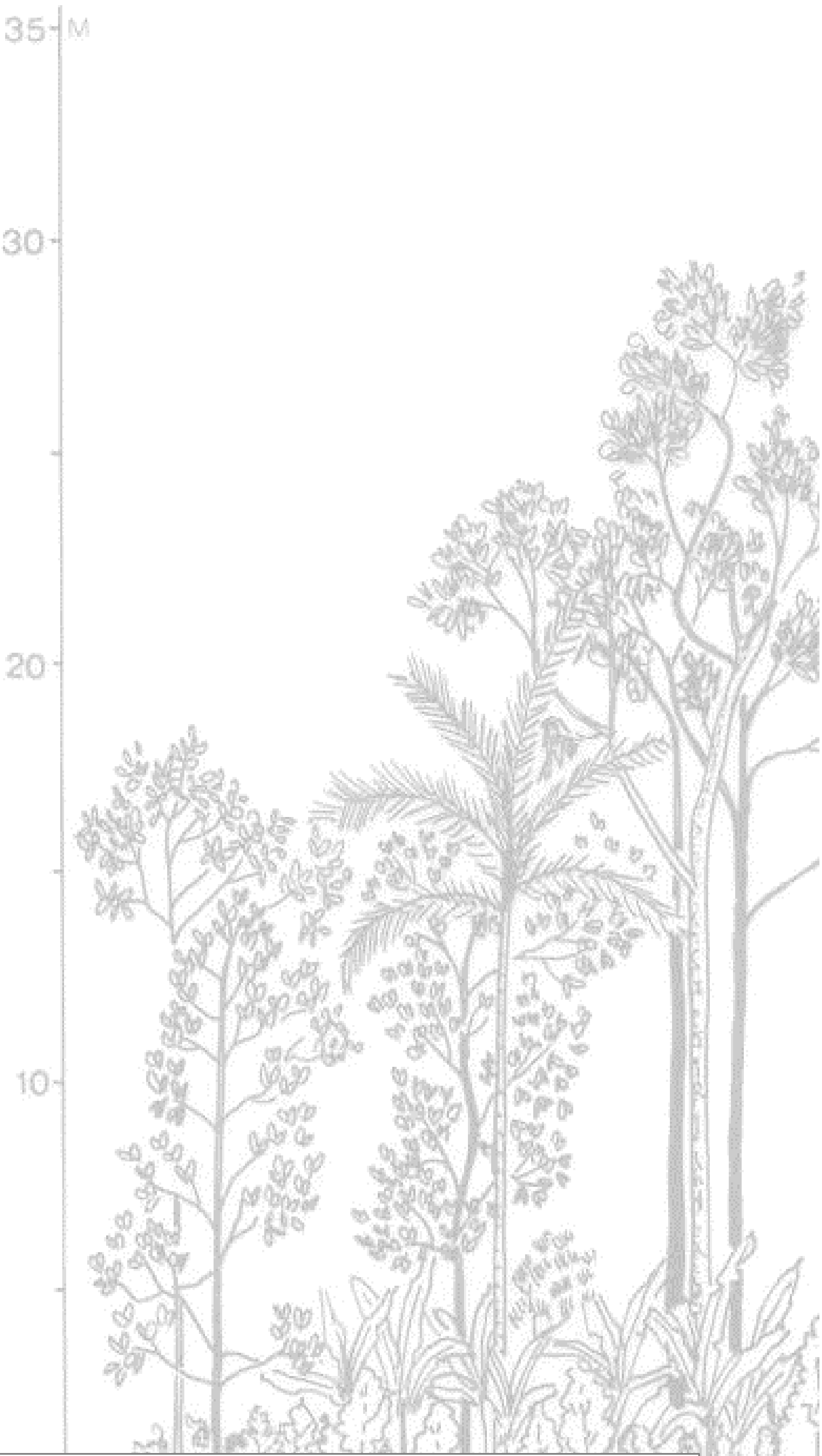

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