

Linking climate change research with food security and poverty reduction in the tropics

Pedro A. Sanchez

International Centre for Research in Agroforestry, Nairobi, Kenya

Abstract

Climate change is a reality and will affect the poor in developing countries in many ways. The effectiveness of global change research could be substantially improved by linking International Geosphere-Biosphere Programme (IGBP) study with Consultative Group on International Agricultural Research (CGIAR) centres based in the tropics. These centres are carrying interdisciplinary research and development on how to achieve food security and reduce rural poverty through the innovative management of natural resources. A CGIAR intercentre working group on climate change (ICWG-CC) identified joint opportunities that take advantage of the comparative advantages of both institutions. CGIAR centres will focus on adaptation and mitigation research in developing countries. A natural resource management research approach is suggested, which consists of six steps: (1) identifying and quantifying the extent of food insecurity, rural poverty and resource degradation; (2) conducting technological and policy research on economic and environmental functions; (3) optimising the trade-offs between global environmental benefits and private farmer benefits; (4) extrapolating and disseminating results, including research on policy implementation; (5) assessing impact and (6) providing feedback.

Two examples of current CGIAR research illustrate this approach. Agroforestry alternatives to slash and burn (ASB) agriculture at tropical forest margins were identified and the trade-offs between carbon sequestration and farmer profitability provided options to policy makers. Land tenure problems were resolved with participatory policy research. Agroforestry practices sequester an additional 57 Mg C per ha, three times that of croplands or grasslands are able to do. Soil nutrient capital is being replenished in subhumid tropical Africa through improved leguminous tree fallows, rock phosphate and biomass transfers of *Tithonia diversifolia*, helping farmers to attain food security. Afterwards, when farmers shift to high-value tree or vegetable crop production, poverty is reduced. The transformation of low productivity croplands to sequential agroforestry is estimated to triple system carbon stocks in 20 years. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Climate change; CGIAR; Soil fertility; Carbon sequestration

1. Introduction

Major changes of a worldwide nature are now taking place that will have profound influence on the earth and its people in the next decades. Climate change is a reality and will affect the poor in developing countries in many ways. While climate change is perhaps the best known aspect of global change,

others are also of major concern: loss of biodiversity, change in nitrogen deposition and changes in atmospheric composition. These are all caused or exacerbated by human activities such as population growth, increasing poverty and food insecurity in developing countries, resource degradation, urbanisation, globalisation of trade, information technology and AIDS.

The International Geosphere-Biosphere Programme (IGBP) is focusing more on the consequences of these global changes with the realisation that the

E-mail address: p.sanchez@cgiar.org (P.A. Sanchez).

determinants of change are closely interlinked. The relevance of IGBP research could be substantially improved by linking more with institutions based in developing countries that are carrying out strategic multidisciplinary research on ‘people-centred’ issues such as poverty and food security along with global environmental issues such as biodiversity, carbon sequestration and greenhouse gas emissions. This study describes the nature of possible synergies between IGBP and the Consultative Group on International Agricultural Research (CGIAR) as illustrated by current approaches and research results. The main drivers of global change in developing country, agriculture and natural resource management that are of mutual concern by the two groups, are summarised in Table 1.

2. IGBP and the CGIAR

The International Council of Scientific Unions established IGBP in 1986, with the following mission (Walker et al., 1999).

To describe and understand the interactive physical, chemical and biological processes that regulate the total earth system, the unique environment that it provides for life, the changes that are occurring in this system and the manner in which they are influenced by human activities.

Two IGBP core projects are particularly relevant to IGBP–CGIAR collaboration: Global Change and Terrestrial Ecosystems (GCTE) and Land-use and Cover-change (LUCC), which is co-sponsored by the International Human Dimensions Programme (IHDP). GCTE interests include the consequences of global change on agriculture and forestry systems, and feedbacks to physical climate system. LUCC interests include understanding and modelling the causes of changes in land-cover and land-use. IHDP is now rapidly developing several core projects that will have great relevance to CGIAR objectives.

The CGIAR was established in 1972 to support international agricultural research centres of excellence working to reverse predicted worldwide famines by improving the productivity of staple food crops in developing countries. Today the 16 centres cover a much wider mandate — other crops, livestock, aquatic resources, forestry, agroforestry, soils, water, plant

genetic resources, and policy research. Its current mission is (CGIAR, 1998)

to contribute to food security and poverty eradication through research promoting sustainable agricultural development based on the environmentally sound management of natural resources. This mission will be achieved through research leadership, partnership, capacity building and policy dialogue.

In May 1998 the CGIAR centre directors established the intercentre working group on climate change (ICWG-CC) to assess current work and develop an explicit research agenda. Since the CGIAR is already involved in other global change issues, it decided to focus specifically on climate change. A report of work in progress (ICWG-CC, 1999) identified the main strengths of the CGIAR that can complement IGBP’s strengths as follows.

- Having about 1000 scientists based in the developing world.
- Expertise in human-dominated ecosystems, complementary to IGBP’s strength in natural ecosystems.
- The interdisciplinary character of the CGIAR, involving many natural and social sciences working together.
- Ground-truthing opportunities offered by hundreds of well-characterised research sites throughout the tropics.
- Long-standing collaboration with national agricultural research systems.
- Access to policy makers in developing countries.

Climate change activities are usually placed in three categories: impacts, adaptation and mitigation, as follows.

1. Impacts are the consequences of shifts in climate on something else (agriculture, fisheries, industry, health, etc.). Impacts research focuses on what will happen.
2. Adaptations are actions to adjust to the consequences of climate change (how to cope with what will happen). Adaptation research aims to decrease the vulnerability of peoples and ecosystems to climate change.
3. Mitigation are actions to prevent further escalation of greenhouse gas emissions (how to decrease global warming). Mitigation is proactive rather than reactive and is aimed at preventing further escalation.

Table 1

Current global change scenarios relevant to developing country agriculture and natural resource management

People (Pinstrup-Andersen et al., 1999, unless specified otherwise)	<p>Population growth will reach 7.5 billion by 2020. 98% of the growth will be in developing countries, and mostly in urban areas.</p> <p>World population is expected to stabilise at about 9 billion people by 2050.</p> <p>Per capita incomes in developing countries will double by 2020 to US\$ 2200 per year or \$6 per day.</p> <p>Half of the current world's population (3 billion) subsists on less than US\$3 per day.</p> <p>1.6 Billion people now live in absolute poverty (<US\$1 per day), mainly in the tropics.</p> <p>0.8 Billion are hungry, mainly in sub-Saharan Africa and South Asia.</p> <p>3.7 Billion people suffer from chronic nutritional insecurity (iodine, iron, zinc and vitamin A deficiencies) with severe health consequences (Welch et al., 1997). This is particularly acute in sub-Saharan Africa where it exacerbates the effects of the HIV/AIDS epidemic.</p> <p>One third of the current pre-school children in the developing world are stunted. Child malnutrition and food insecurity will persist beyond 2020 unless major changes take place.</p> <p>Developing countries will be more adversely affected by climate change than industrialised economies. IPCC projects a reduction of these countries gross domestic production (GNP) of 2–9% per year vs. 1–2% for industrialised countries due to climate change (Houghton et al., 1997).</p>
Agriculture	<p>Food production in developing countries has tripled in the last 30 years, keeping up with population growth, except in sub-Saharan Africa. Nevertheless this is one of the top achievements of humankind in the 20th century.</p> <p>Crop production (grains, roots and tubers) must increase by 40% and meat products by 58% in developing countries by 2020 to meet expected demand caused by population growth and increased incomes.</p> <p>There is large-scale degradation of the natural resource base used for agriculture in the tropics (Oldeman, 1998). Soil fertility depletion is the root cause of food insecurity in Africa (Sanchez et al., 1997a, b).</p> <p>Favoured lands are peaking out. Crop yields in 'green revolution' areas are now showing little increase. Marginal lands are beginning to receive increasing research attention.</p> <p>Farmers are the main actors in land use change.</p>
Climate (Houghton et al., 1997)	<p>Atmospheric CO₂ will increase from the current concentration of 360 to 400–750 ppm by 2100.</p> <p>There will be a steady increase in mean surface air temperatures of 0.1–0.2°C per decade, reaching 1–2.5°C by 2100.</p> <p>Sea level will rise from 15 to 95 cm by 2100.</p> <p>More frequent and severe extreme weather events accompany the above changes (with us now).</p>
Water (Wallace, 2000)	<p>Less rainfall is predicted for much of Africa.</p> <p>More rainfall is predicted for other regions (Inter-Andean valleys, for example).</p> <p>70% of World's population will be at stress levels of available fresh water (<2000 m³ per person/year) by 2050. The current figure is 7% of today's population.</p> <p>Plants do not use 85% of the water resources in irrigated systems.</p> <p>Plants do not use 78% of the water resources in rainfed systems.</p>
Carbon	<p>20% of CO₂ emissions come from tropical deforestation and land use (Houghton et al., 1997).</p> <p>50% of anthropogenic CH₄ emissions come from agriculture, mainly in developing countries (Houghton et al., 1997).</p> <p>The CO₂ fertilisation effect is expected to produce only small crop yield increases (8–15%) with doubled CO₂, provided N is not limiting (Jamieson et al., 2000).</p> <p>There is a large potential to sequester C in tropical terrestrial ecosystems.</p>
Nitrogen (Gregory and Ingram, 2000)	<p>The global N cycle is being altered.</p> <p>Industrial N fixation (140 Tg N per year) now exceeds biological N fixation (100 Tg N per year).</p> <p>70% of anthropogenic N₂O emissions come from agriculture (worldwide).</p> <p>Recovery by crops of fertiliser N is low (10–30%) in developing countries.</p> <p>8–16% of Fertiliser N is emitted to the atmosphere as N₂O.</p>

The ICWG-CC concluded that global climate change is inexorably linked with the CGIAR goals of food security, poverty alleviation and environmental protection. The projected impacts of climate change on developing country crops, livestock, forestry and fisheries are likely to be of enormous significance to food security, poverty reduction and protection of the natural resource base in the next decades. Unless addressed by strategic research and development, these impacts would be largely negative. As an institution dealing with strategic research issues, the CGIAR has no option but to include research into adaptation to, and mitigation of climate change into its agreed agenda (ICWG-CC, 1999). Its priorities should be a shared responsibility in adaptation research and the lead responsibility on mitigation research in developing countries, both done in collaboration with IGBP. Linkages and partnerships between the CGIAR and IGBP will take advantage of the relative strengths of both institutions. Table 2 illustrates the proposed the allocation of responsibilities between the two groups.

The ICWG-CC identified six priority research areas for the CGIAR, three in adaptation research and three in mitigation, as follows.

Adaptation research:

1. integrated gene management to cope with expected changed climates;
2. protection of in situ biodiversity with changed climates;
3. development of tools to cope with less and more erratic water resources.

Mitigation research:

1. increasing carbon stocks in productive systems;
2. improved nitrogen use efficiency with less nitrous oxide emissions;
3. improving water use efficiency.

3. An integrated natural resource management research approach

The approach proposed by Izac and Sanchez (2000) can be used to bring together the objectives of farmers with those of climate change research in CGIAR–IGBP study. The overall purpose is to meet farmer needs for food security and poverty reduction while satisfying societal objectives for environmental protection. The approach and its components are illustrated in Fig. 1.

The first component consists of identifying and quantifying the extent of food insecurity, rural poverty and resource degradation problems to be addressed in a given region. These problems are analysed at the relevant spatial and temporal scales and their driving forces are identified. An example of this process took place in the Alternatives to Slash and Burn (ASB) programme (Garrity and Khan, 1994; Palm et al., 1995; ASB, 1998).

Research in component 2 follows in parallel. Component 2a focuses on enhancing the direct utilitarian functions of natural resources, which consist of food, raw materials and income in the case of agriculture. In component 2b, research activities aim at enhancing the ecosystem functions of natural resources, such as carbon, nutrient and water cycling, erosion control and biodiversity. Depending upon the types of problems and driving forces, the research agenda will focus more on component 2a or 2b, or both equally.

The third component is the assessment of trade-offs between the options that enhance the food and income functions of systems (2a) and those options that enhance the ecosystem functions (2b). The objective is to identify the combination of options that optimise these trade-offs from the different perspectives of major stakeholders such as farmers, community-level

Table 2
Proposed priorities on climate change research shared between the CGIAR and IGBP (ICWG-CC, 1999)

Type of research	CGIAR	IGBP
Impacts (consequences of climate change)	Very little	Lead responsibility globally
Adaptation to climate change	Shared responsibility in developing countries	Lead responsibility in developed countries
Mitigation to minimise further climate change	Lead responsibility in developing countries	Shared responsibility in developed countries

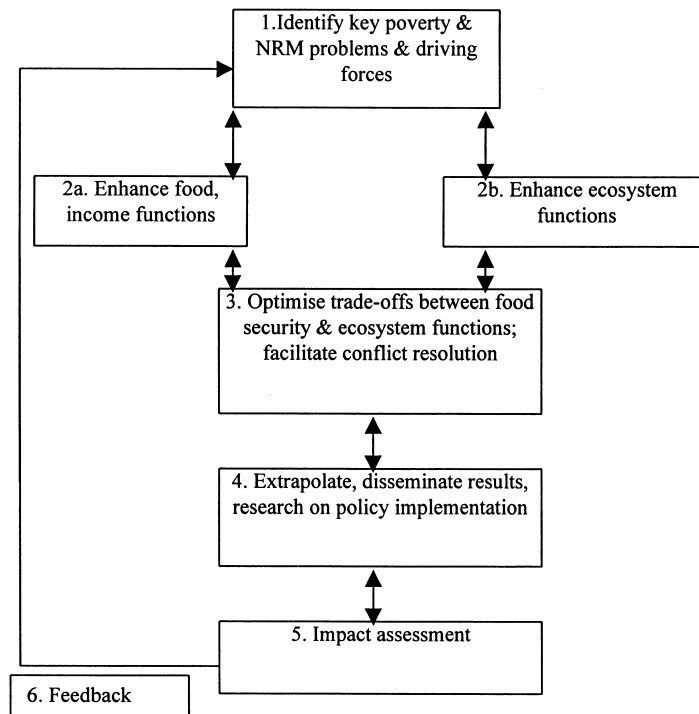


Fig. 1. Principal steps of integrated natural resource management research agenda (Izac and Sanchez, 2000).

decision makers, national and global policy makers. The policy work included in this step focuses on facilitating conflict resolution, for example, between individual farmers and the national society. At the heart of these trade-offs lies the fact that the use and management of natural capital generates a number of positive and negative externalities. The outcome of component 3 is the identification of those improved NRM options that can meet the needs and objectives of various stakeholders and the identification of policy or institutional options that will facilitate the adoption of these options by farmers.

The component 4 involves extrapolating and disseminating results through various means, including modelling, GIS and pilot projects, in which the civil society, farmers' organisations and government extension services are partners. Research on policy implementation, using participatory methods, also takes place in this component. Step 5 is the assessment of the impacts of the adoption of the ranges of options thus devised. Measuring a number of relevant indicators at different spatial and temporal scales does this. The

results are fed back into the research agenda, which comprises step 6.

It is important to note that interdisciplinary teams of scientists are involved in each of the above steps, as ecological, social and economic parameters, and their interactions, are relevant at each step. Such research is conducted for the most part in farmers' fields, rather than at research stations. This is to ensure that a representative range of biophysical and economic conditions is captured, as well as to facilitate the use of participatory research methods (Izac and Sanchez, 2000). Two examples related to climate change mitigation are described to illustrate this approach.

4. Alternatives to slash and burn agriculture at the humid tropical forest margins

The CGIAR ASB programme is an interdisciplinary and multi-institution consortium composed of several CGIAR centres and more than 30 national research institutions, universities, non-governmental organisa-

tions, and advanced research institutions working across humid tropical Southeast Asia, the Amazon and the Congo basin since 1992 (Sanchez and Hailu, 1996). Its aim is to provide viable alternative technologies and policies that tackle major human and environmental problems when people migrate to the forest margins and convert them to unsustainable slash and burn production systems (Sanchez et al., 2000).

4.1. Characterisation and component research

This first step in box 3 for ASB consisted of interdisciplinary characterisation beyond the traditional diagnosis and participatory rural appraisals, using common methodologies (Palm et al., 1995). The consortium then developed and tested standardised research methods for estimating parameters such as agronomic sustainability, returns to land and labour, the effectiveness of institutions as well as, above- and below-ground biodiversity, carbon stocks and greenhouse gas fluxes in different alternative land uses (ASB, 1998). These methods have been applied across land-use chronosequences in benchmark sites in Brazil, Indonesia, Cameroon, Peru and Thailand, constituting components 2a (economic functions) and 2b (environmental functions). One such parameter was carbon. Carbon uptake rates, time-averaged system carbon stocks and differences in C stocks were estimated from 116 sites

with different land uses before and after slash and burn (Palm et al., 2000); the results are illustrated in Table 3.

ASB researchers then identified some of these practices as ‘best bet’ ASB based on the analysis of multiple parameters. A matrix of the ‘best bet’ alternative land uses \times agronomic, economic and environmental parameters was developed at the country level (Tomich et al., 1998, 2000). This matrix was used to estimate the trade-offs between the economic gains and environmental impacts of alternative land uses (step 3).

4.2. Trade-offs

One such trade-off is carbon sequestration versus farmer profitability of several alternative land uses in Southern Cameroon, which is shown in Fig. 2 derived from Gokowski et al. (2000). It is worthwhile to notice that there is no win–win situation (high carbon-high profit), while there is a lose–lose situation (low carbon-low profit). There is however, a group of alternative land uses that provide medium carbon sequestration levels at a wide range of farmer profitability. It is in this range where the trade-offs can be optimised. In this case, a cacao-fruit tree complex agroforestry system optimises the trade-offs between profitability and carbon, i.e. between the interests of farmers and those of the global community. Such information allows policy and other decision makers to

Table 3

Carbon uptake rates and time-averaged system carbon stocks and differences in C stocks due to land transformation at the margins of the humid tropics^a

Land use practice	C uptake rates (Mg C per ha/year)			Duration (year)	C stocks (time-averaged) (Mg C per ha)			Differences in modal C stocks (time-averaged) (Mg C per ha)	
	Low	Modal	High		Low	Modal	High	Forest	Pasture/grasslands
Tropical forest margins									
Primary and logged forests	na ^b	na ^b	na ^b	unknown	192	230	276	–	–201
Cropping after slash and burn	–76	–92	–112	2	39	46	52	–184	+17
Crops/bush fallow	2	3	4	4	32	34	36	–196	+5
Tall secondary forest fallows	5	7	9	23	95	112	142	–118	+83
Complex agroforests	2	3	4	25–40	65	85	118	–145	+56
Simple agroforests	5	7	9	15	65	74	92	–156	+61
Pastures, Imperata grasslands	–0.2	–0.4	–0.6	4–12	27	29	31	–201	–

^a Summary in 116 sites with different land uses before and after slash and burn located in Pedro Peixoto (Acre) and Theobroma (Rondônia), Brazil; Ebolowa, M'Balmayo and Yaounde, Cameroon; Jambi and Lampung, Sumatra, Indonesia; Yurimaguas and Pucallpa, Peru (calculated from the data of Palm et al. (2000) and Woomer et al. (2000), and assuming the following time-averaged soil C stocks (in Mg C per ha): 40 for primary/logged forests and crops after slash and burn; 35 for tall secondary forest fallows and complex agroforests; 30 for bush fallow and simple agroforests and 25 for pastures and *Imperata* grasslands.

^b Not available, close to zero.

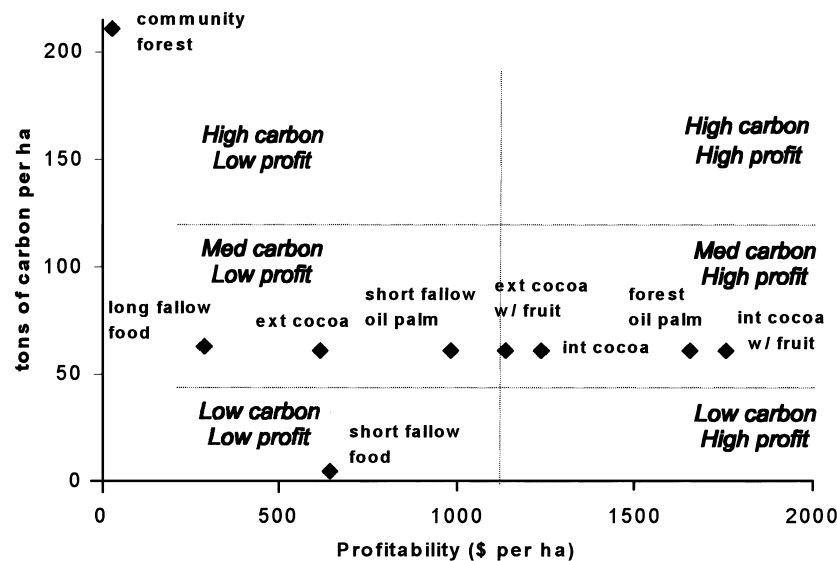


Fig. 2. Carbon sequestration vs. farmer profitability of several alternative land uses in southern Cameroon (Gokowski et al., 2000).

evaluate resource allocation strategies based on local economic returns and global environmental services, and provides guidance as to how and where to intervene via policy change, including investing in dissemination of technologies (Izac and Sanchez, 2000).

4.3. Policy research

Part of the study under step 3 includes policy research and dialogue to facilitate conflict resolution between individual farmers and the national society. Such was the case in one of the most profitable and environmentally sound 'best bets', the complex agroforests of Krui, Sumatra, Indonesia (Michon and de Foresta, 1996). The problem was that farmers did not have land tenure, since the Ministry of Forestry classified their agroforests as State Forest Lands. In 1992, the government awarded a forestry company the right to harvest an estimated 3 million commercially valuable trees planted by these local people. This created a great deal of uncertainty among Krui agroforesters who chose not to plant more trees until they would know for sure that they would be able to harvest the benefits of their work.

The Indonesian Minister of Forestry invited ICRAF policy economists and other ASB scientists to document the attributes of the complex agroforests and

develop policy options for solving this problem (Fay et al., 1998). Policy research started in 1995 and culminated in January 1998, when Indonesia's Minister of Forestry signed a historic decree that established an official precedent for community-based natural resource management in Indonesia. Based on the Minister's concept for a distinctive forest-use classification, 'Kawasan dengan Tujuan Istimewa' (KdTI), the decree recognises the legitimacy of community-managed agroforests on a significant area of State Forest Land in perpetuity (Ministry of Forestry, 1998; Fay et al., 1998; Tomich et al., 1999).

The pilot area covers 29,000 ha and 7000 families have benefited directly (Tomich et al., 1998). This prototype will be applied in numerous other locations in Indonesia to benefit the millions of farmers at the forest margins in terms of income generation, improved resource management and reduction of social conflict. Feedback from these experiences, particularly in other countries will help to refine the ASB approach.

4.4. Carbon sequestration

At the heart of these trade-offs lies the fact that the use and management of natural capital generates a number of positive and negative externalities. One externality, carbon sequestration, could be internalised

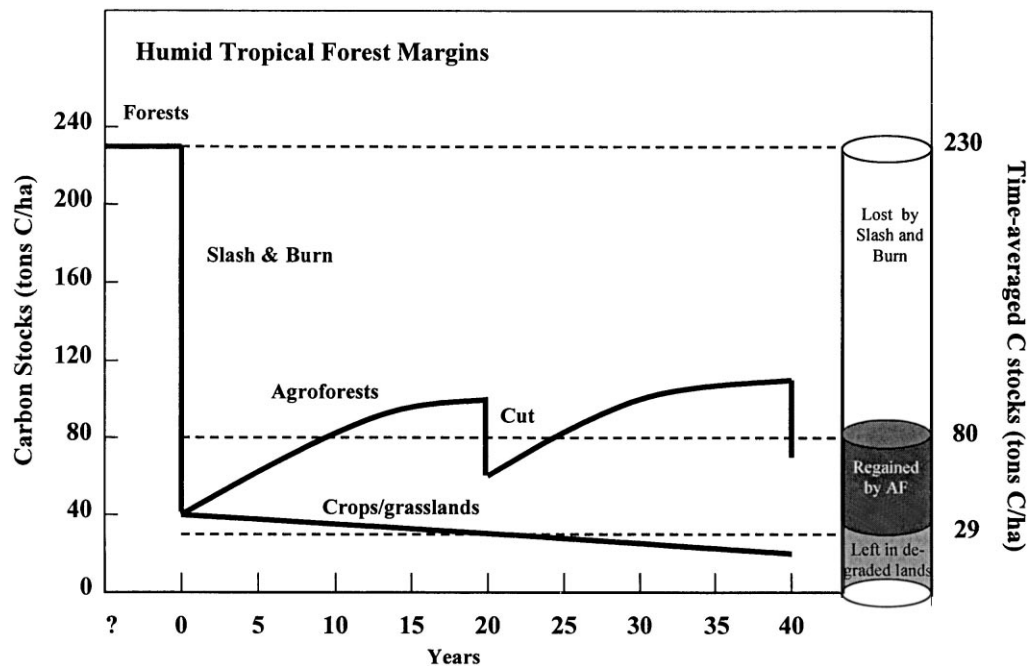


Fig. 3. Time course of system carbon stocks (biomass and soil), solid lines and time-averaged C stocks (dotted lines) in agroforestry systems vs. crop followed by grasslands at the margins of the humid tropical forest.

if farmers receive monetary compensation for the carbon they fix, either through the clean development mechanism in the Kyoto protocol or the emerging carbon markets. ASB research is providing the IPCC study on land use, land use change and forestry with well-quantified estimates of carbon sequestration at the margins of the humid tropical forests. Fig. 3 provides the overall picture of the time course of best-bet agroforestry systems, based on time-averaged above- and below-ground differences in carbon stocks shown in Table 3.

The transformation of the original forest into various types of agroforests results in a smaller decrease in C stocks than the transformation of forests into cropland, pastures or degraded grasslands. After burning and cropping for an average of 2 years, about 80% the C stock is lost. Crop-short bush fallow rotations, pastures and *Imperata* grasslands that subsequently take place had C stocks of about 30 Mg C per ha, most of it in the soil, indicating that about 88% of the carbon stock of the original forest is lost and emitted to the atmosphere in its conversion to croplands or pastures

within 4–12 years. This is a main consequence of unsustainable slash and burn agriculture.

In contrast, agroforests established immediately after slash and burn by planting trees along with food crops regained 35% of the original carbon stock of the forest. Through the establishment of tree-based systems in degraded pastures, croplands, and grasslands, the time-averaged C stocks in the vegetation increases by 50 Mg C per ha in 20–25 years, while that in the soil increases by 7 Mg C per ha (Palm et al., 2000). Agroforestry practices therefore permit the sequestration of an additional 57 Mg C per ha, i.e. three times what croplands or grasslands are able to do.

The total potential area of this practice may be 10.5 million ha annually if carbon credits and enabling government policies are in place (Fay et al., 1998; Tomich et al., 1998). This magnitude consists of two assumptions: (1) 20% of the 15 million ha annually deforested (3 million ha) is put into agroforestry every year and (2) 3% of the 250 million ha of degraded lands at the forest margins (Sanchez et al., 1994) are converted into agroforests every year (7.5 million ha).

The difference in time-averaged C density due to this land use change is between 35 and 90 t C per ha, with a modal value of 57 t C per ha. We further assume that the annual deforestation rate mentioned will stay constant for the next 10 years. If this happens the global contribution of this practice to carbon sequestration would be on the order of 0.105–0.525 Gt C per year with a modal value of 0.315 Gt C per year, one of the largest values of human-induced activities.

5. Replenishing soil fertility in Africa

5.1. The problem

Another example of the NRM approach deals with a problem that was invariably identified by farmers in characterisation and diagnosis exercises throughout the subhumid and semiarid tropics of Africa (Smaling, 1993; Buresh et al., 1997). Soil fertility depletion in smallholder farms is now recognised as the biophysical root cause of declining food security in this region (Sanchez et al., 1997a, b; Sanchez and Leakey, 1997). No matter how effectively other technology or policy constraints are remedied, per capita food production in Africa will continue to decrease unless this root cause is effectively addressed.

5.2. Attaining food security

Given the acute poverty and limited access to mineral fertilisers, an ecologically robust approach was developed by ICRAF and its partners. It consists of bringing natural resources to farmer fields where crops can utilise them: nitrogen from the air by biological N fixation; phosphorus from indigenous phosphate rock deposits, and nutrient-rich shrub biomass from roadsides and farm hedges (Rao et al., 1998; Kwesiga et al., 1999; Jama et al., 2000).

The use of improved leguminous fallows, which can fix 100–200 kg N per ha and transfer it to the soil upon leaf and root litter mineralisation re-establishes nitrogen flows without the carbon costs associated with nitrogen fertiliser production and transport (Schlesinger, 1999). In phosphorus-deficient soils Minjingu rock phosphate from northern Tanzania has proven to be as effective as imported triple superphosphate as well as more profitable (Sanchez et al., 1997b; Niang et al.,

1998). Basal applications of 125–250 kg P per ha as a capital investment are beginning to be used by farmers with an expected residual effect of 5 years. In addition, biomass transfers from hedges of the ubiquitous Mexican sunflower tithonia (*Tithonia diversifolia*) have shown tremendous effects on yields of maize and high-value crops such as vegetables in western Kenya, because of its high nutrient content and rapid mineralisation rate (Gachengo et al., 1999; Jama et al., 2000).

Effects at the farm level are major, maize grain yields have increased from under 1 to 3–6 t per ha, with the added benefits of fuelwood production from the harvested tree fallows, better weed control and an easier soil to till. Most importantly tens of thousands of farm families are becoming food-secure with ancillary social benefits such as less thefts of maize and greater dignity in being able to provide sufficient food for the family (Sanchez, 2000). Extension workers and many NGOs are increasingly motivated as they now can deliver effective advice to farmers.

5.3. Reducing poverty

Having a soil replenished of its nutrients is a major step towards food security, but additional components must be brought into place for poverty elimination. The next step is to shift from maize to high-value products to drastically increase small farmer income and begin to get out of poverty. Farmers can and have already experienced cash income increases from US\$100 to 1000 per year when they have shifted from maize to vegetable crops after replenishing the fertility of the soils in farms of western Kenya (Sanchez, 2000).

A further step will be the switch to newly domesticated tree crops that produce high-value products (Leakey et al., 1996). One example is *Prunus africana*, a timber tree indigenous to montane regions of Africa. A substance is extracted from its bark to treat prostate gland disorders, which has a reported annual market value of US\$220 million (Simons et al., 1998). There is a high demand for this bark from the international pharmaceutical industry and the species has been recognised as threatened by extinction. Trade in the bark of *Prunus africana* is listed as endangered under Appendix II of the convention on international trade in endangered species (CITES) of wild fauna and flora. Harvesters currently go in natural forests

and collect the bark by cutting trees down or debarking them in a manner that kills the trees. The bark of a mature wild tree is worth on average US\$200–2000 to a collector and US\$6500–65,000 to industry (Simons et al., 1998).

Research on the performance and chemical quality of provenances, clones and different aged bark material of *Prunus africana* is ongoing (Dawson and Powell, 1999) and will hopefully lead to successful identification, production, management and adoption of desirable germplasm. This, in turn, will mean that farmers can capture and control a bigger part of the economic value of the bark while no longer over-exploiting the dwindling wild resource. Synthesis by industry of the active ingredients in the bark of *Prunus africana* is too complex to be an option at this time (Simons et al., 1998).

5.4. Carbon sequestration

The depletion of nitrogen and phosphorus has important effects on changes in soil carbon stocks (Kapkiyai et al., 1998; Woomeer et al., 1997). The loss of topsoil organic carbon associated with soil nutrient depletion has been estimated to occur at an average rate of 0.22 Mg C per ha/year (Sanchez et al., 1997a). When soil fertility is replenished preliminary estimates suggest that carbon sequestration rates become positive, averaging 1.5 Mg C per ha/year (Table 4). When

more trees are planted on field boundaries and as orchards, carbon sequestration rate increases further to 3.5 Mg C per ha/year. These are estimates rather than hard data as in the case of the humid tropical forest margins.

Nutrient-depleted fields have little biomass carbon stock; a time-averaged modal figure is estimated to be on the order of 23 Mg C per ha, virtually all below-ground (Table 4). Soil fertility replenishment practices based on improved fallows, rock phosphate and tithonia for 20 years is estimated to result in an increase in time-averaged C stocks by 32 Mg C per ha (Fig. 4). Such stocks are virtually all in the soil, as crop and fallow accumulation may account for only 1 Mg C per ha above-ground. When trees are incorporated after fertility replenishment, total time-averaged stocks reaches 70 Mg C per ha, which includes 24 Mg C per ha in the above-ground biomass and 36 Mg C per ha in the soil. The transformation of low productivity croplands to sequential agroforestry in subhumid smallholder Africa, therefore, can triple carbon stocks (from 23 to 70 Mg C per ha) in a 20-year period.

Assuming such increases can take place in 46% (37.5×10^6 ha) of the smallholder farms of subhumid tropical Africa (Sanchez et al., 1997b), during the next 25 years when we assume equilibrium is reached this practice would provide a global contribution of 0.045–0.191 Gt C per year with a modal value of 0.116 Gt C per year, in subhumid tropical Africa

Table 4

Estimates of carbon uptake rates and time-averaged system carbon stocks and differences in C stocks due to land transformation from low productivity cropland to sequential agroforestry in subhumid tropical Africa

Land use practice	C uptake rates (Mg C per ha/year)			Duration (year)	C stocks (time-averaged) (Mg C per ha)			Differences in modal C stocks (Mg C per ha)
	Low	Modal	High		Low	Modal	High	
Subhumid tropical Africa								
Current nutrient depleted small farms ^a		–0.22		unknown		23		–
Fertility replenished farms with maize-tree fallow rotations ^b	1.0	1.5	2.4	20	20	35	49	+12
Fertility replenished farms as above and more trees on farm ^c		3.5		20		70		+47

^a From Sanchez et al. (1997a) based on the calculations from Smaling's data (Smaling, 1993).

^b Calculations from agronomic data by Kwesiga and Coe (1994); Kwesiga et al. (1999); Rao et al. (1998); Jama et al. (2000). Improved fallows of *Sesbania sesban* and other leguminous tree species planted for 1 year in East Africa and 2 years in southern Africa add 100–200 kg N per ha to the soil. Tree fallows are followed by 1 maize crop in East Africa and 3 consecutive maize crops in southern Africa. Where phosphorus is limited (primarily East Africa), replenishment also includes a basal application of 125–250 kg P per ha as rock phosphate plus biomass transfer of 1.8 t dry matter per ha of *Tithonia diversifolia* to every maize crop (Sanchez et al., 1997a, b).

^c Same as 2 + adding trees as orchards and to farm boundaries (Woomeer et al., 1997).

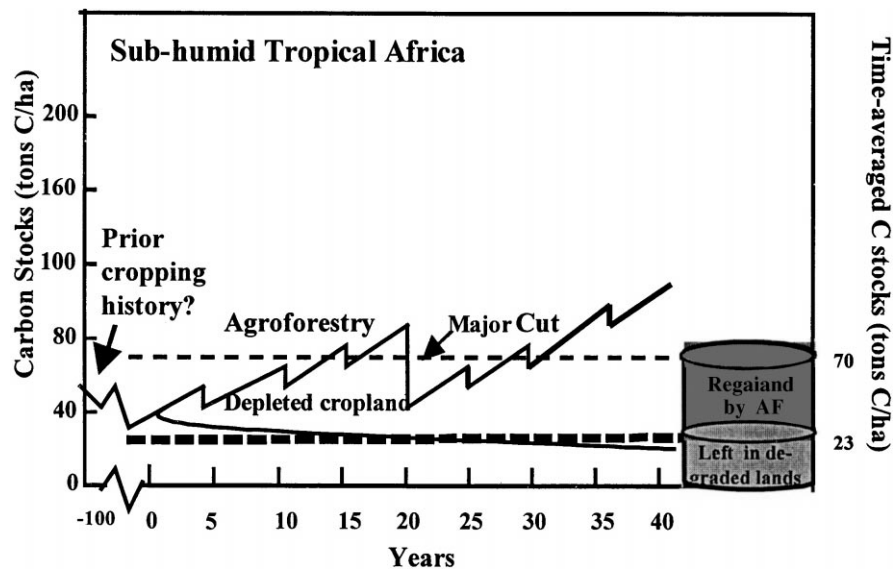


Fig. 4. Project time course and system carbon stocks (biomass and soil) and time-averaged C stocks in sequential agroforestry systems based on soil fertility replenishment and intensification with high value trees in sub-humid tropical Africa.

alone. Carbon sequestration may therefore be quite considerable with agroforestry systems that involve soil fertility replenishment and intensification and diversification of farming with the use of high-value domesticated trees in subhumid Africa.

6. Conclusion

The approach and results described in this study suggest tremendous synergies in combining the strengths of research groups like IGBP and the CGIAR in tackling jointly and simultaneously major biophysical and socio-economic constraints that affect rural policy and food security, and at the same time mitigate the effects of climate change for the benefit of all humankind.

References

- ASB, 1998. Alternatives to slash and burn in Indonesia. Final Report of Phase II. ICRAF, Nairobi, Kenya, p. 139.
- Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), 1997. Replenishing soil fertility in Africa. SSSA Special Publication No. 51. Wisconsin: Soil Science Society of America, Madison, p. 251.
- CGIAR, 1998. CGIAR system review report. Consultative Group on International Agricultural Research, Washington, p. 108.
- Dawson, I.K., Powell, W., 1999. Genetic variation in the Afromontane tree *Prunus africana*, an endangered medicinal species. *Mol. Ecol.* 8, 151–156.
- Fay, C., de Foresta, H., Sarait, M., Tomich, T.P., 1998. A policy breakthrough for Indonesian farmers in the Krui damar agroforests. *Agroforestry Today* 10 (2), 25–26.
- Gachengo, C.N., Palm, C.A., Jama, B., Othieno, C., 1999. *Tithonia* and *Senna* green manures and inorganic fertilizers as phosphorus sources for maize in western Kenya. *Agroforestry Syst.* 44, 21–36.
- Garritty, D.P., Khan, A., 1994. Alternatives to slash and burn: a global initiative. International Centre for Research in Agroforestry, Nairobi, Kenya, p. 73.
- Gokowski, J., Nkamelu, B., Wendt, J.K., 2000. Implications of resource use intensification for environment and sustainable technology systems in the central African rainforest. In: Barret, C., Lee, D. (Eds.), *Agricultural Intensification and the Environment*. Cornell University, submitted for publication.
- Gregory, P.J., Ingram, J.S.I., 2000. Global change and food and forestry production: future scientific challenges. *Agric. Ecosys. Environ.* 82, 3–14.
- Houghton, J.T., Gylvan Meira Filho, L., Griggs, D.J., Maskell, K. (Eds.), 1997. Stabilization of atmospheric greenhouse gases: physical, biological and socioeconomic implications. IPCC Technical Paper III, IPCC Secretariat, Geneva, p. 48.
- Inter-Centre Working Group on Climate Change (ICWG-CC), 1999. The CGIAR and climate change. Progress report presented at International Centers Week 1999. CGIAR Secretariat, Washington, p. 14.

- Izac, A.-M.N., Sanchez, P.A., 2000. Towards a natural resource management research paradigm: an example of agroforestry research. *Agric. Syst.*, in press.
- Jama, B., Palm, C.A., Buresh, R.J., Niang, A.I., Gachengo, C., Nziguhaba, G., Amadalo, B., 2000. *Tithonia diversifolia* green manure for improvement of soil fertility: a review from western Kenya. *Agroforestry Syst.*, in press.
- Jamieson, P.D., Berntsen, J., Ewert, F., Kimball, B.A., Oleson, J.E., Pinter Jr., P.J., Porter, J.R., Semerov, M.V., 2000. Modelling CO₂ effects on wheat with varying nitrogen supplies. *Agric. Ecosyst. Environ.* 82, 23–37.
- Kwesiga, F., Coe, R., 1994. The effect of short rotation *Sesbania sesban* planted fallows on maize yields. *Forest Ecology and Management* 64, 199–208.
- Kapkiyai, J.J., Karanja, N.K., Woomer, P., Qureshi, J.N., 1998. Soil organic carbon fractions in a long-term experiment and the potential for their use as a diagnostic assay in highland farming systems of central Kenya. *Afr. Crop Sci. J.* 6 (1), 19–28.
- Kwesiga, F.R., Franzel, S., Place, F., Phiri, D., Simwanza, C.P., 1999. *Sesbania sesban* improved fallows in eastern Zambia: their inception, development and farmer enthusiasm. *Agroforestry Syst.* 47, 49–66.
- Leakey, R.R.B., Temu, A.B., Melnyk, M., Vantomme, P. (Eds.), 1996. Domestication and commercialization of non-timber forest products in agroforestry systems. *Non-Wood Forest Products* 9, FAO, Rome.
- Michon, G., de Foresta, H., 1996. Agroforests as an alternative to pure plantations for the domestication and commercialization of NTFPs. In: Leakey, R.R.B., Temu, A.B., Melnyk, M. (Eds.), *Domestication and Commercialization of Non-Timber Forest Products for Agroforestry*. *Non-Wood Forest Products* 9, FAO, Rome, pp. 160–175.
- Ministry of Forestry, Indonesia, 1998. Kawasan dengan Tujuan Istimewa (KdTI) di pesisir Krui, Lampung Barat. Surat Keputusan Menteri Kehunatan RI No. 47. Kpts-II/1998 (Sebuah Ulasan). Ministry of Forestry, Jakarta, Indonesia, p. 16.
- Niang, A., de Wolf, J., Nyasimi, M., Hansen, T., Romelsee, R., Mdewa, K., 1998. Soil fertility replenishment and recapitalization project in western Kenya. Progress Report February 1997–July 1998. Pilot project report no. 9. Regional Agroforestry Research Centre — KARI-KEFRI-ICRAF, Maseno, Kenya, p. 42.
- Oldeman, L.R., 1998. Soil degradation: a threat to food security? International Soil Reference and Information cenTre Report 98/01, Wageningen, The Netherlands.
- Palm, C.A., Izac, A.-M.N., Vosti, S., 1995. Procedural guidelines for characterization. ASB Coordination Office, ICRAF, Nairobi, Kenya, p. 33.
- Palm, C.A., Woomer, P.L., Alegre, J.C., Arevalo, L., Castilla, C.E., Cordeiro, D.G., Feigl, B., Hariah, K., Kotto-Same, J., Mendes, A., Moukam, A., Murdiyarso, D., Njomgang, R., Parton, W.J., Ricse, A., Rodrigues, V., Sitompul, S.M., van Noordwijk, M., 2000. Carbon sequestration and trace gas emissions in slash and burn and alternate land uses in the humid tropics. In: Sanchez, P.A., Ericksen, P.J., Juo, A.S.R. (Eds.), *Alternatives to Slash and Burn Agriculture: A Global Synthesis*. American Society of Agronomy Special Publication, submitted for publication.
- Pinstrup-Andersen, P., Pandhya-Lorch, R., Rosengrant, M.W., 1999. World food prospects: critical issues for the early 21st century. 2020 vision food policy report. International Food Policy Research Institute, Washington, p. 32.
- Rao, M.R., Niang, A., Kwesiga, F., Duguma, B., Franzel, S., Jama, B., Buresh, R., 1998. Soil fertility replenishment in sub-saharan Africa. New techniques and the spread of their use on farms. *Agroforestry Today* 10 (2), 3–8.
- Sanchez, P.A., Woomer, P.L., Palm, C.A., 1994. Agroforestry approaches for rehabilitating degraded lands after tropical deforestation. *JIRCAS International Symposium Series* 1, Tsukuba, Japan, pp. 108–119.
- Sanchez, P.A., Hailu, M. (Eds.), 1996. Alternatives to Slash and Burn Agriculture. *Agric. Ecosyst. Environ.* 58, 1–86.
- Sanchez, P.A., Leakey, R.R.B., 1997. Land use transformation in Africa: three determinants for balancing food security with natural resource utilization. *Eur. J. Agronomy* 7, 15–23.
- Sanchez, P.A., Shepherd, K.D., Soule, M.I., Place, F.M., Buresh, R.J., Izac, A.-M.N., Mokwunye, A.U., Kwesiga, F.R., Ndiritu, C.G., Woomer, P.L., 1997a. Soil fertility replenishment in Africa: an investment in natural resource capital. In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), *Replenishing Soil Fertility in Africa*. SSSA Special Publication 51. Soil Science Society of America, Madison, WI, USA, pp. 1–46.
- Sanchez, P.A., Buresh, R.J., Leakey, R.R.B., 1997b. Trees, soils and food security. *Philosophical Trans. R. Soc. London, Ser. B* 353, 949–961.
- Sanchez, P.A., 2000. Delivering on the promise of agroforestry. *Environ. Dev. Sustainability J.*, in press.
- Sanchez, P.A., Ericksen, P.J., Juo, A.S.R. (Eds.), 2000. Alternatives to Slash and Burn Agriculture: A global Synthesis. American Society of Agronomy Special Publication, submitted for publication.
- Schlesinger, W.H., 1999. Carbon sequestration in soils. *Science* 284, 2095.
- Simons, A.J., Dawson, I.K., Duguma, B., Tchoundjeu, Z., 1998. Passing problems: prostate and prunus. *HerbalGram* 43, 49–53.
- Smaling, E.M.A., 1993. An agroecological framework for integrating nutrient management, with special reference to Kenya. Ph.D. thesis, Agricultural University, Wageningen, The Netherlands, p. 250.
- Tomich, T.P., van Noordwijk, M., Vosti, S., Witcover, J., 1998. Agricultural development with rainforest conservation: methods for seeking best-bet alternatives to slash-and-burn, with applications to Brazil and Indonesia. *Agric. Econ.* 19, 159–174.
- Tomich, T.P., Thomas, D.E., Kusumanto, Y., van Noordwijk, M., 1999. Policy research for sustainable upland systems in Southeast Asia. ICRAF, Bogor, Indonesia, p. 14.
- Tomich, T.P., van Noordwijk, M., Budidarsono, S., Gillison, A., Kusumanto, T., Murdiyarso, D., Stolle, F., Fagi, A.M., 2000. Agricultural intensification, deforestation and the environment: assessing tradeoffs in Sumatra, Indonesia. In: Barret, C., Lee, D. (Eds.), *Agricultural Intensification and the Environment*. Cornell University, in press.
- Walker, B., Steffen, W., Canadell, J., Ingram, J. (Eds.), 1999. The Terrestrial Biosphere and Global Change. Implications for Natural and Managed Ecosystems. Cambridge University Press, Cambridge, UK, p. 439.

- Wallace, J.S., 2000. Increasing agricultural water use efficiency to meet future food production. *Agric. Ecosyst. Environ.* 82, 105–119.
- Welch, R.M., Combs Jr., G.F., Duxbury, J.M., 1997. Towards a ‘greener’ revolution. *Sci. Technol.* 14 (10), 50–58.
- Woomer, P.L., Palm, C.A., Qureshi, J.N., Kotto-Same, J., 1997. Carbon sequestration and organic resource management in African smallholder agriculture. In: Lal, R., Kimble, J.M., Follett, R.A., Steward, B.A. (Eds.), *Management of Carbon Sequestration in Soil*. CRC Press, Boca Raton, FL, USA, pp. 153–173.
- Woomer, P.L., Palm, C.A., Alegre, J., Castilla, C., Cordeiro, D.G., Hairiah, K., Kotto-Same, J., Moukam, A., Ricse, A., Rodrigues, V., van Noordwijk, M., 2000. Slash-and-burn effects on carbon stocks in the humid tropics. In: Lal, R., Kimble, J.M., Steward, B.A. (Eds.), *Global Climate Change and Tropical Ecosystems*. CRC Press, Boca Raton, FL, pp. 99–155.