MITIGATING GHG EMISSIONS IN THE HUMID TROPICS: CASE STUDIES FROM THE ALTERNATIVES TO SLASH-AND-BURN PROGRAM (ASB)

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Abstract. Tropical forest conversion contributes as much as 25% of the net annual CO_2 emissions and up to 10% of the N_2O emissions to the atmosphere. The net effect on global warming potential (GWP) also depends on the net fluxes of greenhouse gases from land-use systems following deforestation. Efforts to mitigate these effects must take into account not only the greenhouse gas fluxes of alternative land-use systems but also the social and economic consequences that influence their widespread adoption. The global alternatives to slash-and-burn program (ASB) investigated the net greenhouse gas emissions and profitability of a range of land-use alternatives in the humid tropics. The analysis showed that many tree-based systems reduced net GWP compared to annual cropping and pasture systems. Some of these systems are also profitable in terms of returns to land and labor. The widespread adoption of these systems, however, can be limited by start-up costs, credit limitations, and number of years to positive cash flow, in addition to the higher labor requirements. Projects that offset carbon emissions through carbon sinks in land use in the tropics might be a means of overcoming these limitations. A synthesis of the findings from this program can provide guidelines for the selection and promotion of land-use practices that minimize net global warming effects of slash-and-burn.

Key words: carbon stocks, environmental and economic tradeoffs, net global warming potential, profitability, slash-and-burn.

1. Introduction

Tropical deforestation contributes up to 25% of the net annual CO_2 emissions (Watson et al., 2000) and 10% of the global N_2O emissions (Bouwman et al. 1995), primarily from the slashing and burning of the high-biomass vegetation and decomposition of the soil organic matter. The initial flux of CO_2, CH_4 and N_2O during and immediately following slash-and-burn is similar for most land-use systems. Less is known about carbon stocks and trace gas emissions during the time course of the various land systems established following deforestation (Houghton et al., 1993; Erickson et al., 2001; Erickson and Keller, 1997) compared to the immediate effects from the slash-and-burn process.

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Though studies over the past 10 years provide a substantial basis for making initial estimates of the trace gas fluxes and carbon stocks from these different land-use systems in the humid tropics (Mosier et al, this volume; Verchot et al., 1999; Davidson et al., 2000; Woomer et al., 2000; Erickson et al., 2001), most studies have focused on natural or old-growth forests, pastures in Latin America, paddy rice, and a few other cropping systems. There have been few studies from tree-based systems such as plantations, fallows from slash-and-burn agriculture, and agroforestry systems, yet tree-based systems often dominate the agricultural landscape in the humid tropics (Wood et al., 2000). Efforts to mitigate the global climate change effects of tropical deforestation and land use must take into account not only the greenhouse gas fluxes of these land-use systems but also the social and economic consequences that influence the widespread adoption of the various land-use alternatives following slash-and-burn clearing.

In this paper we synthesize some of the major findings from a global project, the Alternatives to Slash-and-Burn Program (ASB), that can provide guidelines for the selection and promotion of land-use practices that minimize net global warming effects of slash-and-burn. The net global warming potential (GWP) of a range of land-use systems, including many tree-based systems, are estimated from information on carbon stocks and greenhouse gas emissions that were measured in this project. The GWP is based on the CO_2 fluxes resulting from changes in carbon in the vegetation and soils from deforestation and during the rotation time of the land-use systems and the N_2O and CH_4 fluxes from these systems. In addition, the profitability of the different land-use systems is provided to assess which land-use systems have the potential to generate income for the land users and thus have greater chances of adoption. The tradeoffs between global environmental services (e.g. reduced GWP) and private costs and benefits are discussed based on the findings for the different land-use systems.

2. The ASB Program

In 1991, ASB was initiated to address the agronomic, environmental, social, and political implications of slash-and-burn in the humid tropics (Brady, 1996). The overall goal of the program was to compare the environmental and social impacts of current land-use systems and to identify alternatives that were environmentally and agronomically or economically better. In addition, policies that would facilitate the adoption of these promising alternatives were considered.

Teams of national and international scientists were established in key locations, referred to as benchmark areas, around the humid tropical belt representing the range in biophysical and socioeconomic environments in which slash-and-burn is practiced. Standardized sets of parameters and measurements were established for assessing carbon stocks (Woomer and Palm, 1998), trace gas emissions (Palm et al., 2002), agronomic sustainability, profitability, and the institutional settings (Vosti et al., 2000) for the different land-use systems found in the benchmark areas.

The resulting 'ASB trade-off matrix' allows one to compare the environmental, production, and social cost and benefits of the different land-use systems (Tomich et al., 1998a; Vosti et al., 2000). The reader is also referred to Woomer et al. (2000), Palm et al. (1999, 2002), Hairiah et al. (2001), Gockowski et al. (2001), Tsuruta et al. (2000), Tomich et al. (2001, 2002), and Vosti et al. (2001) for more detailed descriptions and results of these studies.

2.1. DESCRIPTION OF THE ASB BENCHMARK SITES AND LAND-USE SYSTEMS

ASB benchmark areas were chosen to represent at the regional and global levels, large, active areas of deforestation caused by slash-and-burn practices (Palm et al., 1995). In this paper, we concentrate on the sites in Cameroon, the western Amazon, and Sumatra, Indonesia. These areas are in the humid tropical zone with annual rainfall generally greater than 2000 mm and dry seasons of less than six months. The sites are characterized by tropical rainforest vegetation and acid, infertile soils (primarily Oxisols and Ultisols). The site in Cameroon is defined over a population gradient with areas of lower population pressure representative of the equatorial Congo Basin rainforest of Congo, Gabon, Central African Republic, and Zaire while areas of higher pressure having greater affinity to the degraded humid forests of coastal West Africa. In Latin America, areas in the states of Rondonia and Acre in the western Amazon of Brazil represent areas of rapid deforestation as a result of colonization programs, while sites in Peru represent other areas of the western Amazon Basin with lower population density and poor infrastructure. Areas in Sumatra, Indonesia represent the equatorial rainforests of Indonesian and Malaysian archipelago where primary forests are being cleared by both indigenous practices and resettlement programs; in addition, degraded imperata grasslands invade the landscape as population densities increase. The contrasts in some of the site characteristics are presented in Table I.

A set of 'meta land-use categories' encompasses the different land-use systems that were described and studied at the ASB benchmark areas. These include forests, either undisturbed, managed, or logged; complex agroforestry systems that include a wide diversity of plant species; simple agroforestry systems and tree crop plantations that usually contain less than 10 plant species as major components of the system; crop-fallow agriculture rotations, including long-term fallows characteristic of shifting cultivation, short-term fallows and improved fallows; annual crops; and pastures and grasslands, including degraded grasslands and improved pastures.

3. Net GWP of ASB Land Uses

The effects of slash-and-burn and subsequent land use on net GWP are estimated from changes in carbon stocks over the time-course of the land-use change and fluxes of nitrous oxide (N_2O) and methane (CH_4).

TABLE I. Selected site characterization parameters for the ASB benchmark areas.

Characterization parameter	Western Amazon, Brazil/Peru	Southern Cameroon	Sumatran lowlands
Rainfall (mm yr^{-1})	1700–2400	1400–1900	2000–3000
Months dry season (less than 100 mm)	June–Sept	Apr–May; Oct–Feb	May–Sept
Dominant original vegetation	Tropical moist forest; semi-deciduous forest	Tropical moist forest; semi-deciduous forest	Tropical moist forest
Predominant soils (US Soil Taxonomy)	Paleud(ust)ults; Hapludustox;	Kandiudults	Hapludox; Kandiudox
Population (people km^{-2})	3–5	4–120	2–175
Farm size (ha household^{-1})	80–100	2–4*	5–10
Agriculture wages (US$ day^{-1})	6.25	1.21	1.67

* Excludes fallow land.

3.1. CARBON STOCKS AND TIME-AVERAGED CARBON

Carbon stocks were measured in the soils (0–20 cm) and aboveground vegetation in a total of 115 different locations in the benchmark areas according to standardized protocols (Woomer and Palm, 1998). The sites encompassed most of the meta land-use categories in each of the benchmark sites. Detailed results from those sites are reported in Kotto-Same et al. (1997), Fujisaka et al. (1998), Tomich et al. (1998a,b), and Woomer et al. (2000).

Data from those studies were used to describe the time course of carbon stocks over the rotation of the different land-use systems and to calculate the aboveground time-averaged C of each system as described and reported in Palm et al. (1999). This methodology allows the comparison of carbon stocks in systems that have tree-growth and harvesting rotations and is similar to the average storage method described in the IPCC Special Report on Land Use, Land-Use Change and Forestry (Watson et al., 2000).

The main findings from these carbon stock measurements indicate that that the C stocks in the vegetation of the primary forests averaged 300 t C ha^{-1}, that of logged or managed forests ranged from a high of 228 t C ha^{-1} in Cameroon to a low of 93 t C ha^{-1} in Indonesia (Table II). Time-averaged aboveground C for the different meta land uses ranged from 50 to 90 t C ha^{-1} in long-fallow shifting cultivation and complex agroforestry systems; 30–60 t C ha^{-1} in simple agroforestry systems, most tree plantations and medium-fallow rotations; and 3–12 t C ha^{-1} in short-fallow rotations, coffee plantations, annual crops, and pastures.

Soil carbon values (0–20 cm) compared to the 45 t C ha^{-1} found in the forest systems were 80–100% in agroforestry systems; 80% in pastures; 90–100% in long-fallow cycles; 65% in short-term fallows, and 50% or less in annual crops

TABLE II. Summary of the aboveground time-averaged C stock (mean and range) of the land-use systems sampled at the ASB sites, the range is given in parentheses (Palm et al., 1999).

Meta land-use systems	Country and specific land use	Time-averaged C of land-use system t C ha^{-1}
Undisturbed forest	Indonesia	306 (207–405)
	Peru	294
Managed/logged forests	Brazil/Peru	150 (123–185)
	Cameroon	228 (221–255)
	Indonesia	93.2 (51.9–134)
Shifting cultivation and crop-fallows	Cameroon	
	Shifting cultivation, 23-year fallow	77.0 (60.2–107)
	Bush fallow, 9.5 years	28.1 (22.1–38.1)
	Chromolaena fallow, 4 years	4.52 (2.68–6.38)
	Brazil/Peru	
	Short fallow, 5 years	6.86 (4.27–9.61)
	Improved fallow, 5 years	11.5 (9.50–13.4)
	23-year fallow	93 (80.5–101)
Complex/extensive agroforests		
Permanent	Cameroon	88.7 (57.2–120)
Rotational	Cacao	
	Indonesia	89.2 (49.4–129)
	Rubber	
	Cameroon	61 (40–83)
	Cacao	
	Indonesia	46.2 (28.9–75.2)
	Rubber	
Simple agroforests/ intensive treecrop	Brazil/Peru	
	Coffee monoculture	11.0 (8.73–12.5)
	Multistrata system	61.2 (47.5–74.7)
	Peach Palm, Oil Palm, rubber	47 (27–61)
	Cameroon	
	Oil Palm	36.4
	Indonesia	
	Pulp trees	37.2 (23.6–50.7)
Grasslands/crops	Brazil/Peru	
	Extensive pastures	2.85
	Intensive pastures	3.06
	Indonesia	
	Cassava/Imperata	<2

and degraded grasslands (Palm et al., 1999). These losses in soil C are similar to those reported by Detwiler (1986) in a review of soil C and land use in the tropics; though changes in pasture soils vary considerably ranging from 0% to 20% losses.

Combined losses of C from the vegetation and soils over the time course of the deforestation and subsequent land use can be as high as 320 t C ha^{-1} or a minimum of 110 t C ha^{-1} if an undisturbed forest is converted to annual cropping or permanent agroforests, respectively. Though much deforestation is now occurring from managed and previously logged forests that have already lost some C, rather than undisturbed forests, current losses would be somewhat less.

3.2. NITROUS OXIDE AND METHANE FLUXES

Estimates of N_2O and CH_4 fluxes require intensive, long-term sampling. This was not possible at most of the ASB sites. So, in order to obtain some estimate of the N_2O and CH_4 fluxes relative to net CO_2 fluxes from changes in land use, flux data from a long-term experiment in the western Amazon in Peru (Palm et al., 2002) were used for most of the meta land-use systems along with data from the literature for other land-use systems in the Amazon.

The land-use systems sampled in Yurimaguas, Peru included two annual cropping systems, one a high-input maize soybean rotation with 100 kg N ha^{-1} fertilizer applied to each maize crop, liming, and tillage and the other a low-input system with an upland rice–cowpea–legume cover crop rotation; four tree-based systems including a 13-year- and a 23-year-old secondary forest fallow, multistrata agroforestry system, and a peach palm tree plantation. Other than the 23-year-old secondary forest all other land-use systems were 13-years-old at the time of sampling. Gas fluxes were calculated from monthly samples taken over a 2-year period as described in Palm et al. (2002).

3.2.1. Nitrous oxide fluxes

The annual N_2O flux from 23-year-old secondary forest soil was 0.80 kg N ha^{-1} or 9.1 μg N m^{-2} h^{-1} (Palm et al., 2002), within the range of most other secondary forests reported for the Neotropics on acid, infertile soils (Davidson et al., 2000, 2001; Erickson et al., 2001). This value is about half that reported for primary forests on similar soils in the region (Davidson et al., 2001); therefore a value of 20 μg N m^{-2} h^{-1} was used as an estimate for primary forests, since none were evaluated in the Peru study (Table III). N_2O fluxes from the three tree-based systems in this study that had been established 13 years previously ranged from 6.4 to 10.2 μg N m^{-2} h^{-1}, again within the range for secondary forests in the region. Fluxes from the two cropping systems were higher than the tree-based systems, averaging 14.51 and 26.6 μg N m^{-2} h^{-1} for the low- and high-input cropping systems, respectively. The fluxes from the high-input cropping system were an order or two of magnitude lower than those measured for other fertilized systems in the humid and subhumid tropics (Davidson et al., 1996; Erickson and Keller, 1997; Veldkamp and Keller, 1997; Matson et al., 1998) and probably reflect the lower N application rates as well as the split application in this study (Palm et al., 2002).

TABLE III. The N_2O and CH_4 fluxes and changes in C stocks of slash-and-burn and different land-use systems in the Peruvian Amazon.

Land-use system	N_2O flux[a] (μg N m^{-2} h^{-1})		CH_4 flux[a] (μg C m^{-2} h^{-1})	Net C lost from vegetation[e] (t C ha^{-1} 25 yr^{-1})	Net C lost from soil[e] (t C ha^{-1} 25 yr^{-1})
	From burn	Land use			
Primary forest		20.0[b]	−40.0	0[f]	0[f]
25-year crop-fallow	1.82[d]	9.1	−30.0	135	5
Multistrata agroforest	1.82[d]	6.4	−24.2	165	9
Peach palm plantation	1.82[d]	10.2	−18.4	185	9
Low-input cropping	1.82[d]	14.5	−18.2	222	9
High-input cropping	1.82[d]	26.6	+15.2	222	22.5
Pasture	1.82[d]	7.0[c]	0	222	0

[a] From Palm et al. (2002) except for primary forest and pasture.

[b] From Davidson et al. (2001).

[c] From Verchot et al. (1999).

[d] From Erickson and Keller (1997); 4 kg N ha^{-1} from slash-and-burn, distributed over 25 years.

[e] Includes effects of deforestation and assuming 225 and 45 t C ha^{-1} in the initial forest vegetation and topsoil (0–20 cm) and time-averaged C of each land-use system for 25-year rotation.

[f] Assumes primary forest vegetation and soil are in equilibrium with respect to C stocks.

Nitrous oxide fluxes from pastures on acid, infertile soils of the Amazon were taken from the literature to provide a comparative flux from this important land use in the region. Annual N_2O fluxes from pastures range from 0.1 to about 2 kg N ha^{-1} yr^{-1} (Verchot et al., 1999; Erickson and Keller, 1997). At intermediate value of 7.0 μg N m^{-2} h^{-1} (or 0.6 kg N ha^{-1} yr^{-1}) was used for comparing pastures with the other land uses (Table III). Although a much higher flux, 5.7 N ha^{-1} yr^{-1}, was measured from a recently established pasture in the central Amazon (Luizao et al., 1989); it is now considered that this high value was probably transitory following deforestation. Similar patterns have been found following establishment of pastures in Costa Rica (Erickson and Keller, 1997).

3.2.2. Methane fluxes

The annual flux of CH_4 of −2.6 kg C ha^{-1} yr^{-1} or −30.0 μg C m^{-2} h^{-1} from the secondary forest (Table III; Palm et al., 2002) falls within the range reported for primary forests in the Amazon (Steudler et al., 1996; Verchot et al., 2000). The CH_4 consumption rates of the tree-based systems and the low-input cropping systems ranged from 54% to 86% that of the secondary forest. In contrast, there was a net CH_4 production of 15.2 μg C m^{-2} h^{-1} in the high-input cropping system. Both the higher flux of N_2O and production of CH_4 in the high-input cropping system were associated with higher soil bulk density and %wfps due to the deterioration of the soil structure from the long-term tillage operations in this system.

Others have reported that conversion of humid tropical forest to cropping systems decreased the CH_4 consumption rates by 75% (Keller et al., 1990) but did not result in a shift to net annual CH_4 production. Conversion of humid forests to pastures often results in net CH_4 production rather than consumption (Keller and Reiners, 1994; Steudler et al., 1996) though Verchot et al. (2000) found production CH_4 in the rainy season but annual net CH_4 consumption. Given this range that included slight CH_4 production and CH_4 consumption, a value of 0 was used for CH_4 flux from pasture soils in this comparative analysis.

3.3. NET GWP OF SLASH-AND-BURN SYSTEMS: AN EXAMPLE FROM PERU

In order to make an overall comparison of the net GWP from the emissions of CO_2 from the biomass burning as a result of deforestation and the subsequent changes in carbon stocks in the soil and vegetation and the fluxes of CO_2, N_2O, and CH_4 from the different land-use systems, information on time-averaged carbon stocks from the different land-use systems and N_2O, and CH_4 fluxes from the Peru site was combined (Table III). This was the only site with extensive C stock and gas flux measurements required to make these estimates. So, while these estimates of GWP are not meant to be representative of the entire humid tropics, the values are intended to give an indication of the relative effects of CO_2, N_2O, and CH_4, as well as the relative effects of the different phases of deforestation, and the different types of land use on GWP. Information in the previous sections does show that the C stock changes and gas fluxes from the different land uses in Peru generally fall within the ranges reported for other parts of the Amazon and the resulting estimates of GWP should be considered to be within the ranges expected for the region.

The net GWP of the different land-use systems in Peru were calculated using the following assumptions and conditions:

(1) Carbon stocks of the aboveground vegetation and topsoil (0–20 cm) of the forest systems that were slashed and burned were 225 and 45 t C ha^{-1}, respectively. Losses of CO_2 from biomass burning were assumed to be 100% of the aboveground C of the forest and were averaged over a 25-year time frame, or 9 t C ha^{-1} yr^{-1}.
(2) N_2O flux from biomass burning with deforestation was assumed to be about 4 kg N ha^{-1} (Erickson and Keller, 1997), distributed over a 25-year time span would equal 0.16 kg N ha^{-1} yr^{-1} (1.82 μg N m^{-2} h^{-1}).
(3) Net losses of C in the above ground vegetation and topsoil (0–20 cm) over the 25 years were then determined as the initial C stocks of the forest minus the time-averaged value for each system that were calculated and standardized for the 25-year time frame for all systems. Only one value is given for the two fallow systems since their time-averaged C would be the same for the 25-year rotation. It is important to note that changes in C stocks in belowground vegetation are not considered here and so the values given in Table III are underestimates.

(4) N_2O and CH_4 fluxes from the land-use systems in Peru were assumed to be averages for the 25-year time span. The measurements from Peru were flux estimates for land-use systems 13 years following slash-and-burn and do not include the time course since deforestation from which to calculate time-average fluxes. Other studies from chronosequences indicate that N_2O fluxes from pastures in the Amazon decline as much as 50% over 20 years (Erickson and Keller, 1997; Verchot et al., 1999) while fluxes from secondary forests increase by as much as 100% over the first 20 years. These trends suggest that the fluxes from the 13-year-old systems in Peru, being at the midpoint of the 25-year time frame, would provide a reasonable time-averaged flux for 25-year period rotations. Fluxes for the 'old-growth' forest and pastures were taken from the literature as noted in Sections 3.2.1 and 3.2.2.

(5) Net GWP was calculated by converting changes in C stocks and fluxes of N_2O and CH_4 to mol CO_2 m^{-2} yr^{-1}, using net radiative forcing values of 1, 310, and 21 for CO_2, N_2O, and CH_4, respectively (Watson et al., 2000).

The most notable result from the analysis of the net GWP indicates that the CO_2 released from the vegetation as a result of biomass burning from deforestation (75 mol C m^{-2} yr^{-1}; dashed line in Figure 1) far outweigh the subsequent emissions of CO_2, N_2O, and CH_4 emissions from the soils of the different land-use systems. A similar conclusion was reached for the Sumatra benchmark sites by Tomich et al. (1998b). The GWP due to net CO_2 emission from the decomposition of soil organic matter following deforestation, 0–8 mol C m^{-2} yr^{-1}, was as high or higher than that of the combined N_2O and CH_4 despite the higher net radiative forcing values for the latter two gases (Figure 1) and the GWP from CH_4 production in the high-input cropping system 0.41 mol C m^{-2} yr^{-1} or consumption in the other systems, -0.28 to -0.46 mol C m^{-2} yr^{-1}, were negligible in comparison to the GWP from CO_2.

Once the slash-and-burn process has occurred then the sum of the radiative forcing effects of CO_2 and $N_2O + CH_4$ are highest in the high-input cropping system, due to larger losses of soil organic matter, a higher N_2O flux as a result of fertilization, and a loss of the soil CH_4 sink and in fact a net CH_4 source from the soil in this system. Considering only the portion of GWP due to the combined $N_2O + CH_4$ fluxes, it is interesting to note that estimates for the primary forest (3.27 mol C m^{-2} yr^{-1}) are second only to the high-input cropping system (5.57 mol C m^{-2} yr^{-1}). This is due to the high N_2O flux from the forest soil and despite the fact that this system has the highest CH_4 sink. In contrast to most perceptions, the GWP due to $N_2O + CH_4$ for the other systems are lower than that of the primary forest system. Even the low-input cropping system was 30% less than that of the forest, while the remaining tree-based systems had values 60% less than the primary forest.

Most of the tree-based systems at the ASB benchmark sites are not intensively fertilized so the radiative effects of N_2O are not large. Many intensive tree crop systems in the humid tropics, such as coffee, peach palm, and banana are fertilized at rates often exceeding 300 kg N ha^{-1} yr^{-1} (Szott and Kass, 1993; Veldkamp and

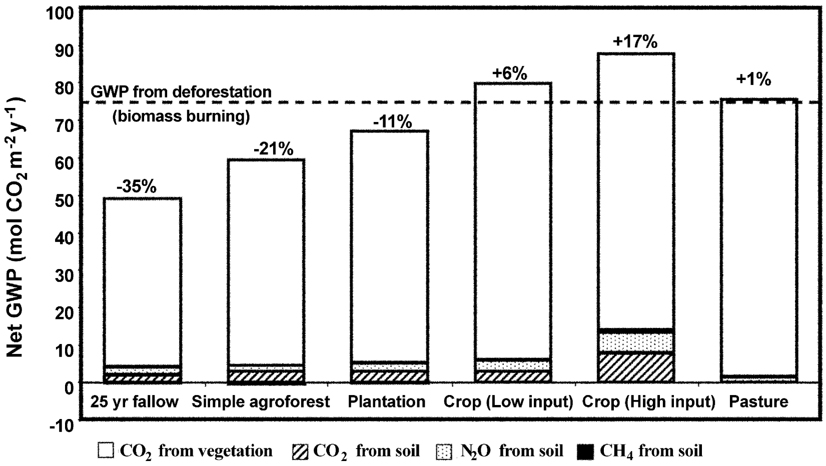

Figure 1. Sources of the net GWP over a 25-year period for the different land-use systems in the Peruvian Amazon. The dashed line represents the GWP resulting from deforestation and biomass burning. Details of the calculations are shown in Section 3.3.

Keller, 1997). There is insufficient information to determine if gaseous N losses will increase significantly from these tree-based systems with fertilization but emissions should depend largely on the rates and timing of fertilizer application relative to plant demand and age of the system.

In comparing the net GWP of the different land-use systems with the GWP from the deforestation and biomass burning, the tree-based systems all reduce this initial flux by 11–35% (Figure 1); this decrease being attributed primarily to the sequestration of C in the vegetation. In contrast, the net GWP of the two cropping systems increased the initial GWP from burning by 6% to almost 20% due to losses of soil C and, in the case of the high input cropping system, higher N_2O losses and net CH_4 production. The net GWP of the pasture system essentially remained the same as that resulting from biomass burning.

Efforts to mitigate this dominating effect of the release of CO_2 from the slash-and-burn process should obviously focus on reducing rates of deforestation or establishing tree-based land-use systems that sequester more C in the vegetation and soil compared to annual cropping systems and pasture. Efforts to mitigate the high GWP from the high-input cropping system, from the combined CO_2, N_2O, and CH_4 fluxes from the soil, would be to synchronize better the timing of N fertilizer applications with those of plant demand and to improve the soil structure and increase soil organic matter content through conservation tillage operations.

4. Social and Economic Factors of Slash-and-Burn Systems

It is one thing to indicate which land-use systems have the highest GWP and to make recommendations as to how these effects can be reduced by managing the systems differently; it is another thing to expect land users to adopt these systems or practices because of the global environmental effects. Many of the recommendations for mitigating the greenhouse gas effects of land use in the tropics, such as reducing deforestation, establishing and maintaining tree-based systems, and increasing soil organic matter, all include additional inputs of labor and capital. Whether future profits from these different land-use systems will eventually offset these additional costs will help determine which, if any, of the systems land-users will adopt.

The categories included in the ASB social and economic analysis are profitability, including returns to land and labor, and establishment costs; household food security, including nutritional value, food entitlement, and risks (Vosti et al., 2000). Of these categories, financial profitability, labor requirements, and food security were considered essential for the assessment. Systems that generate inadequate levels of financial profits, require more labor input than household can provide or hire or that competes with other traditional systems, or compromise the ability to produce or buy sufficient food will not be attractive to farmers. In addition to profitability and household food security, the institutional capacity such as potential bottlenecks and equity issues may affect the adoptability of the different land-management systems.

4.1. PROFITABILITY OF ASB LAND-USE SYSTEMS

The ASB methods for profitability applied the ‘policy analysis matrix’ approach of Monke and Pearson (1989) for assessing economic outcomes and policy distortion. For the purpose of comparing profitability the private, or farmer, prices were used. Private prices are those actually paid by farmers and include distortions such as taxes, subsidies, and non-tariff barriers. Private prices, as opposed to social prices that estimate prices in absence of such distortions, are most relevant for considering the likelihood of adoption.

Values for assessing profitability at each site were obtained by extensive field studies to determine inputs (including labor) and output levels for the various land-use system components and prices were drawn from the fieldwork and secondary sources. Financial profitability includes establishment costs and costs and benefits of the production activities of each land-use system. These costs/benefits are then discounted to provide summary measures (e.g. net present value, NPV, that was used in the ASB analyses) that can be used to compare LUS across and especially within benchmark sites. For ASB purposes of comparing across land-use systems and benchmark sites the NPV of costs and returns were calculated over a 20- to 25-year time span for each system, using discount rates of 10–15%. Summary measures of financial profitability were expressed as returns to land and to labor, reported in 1996US$. Returns to land represent the implicit rental rate on land dedicated to a specific LUS and returns to labor represent the break-even daily wage for family labor input to a system. The daily wage rates were US $6.00, 1.21, and 1.70 for Brazil, Cameroon, and Indonesia, respectively (Table I). Those land-use systems with returns to labor above that of the wage rate will be more readily adopted.

Details of the economic findings and analysis of trade-offs between environmental and economic indicators from Brazil, Cameroon, and Indonesia can be found in Vosti et al. (2001); Gockowski et al. (2001), and Tomich et al. (1998b, 2001, 2002), and are summarized in Table IV. There is a broad range in the profitability, calculated at private prices, across and within the meta land-use categories.

In general, food crop systems were not profitable. The short-fallow crop rotations, characteristic of areas with higher demographic pressure, were not profitable in Indonesia. Such systems have basically disappeared from the landscape in Brazil and are becoming scarce in Indonesia, perhaps a reflection of the negative returns to land and returns to labor below that of the wage rate. This land-use system is still practiced to some degree, perhaps as a means of assuring food security. In contrast, the longer fallow systems characteristic of the Cameroon site were profitable with high returns to land and returns to labor similar to the wage rate; such systems are a prevalent feature of the landscape there. Annual cropping systems were only found in Indonesia and were profitable only if fertilizers were not used but then the agronomic sustainability of the systems was compromised.

Agroforestry and plantation systems were found to some extent at all sites and in most cases were profitable and provided the highest returns to land and labor. But even within the different tree-based systems some systems were not profitable. As examples, oil palm plantations in Indonesia were highly profitable compared to net losses in monoculture rubber plantations. The rubber agroforests, in contrast, were potentially the most profitable (Tomich et al., 2001; Williams et al., 2001). The more diversified tree-based systems in Cameroon, such as cocoa-fruit agroforests compared to cocoa plantations, also provided higher returns than the more intensive systems due to the earlier harvests and diverse crops for revenue (Gockowski et al., 2001). Pasture systems of the western Amazon or Brazil were also profitable, with returns to land being two orders of magnitude higher in improved as compared to traditional pastures and returns to labor were tripled (Vosti et al., 2001).

4.2. Economic and Environmental Trade-offs of ASB Land-Use Systems

Many of the land-use systems in the humid tropics are profitable and therefore provide an incentive to deforest, which in turn leads to increased greenhouse gas emissions. If deforestation is to occur then from a global environmental perspective it would be most desirable to establish those systems with the lowest net GWP; for the forest margins of the humid tropics these would be the tree-based systems that sequester the most carbon as indicated in Section 2.3. For lands already deforested, converting to land-use systems with higher C stocks should be advocated.

Trade-off matrices were used to identify those ASB land-use systems that may provide both reduced greenhouse gas emissions, through increased C stocks, and potential profitability. The tree-based systems with relatively high C sequestration values (Table II) and higher profitability (Table IV) included oil palm plantations and cocoa agroforests, particularly those interplanted with valuable fruit trees for

TABLE IV. Profitability in terms of returns to land and labor and labor requirements for the different meta land-use systems for the ASB benchmark sites in Indonesia, Brazil, and Cameroon (from Tomich et al., 2001; Vosti et al., 2001; ASB, 2000).

Meta land use	Returns to land (farmer prices, \$ ha^{-1})			Returns to labor (farmer prices, \$ person^{-1} day^{-1})			Time-averaged labor (day ha^{-1} yr^{-1})		
	Sumatra, Indonesia[a]	Acre, Brazil[b]	Southern Cameroon[c]	Sumatra, Indonesia[d]	Acre, Brazil[b]	Southern Cameroon[c]	Sumatra, Indonesia[d]	Acre, Brazil[b]	Southern Cameroon[c]
Forest									
Managed	3 to 7	416	NA	5	1	NA	0.3	1	NA
Logged	−54 to −335		NA	−7 to 1	20	NA	31	1.2	NA
Agroforests									
Complex	1 to 918	NA	424 to 1409	2 to 3	NA	1.6 to 2.4	111 to 150	NA	43 to 97
Simple	−70 to 115	870 to 1955	736 to 1471	1.5 to 2.5	9 to 13	1.8 to 2.4	108 to 133	27 to 59	72
Crops-fallow									
Short fallow	−90 to 32	−17	283 to 623	1.2	6	1.7 to 1.8	15 to 25	23	44 to 115
Annual crops	−30 to 227	NA	NA	1.8	NA	NA	98 to 104	NA	NA
Pasture	NA	2 to 710	NA	NA	7 to 22	NA	NA	12	NA

[a] From Tomich et al. (1998). [b] From Vosti et al. (2001). [c] From ASB (2000). [d] From Tomich et al. (2001).

Cameroon (Gockowski et al., 2001); oil palm plantations and rubber agroforests in Sumatra (Tomich et al., 2001); and coffee and rubber or timber agroforestry systems in Brazil (Vosti et al., 2001).

Many of the land-use systems with low C stocks, such as short-term fallows and annual cropping systems or degraded grasslands, have either net losses or low-potential profitability so conversion to some of the profitable tree-based systems make both environmental and economic sense. An analysis by Tomich et al. (1997) shows that agro-reforestation of the degraded *Imperata* grasslands in Indonesia to *Acacia mangium* plantations or rubber agroforests were indeed profitable. These tree-based systems have time-averaged C stocks of 60 t C ha^{-1} compared to 5 for the grasslands (Table II). The low C stock pasture systems of Latin America, in contrast to the degraded grasslands of Southeast Asia, are more profitable and require less labor than most of the higher C stock tree-based systems. Finding incentives for mitigating the greenhouse gas effects of these profitable pasture systems will be more difficult.

4.3. LABOR AND CAPITAL CONSTRAINTS TO THE MITIGATION OF GREENHOUSE GASES IN ASB SYSTEMS

Despite the profitability and positive environmental aspects of many of the tree-based systems at the ASB sites, there are economic and tenure issues that may prevent large-scale adoption of these compared to other land uses. An example from Sumatra, Indonesia shows the annual labor requirements over the 25-year rotation of agroforests was 125 days ha^{-1} yr^{-1} while those of logging or crop-fallows are 30 and 20 days, respectively (Table IV; Tomich et al., 2001). Evidence from Southeast Asia demonstrates that local people will invest in establishing tree-based systems if they have secure claims over the products, access to markets and natural risks, such as fire, are not too high (Tomich et al., 2002).

The simple agroforestry systems in Brazil had labor requirements 2–5 times higher than pasture systems and this combined with lower returns to labor than improved pasture systems would suggest less likelihood of adoption (Table IV; Vosti et al., 2001). As pointed out by Gockowski et al. (2001) in areas of low population density that are characteristic of most slash-and-burn areas, land-use systems that are land saving will only be adopted if they also increase the returns to labor. When these systems are evaluated at private costs then labor is generally the scarce resource.

Because agroforestry and other tree-based systems typically involve a time lag in production, time plays a factor in farmers' evaluation of monetary returns. A simple measure of this constraint to adoption is the number of years to positive cash flow. In Indonesia, the number of years to positive cash flow was 2 and 10 for annual crops and agroforestry systems, respectively (Tomich et al., 2001). In Brazil, although an intensive coffee agroforestry system provides high returns to labor, adoption may be limited by start-up costs, credit limitations and number of years to positive cash flow, in addition to the higher labor requirements (Vosti et al., 2001). In Cameroon, farmers have adapted to this time lag for production with perennial crops by interplanting food crops, especially plantains and tannia *(Xanthosoma sagittifolium)* during the initial establishment phase. This provides revenues while at the same time providing the shade necessary for the dry season survival of the tree crop seedlings.

5. Carbon Offset Projects as Mechanism for Mitigating Greenhouse Gas Effects of Slash-and-Burn Systems

Efforts to mitigate the greenhouse gas effects of slash-and-burn systems, either through reduction in rates of deforestation or establishment of tree-based systems, may require incentives to the land-users. The process of deforestation, in general, is profitable, so land-users would need some sort of compensation and the adoption of tree-based systems may require government support in terms of land or tree tenure, access to markets, or other institutional support. Opportunities to provide the necessary compensation or institutional support to reduce rates of deforestation or to establish land-use systems with higher C stocks may eventually develop from the proposed clean development mechanism (CDM) in Article 12 of the 'Kyoto Protocol'. The Kyoto Protocol raises the possibility of offsetting C emissions with C 'sinks' in land use, land-use change, and forestry (LULUCF). Establishment of tree-based systems on cropland and grasslands has been identified as the largest potential sink of C globally though land-use change (Watson et al., 2000).

While the CDM may offer gross financial benefits, there has been little analysis of the opportunity costs of foregone resource exploitation and development opportunities. Simply stated, would payments for C sinks at $25 per Mg C, one estimate of the trading price for C, be sufficient for land-users in the tropical forest margins of the humid tropics to reduce deforestation? Tomich et al. (2002) estimated that farmgate (or forestgate) payment per Mg of C needed to offset incentives for forest clearing in Indonesia would be $0.10 per Mg for community-based forest management, under $4 per Mg for large-scale oil palm plantations, and as high as $10 per Mg for rubber agroforests. This suggests that a world price of $25 per Mg of C could shift incentives from forest conversion to conservation, if these payments reach the people making the decisions and agreements are enforceable. In Cameroon the net present value of carbon sequestered when converting short-fallow cropping systems to cocoa agroforests was shown to depend on the marginal value of Mg C, the social discount rate, the production cycle of the agroforest, and the rate of C sequestration over time (J. Gockowski and S. Dury, personal communication). At $20 per Mg of C, the net present values for sequestered C ranged from $550 to $740 per ha. Carbon credits for smallholder-based agroforestry systems offer a potentially powerful policy option for building assets among the rural poor if institutional mechanisms can be devised.

It is not clear how such institutions for transferring C credits would work and little is known about the actual transaction costs when smallholder communities are involved in C trade. Included in these costs would be baseline and monitoring measurements in addition to those costs normally associated with project development and implementation. Transaction costs are important: if they are too high compared to the global price of C stocks, smallholders' incentives will be inadequate to induce a change in land use.

Multidisciplinary data generated through the ASB has provided a means for assessing the tradeoffs between global environmental and private economic aspects of land-use systems in the humid tropics. The analysis showed that many tree-based systems had moderate levels of carbon storage and overall reduced net GWP compared to annual cropping and pasture systems, and thus provide some global benefit. A subset of these systems would also be attractive to small scale land users in the tropics because they are profitable in terms of returns to land and labor. The widespread adoption of these systems, however, can be limited by start-up costs, credit limitations, and number of years to positive cash flow, in addition to the higher labor requirements. Projects that offset carbon emissions through carbon sinks in land use in the tropics might be a means of overcoming these limitations. Studies are needed across a range of circumstances in the humid tropics to improve estimates of the direct opportunity costs of shifting to or conserving land uses that can store more C as well as an assessment of the transactions costs for implementing such projects.

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