10.1098/rsta.2002.1023

THE ROYAL
SOCIETY

Potential carbon mitigation and income in developing countries from changes in use and management of agricultural and forest lands

By John O. Niles[1], Sandra Brown[2], Jules Pretty[3], Andrew S. Ball[3] and John Fay[4]

[1] *Energy and Resources Group, University of California, Berkeley, CA 94720-3050, USA* (joniles@socrates.berkeley.edu)
[2] *Winrock International, Suite 1200, 1621 N. Kent St, Arlington, VA 22209, USA* (sbrown@winrock.org)
[3] *Centre for Environment and Society and Department of Biological Sciences, University of Essex, Wivenhoe Park, Colchester CO4 3SQ, UK* (jpretty@essex.ac.uk; andrew@essex.ac.uk)
[4] *Center for Conservation Biology, Stanford University, Stanford, CA 94305-5020, USA* (jpfay@stanford.edu)

The many opportunities for mitigating atmospheric carbon emissions in developing countries include reforesting degraded lands, implementing sustainable agricultural practices on existing lands and slowing tropical deforestation. This analysis shows that over the next 10 years, 48 major tropical and subtropical developing countries have the potential to reduce the atmospheric carbon burden by about 2.3 billion tonnes of carbon. Given a central price of $10 per tonne of carbon and a discount rate of 3%, this mitigation would generate a net present value of about $16.8 billion collectively for these countries. Achieving these potentials would require a significant global effort, covering more than 50 million hectares of land, to implement carbon-friendly practices in agriculture, forest and previously forested lands. These estimates of host-country income potentials do not consider that outside financial investment may or may not be available. Our calculations take no account of the additional benefits of carbon sequestration in forest soils undergoing reforestation, increased use of biomass and reduced use of fossil-fuel inputs and reduced agricultural emissions. In all events, realizing these incomes would necessitate substantially greater policy support and investment in sustainable land uses than is currently the case.

Keywords: carbon; forests and forestry; tropical and sub-tropical forests; sustainable agriculture; deforestation; ecosystem services

1. Introduction

The recent Third Assessment Report of the Intergovernmental Panel on Climate Change confirmed earlier findings that emissions avoidance and carbon sequestra-

One contribution of 20 to a special Theme Issue 'Carbon, biodiversity, conservation and income: an analysis of a free-market approach to land-use change and forestry in developing and developed countries'.

tion by changes in the use and management of forests can make a meaningful, if limited, contribution to reducing atmospheric CO_2 (Brown *et al*. 1996; Kauppi & Sedjo 2001). However, forestry and land-use issues remain some of the more controversial components of the evolving global climate-change response. Underlying this debate is an urgent need to estimate how reforesting degraded lands, avoiding deforestation and adopting sustainable agriculture practices in developing countries could realistically contribute to climate-change mitigation. Developing countries have no specific emission-reduction targets under current climate-change deliberations. Nevertheless, there are many opportunities for mitigating atmospheric carbon in sustainable land management. Detailed nation-by-nation global estimates of land-based mitigation in developing countries have been bypassed in recent scientific literature (Nakicenovic *et al*. 2000; Watson *et al*. 2000).

Our research addresses this science-policy shortfall by elaborating multiple land-use carbon mitigation potentials and associated incomes for 48 host nations. Here we present new analyses for reforesting degraded lands, implementing sustainable agricultural practices on existing lands and for slowing tropical deforestation.

Of the three mitigation strategies mentioned above, only reforestation appears to be eligible for financing under the most recent rules agreed to under the Kyoto Protocol (UNFCCC 2001). Notwithstanding this restriction, integrating a broad array of sustainable forestry and agriculture is likely to lead to more effective outcomes at both the project level and at larger scales (Niles & Schwarze 2001). For example, improved agriculture practices, although not eligible for financing under Kyoto, will help to enable forest restoration, as improved practices and corresponding increases in agricultural yields will stabilize land-use change and reduce competition for use of lands more suited for forest cover. Similarly, improved agriculture practices will reduce pressure on the need to clear more land, usually at the expense of forests. Sustainably managed new forests will also reduce timber and fuelwood pressures on existing natural forest, possibly avoiding deforestation. Equally, financial incentives to conserve remaining forests will effectively translate into incentives to manage both new forests and existing farmlands more sustainably. Thus, these three strategies will be more effective when done in concert. However, financing outside of the current Kyoto regime in the short term will be needed for avoiding deforestation and adopting sustainable agriculture.

2. Land-based opportunities to mitigate carbon emissions

Many land-based opportunities to increase carbon stocks or avoid carbon emissions exist. For forests, carbon stocks can be increased and carbon emissions avoided by

(1) protecting secondary and other degraded forests to allow them to regenerate naturally;

(2) restoring native forests through assisted and natural regeneration;

(3) maintaining existing forest-carbon stocks and sink processes by avoiding deforestation;

(4) establishing plantations on non-forested lands; and

(5) managing forests sustainably to provide biomass energy.

(Trexler & Haugen 1995; Brown *et al*. 1996; Sathaye & Ravindranath 1998; Watson *et al*. 2000.) Here, we analyse the first three of these. The other two remain to be addressed by others.

On agricultural lands, carbon stocks can be increased in the soil and in woody vegetation by

(1) adopting zero- or minimum-tillage practices on arable land;

(2) improving rangeland management;

(3) using green manures and cover crops;

(4) amending soil with straw and manures; and

(5) increasing the tree cover on agricultural or pasture lands with agroforestry.

(Pretty 1995; Drinkwater *et al*. 1998; Lal *et al*. 1998; Smith *et al*. 1998; Tilman 1998; Smith 1999; Petersen *et al*. 2000; Robertson *et al*. 2000; Sanchez & Jama 2000; USDA 2000; Pretty & Ball 2001; Robert *et al*. 2001; WCCA 2001.)

3. Methods

To assess how much carbon developing countries could prevent from entering the atmosphere (by reducing emissions) or remove from the atmosphere (by sequestration), country-specific potential areas for reforestation through natural and assisted regeneration (excluding commercial plantations), adoption of sustainable agricultural practices and avoided deforestation were estimated from a variety of sources (see below). We did not include commercial plantations in this analysis, as establishing additionality (a criteria of projects under the Kyoto Protocol) may be difficult because their area in developing countries is increasing, they produce direct financial benefits and involve practices that are well understood and may be adopted regardless of concerns for carbon (Chomitz 2000).

Data on the area and rate of adoption of forestry and agricultural practices were multiplied by estimates of the change in carbon stocks that the various land-management options produce in individual countries. Owing to data limitations, not all developing countries may yet be assessed for all types of activities. Furthermore, we did not address bio-energy, reductions in agricultural inputs, changes in soil carbon associated with averted deforestation and reforestation, or maintained sinks in protected forest.

To be consistent across mitigation options, we used low (conservative) to central estimates of carbon stock changes for any activity. This reflects that there are still relatively few studies of actual long-term carbon mitigation activities in developing countries. Some reasonable burden of proof for crediting carbon-friendly mitigation is likely to restrain reported carbon mitigation to conservative values (Sathaye *et al*. 1997). Adoption rates of various practices remain the largest source of uncertainty in our analysis. There is very little information on these estimates to conduct sensitivity analyses, so we report only central estimates here. The specifics of the analyses by mitigation option are described below.

4. Reforestation and regeneration

As far as mitigation in developing countries, planting trees is the only land-use option valid in the first commitment period (2008–2012). Under terms of the so-called 'Bonn agreement', developed nations may sponsor a limited amount of reforestation and afforestation projects in developing countries. Any carbon offsets that pass various litmus tests of credibility can be used by a sponsoring developed nation to meet its so-called Kyoto commitment. Limits were placed on the overall amount of credit that any developed country could generate to reduce atmospheric carbon. Furthermore, individual projects were limited in their size, each one only able to generate 15 kt of carbon-dioxide equivalent annually (UNFCCC 2001).

Two broad categories of projects fall under the rubric of reforestation and afforestation. Some projects rely primarily on more environmentally friendly techniques, such as assisted regeneration, agro-forestry and forest restoration, to maintain or restore the natural environment. Other projects, primarily industrial plantations, will seek to grow carbon as fast as possible. There will be a spectrum of projects within these two main camps, and the distinctions are somewhat artificial. Our results only apply to the more environmentally benign category of tree planting that includes natural regeneration, reforesting degraded lands and agro-forestry, and *not plantations*, for two primary reasons.

(1) In tropical countries, plantations are already being planted at a rate of *ca.* 1.9 million hectares per year (Brown 2000). Proving that a plantation is additional (that is, that it would not have been planted in the absence of carbon incentives) will be difficult. In contrast, there is currently very little reforestation of degraded lands, agro-forestry or accelerating natural forest regeneration.

(2) Just over half the tropical plantations are a result of converting a natural forest to a managed one (Brown 2000). This raises a host of environmental concerns as well as net carbon benefits and accounting issues. Therefore, our analysis proceeds from the premise that, while plantations may be beneficial in many instances, proving the inspiration and consequences for industrial plantations will be difficult and we do not estimate this potential.

To calculate this carbon-uptake potential for non-commercial plantation tree planting, we used data for areas of lands that could be reforested with natural and assisted regeneration from Trexler & Haugen (1995). They based the estimated areas on the amount of deforested land present at the time of the study that could be regenerated without significant inputs, an assessment of the forces impeding regeneration and the likelihood of influencing them, and expert opinions on a country's environmental priorities and foreseeable interest in promoting regeneration. Trexler & Haugen projected areas undergoing regeneration from 1990 to 2040 and we used the areas projected for the period 2000–2010. For China, we estimated the rate of natural reforestation in the future (384 000 hectares per year) could equal half of the annual plantation rates reported for the years 1989–1993 and 1994–1998 (Fang *et al.* 2001). Several studies were used to check the availability of land for forest restoration (FAO 1998; Nilsson & Schopfhauser 1995), as well as a nation-specific query of a USGS map (USGS 1997) of forest degradation. No constraints were found to limit these rates of forest recovery for a ten-year period.

Table 1. *Annual carbon mitigation and associated incomes via forest restoration for the years 2003–2012*

countries	reforestation rate (1000 ha yr^{-1})	carbon over 2003–2012 (MtC)	net present value 2003–2012 (US$ million)
Latin America			
Bolivia	5	0.7	4.8
Brazil	750	103.1	713.7
Colombia	100	13.8	95.2
Costa Rica	10	1.4	9.5
Ecuador	50	6.9	47.6
Guatemala	25	3.4	23.8
Guyana	10	1.4	9.5
Honduras	50	6.9	47.6
Mexico	500	13.8	95.2
Nicaragua	30	4.1	28.5
Panama	10	1.4	9.5
Paraguay	20	0.6	3.8
Peru	100	13.8	95.2
Venezuela	50	6.9	47.6
subtotal	**1710**	**177.9**	**1231.4**
Africa			
Angola	20	0.6	3.8
Benin	20	0.6	3.8
Botswana	3	0.1	0.5
Burkina Faso	50	0.8	5.7
Cameroon	30	4.1	28.5
Central African Rep.	2	0.3	1.9
Chad	2	0.0	0.2
Cote d'Ivoire	50	6.9	47.6
Dem. Rep. Congo	100	13.8	95.2
Ethiopia	20	1.9	13.3
Kenya	5	0.1	1.0
Madagascar	10	1.0	6.7
Mali	5	0.1	0.6
Mozambique	60	1.7	11.4
Niger	5	0.1	0.6
Nigeria	10	1.0	6.7
Senegal	25	0.4	2.9
South Africa Sudan	100	2.8	19.0
Tanzania	100	2.8	19.0
Uganda	10	1.4	9.5
Zambia	5	0.1	1.0
Zimbabwe	50	1.4	9.5
subtotal	**682**	**41.7**	**288.3**

Table 1. (*Cont.*)

countries	reforestation rate (1000 ha yr^{-1})	carbon over 2003–2012 (MtC)	net present value 2003–2012 (US$ million)
Asia			
Bangladesh	5	0.1	1.0
China	384	21.1	146.2
India	150	4.1	28.5
Indonesia	15	2.1	14.3
Laos	20	2.8	19.0
Malaysia	100	13.8	95.2
Myanmar	120	16.5	114.2
Papua New Guinea	100	13.8	95.2
Philippines	100	13.8	95.2
Thailand	50	4.8	33.3
Vietnam	25	3.4	23.8
subtotal	**1069**	**96.2**	**665.7**
grand total	**3461**	**315.8**	**2185.4**

The area undergoing regeneration was then multiplied by area-weighted estimates of the potential for carbon accumulation, rates ranging from 0.5 to 2.5 $\text{tC ha}^{-1}\ \text{yr}^{-1}$ for dry tropical regions to 2.5 to 5.0 $\text{tC ha}^{-1}\ \text{yr}^{-1}$ for humid tropical areas. These rates only consider carbon accumulation in vegetation; we did not include soil carbon, a factor that could elevate this range (Post & Kwon 2000). Appropriate rates were selected based on case studies or, where not possible, a country's general climatic profile. These rates of carbon uptake have been modified from those used by Trexler & Haugen, based on a variety of literature sources for general climatic zones and specific countries (Brown & Lugo 1982; Tomich *et al*. 1998; Uhl *et al*. 1988; Brown & Lugo 1990; Brown & Gaston 1995; Brown *et al*. 1995; Hughes *et al*. 1999; Silver *et al*. 2000; Fang *et al*. 2001). Rates of carbon accumulation are poorly known for most parts of the world and there is a considerable range in estimates. Due to many of the difficulties of establishing viable forest restoration (Reid & Rice 1997) and to account for likely monitoring and verification requirements (Sathaye *et al*. 1997), we used the lower end of the range for all countries in estimating the potential amount of carbon that could be sequestered (table 1).

We assumed that if appropriate incentives develop this year or next, countries could begin reforestation programmes in 2003. Given that reforestation programmes will create cumulative carbon benefits, a timed carbon stream was calculated and then summed for the next 10 years (table 1). Lands that are restored in 2003 (the beginning of our study period) will accumulate carbon for the full 10 years, while lands restored in 2012 will only accumulate carbon for that year.

The total amount of carbon that could be sequestered by reforestation to create native forests over the ten-year period is 316 million tonnes on 3.5 million hectares of land. The greatest potential exists in countries of Latin America (56% of the total), followed by Asia (30% of the total) and Africa (14% of the total).

Table 2. *Carbon-sequestration rates* (tC $\mathrm{ha}^{-1}\ \mathrm{yr}^{-1}$) *according to four scenarios for sustainable agricultural management*

agricultural system	low	medium	high	very high
arable	0.3	0.65	1.3	3.1
rice paddy	0.1	0.1	0.1	0.1
permanent crops/agroforestry	0.4	0.6	0.6	0.8
permanent pasture	0.3	0.5	0.7	0.9

Source: adapted from Watson *et al.* (2000) and Pretty & Ball (2001).

5. Sustainable agricultural practices

Agricultural systems contribute to carbon emissions through several mechanisms:

(1) the cultivation of soils resulting in the loss of soil organic matter;

(2) the clearing of forests to create new cropland;

(3) the direct use of fossil fuels in farm operations; and

(4) the indirect use of embodied energy in inputs that are energy intensive to manufacture.

(Reicosky *et al.* 1995; Rasmussen *et al.* 1998; Robertson *et al.* 2000; USDA 2000; Pretty & Ball 2001.)

Agriculture can also sequester carbon when organic matter accumulates in the soil, or in aboveground woody biomass used in agroforestry systems or for production of biomass for energy sources that substitute for fossil fuels. Soil organic matter, and thus carbon, can be increased to new higher equilibria with sustainable management practices. The greatest dividend comes from conversion of annual crops to agroforests, as there is a benefit from both increased soil organic carbon and the accumulation of carbon in woody biomass. Grasslands within rotations, zero-tillage (or no-till) farming, green manures and cover crops, and high amendments of straw and manures to the soil, also lead to substantial carbon sequestration.

While sustainable agricultural practices were not included in the list of carbon-mitigation techniques that could generate credits under the Kyoto Protocol, sustainable agriculture programmes will be essential for implementation of forest restoration projects. Sustainable agriculture in developing countries can lead to a decreased need for additional forest clearing, particularly those that lead to improvements in soil fertility (Sanchez & Jama 2000). For agricultural practices, we use FAO statistical data on area of arable land, permanent crops and permanent pastures for the 48 selected countries of Africa, Asia and Latin America to calculate the carbon-sequestration potential of agricultural lands. The potential area for carbon sequestration under improved sustainable agricultural practices were assessed on the basis of recent data on more than 200 sustainable agriculture projects (Pretty 1997, 1999; Pretty & Hine 2001), a range of agro-ecological zones, crop types and a range of land-area categories (table 2). As the focus of this analysis is on what sustainable methods can do to increase marginal quantities of soil and aboveground carbon, we do not take account of existing stocks of carbon, but rather the incremental gain over existing stocks.

We used four scenarios derived from a hierarchy of improved sustainable agriculture practices, and are conservative in our estimates of rates of carbon accumulation (cf. Watson *et al*. 2000; Pretty & Ball 2001). For arable, this relates to

(1) arable low—zero tillage with intensive cropping;

(2) arable medium—zero tillage with mixed rotations;

(3) arable high—zero tillage with mixed rotations, cover crops and green manures, composts; and

(4) arable very high—agroforestry plus cover crops and green manures, composts.

The following equation was used to calculate the potential annual carbon sequestration, C_{seq}, through adoption of sustainable agriculture technologies and practices,

$$C_{\mathrm{seq}} = ((A_{\mathrm{a}} - A_{\mathrm{ir}})C_{\mathrm{a}}R) + (A_{\mathrm{ir}}C_{\mathrm{i}}) + (A_{\mathrm{pt}}C_{\mathrm{pt}}R) + (A_{\mathrm{pa}}C_{\mathrm{pa}}RG_{\mathrm{r}}),$$

where

A_{a} = area under arable crops,
A_{ir} = area under irrigated rice,
A_{pt} = area under permanent crops,
A_{pa} = area under permanent pasture area,
C_{a} = annual per-hectare carbon sequestration under arable,
C_{i} = annual per-hectare carbon sequestration under irrigated rice,
C_{pt} = annual per-hectare carbon sequestration under permanent crops,
C_{pa} = annual per-hectare carbon sequestration under permanent pasture,
R = ratio to correct for agroecological zone (varying from 0.2 to 1.0),
G_{r} = ratio to correct for pasture likely to be subject to improvement (all 0.1),

with areas measured in millions of hectares and carbon-sequestration rates measured in $\mathrm{tC\ ha^{-1}\ yr^{-1}}$.

We apply an agroecological zone factor to correct carbon sequestration for climate, with the following multipliers: 1.0 for humid tropics; 0.8 for humid temperate; and 0.4 for both dry temperate and dry tropical. Some countries cross these zones, and so are allocated a factor derived from the proportion of area in each zone.

It is estimated that some 70% of grasslands worldwide are degraded, mainly due to overgrazing. Improved management can lead to carbon sequestration, particularly by improving root growth in grasses. Management practices include grazing control to maximize growth, fire management, soil improvements, varietal choice, addition of nitrogen-fixing legumes and use of permanent grasses with deep-rooting systems. We correct the data with a grassland factor to represent the proportion of permanent grasslands likely to be subject to these types of intervention. Most remote, upland and arid grasslands will not be sites for significant increases in carbon sequestration. It is assumed that technically only 10% of grasslands could be improved.

An irrigated rice factor was used to correct for the amount of irrigated rice in each country. Irrigated rice can accumulate a maximum of $0.5\ \mathrm{tC\ ha^{-1}\ yr^{-1}}$ with the use of organic matter, fertilizers and plant-residue management. We also correct for reported area of paddy rice, as this is greater than actual hectares owing to double and triple cropping. Carbon-uptake rates cannot approach those of other crops, where zero tillage, cover crops, green manures, mixed rotations and agroforestry can lead to greater annual improvements in soil organic carbon. Data on the amount of irrigated rice for each country were used to reduce the arable area subject to carbon sequestration at higher rates.

In our analyses, we do not account for a potential double benefit arising when shifting agriculturalists adopt settled sustainable agriculture methods, as this is analysed in the avoided-deforestation section. However, these two scenarios are not completely separate. If some of the 300–500 million farmers practicing shifting cultivation in and around tropical forests were to adopt sustainable agriculture using regenerative methods, and so farm permanently the same piece of land, then they would be both accumulating carbon in their soils and not cutting down and burning the forest. We also do not account for other land-use conversions that could lead to carbon sequestration or carbon emissions (such as wetland conversions).

In the aggregate analysis reported here (table 3), medium sequestration rates of carbon sequestration were used. For example, for arable land, uptake rates of $0.65\,\mathrm{tC\,ha^{-1}\,yr^{-1}}$ were used, which is considerably less than the $3.1\,\mathrm{tC\,ha^{-1}\,yr^{-1}}$ possible with agroforestry, cover crops and composts.

In the long term, all agricultural lands could theoretically adopt sustainable agriculture practices that lead to carbon sequestration at medium scenario rates. Based on data for adoption rates of sustainable agriculture practices in the past decade (Pretty 1997, 1999; Pretty & Hine 2001), we estimate that 20% of current agricultural lands could be under sustainable agriculture over the next 10 years. Some countries, such as Argentina and Brazil, may achieve this much sooner. These agricultural practices are expected to continue to sequester carbon for at least 20 years (Smith *et al*. 1998; Sanchez & Jama 2000; Pretty & Ball 2001; WCCA 2001; Batjes 2000).

The total increase in carbon stocks from improved agriculture is 420 million tonnes (table 3). For agriculture, the greatest opportunity for increased carbon stocks occurs in Asian countries, followed by Latin American and African countries.

6. Avoided deforestation

Tropical deforestation causes an estimated 20% of worldwide anthropogenic carbon emissions. As such, many scientists and non-governmental actors strongly believed that any avoided emissions from protecting tropical forests should be eligible (and thus valuable) under Kyoto carbon accounting. However, measures to protect threatened tropical forests, according to the Bonn agreement, will not be eligible carbon offsets for use in the first commitment period of the Protocol. This political decision was hotly contested, with a host of nations, groups and individuals opposed to including tropical forest conservation in the treaty and others adamantly in favour (Niles 2002).

Measures to prevent the continued deforestation in the tropics would enable and complement reforestation and sustainable agriculture in several ways. First of all, if sustainable agricultural is implemented, this will tend to decrease land pressures for converting standing forests for production. Additionally, financial incentives to

Table 3. *Annual carbon mitigation and associated incomes via sustainable agriculture for the years 2003–2012*

countries	sustainable agriculture adoption rate (Mha yr^{-1})	carbon over 2003–2012 (MtC)	net present value 2003–2012 (US$ million)
Latin America			
Bolivia	0.7	2.4	16.6
Brazil	5.1	44.8	310.4
Colombia	0.9	5.0	34.8
Costa Rica	0.1	0.5	3.2
Ecuador	0.2	1.7	11.5
Guatemala	0.1	1.4	9.8
Guyana	0.0	0.4	2.8
Honduras	0.1	1.5	10.6
Mexico	2.1	23.8	164.6
Nicaragua	0.2	2.2	15.2
Panama	0.0	0.5	3.7
Paraguay	0.5	2.3	15.6
Peru	0.6	3.1	21.6
Venezuela	0.4	3.4	23.7
subtotal	**11.0**	**93.1**	**644.1**
Africa			
Angola	1.2	2.2	15.1
Benin	0.0	1.1	7.4
Botswana	0.5	0.7	4.6
Burkina Faso	0.2	1.1	7.8
Cameroon	0.2	5.2	35.7
Central African Rep.	0.1	1.6	11.1
Chad	1.0	2.0	13.9
Cote d'Ivoire	0.4	4.6	31.7
Dem. Rep. Congo	0.5	6.4	44.2
Ethiopia	0.6	3.5	23.9
Kenya	0.5	1.8	12.1
Madagascar	0.6	1.7	11.7
Mali	0.7	2.0	14.0
Mozambique	0.9	2.0	13.5
Niger	0.3	1.7	11.8
Nigeria	1.4	9.7	66.8
Senegal	0.2	1.0	6.8
South Africa	2.0	6.3	43.8
Sudan	2.5	7.3	50.2
Tanzania	0.8	2.1	14.7
Uganda	0.2	2.4	16.9
Zambia	0.7	2.2	15.0
Zimbabwe	0.4	1.3	9.2
subtotal	**15.9**	**69.7**	**482.1**

Table 3. (*Cont.*)

countries	sustainable agriculture adoption rate (Mha yr^{-1})	carbon over 2003–2012 (MtC)	net present value 2003–2012 (US$ million)
Asia			
Bangladesh	0.3	5.3	36.9
China	11.3	84.3	583.5
India	4.5	78.2	541.3
Indonesia	0.9	21.3	147.1
Laos	0.0	0.6	4.3
Malaysia	0.2	5.1	35.5
Myanmar	0.2	7.0	48.1
Papua New Guinea	0.0	0.5	3.1
Philippines	0.3	6.7	46.5
Thailand	0.5	13.6	94.4
Vietnam	0.2	4.6	32.1
subtotal	**18.5**	**227.3**	**1572.9**
grand total	**49.6**	**420.6**	**2910.8**

conserve forests will translate into incentives for both forest restoration and sustainable agriculture. Thus, while these strategies are often referred to in discrete terms, in fact, holistic forest and land management would be a more effective way to use land practices to mitigate atmospheric carbon, while also securing a host of other secondary benefits.

For our analysis, the potential emission reductions via avoided deforestation were calculated by multiplying the most recent estimates of annual forest loss times area-weighted carbon stocks for forests in most major tropical countries (expansion of analysis by Niles (2000*a*) through addition of more countries). We assumed that deforestation rates would remain constant because there are no other reliable projections of probable forest loss, and on a global basis, gross deforestation has remained relatively constant for the past few years (FAO 1997, 2001). The one study making future projections did not show an appreciable change using various studies for the period 2000–2010 (Alcamo & Swart 1998). Data from the FAO (1999) were used to estimate forest loss with a few exceptions. For Brazil, the average of the FAO estimate and Brazil's National Institute for Space Research (INPE 2000) average rate for 1989–1998 was used to estimate deforestation rates. For the Philippines, the average of FAO and two estimates in Lasco & Pulhin (2000) were used.

Multiple data sources for carbon stocks were used for various areas including Africa (Brown & Gaston 1995), Asia (Brown *et al.* 1993) China (Ni 2001; Fang *et al.* 2001) and the Americas (FAO 2001), as well as specific modifications from other sources (Brown 1997; Masera *et al.* 1997; Fearnside 1997; Trexler & Haugen 1995; Houghton *et al.* 2000; Tomich *et al.* 1998; Nilsson & Schopfhauser 1995; Niles 2000*a*, *b*). For the 48 countries evaluated, we estimate total emissions from deforestation to be 1.3 GtC yr^{-1} (*ca.* 17% of worldwide carbon releases), a nation-specific calculation very close to other published estimates (Watson *et al.* 2000). There is still large uncertainty for many parameters needed to make accurate estimates of greenhouse gas emissions from tropical deforestation. These uncertainties include gross rates of deforestation (Mathews 2001), forest degradation (Nepstad *et al*. 1999), carbon stocks, burning efficiencies (Delmas *et al*. 1995), other gas fluxes (Alcamo & Swart 1998) and gas fluxes on lands following deforestation (Fearnside 1997). Nevertheless, in terms of total potential carbon-emission reductions, the greatest source of data uncertainty is in estimates of the ability of nations to undertake durable tropical forest conservation.

To estimate the maximum amount of deforestation that could be halted, we modified a prior study that estimated, on a decadal basis, individual countries' abilities to slow deforestation rates (Trexler & Haugen 1995). This study's estimates of possible avoided deforestation for the years 1995–2000 proved too optimistic in light of the recent assessment by the FAO (2001). This may be due to market failures for avoided carbon emissions or other ecosystem services provided by tropical forests (Kremen *et al*. 2000). Efforts to slow tropical deforestation in recent years have mostly failed and gross tropical deforestation rates have probably risen slightly in recent years to approximately 16 million hectares (FAO 2000*a*, *b*; Mathews 2001). Furthermore, widespread forest degradation remains poorly understood or quantified.

The Trexler & Haugen study is unique in that it has pan-tropical coverage and its conclusions were derived from country-specific information based on surveys of land tenure, development plans, forestry experience, political stability and other key variables. We updated several features of this seminal study, namely carbon stocks and carbon uptake rates, rates of deforestation, as well as other minor changes. We assumed that the ratio of forest destruction stopped would be equal across biomass variances, so that the percent of avoided deforestation would be the percent of avoided emissions. If all 48 countries considered carried out significant efforts to stall deforestation, we estimate a maximum of 157 million tonnes of carbon could be reduced annually (table 4). This maintenance of tropical forest ecosystems could secure tens of millions of additional tonnes in sequestered carbon over several decades from possibly CO_2 fertilization as well as other, yet unknown, causes (Phillips *et al*. 1998; Malhi & Grace 2000; Niles 2000*b*; Lugo & Brown 1992). This potential added benefit was not included in our analysis because this ecosystem service is not the result of direct human management and CO_2 fertilization remains relatively uncertain.

7. Calculation of host-country benefits

The income from any potential carbon-offset trades is difficult to predict. There is continuing uncertainty as to the fate of the Kyoto Protocol as well as critical rules for developing country participation in forest and land-use activities. As the rules for the Kyoto Protocol now stand, only certain types of forest planting will be eligible for incorporation (and thus financing) in the Protocol's framework. We estimated host-country benefits from a carbon perspective for all three mitigation categories addressed in this paper for several reasons. First, the US and other countries recalcitrant to join the Protocol may develop land-use incentives for developing countries in a parallel framework, and there is some suggestion that this is in the works (US State Department 2001). Second, it may be useful for future rounds of negotiations

Table 4. *Annual carbon mitigation and associated incomes via avoided deforestation for the years 2003–2012*

countries	annual deforestation (1000 ha yr^{-1})	deforestation halted (1000 ha yr^{-1})	carbon over 2003–2012 (MtC)	net present value 2003–2012 (US$ million)
Latin America				
Bolivia	581	116.2	133.6	1 018.4
Brazil	2 554	383.1	603.4	4 598.4
Colombia	262	52.4	52.4	399.3
Costa Rica	41	10.3	11.3	85.9
Ecuador	189	75.6	68.8	173.9
Guatemala	82	12.3	22.8	524.3
Guyana	9	0.5	0.6	4.3
Honduras	102	20.4	10.7	81.6
Mexico	508	50.8	38.1	290.4
Nicaragua	151	7.6	8.9	67.6
Panama	64	12.8	20.6	157.1
Paraguay	327	65.4	65.4	498.4
Peru	217	10.9	10.4	79.4
Venezuela	503	50.3	50.3	383.3
subtotal	**5 590**	**868.4**	**1 097.3**	**8 362.3**
Africa				
Angola	237	11.9	4.3	33.0
Benin	60	15.0	4.4	33.2
Botswana	71	7.1	0.5	3.5
Burkina Faso	32	3.2	0.5	4.1
Cameroon	129	12.9	14.0	106.7
Central African Rep.	128	12.8	12.8	97.5
Chad	94	9.4	2.0	15.4
Cote d'Ivoire	31	6.2	5.1	39.0
Dem. Rep. Congo	740	37.0	63.6	485.0
Ethiopia	62	3.1	0.8	6.1
Kenya	3	0.2	0.0	0.2
Madagascar	130	13.0	12.7	97.1
Mali	114	5.7	1.3	9.8
Mozambique	116	5.8	1.7	12.6
Niger	0	0.0	0.0	0.0
Nigeria	121	12.1	3.0	22.6
Senegal	50	10.0	1.6	12.2
South Africa	15	0.8	0.1	0.9
Sudan	353	35.3	11.3	86.1
Tanzania	323	64.6	14.5	110.8
Uganda	59	8.9	4.5	34.4
Zambia	264	26.4	6.2	47.3
Zimbabwe	50	6.0	0.4	2.7
subtotal	**3299**	**312.1**	**167.8**	**1278.5**

Table 4. (*Cont.*)

countries	annual deforestation (1000 ha yr^{-1})	deforestation halted (1000 ha yr^{-1})	carbon over 2003–2012 (MtC)	net present value 2003–2012 (US$ million)
Asia				
Bangladesh	9	0.5	0.4	3.0
China	87	13.1	4.0	30.3
India	0	0.0	0.0	0.0
Indonesia	1 084	108.4	142.0	1 082.2
Laos	148	7.4	8.3	63.2
Malaysia	400	20.0	23.1	176.0
Myanmar	387	19.4	22.3	170.3
Papua New Guinea	133	6.7	7.4	56.8
Philippines	262	26.2	29.2	222.6
Thailand	329	49.4	45.6	347.9
Vietnam	135	13.5	17.7	134.8
subtotal	**3 029**	**267.1**	**300.5**	**2 289.9**
grand total	**11 918**	**1 447.6**	**1 565.5**	**11 930.5**

to know not only the potential to manage carbon, but also the potential for developing countries to realize economic gain if carbon is used as a currency for engaging in mitigation activities.

Early carbon-exchange and trading systems have carbon-emission-reduction credit values set between US$1–38 per tonne of carbon, though most commonly in the $2.50–$5.00 range. We used a $10 per tonne of carbon value to represent a mid-level estimate of the price of carbon reductions or sequestration. While the current prices are generally between $10 and $30 per tonne of carbon, this may be due to the speculative nature of a market for worldwide carbon management.

Should a market emerge in the coming years, it is reasonable to expect that the cost of carbon would rise by a factor of two. In 1998, the then chair of the White House Council of Economic Advisors predicted that under a global system of trading, carbon would cost $14–$23 per tonne of carbon (Yellen 1998). Because many of the carbon values that we are estimating will occur in the years before any potential commitment periods for a global change treaty, we felt $10 per tonne of carbon represented a best-guess scenario for the value of a tonne reduced or sequestered in the year 2003. Furthermore, we assumed that this price would remain fixed in absolute dollars for the period of 2003–2012 and would thus decline slowly in real terms. To compute the income derived from the activities we outlined, standard net present value (NPV) procedures based on a 3% discount rate for each of the ensuing 10 years were used to calculate the total value of the income stream for various activities over the 10 years. All values reported in the above tables are in net present 2003 dollars.

Over the next 10 years, slowing tropical deforestation offers the largest potential opportunity for mitigating carbon emissions—just short of 1.6 billion tonnes (table 5). This would generate a value of about $11.9 billion over the ten-year period. The carbon-mitigating potential of adopting sustainable agriculture prac-

Table 5. *Summary of carbon mitigation and incomes via forest restoration, sustainable agriculture and avoided deforestation for the years 2003–2012*

regions	forest restoration (MtC)	sustainable agriculture (MtC)	avoided deforestation (MtC)	total carbon from all activities (MtC)	total net present value, all activities (US$ million)
Latin America	177.9	93.1	1 097.3	1 368.3	10 237.8
Africa	41.7	69.7	167.8	279.2	2 048.9
Asia	96.2	227.3	300.5	624.0	4 528.5
grand total	**315.8**	**390.1**	**1 565.6**	**2 271.5**	**16 815.2**

tices is almost 0.4 billion tonnes of carbon over the same period, with a value of about $2.8 billion. Natural forest restoration, the mitigation category allowed in the Kyoto Protocol, appears able to sequester just over 0.3 billion tonnes for a total value of around $2.1 billion. Looking at these countries, for which there were sufficient data, the largest total potential is in the 14 Latin America countries (60% of the total by carbon), followed by the 11 Asian countries (27%) and by the 23 African countries (12%).

These estimates of host-country income potentials do not consider that outside financial investment may or may not be available. The investment climate in many developing countries is, like everywhere in the world, full of risks. Realizing these incomes would necessitate a substantially greater investment in sustainable land uses than is currently the case. Currently, the developed world is spending less than half a billion dollars on sustainable forest management and biodiversity (Frumhoff *et al.* 1998). The United Nations has estimated that tens of billions of dollars annually are needed to adequately address deforestation and forest degradation (United Nations 1999).

8. Conclusions

The potential carbon-mitigation options discussed here present a practical highest limit to the amount of carbon that could be maintained in vegetation and soils or sequestered from the atmosphere with an ambitious decline in tropical deforestation and widespread implementation of carbon-friendly sustainable agriculture practices and natural forest reforestation/regeneration schemes in developing countries located in the tropical and subtropical latitudes. These estimates are not likely to represent scenarios for land management in the coming decade (cf. Black-Arbalaez *et al.* 2000) unless significant commitments to taking action to reduce the potential for climate change are made. Inertia, poverty, infrastructure, markets, institutions, competing land uses and a wide range of other factors will limit the realization of these potentials (cf. Seymour & Dubash 2000), as well as a lack of supportive national and international policy frameworks. On the other hand, our calculations take no account of the additional benefits of carbon sequestration in forest soils undergoing reforestation, increased use of biomass and reduced use of fossil-fuel inputs and reduced agricultural emissions. They also underestimate the potential carbon sequestration on sustainable agriculture with a complete package of zero tillage, green manures and agroforestry. And most important, given the recent political decisions surrounding the Kyoto Protocol, two of three categories represented here (sustainable agriculture and avoided deforestation) are not eligible for additional financing. Without markets for new behaviour and land management in developing countries, realizing these 'potentials' will almost certainly never be approached.

On balance we believe our estimates represent an upper bound for carbon mitigation in the various counties for the practices studied. More research is needed on reducing the uncertainty of, and raising the ability to meet, plausible implementation rates. In order for any of these potentials to be realized, there will need to be novel markets and effective policy mechanisms for ensuring sound implementation of land-use practices that conserve or sequester carbon. These measures will need to compensate amenable developing nations and their people for lost opportunity values that competing land uses would otherwise provide and ensure that carbon mitigation is done in an equitable and fair manner.

References

Alcamo, J. & Swart, R. 1998 Future trends of land-use emissions of major greenhouse gases. *Mitigat. Adapt. Strategies Glob. Change* **3**, 343–381.

Batjes, N. 2000 Options for increasing soil-organic matter levels in support of sustainable agriculture and carbon sequestration in West Africa: an exploratory study with special attention to three pilot sites in Senegal. In *Int. Workshop on Carbon Sequestration in Soil, Dakar, Senegal, 25–27 September 2000.*

Black-Arbalaez, T. (and 20 others) 2000 National strategy study for implementation of the CDM in Colombia: executive summary. National World Bank Strategy Studies and Ministerio del Medio Ambiente, Bogota, Colombia.

Brown, S. 1997 Estimating biomass and biomass change of tropical forests: a primer. FAO Forestry Paper no. 134. Rome: Food and Agriculture Organization.

Brown, C. 2000 The global outlook for future wood supply from forest plantations. Working Paper no. GFPOS/WP/03. Rome: Food and Agriculture Organization.

Brown, S. & Gaston, G. 1995 Use of forest inventories and geographic information systems to estimate biomass density of tropical forests: application to tropical Africa. *Environ. Monit. Assess.* **38**, 157–168.

Brown, S. & Lugo, A. E. 1982 The storage and production of organic matter in tropical forests and their role in the global carbon cycle. *Biotropica* **14**, 161–187.

Brown, S. & Lugo, A. E. 1990 Tropical secondary forests. *J. Trop. Ecol.* **6**, 1–32.

Brown, S., Iverson, L., Prasad, A. & Liu, D. 1993 Geographic distribution of carbon in biomass and soils of tropical Asian forests. *Geocarto Int.* **4**, 45–59.

Brown, S., Lenart, M. & Mo, J. 1995 Structure and organic matter dynamics of a human-impacted pine forest in a MAB reserve in subtropical China. *Biotropica* **27**, 276–289.

Brown, S., Sathaye, J., Cannell, M. & Kauppi, P. 1996 Management of forests for mitigation of greenhouse gas emissions. In *Climate change 1995: impacts, adaptations and mitigation of climate change: scientific-technical analyses* (ed. R. T. Watson, M. C. Zinyowera & R. H. Moss). Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change, pp. 773–798. Cambridge University Press.

Chomitz, K. M. 2000 *Evaluating carbon offsets from forestry and energy projects: how do they compare?* Washington, DC: Development Research Group, World Bank.

Delmas, R., Lacaux, J. & Brocard, D. 1995 Determination of biomass burning emission factors: methods and results. *Environ. Monit. Assess.* **38**, 181–204.

Drinkwater, L. E., Wagoner, P. & Sarrantonio, M. 1998 Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature* **396**, 262–265.

Fang, J., Chen, A., Peng, C., Zhao, S. & Ci, L. 2001 Change in forest biomass carbon storage in China between 1949 and 1998. *Science* **292**, 2320–2322.

Fearnside, P. 1997 Greenhouse gases from deforestation in Brazilian Amazonia: net committed emissions. *Climatic Change* **35**, 321–360.

FAO 1997 *State of the world's forests: 1997.* Rome: Food and Agriculture Organization.

FAO 1998 *Asia-Pacific forestry towards 2010. Report of the Asia-Pacific forestry sector outlook study.* Rome: Food and Agriculture Organization.

FAO 1999 *State of the world's forests: 1999.* Rome: Food and Agriculture Organization.

FAO 2000*a* Carbon sequestration options under the Clean Development Mechanism to address land degradation. World Soil Resources Reports 92. Rome: Food and Agriculture Organization.

FAO 2000*b* *Global forest resources assessment 2000.* (Available at http://www.fao.org/forestry/fo/fra/index.jsp.)

FAO 2001 *State of the world's forests: 2001.* Rome: Food and Agriculture Organization.

Frumhoff, P., Goetz, D. & Hardner, J. 1998 *Linking solutions to climate change and biodiversity loss through the Kyoto Protocol's Clean Development Mechanism.* Cambridge, MA: Union of Concerned Scientists.

Houghton, R. A., Skole, D. A., Nobre, C. A., Hackler, J. L., Lawrence, K. T. & Chomentowski, W. H. 2000 Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon. *Nature* **403**, 301–304.

Hughes, R. F., Kauffman, J. B. & Jaramillo, V. J. 1999 Biomass, carbon, and nutrient dynamics of secondary forests in a humid tropical region of Mexico. *Ecology* **80**, 1892–1907.

INPE 2000 *Monitoring of the Brazilian amazon forest by satellite.* Brazil: Instituto Nacional de Pesquisas Espacias.

Kauppi, P. & Sedjo, R. 2001 Technical and economic potential of options to enhance, maintain and manage biological carbon reservoirs and geo-engineering. In *Climate change 2001: mitigation* (ed. B. Metz, O. Davidson, R. Swart & J. Pan). Contribution of Working Group III to the Third Assessment Report of the IPCC. Cambridge University Press.

Kremen, C., Niles, J., Dalton, M., Daily, G., Ehrlich, P., Guillery, P. & Fay, J. 2000 Economic incentives of rain forest conservation across scales. *Science* **288**, 1828–1832.

Lal, R., Kimble, J. M., Follett, R. F. & Cole, C. V. 1998 *The potential of US cropland to sequester carbon and mitigate the greenhouse effect.* Chelsea, MI: Ann Arbor Press.

Lasco, R. D. & Pulhin, F. B. 2000 Forest land use change in the Philippines and climate change mitigation. *Mitigat. Adapt. Strategies Glob. Change* **5**, 81–97.

Lugo, A. E. & Brown, S. 1992 Tropical forests as sinks of atmospheric carbon. *Forest Ecol. Manag.* **54**, 239–256.

Malhi, Y. & Grace, J. 2000 Tropical forests and atmospheric carbon dioxide. *Trends Ecol. Evol.* **15**, 332–337.

Masera, O. R., Ordonez, M. J. & Dirzo, R. 1997 Carbon emissions from Mexican forests: current situation and long-term scenarios. *Climatic Change* **35**, 265–295.

Mathews, E. 2001 *Understanding the FRA: forest briefing no. 1.* Washington, DC: World Resources Institute.

Nakicenovic, N. (and 27 others) 2000 *Special report on emission scenarios.* A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Nepstad, D. (and 11 others) 1999 Large-scale impoverishment of Amazonian forest by logging fire. *Nature* **398**, 505–508.

Ni, J. 2001 Carbon storage in terrestrial ecosystems of China: estimates at different spatial resolutions and their responses to climate change. *Climatic Change* **49**, 339–358.

Niles, J. 2000*a* Preliminary estimate for 25 nations of the potential for forest conservation in the Clean Development Mechanism. Unpublished report, Stanford University, Stanford, CA.

Niles, J. 2000*b* The additional benefits of reducing carbon emissions from tropical deforestation. Morrison Institute for Population and Resource Studies, Working Paper Series, No. 0084. Stanford University, Stanford, CA.

Niles, J. 2002 Tropical forests and climate change. In *Climate change policy: a survey* (ed. S. Schneider, A. Rosencranz & J. Niles). Washington, DC: Island Press.

Niles, J. & Schwarze, R. 2001 The value of careful carbon accounting. *Climatic Change* **49**, 371–376.

Nilsson, S. & Schopfhauser, W. 1995 The carbon sequestration potential of a global afforestation program. *Climatic Change* **30**, 267–293.

Petersen, C., Drinkwater, L. E. & Wagoner, P. 2000 *The Rodale Institute's farming systems trial. The first 15 years.* Kutztown, PA: Rodale Institute.

Phillips, O. (and 10 others) 1998 Changes in the carbon balance of tropical forests: evidence from long-term plots. *Science* **282**, 439–442.

Post, W. & Kwon, K. 2000 Soil carbon sequestration and land-use change: processes and potential. *Glob. Change Biol.* **6**, 317–327.

Pretty, J. N. 1995 *Regenerating agriculture: policies and practice for sustainability and self-reliance.* London: Earthscan.

Pretty, J. N. 1997 The sustainable intensification of agriculture. *Nat. Resources Forum* **21**, 247–256.

Pretty, J. N. 1999 Can sustainable agriculture feed Africa? *Environ. Dev. Sustain.* **1**, 253–274.

Pretty, J. & Ball, A. 2001 Agricultural influences on carbon emissions and sequestration: a review of evidence and the emerging trading options. Occasional Paper 2001-03, Centre for Environment and Society, University of Essex.

Pretty, J. & Hine, R. 2001 Reducing poverty with sustainable agriculture. Final Report of Research Project. University of Essex, Colchester. (Available at http://www2.essex.ac.uk/ces.)

Rasmussen, P. E., Goulding, K. W. T., Brown, J. R., Grace, P. R., Janzen, H. H. & Körschens, M. 1998 Long term agroecosystem experiments: assessing agricultural sustainability and global change. *Science* **282**, 893–896.

Reicosky, D. C., Kemper, W. D., Langdale, G. W., Douglas, C. L. & Rasmussen, P. E. 1995 Soil organic matter changes resulting from tillage and biomass production. *J. Soil Water Conserv.* **50**, 253–261.

Reid, J. & Rice, R. 1997 Assessing natural forest management as a tool for tropical forest conservation. *Ambio* **26** 382–386.

Robert, M., Antoine, J. & Nachtergaele, F. 2001 *Carbon sequestration in soils. Proposals for land management in arid areas of the tropics.* Rome: AGLL, FAO.

Robertson, G. P., Paul, E. A. & Harwood, R. R. 2000 Greenhouse gases intensive agriculture: contributions of individual gases to radiative warming of the atmosphere. *Science* **289**, 1922.

Sanchez, P. A. & Jama, B. A. 2000 Soil fertility replenishment takes off in east Southern Africa. In *Int. Symp. on Balanced Nutrient Management Systems for the Moist Savanna and Humid Forest Zones of Africa, Cotonou, Benin, 9 October 2000.*

Sathaye, J. & Ravindranath, N. H. 1998 Climate change mitigation in the energy and forestry sectors of developing countries. *A. Rev. Energy Environ.* **23**, 387–437.

Sathaye, J., Makundi, B., Goldberg, D., Andrasko, K. & Sanchez, A. 1997 Sustainable forest management for climate change mitigation: monitoring and verification of greenhouse gases. *Mitigat. Adapt. Strategies Glob. Change* **2**, 87–339.

Seymour, F. & Dubash, N. 2000 *The right conditions: the World Bank, structural adjustment and forest policy.* Washington, DC: World Resources Institute.

Silver, W. L., Ostertag, R. & Lugo, A. E. 2000 The potential for carbon sequestration through reforestation of abandoned tropical pastural and agricultural lands. *Restor. Ecol.* **8**, 394–407.

Smith, K. A. 1999 After Kyoto protocol: can scientists make a useful contribution? *Soil Use Manag.* **15**, 71–75.

Smith, P., Powlson, D. S., Glendenning, M. J. & Smith, J. U. 1998 Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming. *Glob. Change Biol.* **4**, 679–685.

Tilman, D. 1998 The greening of the green revolution. *Nature* **396**, 211–212.

Tomich, T., Noordwijk, M., Budidarsono, S., Gillison, A., Trikurniati, K., Murdyaso, D., Stolle, F. & Fagi, A. 1998 *Alternatives to slash-and-burn in Indonesia: summary report and synthesis of phase II.* Bogor, Indonesia: ASB-Indonesia and CRIFC.

Trexler, M. & Haugen, C. 1995 *Keeping it green: tropical forestry opportunities for mitigating climate change.* Washington, DC: World Resources Institute and Environmental Protection Agency.

Uhl, C., Buschbacher, R. & Serrao, E. A. S. 1988 Abandoned pastures in eastern Amazonia I. Patterns of plant succession. *J. Ecol.* **76**, 663–681.

United Nations 1999 Matters left pending on the need for financial resources: Secretary General's Report, United Nations Commission on Sustainable Development, Intergovernmental Forum on Forests. Third Session, 3–14 May 1999. Document E/CN.17/IFF/1999/4.

UNFCCC 2001 (United Nations Framework Convention on Climate Change) *Review of the implementation of commitments and of other provisions of the Convention.* Decision FCCC/CP/2001/L.7. (Available at http://www.unfccc.int/resource/docs/cop6secpart/l07.pdf.)

USDA 2000 (US Department of Agriculture) *Growing carbon: a new crop that helps agricultural producers and the climate too.* Washington, DC: Natural Resources Conservation Service.

USGS 1997 (US Geological Survey) *The global ecosystem land cover characterization.* (Available at http://edcdaac.usgs.gov/glcc/glcc.html.)

US State Department 2001 Remarks to The Royal Institute of International Affairs Conference, Dr. Harlan L. Watson, Senior Climate Negotiator and Special Representative, US Department of State. (Available at http://www.state.gov/g/oes/climate/index.cfm?docid=5273.)

Watson, R. T., Noble, I. R., Bolin, B., Ravindranath, N. H., Verardo, D. J. & Dokken, D. J. (eds) 2000 *Land use, land-use change and forestry.* Special report to the Intergovernmental Panel on Climate Change. Cambridge University Press.

WCCA 2001 *Conservation agriculture: a worldwide challenge. World Congress on Conservation Agriculture, Madrid.* Rome: Food and Agriculture Organization.

Yellen, J. 1998 Testimony before the House Commerce Subcommittee on energy and power. (Available at http://www.state.gov/www/policy_remarks/1998/980519_yellen_climate.html.)