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Challenges to estimating carbon emissions from tropical deforestation

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Abstract

An accurate estimate of carbon fluxes associated with tropical deforestation from the last two decades is needed to balance the global carbon budget. Several studies have already estimated carbon emissions from tropical deforestation, but the estimates vary greatly and are difficult to compare due to differences in data sources, assumptions, and methodologies. In this paper, we review the different estimates and datasets, and the various challenges associated with comparing them and with accurately estimating carbon emissions from deforestation. We performed a simulation study over legal Amazonia to illustrate some of these major issues. Our analysis demonstrates the importance of considering land-cover dynamics following deforestation, including the fluxes from reclearing of secondary vegetation, the decay of product and slash pools, and the fluxes from regrowing forest. It also suggests that accurate carbon-flux estimates will need to consider historical land-cover changes for at least the previous 20 years. However, this result is highly sensitive to estimates of the partitioning of cleared carbon into instantaneous burning vs. long-timescale slash pools. We also show that carbon flux estimates based on 'committed flux' calculations, as used by a few studies, are not comparable with the 'annual balance' calculation method used by other studies.

Keywords: Amazon, carbon, deforestation, emissions, forest, historical, land-cover, land-use, model, tropical

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Introduction

Deforestation and other land-cover changes typically release carbon from the terrestrial biosphere to the atmosphere as CO_2 (carbon dioxide), while recovering vegetation in abandoned agricultural or logged land removes CO_2 from the atmosphere and sequesters it in vegetation biomass and soil carbon. Emissions from land-use and land-cover change are perhaps the most uncertain component of the global carbon cycle, with enormous implications for balancing the present-day carbon budget and predicting the future evolution of climate change. Over the last two decades, Houghton and colleagues (Houghton *et al*., 1983, 1985; Houghton, 1999, 2003a) have compiled land-cover change information from various national inventory records and used them, within a carbon-cycle model, to estimate global carbon emissions of $2.2\,\mathrm{Pg\,C\,yr^{-1}}$ in the 1990s (compared with $6.4\,\mathrm{Pg\,C\,yr^{-1}}$ from fossil-fuel emissions) and a total release of 156 PgC over the 1850–2000 period (compared with 283 Pg C from fossil-fuel emissions). The average carbon emissions from land-cover change in the 1990s is of the same order of magnitude as the residual carbon sink (Prentice *et al*., 2001), thereby highlighting the importance of accurately estimating land-use carbon emissions for balancing the global carbon budget.

Recently, several new estimates of carbon emissions from land-cover change have emerged (Table 1; Fig. 1).

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Table 1 Estimates of carbon emissions from land-cover change

Study	1980s ($Pg\,C\,yr^{-1}$)	1990s ($Pg\,C\,yr^{-1}$)	Data source for land-cover change	Spatial coverage and resolution	Land-cover change before 1980s included?	Carbon cycle model
Houghton (2003a)	2.0	2.2	FAO Forest Resources Assessment, and other land-cover inventory	Global, 9 regions	Yes	Book-keeping model
Fearnside (2000)	2.4	–	FAO Forest Resources Assessment, and other land-cover inventory	Pan-tropics, 6 regions	No. Used a "committed flux" estimate.	Book-keeping model
McGuire *et al.* (2001)	0.9–1.6*	–	Cropland inventory	Global, spatially-explicit	Yes	Ecosystem models
DeFries *et al.* (2002)	0.6 (0.3–0.8)	0.9 (0.5–1.4)	AVHRR deforestation, based on percent tree cover change	Pan-tropics, spatially-explicit	No	Book-keeping model
Achard *et al.* (2004)	–	1.1 ± 0.3	Landsat deforestation from TREES project for humid tropics; FAO Remote Sensing Analysis for dry tropics (FAO, 2001b)	Pan-tropics, estimates for 3 tropical regions based on sample of 30 m scenes	No, but used a 10-year "committed flux" estimate as a proxy.	Book-keeping model

*McGuire *et al.* (2001) estimated carbon emissions from cropland change of 0.6–1 $Pg\,C\,yr^{-1}$. To include the influence of other land-use changes, we scaled this estimate by 61% – the ratio of cropland emissions to total land-cover change emissions in the 1980s as estimated by Houghton (2003a) – to derive total land-cover change emissions, as in House *et al.* (2003).

Fearnside (2000) estimated that tropical land-cover changes resulted in a net emission of 2.4 $Pg\,C\,yr^{-1}$ during the 1981–1990 period. McGuire *et al.* (2001) and the Carbon Cycle Model Linkage Project (CCMLP), based on the historical cropland change dataset of Ramankutty & Foley (1999) that is largely based on national and subnational land-cover inventory data, estimated that the global establishment and abandonment of croplands released 0.6–1 $Pg\,C\,yr^{-1}$ in the 1980s (we scale up by 61% to estimate emissions from all land-cover changes of 0.9–1.6 $Pg\,C\,yr^{-1}$; see Table 1). More recently, DeFries *et al.* (2002) and Achard *et al.* (2002, 2004) have used remotely sensed tropical deforestation data (from the Advanced Very High Resolution Radiometer, AVHRR, and Landsat TM, respectively) to estimate releases of 0.3–0.8 $Pg\,C\,yr^{-1}$ in the 1980s and 0.5–1.4 $Pg\,C\,yr^{-1}$ in the 1990s (Table 1; Fig. 1). These satellite-based estimates and the CCMLP study suggested that Houghton and colleagues and Fearnside (2000) have overestimated carbon emissions from land-cover change by up to a factor of two, mainly because of different estimates of the rates of tropical deforestation (DeFries & Achard 2002; House *et al.*, 2003).

However, these five different studies are not directly comparable. The studies covered different geographic ranges and time periods, considered different types of land-cover changes, made different assumptions about historical land-cover change, and used different carbon cycle models (Table 1). For example, the McGuire *et al.* (2001) and Houghton (2003a) estimates were global, while Fearnside (2000), DeFries *et al.* (2002) and Achard *et al.* (2002, 2004) estimates covered the tropics alone[1]. However, this difference in the geographic domain may be reconcilable because the vast majority of rapid land-cover changes in the 1980s and 1990s are believed to have occurred in the tropics (Lepers *et al.*, 2005).

Another key difference in these studies lies in their treatment of carbon emissions. Houghton (2003a) and McGuire *et al.* (2001) estimated contemporary carbon fluxes ('annual balance' estimate) including the full time trajectory of historical land-cover changes and 'inherited' carbon fluxes. Fearnside (2000), on the other hand, excluded historical land-cover changes, but used a 'committed flux' estimate (as opposed to annual balance) for 1980s deforestation that accounted for all the carbon fluxes from then until a new equilibrium landscape was established in the future (see Fearnside (1997) for a detailed explanation of the difference between annual balance and committed flux estimates). DeFries

[1]Note that the Achard *et al.* (2002) study only covered the humid tropics; however Achard *et al.* (2004) calculated carbon emissions for the entire tropics using deforestation estimates for the dry tropics from the FAO remote sensing analysis (FAO, 2001b)

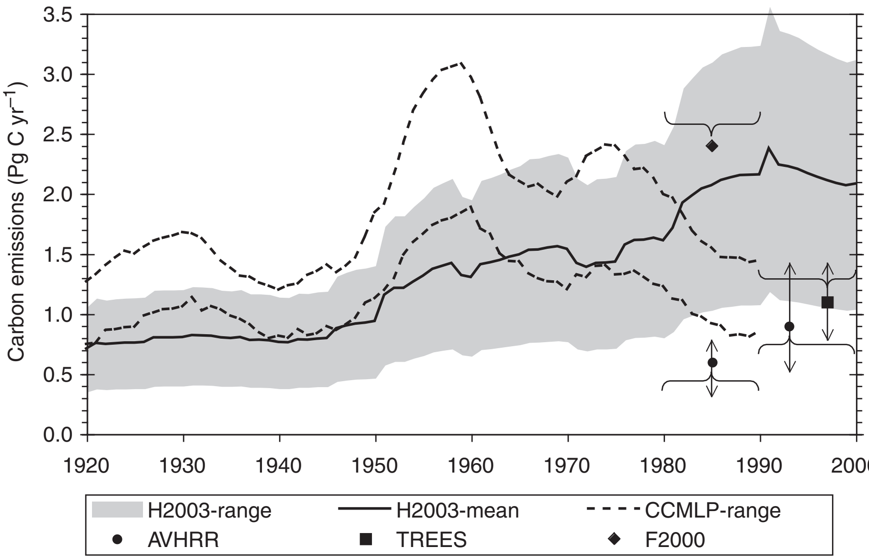

Fig. 1 Intercomparison of five different estimates of carbon emissions from global land-cover change. The Houghton (2003a; H2003) and McGuire *et al.* (2001; Carbon Cycle Model Linkage Project; CCMLP) estimates were global, while the DeFries *et al.* (2002; AVHRR), Achard *et al.* (2004; TREES), and Fearnside (2000; F2000) studies were pan-tropical. H2003 and CCMLP estimated annual values, while the other three studies estimated decadal averages.

et al. (2002) also excluded the influence of land-cover changes before the 1980s, while Achard *et al.* (2002, 2004) used a 10-year 'committed flux' estimate as a proxy for past land-cover changes. Another difference among these studies centers around their treatment of terrestrial ecosystem processes: CCMLP study used process-based global ecosystem models, while the other four studies used 'book-keeping' terrestrial carbon cycle models.

The studies also differed in their consideration of land-use practices. While Houghton (2003a) and Fearnside (2000) considered several different types of land-cover change (deforestation, cropland establishment and abandonment, shifting cultivation, logging and forest degradation), McGuire *et al.* (2001) only considered the establishment and abandonment of croplands, DeFries *et al.* (2002) focused on deforestation and regrowth, and Achard *et al.* (2002, 2004) estimated tropical deforestation, degradation, and regrowth. However, while DeFries *et al.* (2002) and Achard *et al.* (2002, 2004) estimated regrowth occurring in the 1980s and 1990s, Fearnside (2000) only considered land-cover change initiated in the 1980s and its consequence for landscape change in the future, and excluded any regrowth that might have occurred from previous land-use history.

Here, we suggest that while there are now five different estimates of carbon emissions from tropical deforestation, a simple comparison of the estimates does not encompass the full range of uncertainty regarding land-cover change emissions of carbon (see also Houghton 2003b). The five studies have used different land-cover datasets, covered different domains and time periods, and different methods to compute carbon fluxes, and are, therefore, not strictly comparable (Table 1). In addition to these five studies, two other recent studies (Cramer *et al.* 2004, Jain & Yang, 2005) have estimated carbon emissions from land-use change using some combination of the same datasets as the earlier five studies, but different carbon models. We, therefore, do not consider those studies further. In this paper, we explore some of the key issues related to the estimation of carbon emissions from tropical deforestation and perform a case-study simulation over the legal Amazon to illustrate some of these concepts.

Elements of a full analysis of carbon emissions from tropical deforestation

A complete analysis of carbon emissions from tropical deforestation involves the quantification of several key elements, including rates and dynamics of land-cover change, initial stock of carbon in vegetation and soils, mode of clearing and fate of cleared carbon, response of soils following land-cover change, influence of historical land-cover legacies, and finally the representation of processes in the models used to integrate all of these elements. We discuss each of these elements in turn, and uncertainties in our state of the knowledge.

Deforestation rates

Estimating deforestation is complicated by the fact that there are more than 90 different definitions of forest being used around the world (Lepers *et al*. 2005). The Food and Agriculture Organization's (FAO) definition of forest, which is the most widely used, includes natural forests and forest plantations with tree canopy cover greater than 10%. Most definitions concur that deforestation is the conversion of forest to another land cover, or the reduction in tree canopy cover below the 10% threshold. Sometimes, large-scale deforestation can occur from an event unrelated to land use (e.g. exceptional Indonesian fires in 1997–1998), and potentially followed by salvaging of the standing dead vegetation. Such events are not considered deforestation events, but there is the possibility of confusion in observations.

The five studies discussed here used different types of deforestation data and accordingly had different definitions (Table 1). Houghton (2003) (H2003 hereafter) estimated land-cover change in the 1980s and 1990s using country-level deforestation statistics from the FAO Forest Resources Assessment (FAO, 2001a) (hereafter FRA), and therefore followed the FAO definition of deforestation. Fearnside (2000; F2000 hereafter) also used the FRA to estimate land clearing for the 1980s (and other sources for the Brazilian Amazon alone). However, the FRA data are essentially a compilation of reports from individual nations and have been criticized for lack of consistency between countries and between assessments (Grainger, 1996; Matthews, 2001). McGuire *et al*. (2001) (CCMLP hereafter) did not directly estimate deforestation, but rather inferred changes in land cover from the expansion or abandonment of croplands derived from FAO's FAOSTAT agricultural statistics database and other subnational statistics (Ramankutty & Foley, 1999; FAO, 2004). The studies of DeFries *et al*. (2002) (AVHRR hereafter) and Achard *et al*. (2002, 2004) (TREES hereafter) estimated deforestation rates using satellite remote sensing. The AVHRR study estimated deforestation to occur when the change in percent tree cover of an 8 km pixel exceeded a threshold of 14%. The TREES study defined deforestation as the conversion of forests (closed, open, or fragmented forests, plantations, and forest regrowths) to nonforest lands (mosaics, natural nonforest such as shrubs or savannas, agriculture, and nonvegetated). TREES estimated deforestation rates only for the humid tropics (corresponds closely with the FAO definition of 'closed broadleaved forest', FAO 2001a), but Achard *et al*. (2004) extended this to the entire tropics by using the deforestation rates estimated for the dry tropics by the FAO Remote Sensing Survey (FAO, 2001b).

Estimates of deforestation rates vary greatly (Table 2). For example, FRA's estimates of deforestation rates for the 1990s were 23% higher than the TREES estimate for the humid tropics and 62% higher than the AVHRR estimate for the entire tropics (for an intercomparison, see DeFries & Achard, 2002). Both the AVHRR and TREES estimates are 30% lower than FRA even after excluding dry tropical Africa, where the data is most uncertain and the divergence in estimates the greatest (Houghton & Goodale, 2004). Indeed, FAO's Remote Sensing Survey also suggests that the FRA (country data) estimates may be too high in tropical Africa particularly for certain countries (e.g. Sudan and Zambia), but also points out the difficulty of remote sensing analysis in the dry tropics (FAO, 2001b). The two pantropical estimates covering both the 1980s and 1990s also identify different trends in deforestation rates. The AVHRR estimate indicates that deforestation rates increased between the 1980s and 1990s (Table 2) while the FRA estimate indicates a decrease (FAO, 2001a).

Table 2 Comparison of different estimates of tropical deforestation rates

	All tropics (Mha yr^{-1})			Humid tropics (Mha yr^{-1})	
	FAO Country Survey	AVHRR	FAO Remote Sensing	FAO Country Survey	TREES*
Net forest change in the 1990s					
Tropical Asia	−2.4	−2.0	−2.0	−2.5	−2.0
Tropical Africa	−5.2	−0.4	−2.2	−1.2	−0.7
Tropical Latin America	−4.4	−3.2	−4.1	−2.7	−2.2
Pantropics	−12.0	−5.6	−8.3	−6.4	−4.9
Net forest change in the 1980s					
Tropical Asia	−2.4	−1.2			
Tropical Africa	−3.9	−0.3			
Tropical Latin America	−7.1	−3.6			
Pantropics	−13.4	−5.1			

*This refers to the Achard *et al*. (2002) study. Achard *et al*. (2004) used the same values for the humid tropics, and the FAO Remote Sensing data for the entire tropics.

Land-cover dynamics following deforestation

To accurately estimate carbon fluxes from land-cover change, it is also critical to understand the land-cover dynamics following deforestation (Figs 2 and 3). Depending on the fate of the land following the initial clearing, biomass of vegetation can remain at a much lower level than in the primary forest that was cleared (in the case of permanent agriculture), or remain at some intermediate level associated with a secondary forest (in the case of shifting cultivation), or accumulate back to nearly the same level as before deforestation (in the case of agricultural abandonment and regrowth, or logging and regrowth). Consequently, it is important to track the extent and age of regrowing vegetation on deforested land.

Tracking the fate of cleared land at the global scale is exceptionally challenging. To do so requires observations at high spatial and temporal resolutions, detailed classification schemes, and careful change detection, in order to be able to separate *gross* deforestation from *net* deforestation (allow regrowing secondary forests and plantations to offset gross rates of clearing). Indeed, the five studies discussed in this paper have not fully considered the impact of land-cover dynamics following deforestation in estimating carbon emissions. The AVHRR study was not able to fully separate gross from net deforestation due to the 8 km spatial resolution and inherent problems with the AVHHR sensor (e.g. geolocation errors, intersensor calibration) (Agbu & James, 1994). The CCMLP, H2003, and F2000 studies relied on national and subnational statistics that aggregate change over large regions, and thus also likely underestimated the transitions between forest, agricultural land, and secondary regrowth. The TREES study, based on carefully classified Landsat imagery (30 m spatial resolution), and separated by 7 years in time (1990–1997) provides the most comprehensive observations of land-cover dynamics associated with tropical deforestation. However, it only covers the humid tropics and does not provide 'wall-to-wall' coverage as it is based on a sampling scheme.

Another important issue to consider is the reclearing of secondary vegetation. Deforested land in the tropics often enters a fallow-cropping cycle, where land is cultivated for a few years, abandoned, and then allowed to regrow into fallow or secondary vegetation which is often recleared. Secondary fallows may be cleared several times during a typical fallow-cropping cycle. In the Brazilian Amazon, for example, the reclearing rates of secondary forest may rival the primary forest clearing rates (Hirsch *et al.*, 2004). Steininger (2004) also estimated significant carbon emissions from the reclearing of secondary forests in the Amazon.

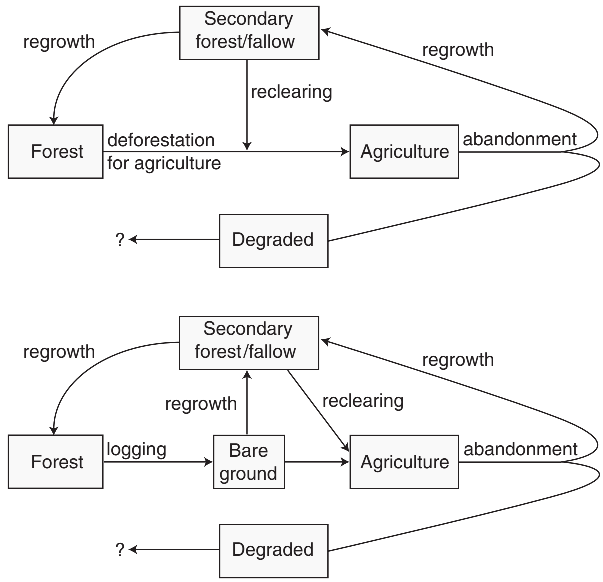

Fig. 2 Land-cover dynamics following forest clearing or logging. Land-cover transitions between agriculture, secondary forest, degraded land, and other land uses. It is critical to know how much land is put to the different uses, and how long it remains in those uses.

Vegetation and soil carbon stocks

Uncertainty in vegetation carbon stocks is a less appreciated source of error in estimates of the carbon emissions from land-cover change (Houghton, 2005). The five studies used varying estimates of initial vegetation biomass, and this partly contributes to differences in carbon emissions (see Table 3). In particular, while the AVHRR and H2003 studies used identical biomass estimates (Houghton, 2005), TREES and F2000 used different values, and CCMLP used model-simulated biomass (that were not reported in the McGuire *et al.*, 2001 study). Achard *et al.* (2004) and Houghton (2005) explicitly considered the implications of uncertainty in biomass for estimates of carbon emissions. Indeed, uncertainty in biomass estimates has been a key source of disagreement regarding estimates of carbon emissions from tropical deforestation (Eva *et al.*, 2003, Fearnside & Laurance, 2003, 2004). Further, estimates of the spatial distribution of soil carbon stocks is even more uncertain than biomass, and both of these critical components of the terrestrial carbon budget need to be better characterized (see Houghton *et al.* 2001; Houghton 2005 for reviews).

Mode of clearing and fate of cleared carbon

To accurately estimate the transient behavior of carbon emissions from land-cover change, it is important to

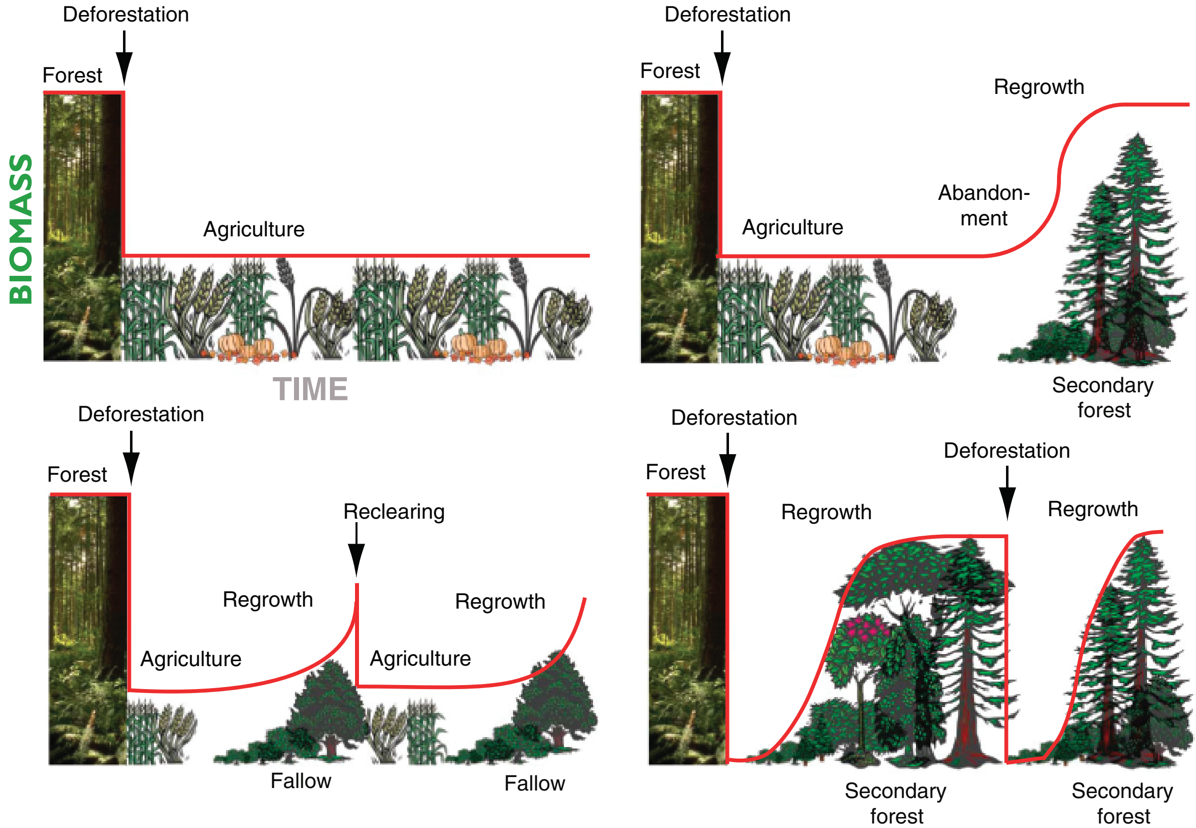

Fig. 3 Different pathways of carbon dynamics following deforestation. Depending on the land-use practices following deforestation, vegetation carbon can either remain at a lower level, or re-accumulate if the land is abandoned and allowed to regrow back into a forest.

understand the method of land clearing. For example, if deforestation occurs through slash and burn, most of the carbon is released to the atmosphere within a year during the burning process, while if deforestation occurs through clearcut or selective logging, most of the useful wood is removed offsite and is used to make products such as paper, furniture, and other wood products which oxidize over much longer timescales.

H2003 used a book-keeping model to track the fate of carbon following deforestation. According to this model, a certain fraction of the biomass is burned during clearing, another fraction is left on site and decays in the soil, and the remaining portion is removed offsite. The removed biomass is partitioned into various product pools that decay at 1-, 10-, 100- and 1000-year timescales (H2003 uses different parameters for each of the nine regions). The CCMLP study, AVHRR, and TREES, all used similar formulations as H2003 for considering the fate of carbon following deforestation. Therefore, the differences between these four estimates are not likely a result of this factor. However, quantitative estimates of the mode of clearing and the fate of products are not easily available. For example, significant uncertainties persist regarding estimates of how much carbon is burnt at the time of clearing, or in subsequent years (Fearnside, 2000). Therefore, the fact that all four studies adopted similar formulations does not imply consensus, but rather a lack of alternatives. F2000 implicitly accounts for the carbon emissions from fuelwood removal and charcoal formation by using biomass values that are not reduced to reflect the removal of these products. Moreover, the committed flux estimate used by F2000 implicitly accounts for the time dynamics of carbon fluxes into the future until a replacement equilibrium landscape is achieved.

Response of soil carbon

Typically, right after deforestation, soil carbon stock increases for a short while from the incorporation of the slash left from clearing (Houghton *et al*., 1983). However, soil carbon stock soon decreases because the litter input to the soil is typically lower in deforested land (although in some cases, soil carbon stocks can increase; see review by Murty *et al*., 2002). This decrease continues for a couple of years to decades, and, depending on the land-use practice on the deforested land,

Table 3 Comparison of biomass* estimates used by the five studies

Forest type or region†	AVHRR/H2003‡	F2000§	TREES¶ Humid forest	TREES¶ Non-TREES domain
Latin America				
By region				
Central America & Caribbean	–	87	103–155 (129)‖	38–56 (47)
Pan-Amazon	–	166		
Brazilian Amazon	–	217**	149–223 (186)	
By forest type				
Tropical equatorial forest	200	–	–	–
Tropical seasonal forest	140	–	–	–
Warm coniferous forest	168	–	–	–
Temperate broadleaved forest	100	–	–	–
Tropical woodland	55	–	–	–
Sub-Saharan Africa				
All forests	–	112	115–171 (143)††	29–43 (36)‡‡
Closed forest	136	–	–	–
Open forest	30	–	–	–
Tropical Asia				
All forests	–	164	121–181 (151)§§	
Tropical moist forest	250	–	–	–
Tropical seasonal forest	150	–	–	–

*Estimates of above- and belowground forest biomass (Mg Cha^{-1}); Carbon content of original biomass assumed to be 0.50.

†The AVHRR & H2003 studies distinguished between different forest types, but did not consider subregions, while TREES distinguished between humid and nonhumid (non-TREES domain) forests, whereas F2000 distinguished biomass only by subregions and not forest type.

‡Used values from Houghton *et al.* (2001).

§Used values from FAO (1993). FAO biomass data refer only to aboveground portions of live trees $\geq$10 cm DBH (Brown, 1997, p. 4). Corrections for omitted components applied to all countries (from Fearnside, 1994): vines = +5.3%, other nontree components = +0.2% and trees <10 cm DBH = +12.0%. Belowground percentage assumed same as Amazonian forest, or 33.6% of aboveground live biomass (Fearnside, 1994).

¶This is from the Achard *et al.* (2004) study. Used values from Brown (1997) and increased them by 20% to account for belowground biomass; uncertainty range was generated as ±20% around the mean values shown in parentheses.

‖Excludes the Atlantic forests of Brazil.

**Additional corrections applied to Brazilian data: +15.6% for form factor, +3.6% for trees 30.0–31.8 cm DBH, –6.6% for hollow trees, –0.9% for bark, and +2.4% for palms (Fearnside, 1994).

††Value for tropical moist Africa, including Guineo-Congolian zone and Madagascar.

‡‡Largely dry tropical forest.

§§The TREES domain for this region also includes dry tropical biome of continental Southeast Asia in addition to the humid tropical biome.

ultimately comes to a balance with the new litter inputs. If the land is abandoned and the forest regrows, the soil carbon stock can build up again back to the original level, taking several decades to achieve a new equilibrium. Full recovery of soil carbon stocks following deforestation depends on the length of time allowed for recovery and intensity of land use.

All five studies accounted for changes in soil carbon associated with land-cover change. However, the CCMLP study used process-based ecosystem models to simulate changes in soil carbon, while three studies (H2003, TREES, and AVHRR) used the book-keeping model of H2003 with *a priori* prescribed soil response curves, and F2000 calculated the total committed flux from soil carbon change. The process-based models are able to account for climate controls on decomposition rates through the different years, while book-keeping models prescribe these as invariant functions. It is not clear whether any of the differences seen in Fig. 1 are a result of these differences in soil carbon models. Indeed, a recent study by Jain & Yang (2005) indicated that differences in models were not the main cause for the differences between CCMLP and H2003 studies; Jain & Yang (2005) used an identical ecosystem model forced with the CCMLP and H2003 land-use data and obtained different emissions.

Incorporating historical land-cover change

Historical land-cover changes continue to influence carbon fluxes today due to the response of long-time-scale pools of carbon. The delayed release of carbon from product and slash pools that have resulted from earlier deforestation, or the continued uptake of carbon in the vegetation and soils within secondary forests, results in 'inherited' carbon emissions or uptake that influences the present-day carbon budget. For example, recovering forests in the eastern United States are estimated to be a major portion of the present-day carbon budget for that region (Caspersen *et al*., 2000, Pacala *et al*., 2001). Therefore, it is critical to include historical land-cover changes while estimating carbon fluxes.

H2003 and CCMLP explicitly accounted for historical land-cover changes in their studies. The AVHRR study did not consider the influence of land-cover changes before the 1980s in their study; they assumed that carbon stocks were in equilibrium in 1980. F2000 did not account for inherited carbon flux, but estimated a 'committed flux' from land-cover change in the 1980s, which is the 'long-term net result of converting a given area of forest to the equilibrium landscape that will eventually replace it.' This estimate represents the present and future carbon emissions committed to the atmosphere from land-cover change in the 1980s. However, such an estimate is not comparable with the annual carbon balance for the 1980s (what the atmosphere actually sees in the 1980s). The TREES study used a 10-year committed flux estimate as a proxy for historical changes, suggesting that a 10-year window would be comparable with the actual carbon balance in the 1980s. They interpreted their committed flux as a moving-average window that can be considered to be either backward looking or forward looking, and over which deforestation and regrowth rates are assumed to be the same as present-day. Whether the committed flux is an adequate proxy for historical fluxes and comparable with annual balance depends on the nature of the historical land-cover changes, and therefore, should be used with great caution. It may, however, be an improvement over assuming no historical land-cover changes at all. We will illustrate the utility of the committed flux estimate later using Amazonia as an example.

Carbon cycle model

All studies estimating carbon emissions from land-cover change at the regional-to-global scale utilize models (often simple spreadsheets) to integrate information, and to predict the spatial and temporal trajectories of carbon fluxes. While the rates of land-cover change, and initial stocks of carbon are prescribed, the models predict the fate of vegetation carbon stocks if the land is abandoned and vegetation regrows, the dynamics of soil carbon, and the fate of carbon removed off-site. These carbon dynamics, especially that of vegetation and soil carbon, can be predicted either using process-based ecosystem models or can be prescribed *a priori* based on observations as done in book-keeping models. The process-based ecosystem models can account for nonlinearities in carbon dynamics, most significantly the climate controls on decomposition processes, that are considered unvarying in the book-keeping models.

The CCMLP study used spatially explicit process-based ecosystem models to simulate carbon dynamics associated with land-cover change (although CCMLP also used a book-keeping model to predict the fate of carbon removed offsite), while the AVHRR and TREES studies used the book-keeping model of H2003. The AVHRR study applied the book-keeping model in a spatially explicit fashion, while TREES and H2003 applied the model over large regions assuming quantities such as biomass and soil carbon stocks, as well as the land-cover changes, to be homogenous within the regions. F2000 did not perform a time-dependent calculation, but rather estimated committed fluxes. The ramification of these differences in models is not obvious, although House *et al*. (2003), comparing the CCMLP study with H2003, found that the CCMLP carbon fluxes followed land-conversion rates with a lag of about 5 years, while H2003 showed some long-term memory, whereby carbon emissions continued to go up after land-conversion rates stabilized. This difference might result from differences in the carbon cycle models, especially the response of the long-term soil carbon pools. However, as mentioned earlier, Jain & Yang (2005) indicated that differences in models were not the main cause for the differences between CCMLP and H2003 studies.

Illustration – carbon emissions from land-cover change in the Amazon

We perform a simulation study over legal Amazonia to illustrate some of the key issues related to estimating carbon emissions from land-cover change that were highlighted in previous sections. We derive annual deforestation rates from the PRODES database, the Brazilian Space Agency's (INPE) Landsat analysis for 1989–2003 (Fig. 4, INPE, 2000). INPE also provides a decadal-mean estimate of deforestation for 1978–1988. Also, from Tardin *et al*. (1980; as cited in Fearnside, 1982), we obtain cumulative deforested areas of

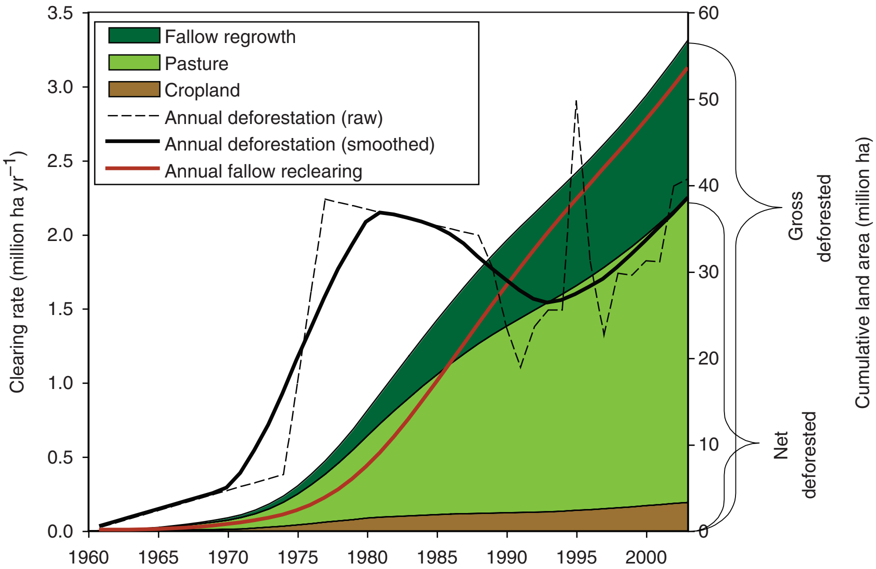

Fig. 4 Deforestation and fallow reclearing rates in the legal Amazon from 1961–2003 (primary *y*-axis); and land-cover transitions following deforestation estimated by a Markov transition model (cumulative values shown on secondary *y*-axis).

28 595 km^2 by 1975 and 77 172 km^2 by 1978. Using these estimates, we estimate annual deforestation rates during the 1961–1988 period by interpolation, assuming deforestation rates to be zero before 1961, and assuming linear growth in deforestation rates during 1961–1974, 1975–1977, and 1978–1988. We also smooth the estimated annual deforestation rates because we are interested in the long-term trends, and not interannual variability (Fig. 4).

INPE only provides estimates of *gross* deforestation (i.e. initial clearing of mature forest, INPE, 2000). To understand the land-cover dynamics following deforestation, we developed a land-cover transition model. We adapted the Markov matrix of land-cover transition probabilities developed by Fearnside (1996), to predict transitions between primary forest, cropland, pasture, and fallow or secondary forest [e.g. Cardille & Foley, 2003; see Appendix A1]. The model predicts that of the total deforested land over the 1961–2003 period, roughly 6% remains in croplands, 62% remains in pastures, but almost 32% of the deforested land is in regrowing vegetation (Fig. 4). The resulting areas of agricultural land are roughly consistent with the agricultural census data from IBGE (the Brazilian Institute of National Statistics and Geography), and the proportion of regrowing forests is consistent with the study of Houghton *et al*. (2000). The model simulation also estimates that the annual rate of clearing of secondary vegetation exceeds the deforestation rates after 1990; this high rate of secondary vegetation reclearing is consistent with other studies in the Amazon (Hirsch *et al*., 2004; Steininger, 2004). However, this reclearing is mostly of young fallow vegetation representing lower biomass clearing, rather than the higher biomass of mature forest. Whether this reclearing can be observed depends on the observation method: INPE Landsat analysis observes the initial clearing of mature forest, but does not revisit that location in future analysis and therefore will not estimate reclearing (Hirsch *et al*., 2004), while the AVHRR and TREES analysis do not distinguish between the clearing of mature and secondary forests.

To estimate the flux of carbon associated with the land-cover dynamics in Fig. 4, we built a simple bookkeeping carbon cycle model for legal Amazonia, similar to that of Houghton *et al*. (2000; see Appendix A2). This model predicts annual carbon balances from land-cover change through time. Our results are similar to those presented in Houghton *et al*. (2000) (Fig. 6a). The instantaneous burnt flux varies from year to year depending on the annual deforestation and fallow reclearing rates. The regrowth flux is small initially, and of opposite sign, but increases over time and attains the same magnitude as the burnt flux toward the end of the time period. But the greatest annual flux toward the end of the time period results from the decay of accumulated products and slash in the soil (but mostly the slash pool, into which 70% of the initial cleared carbon is allocated). Indeed, during the 1990s in the Amazon, the results indicate that the magnitude of the net flux is mostly determined by the magnitude of the product and slash decay flux. The flux from regrowing vegeta-

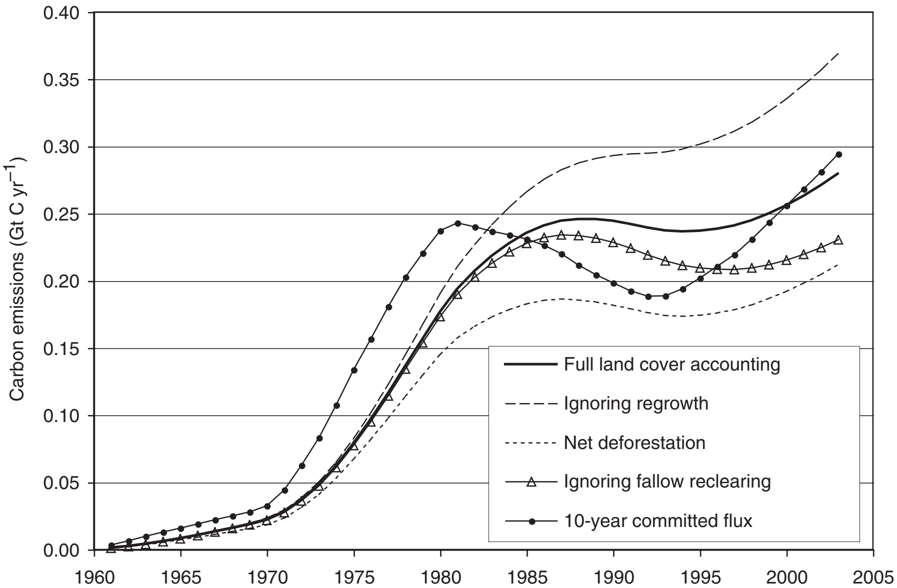

Fig. 5 The influence of different assumptions/methods on estimated carbon fluxes from the land-cover changes in Fig. 4.

tion also accumulates to attain the same magnitude (but opposite sign) as the burnt flux. This result highlights the importance of considering the fate of deforested land, the slash and products resulting from the clearing, and *historical* changes in land cover because the products and slash are a result of accumulated carbon from past land-cover changes.

We performed some additional sensitivity experiments using our book-keeping model. To evaluate the error in carbon flux estimates that would result from ignoring the full land-cover dynamics following deforestation (Fig. 5), we performed simulations ignoring regrowth, and assuming that regrowing vegetation instantaneously attain equilibrium carbon stocks (labeled net deforestation in Fig. 5). As anticipated, the estimate based on net deforestation (like the CCMLP study which inferred deforestation based on changes in agricultural land) underestimates the actual carbon emissions because it may take up to 100–150 years for regenerating forests to attain the 'equilibrium' biomass of mature forests (Brown & Lugo, 1990). On the other hand, an estimate based on gross deforestation alone would overestimate carbon fluxes by neglecting the accumulation of carbon in regrowing vegetation.

We performed another simulation where we ignored the release of carbon from the reclearing of fallow or secondary vegetation; this assumption, where the regrowth is accounted for but reclearing is not, also underestimates carbon emissions (by 17% toward the end of the simulation in 2003 and average of 12% in the 1990s). Note that while the fallow reclearing rates exceed the deforestation rates after 1990 (Fig. 4), the carbon emissions from reclearing are much lower because the biomass of recleared secondary vegetation is much smaller than that of primary forest.

Next, we compared committed-flux calculations with the annual carbon balance approach. The estimate based on 10-year committed flux misses some of the long-term dynamics in carbon fluxes related to the release from slash and product pools. In general, the committed flux estimate overestimates carbon emissions when deforestation rates are going up, and underestimates emissions when deforestation rates are decreasing. This suggests that the committed flux calculations are not directly comparable with the annual-balance calculations. F2000 estimated an equilibrium committed flux, which calculates carbon flux commitments far into the future until an equilibrium landscape is established, and therefore likely overestimates carbon fluxes.

Finally, we did an experiment to explicitly evaluate the role of historical land-cover changes in present-day carbon budgets (Fig. 6b). To do so, we reran the model to calculate annual carbon balances starting from equilibrium in 1981, and again in 1991 (ignoring all carbon fluxes and activity before those dates). The results clearly indicate that historical land-cover changes have a large impact on the 1980s and 1990s carbon fluxes in Amazonia. The simulations show that neglecting land-cover change before 1980 underestimates the 1980s carbon fluxes by $\sim$38%, and the 1990s fluxes by $\sim$13%. Starting calculations in 1991 greatly underestimates the 1990s carbon fluxes, by $\sim$62%. Again, this is a

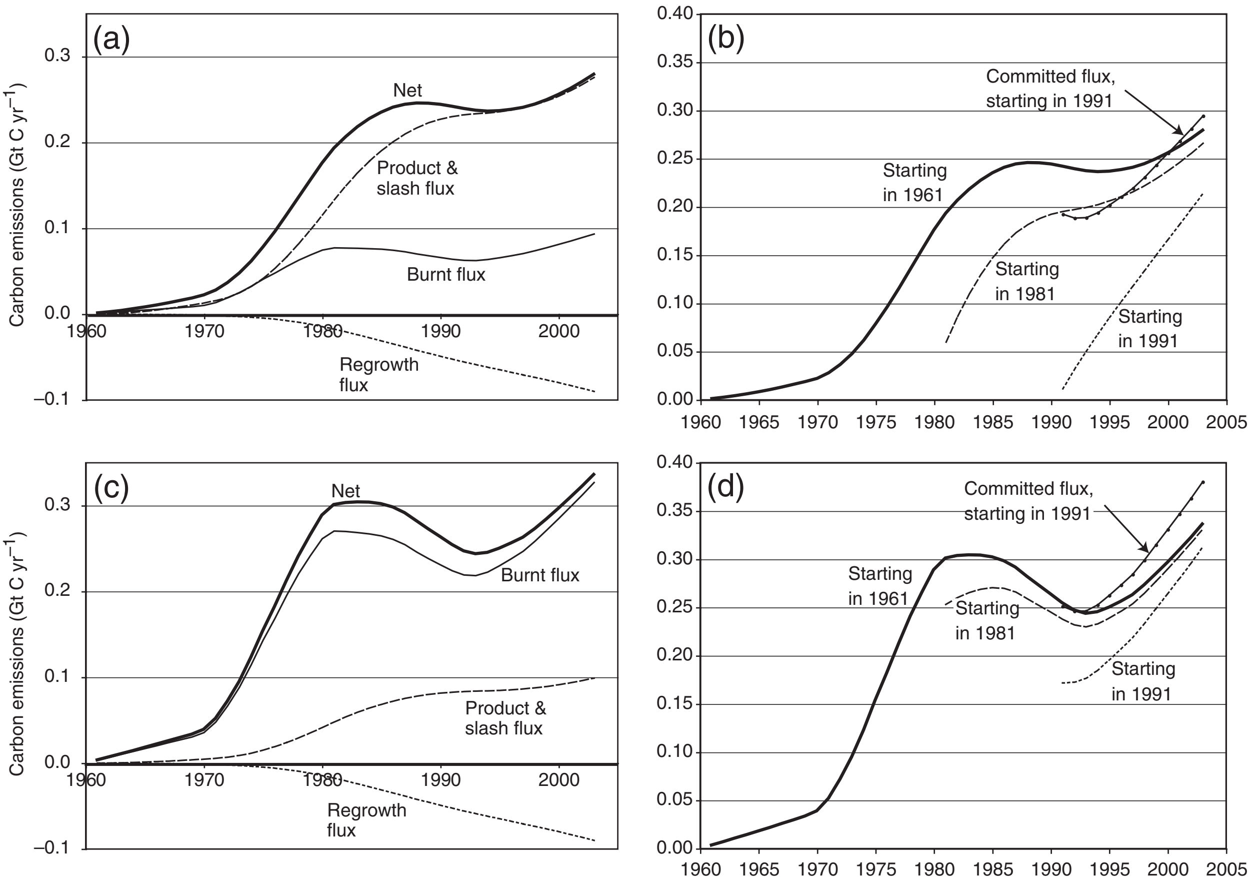

Fig. 6 (a) Carbon fluxes from the land-cover changes in Fig. 4, calculated using a book-keeping carbon cycle model; (b) the influence of including historical land-cover changes on present-day carbon emissions; (c) and (d) same as (a) and (b), but a sensitivity study partitioning cleared carbon as follows: 70% burnt, 20% slash, 8% products, and 2% elemental carbon.

result of the emissions from product and slash pools that accumulated from historical land-cover change, and suggests underestimates by the AVHRR study. A simulation staring only in 1991, but using the committed-flux approach to compensate for excluding historical land-cover changes (like TREES), underestimates carbon fluxes by only 12%; however, as already discussed, committed-flux calculations are not comparable with annual carbon balance calculations and should be used with great caution.

Finally, we should emphasize that our results are greatly influenced by our parameter choices. In particular, some of the parameters, especially the partitioning of cleared carbon, are highly uncertain, and depend on combustion efficiency (Fearnside, 2000). We have assumed, during the initial clearing that only 20% of the cleared carbon burns, while 70% remains as slash. It is mainly the delayed decay of this slash pool that introduces long-term dynamics in carbon fluxes. However, it is very likely that much of the slash burns during fires in subsequent years (Cochrane, 2003, 12–28% cited in Sorrensen, 2000). Fearnside (2000) suggests that almost all of the original forest carbon is released within a decade. Therefore, we did an additional sensitivity experiment with our model wherein we reversed the partitioning of carbon into the burnt and slash pools to represent an extreme situation where most of the cleared carbon is burnt (Fig. 6c and d). This experiment clearly highlights the significance of partitioning parameters on long-term carbon dynamics. With more carbon allocated to burning, the burnt flux strongly determines the net flux, and the net flux is higher because of the diminished role of delayed emissions from long-term carbon pools. Also, the importance of historical land-cover changes diminishes; simulations starting in 1981 now underestimate carbon fluxes in the 1980s by ~11%, but only slightly underestimate (by ~4%) the 1990s fluxes. On the other hand, starting calculations in 1991 still underestimates the 1990s carbon fluxes by ~21%, while starting in 1991 but using a committed-flux approach overestimates carbon emissions by 6%.

Discussion and conclusions

In this paper, we suggest that five existing studies of global emissions of carbon from land-cover change are not directly comparable and recommend key considerations for future studies that could reduce uncertainty. We present the various elements of a complete land cover and carbon budget scheme, and performed simulations over legal Amazonia to illustrate the influence of these elements. These simulations suggest that to accurately estimate carbon emissions from land-cover change, it is important to: (1) consider the full land-cover dynamics during and *following* deforestation; (2) explicitly include historical land-cover change for several decades; and (3) accurately estimate the fate of cleared carbon. Of course, it is also most critical to use the most reliable datasets on deforestation rates and biomass, and to assess whenever possible the impact of uncertainties/errors in the input datasets on the resulting estimates (Houghton, 2003b, 2005; Mayaux *et al*., 2005).

Our analysis suggests that the CCMLP study has potentially underestimated land-cover change carbon emissions because of its consideration of only net land-cover changes, while the AVHRR study has potentially underestimated emissions because of not including long-term historical land-cover changes. The TREES study also neglected historical land-cover changes, but used a 10-year committed flux estimate to compensate for neglecting historical land-cover change; but we have shown here that the committed flux estimate is not directly comparable with an annual-balance estimate. While the H2003 study performed a complete analysis of the carbon budget, it may have overestimated carbon fluxes because the rates of deforestation in that study (taken from FAO FRA country surveys) were higher than AVHRR, TREES, and FAO remote sensing surveys (FAO, 2001b; DeFries & Achard, 2002; Houghton, 2003b; Mayaux *et al*., 2005), and potentially underestimated fluxes because the coarse spatial resolution of the data may only have captured *net* changes and not *gross* changes in land cover. The F2000 estimate of equilibrium committed flux likely overestimates carbon fluxes because it estimates commitment far into the future until an equilibrium landscape is established; moreover, it also uses the higher deforestation rates of the FAO FRA. In summary, while the existing studies suggest bounds on the estimates of carbon emissions from tropical deforestation, a more accurate estimate will require further efforts to incorporate the suggested recommendations.

Acknowledgements

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Appendix: model descriptions

Here, we provide the details on the land-cover transition model and the book-keeping carbon cycle model.

Land-cover transition model

Let $D(t)$, $t = 1961, 1962, \ldots, 2003$ be the deforestation rates at time 't' in million ha yr^{-1}.

Let $A_C(t,\tau),_{\tau=1,2,\ldots,t-1961+1}^{t=1961,1962,\ldots,2003}$ be the cropland area (Mha yr^{-1}) at time 't', age-cohort 'τ',

let $A_P(t,\tau),_{\tau=1,2,\ldots,t-1961+1}^{t=1961,1962,\ldots,2003}$ be the pasture area (Mha yr^{-1}) at time 't', age-cohort 'τ', and

let $A_SF(t,\tau),_{\tau=1,2,\ldots,t-1961+1}^{t=1961,1962,\ldots,2003}$ be the area of secondary forest (Mha yr^{-1}) at time 't', age-cohort 'τ'.

A first-order Markov model of transition probabilities between land-cover classes can be specified as follows:

$$\begin{bmatrix} A_C \\ A_P \\ A_{SF} \end{bmatrix}^{t,\tau} = \begin{bmatrix} \alpha_{C,C} & \alpha_{P,C} & \alpha_{SF,C} \\ \alpha_{C,P} & \alpha_{P,P} & \alpha_{SF,P} \\ \alpha_{C,SF} & \alpha_{SF} & \alpha_{SF,SF} \end{bmatrix} \begin{bmatrix} A_C \\ A_P \\ A_{SF} \end{bmatrix}^{t-1,\tau-1},$$

where the matrix α contains the land-cover transition probabilities.

However, a transition from one land-cover class to another should reset the cohort age to 1, and therefore, the above form of the equation is applied as follows:

First, the deforested land every year is partitioned into the 1-year age classes as follows:

$$\begin{aligned} A_C(t,1) &= D(t) \times 0.347 \\ A_P(t,1) &= D(t) \times 0.653 \\ A_{SF}(t,1) &= 0. \end{aligned}$$

Next, to the 1-year-age cohorts, we add the area that results from the transition from other land-cover classes:

$$\begin{bmatrix} A_C \\ A_P \\ A_{SF} \end{bmatrix}^{t,1} = \begin{bmatrix} 0.347\,D(t) \\ 0.653\,D(t) \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & \alpha_{P,C} & \alpha_{SF,C} \\ \alpha_{C,P} & 0 & \alpha_{SF,P} \\ \alpha_{C,SF} & \alpha_{P,SF} & 0 \end{bmatrix} \begin{bmatrix} A_C \\ A_P \\ A_{SF} \end{bmatrix}^{t-1,\tau-1}.$$

Finally, for age cohorts older than 1 year, we estimate the within-class transition of land-cover classes:

$$\begin{bmatrix} A_C \\ A_P \\ A_{SF} \end{bmatrix}^{t,\tau} = \begin{bmatrix} \alpha_{C,C} & 0 & 0 \\ 0 & \alpha_{P,P} & 0 \\ 0 & 0 & \alpha_{SF,SF} \end{bmatrix} \begin{bmatrix} A_C \\ A_P \\ A_{SF} \end{bmatrix}^{t-1,\tau-1},$$

for $\tau = 2,3, \ldots, t$.

Fearnside (1996) estimated land-cover transition probabilities between six different land-cover classes for the Amazon. Here, we adapted his model, but lumped it to consider only three land-cover classes. The transition probabilities for our three-class model are

$$\alpha = \begin{bmatrix} 0.450 & 0.000 & 0.063 \\ 0.468 & 0.895 & 0.115 \\ 0.082 & 0.105 & 0.822 \end{bmatrix}.$$

The initial conditions for this model are

$$A_C(0,0) = 0; A_P(0,0) = 0; A_{SF}(0,0) = 0.$$

From the results of this model, we can also calculate the annual rate of reclearing of secondary vegetation as

$$A_{SF,\,clear}(t,\ \tau) = A_{SF}(t-1, \tau-1)(\alpha_{SF,\,C} + \alpha_{SF,P}).$$

Book-keeping carbon cycle models

Estimates based on complete accounting of annual carbon balance

Carbon stock in vegetation = C_{veg} = 177 tons-C ha^{-1} (Houghton *et al*., 2001).

The biomass cleared is partitioned into biomass burnt instantaneously (f_{burn}), biomass left as slash on the site (f_{slash}), biomass transferred to product pools (f_{prod}), and biomass that goes into elemental carbon (f_{elem}) as follows:

$$f_{burn} = 0.2; f_{slash} = 0.7; f_{prod} = 0.08, f_{elem} = 0.02.$$

The various carbon fluxes include flux from instantaneous burning ($C_{f,\ burn}$), flux from decay of product, slash and elemental carbon pools ($C_{f,\ decay}$), and flux due to carbon uptake by regrowing secondary forests ($C_{f,\ regrowth}$).

The biomass cleared every year is the sum of biomass from deforestation and the biomass from cleared secondary vegetation:

$$Bio_{clear}(t) = Bio_{defore}(t) + Bio_{SF\,clear}(t)\mathrm{Gt\,C\,yr^{-1}}.$$

The biomass cleared from deforestation is

$$Bio_{defor}(t) = 0.001\,C_{veg}\,D(t)\ \ \mathrm{Gt\,C\,yr^{-1}}.$$

where the factor '0.001' converts units of *D(t)* from M ha yr^{-1} to billion ha yr^{-1}.

The biomass from recleared secondary vegetation is

$$Bio_{SF\,clear}(t) = 0.001 \sum_{\tau=1}^{t} C_{SF}(\tau 1)\,A_{SF,\,clear}(t,\ \tau)\mathrm{Gt\,C\,yr^{-1}},$$

where C_{SF}, the biomass in secondary vegetation, is calculated as follows:

$$C_{SF}(\tau) = \begin{cases} C_{veg}0.7\tau/25\,\mathrm{Gt\,C}, & \text{if } \tau \le 25 \text{ years} \\ C_{veg}(0.7 + 0.3(\tau - 25)/50)\,\mathrm{Gt\,C}, & \text{if } 25 < \tau \le 75 \text{ years} \\ C_{veg}\mathrm{Gt\,C}, & \text{if } \tau > 75 \text{ years.} \end{cases}$$

Note that this biomass is calculated for age-cohort $\tau-1$ because the cleared biomass has the biomass of the previous year.

The burnt flux is calculated as follows:

$$C_{f,burn}(t) = Bio_{clear}(t)\,f_{burn}\quad \mathrm{Gt\,C\,yr^{-1}}.$$

The annual transfer of carbon to the slash, product, and elemental carbon pools are

$$\begin{aligned} C_{in,\,slash}(t) &= Bio_{clear}(t)\,f_{slash}\quad \mathrm{Gt\,C\,yr^{-1}}, \\ C_{in,\,prod}(t) &= Bio_{clear}(t)\,f_{slash}\quad \mathrm{Gt\,C\,yr^{-1}}, \\ C_{in,\,elem}(t) &= Bio_{clear}(t)\,f_{elem}\quad \mathrm{Gt\,C\,yr^{-1}}. \end{aligned}$$

The slash, product and elemental pools experience exponential decay. Thus, the carbon flux dynamics of the slash, product, and elemental pools can be expressed using the differential equation:

$$\frac{dC}{dt} = C_{in} - \lambda C,$$

where C_{in} is the transfer of carbon from deforestation, and λ is the decay rate. Thus, the carbon dynamics for the various pools can be calculated using

$$\begin{aligned} C_{slash}(t) &= C_{slash}(t-1)(1-\lambda_{slash}) + C_{in,slash}(t) \quad \mathrm{Gt\,C},\\ C_{prod}(t) &= C_{prod}(t-1)(1-\lambda_{prod}) + C_{in,prod}(t) \quad \mathrm{Gt\,C},\\ C_{elem}(t) &= C_{elem}(t-1)(1-\lambda_{elem}) + C_{elem,0}(t) \quad \mathrm{Gt\,C},\end{aligned}$$

and the fluxes of carbon from the decay of these pools is calculated as

$$C_{f,\,decay}(t) = \lambda_{slash}\, C_{slash}(t-1) + \lambda_{prod}\, C_{prod}(t-1) + \lambda_{elem}\, C_{elem}(t-1)\ \mathrm{Gt\,C\,yr^{-1}},$$

where $\lambda_{slash} = 0.1$, $\lambda_{prod} = 0.1$, and $\lambda_{elem} = 0.001$.

Regrowing forests are assumed to recover 70% of their original biomass in 25 years and the remaining 30% over the next 50 years. The carbon flux from uptake by regrowing forests is

$$C_{f,\,regrowth}(t) = \begin{cases} -\sum_{\tau=0}^{25} A_{SF}(t,\tau)\, C_{veg}\, 0.7/25\ \mathrm{Gt\,C\,yr^{-1}}, & \text{if } \tau \le 25 \text{ years} \\ -\Big[\sum_{\tau=0}^{25} A_{SF}(t,\tau)\, C_{veg}\, 0.7/25 + \sum_{\tau=26}^{75} A_{SF}(t,\tau)\, C_{veg}\, 0.3/50\ \mathrm{Gt\,C\,yr^{-1}}\Big] & \text{if } 25 < \tau \le 75 \text{ years} \\ 0\ \mathrm{Gt\,C\,yr^{-1}}, & \text{if } \tau > 75 \text{ years.} \end{cases}$$

Total net emissions from land-cover change is

$$C_{f,net}(t) = C_{f,\,burn}(t) + C_{f,\,decay}(t) + C_{f,\,regrowth}(t)\ \mathrm{Gt\,C\,yr^{-1}}.$$

Note that the cropland and pasture area estimates are not used in the carbon calculations. Only the area of secondary forest plays a role in carbon flux estimates. The cropland and pasture areas represent very little biomass compared with the forested landscapes, and therefore, not included here in our illustrative simulations.

Estimates ignoring regrowth flux or assuming only net deforestation

Carbon flux estimates ignoring the regrowth flux can be calculated using the same formulations as in A2.1, but using

$$C_{f,net}(t) = C_{f,\,burn}(t) + C_{f,\,decay}(t) \quad \mathrm{Gt\,C\,yr^{-1}}.$$

For carbon-flux estimates using net deforestation assumptions, we first calculate net deforestation rates as follows:

$$D_{net}(t) = D(t) - \left[\sum_{\tau=1}^{t} A_F(t,\tau) - \sum_{\tau=1}^{t} A_{SF}(t-1,\tau-1)\right] \mathrm{Mha\,yr^{-1}}.$$

Then, we calculate carbon fluxes using the same equations as in A2.1, but replacing $D(t)$ with $D_{net}(t)$ and setting $Bio_{SF\ clear}(t) = 0$.

Estimates ignoring reclearing of fallow or secondary

Carbon flux estimates ignoring the reclearing of secondary vegetation can be calculated using the same formulation as in A2.1, but setting $Bio_{SF\ clear}(t) = 0$.

Estimates based on the committed flux approach

The committed flux calculations do not include any historical information. Therefore, the slash, product, and elemental carbon pools do not accumulate carbon. Every year, a new cohort of carbon pools is established from the deforestation of that year, and the total area of regrowth during that year is also calculated. Then, for a 10-year committed-flux estimate, the fluxes from decays of the various carbon pools, as well as from the regrowth of secondary forests are estimated for the next 10 years.

The burnt flux estimate is identical to the full-accounting calculations:

$$C_{f,\,burn}(t) = Bio_{clear}(t)\, f_{burn} \quad \mathrm{Gt\,C\,yr^{-1}}.$$

The annual transfer of carbon to the slash, product, and elemental carbon pools are

$$\begin{aligned} C_{in,slash}(t) &= Bio_{clear}(t)\, f_{slash} \quad \mathrm{Gt\,C\,yr^{-1}},\\ C_{in,prod}(t) &= Bio_{clear}(t)\, f_{prod} \quad \mathrm{Gt\,C\,yr^{-1}},\\ C_{in,\,elem}(t) &= Bio_{clear}(t)\, f_{elem} \quad \mathrm{Gt\,C\,yr^{-1}}.\end{aligned}$$

The slash, product and elemental pools experience exponential decay. The decay of the slash, product, and elemental pools can be calculated for the next 10 years as

For $\tau = 1, 2, \ldots, 10$ years,

$$\begin{aligned} C_{slash}(t,\tau) &= C_{in,slash}(t)\, e^{-\lambda_{slash}\tau} \quad \mathrm{Gt\,C},\\ C_{prod}(t,\tau) &= C_{in,prod}(t)\, e^{-\lambda_{prod}\tau} \quad \mathrm{Gt\,C},\\ C_{elem}(t,\tau) &= C_{in,elem}(t)\, e^{-\lambda_{elem}\tau} \quad \mathrm{Gt\,C},\end{aligned}$$

and therefore, the total committed flux of carbon from the decay of these pools over the next 10 years can be calculated as

$$C_{\mathrm{f,\,decay}}(t) = C_{\mathrm{in,slash}}(t)(1 - \mathrm{e}^{-10\lambda_{\mathrm{slash}}}) + C_{\mathrm{in,prod}}(t)(1 - \mathrm{e}^{-10\lambda_{\mathrm{prod}}}) + C_{\mathrm{in,elem}}(t)(1 - \mathrm{e}^{-10\lambda_{\mathrm{elem}}})\ \mathrm{Gt\,C\,yr^{-1}}.$$

In the case of secondary forest regrowth, a committed flux calculation estimates the rate of regrowth, but does not account for the different age-classes of the regrowing forest. Each year, based on an estimate of total area of regrowth, a new cohort of regrowing forest is established, and its carbon accumulation over the next 10 years is estimated. Thus, the total amount of regrowth in each year is calculated as

$$A_{\mathrm{regrowth}}(t) = \left[\sum_{\tau=1}^{t} A_{\mathrm{SF}}(t,\tau) - \sum_{\tau=1}^{t} A_{\mathrm{SF}}(t-1,\tau-1)\right]\ \mathrm{Mha\,yr^{-1}}.$$

Regrowing forests recover 70% of their original biomass in 25 years. Thus, the total committed flux over the next 10 years from carbon accumulation in regrowth can be calculated as

$$C_{\mathrm{f,\,regrowth}}(t) = -0.001\ A_{\mathrm{regrowth}}(t)\, C_{\mathrm{veg}}\, 0.7 \times 10/25\ \mathrm{Gt\,C\,yr^{-1}}.$$

Total net emissions from land-cover change is

$$C_{\mathrm{f,\,net}}(t) = C_{\mathrm{f,\,burn}}(t) + C_{\mathrm{f,\,decay}}(t) + C_{\mathrm{f,\,regrowth}}(t)\ \mathrm{Gt\,C\,yr^{-1}}.$$

