

# How well do we know the flux of CO<sub>2</sub> from land-use change?

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## ABSTRACT

Five new estimates of global net annual emissions of carbon from land use and land-use change collectively describe a gradually increasing trend in emissions, from  $\sim 0.6 \text{ PgC yr}^{-1}$  in 1850 to  $\sim 1.3 \text{ PgC yr}^{-1}$  in the period 1950–2005, with an annual range that varies between  $\pm 0.2$  and  $\pm 0.4 \text{ PgC yr}^{-1}$  of the mean. All estimates agree in the upward trend from 1850 to  $\sim 1950$  but not thereafter. In recent decades, when rates of land-use change and biomass density should be better known than in the past, the estimates are *more* variable. Most analyses have used three quasi-independent estimates of land-use change that are based on national and international agricultural and forestry data of limited accuracy in many countries. Further, the estimates of biomass used in the analyses have a common but limited literature base, which fails to address the spatial variability of biomass density within ecosystems. In contrast to the sources of information that have been used to date, a combination of existing ground and remote sensing data are available to determine with far higher accuracy rates of land-use change, aboveground biomass density, and, hence, the net flux of carbon from land use and land-use change.

## 1. Introduction

The net flux of CO<sub>2</sub> from changes in land use is important in the global carbon cycle for a number of reasons. First, changes in land use have caused a net release of carbon to the atmosphere over the last centuries and decades. Estimates vary, however, and the annual net release is more uncertain than other terms in the global carbon budget (Le Quéré et al., 2009). Nevertheless, the net release of carbon from land-use change, along with the other terms in the global carbon budget, helps define (by difference) a residual terrestrial sink. Although it would perhaps be convenient to have a single terrestrial term for the global carbon budget, methods are not yet available for direct measurement of either the net terrestrial flux or the residual terrestrial flux. In contrast, changes in land use may be documented with data from historical censuses and remote sensing, and the associated changes in carbon stocks are known well enough to enable calculation of that portion of the net terrestrial flux attributable to land use and land-use change.

Estimates of the net emissions of carbon from land use and land-use change are also important in determining whether the airborne fraction is changing. The airborne fraction, defined as the annual growth in atmospheric CO<sub>2</sub> divided by total annual emissions (fossil and land use), is the single best index of whether

or not the global sinks of carbon (ocean and land) are continuing to increase in proportion of emissions (Canadell et al., 2007; Le Quéré et al., 2009). If the net flux of carbon from land-use change were well enough known, it would help constrain both the residual terrestrial flux and trends in the airborne fraction (Knorr, 2009).

This paper reviews the factors that account for differences among recent estimates of carbon sources and sinks from land use and land-use change. The analysis extends earlier reviews (House et al., 2003; Ramankutty et al., 2007; Ito et al., 2008) by considering several new global estimates. The emphasis on global estimates limits the comprehensiveness of the review. Space does not permit consideration of regional analyses, such as the recent report of carbon sequestration in the former Soviet Union as a result of agricultural abandonment (Vuichard et al., 2008).

## 2. What is land use and land-use change?

Ideally, changes in land use would be defined broadly to include not only changes in land cover (e.g. conversion of forest to cropland), but all forms of land management. The reason for this broad ideal is that the net flux of carbon attributable to management is that portion of a terrestrial carbon flux that might qualify for credits and debits under a post-Kyoto agreement. Unfortunately, it is perhaps impossible to separate management effects from indirect (e.g. CO<sub>2</sub> fertilization, N deposition or climate) and natural effects. Furthermore, the ideal requires more

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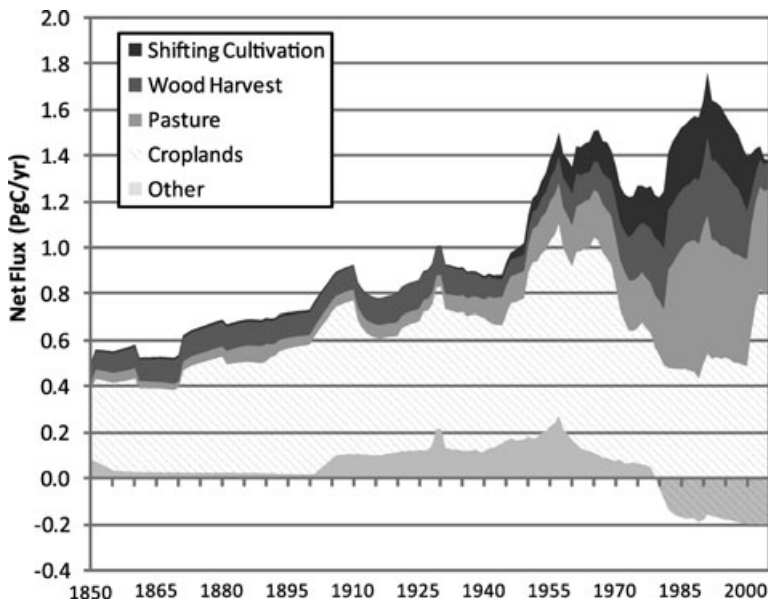


Fig. 1. Net global sources and sinks of carbon from different types of land use and land-use change (Houghton, this study). The net source from 'other' is largely land degradation in China (Houghton and Hackler, 2003). The net sink attributed to 'other' is largely from afforestation in China and from agricultural abandonment in the United States and Europe.

data, at higher spatial and temporal resolution, than are practical (or currently possible) to assemble. Thus, most analyses of land-use change have focused on the dominant (or documentable) activities and, to a large extent, ignored others. The dominant types, listed below, are divided into two categories: those that involve the conversion of one type of ecosystem to another (land-use change), and those that involve management with no change in land cover (land use) (e.g. harvest of wood). The relative importance of different land uses from the perspective of carbon sources and sinks is shown in Fig. 1.

## 2.1. Land-use change: conversions

**2.1.1. Croplands.** Globally, the conversion of lands to croplands has been responsible for the largest emissions of carbon from land-use change. The emissions are large because the area of croplands has grown substantially in the last centuries and because the changes in carbon stocks per hectare are large when lands, especially forests, are converted to croplands. Not only is most of the initial biomass of forests lost to the atmosphere, but cultivation of native soils, whether forest or prairie soils, releases 25–30% of the organic carbon stored in the top metre (Post and Kwon, 2000; Guo and Gifford, 2002; Murty et al., 2002). The annual net flux of carbon from croplands in Fig. 1 is a net flux; it includes both the emissions of carbon from conversion of native ecosystems to croplands and the uptake of carbon in forests growing on abandoned croplands.

**2.1.2. Pastures.** The net emissions from expansion and contraction of pastures or grazing lands have been less than emissions from croplands because many pastures have expanded into natural grasslands (thus changing aboveground carbon stocks little) and because pastures are generally not cultivated, and thus lose little carbon from soils. Where pastures have expanded into

forests, particularly in Central and South America, the net emissions have dominated those from other changes in land use.

**2.1.3. Shifting cultivation.** Shifting cultivation is a rotational form of cropping, where crops alternate with periods of forest recovery (fallow). Although the activity represents a land use (Section 2.2) as well as a land-use change, it is included here because increases in the area of shifting cultivation involve land conversion, usually forest or savanna. On average, the carbon stocks per hectare are smaller under shifting cultivation than in forests but larger than in permanent croplands. Thus, the emissions of carbon per hectare are less than they are for conversion of forest to cropland or pasture. The areas in shifting cultivation and fallow are not as well documented as they are for permanent croplands or pastures. The FAO, for example, includes the cropping portion of shifting cultivation in 'arable and permanent crops' but not the fallow portion if it is greater than 5 years old. These criteria are not applied consistently in all countries.

**2.1.4. Other.** Occasionally, the loss of forests does not appear as an increase in any of the land uses described earlier. For example, the loss of forest area in China between 1900 and 1980 was more than three times greater than the increase in croplands and pastures (Houghton and Hackler, 2003). If the data are accurate, they suggest a large source of carbon that is attributable to neither croplands nor pasture. The authors attributed it to 'degraded land'; it appears as the 'other' source at the bottom of Fig. 1.

## 2.2. Land use: management practices within ecosystems

**2.2.1. Wood harvest.** The net annual emissions of carbon from wood harvest in Fig. 1 include both the emissions from industrial wood and fuelwood harvest (i.e. emissions from the burning and decay of products removed from the forest as well as

logging residues left on site) and the uptake of carbon in forests recovering from harvests. Because a constant rate of logging would eventually yield a net flux of nearly zero as decay and regrowth offset each other, the net emissions indicate that rates of logging have been generally increasing globally.

**2.2.2. Fire management.** The emissions of carbon from fires associated with the clearing of forests for croplands and pastures are included in analyses of land-use change, but fire management is largely missing from most analyses despite the fact that fire exclusion, fire suppression and controlled burning are practiced in many parts of the world. In many regions, fire management may cause a terrestrial sink (Houghton et al., 1999; Marlon et al., 2008). In other regions it increases the net source. In particular, the draining and burning of peatlands in Southeast Asia are thought to add another 0.3 PgC yr<sup>-1</sup> to land-use emissions (not included in Fig. 1) (Hooijer et al., 2009). Only those fires resulting from direct human activity should be included in the flux of carbon from land use, but attributing fire to management, as opposed to natural processes, can be problematic.

**2.2.3. Agricultural management.** Agricultural management includes cropping practices, irrigation, use of fertilizers, different types of tillage, etc. The activities affect changes in the carbon density of soils, but, other than the losses of carbon resulting from cultivation of native soils, changes in agricultural management have not generally been included in global analyses of land-use change.

**2.2.4. Other.** There are many other types of land use that may affect the carbon density of ecosystems, either degrading the stocks or enhancing them. Most forms of management other than wood harvest and fire management have not been included in analyses of land use and land-use change.

### 2.3. Processes included in analyses but not appearing in Fig. 1

**2.3.1. Plantations.** The net flux of carbon in plantations is important locally but small globally. The exception, of course, is the conversion of peat forests in Southeast Asia to oil palm plantations, included here as fire management and the expansion of croplands rather than plantations. Although individual plantations are temporary sinks while they are growing, plantations, globally, are not a large sink of carbon for two reasons. First, plantations are often established on forest lands, and the net flux of carbon includes both the emissions from deforestation and the uptake in growing plantations. Further, many plantations are timber or fuelwood plantations, periodically harvested, and thus with an average carbon density lower than that of the natural forest.

**2.3.2. Settled lands.** Urban areas account, by one estimate, for >70% of anthropogenic releases of carbon and 76% of wood used for industrial purposes (Churkina et al., 2010). Most of these releases are derived from products outside of urban areas, however. In keeping with the accounting used in this review, the

sources and sinks of carbon in urban and exurban developments are those fluxes that result from the conversion of land to such areas or the management of biotic resources within them. Because the area of urban ecosystems is small, globally, <0.5% (Schneider et al., 2009) to 2.4% (Potere and Schneider, 2007), and because many settled lands are already included in agricultural lands and forests, urban areas have been largely ignored in analyses of land use and land-use change. However, exurban areas were nearly 15 times greater than urban areas in the United States in 2000 (Brown et al., 2005). Furthermore, recent deforestation in developed countries is largely for residential, industrial and commercial use rather than for agriculture (Jeon et al., 2008). Newly established areas may be net sources initially but may become net sinks if trees are re-established. The net global source/sink for settled lands is likely small but uncertain in sign. It should receive more attention than it has to date.

Global summaries of the net flux of carbon from land use and land-use change give the false impression that such activities yield only emissions of carbon, and not sinks. The sources of carbon shown in Fig. 1, however, are net sources, including both the emissions from conversion or use and the sinks in forests recovering on abandoned or harvested lands. The only global sink to appear in Fig. 1 is the recent sink, after ~1980, largely a result of agricultural abandonment in Europe and the United States and afforestation in China. Although not apparent, most of the other categories of land use and land-use change include carbon sinks as a result of past and present management practices. The global results presented here are thus not necessarily inconsistent with measured increases in forest biomass (e.g. Kauppi et al., 2006).

### 2.4. Processes not included in land use and land-use change

Not all carbon sinks are the result of management. The existence of a residual terrestrial sink in the global carbon balance indicates that processes other than management affect the storage of carbon on land. Natural disturbances and environmental factors, for example, may either enhance or degrade carbon stocks, yet are not directly attributable to, and not included in analyses of, land use and land-use change. Often the effects of land use and land-use change are isolated by running a series of model experiments with and without land-use change and with and without environmental trends. The implications of the land-use flux for the residual terrestrial flux are discussed in Section 4.

## 3. Recent estimates of carbon emissions from land use and land-use change

Recent estimates of the net emissions of carbon from land use and land-use change are shown in Fig. 2 and summarized in Tables 1 and 2 (see Pongratz et al. (2009) for a more complete summary of earlier estimates and van der Werf et al. (2009b)

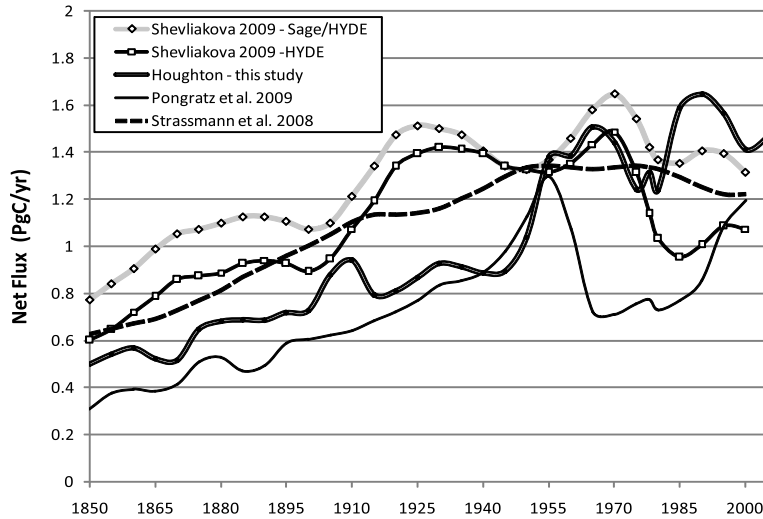


Fig. 2. Estimates of the global annual net flux of carbon from land-use change. The five estimates have been smoothed from the original estimates by interpolating between points taken at 5-year intervals.

Table 1. Net emissions of carbon (PgC) from global changes in land use

Time interval	PgC <sup>a</sup>	Data source	Reference
Pre-history to 1990	182–199	Pre-disturbance maps	DeFries et al. (1999)
Pre-history to 2000	171	SAGE & HYDE	Pongratz et al. (2009)
1850–2000	155	Houghton (2003)	Houghton (2003)
1850–2005	156	Houghton (2006)	Houghton (this study)
1850–2000	164	HYDE-Hurtt <sup>b</sup>	Shevliakova et al. (2009)
1850–2000	188	SAGE-Hurtt <sup>c</sup>	Shevliakova et al. (2009)
1850–2000	108	SAGE & HYDE	Pongratz et al. (2009)
1700–1990	240	HYDE-Hurtt <sup>b</sup>	Shevliakova et al. (2009)
1700–1990	294	SAGE-Hurtt <sup>c</sup>	Shevliakova et al. 2009
1700–1999	188	HYDE3.0	Strassmann et al. (2008)
1700–2000	138	SAGE & HYDE	Pongratz et al. (2009)

<sup>a</sup>Net loss of carbon from land-use change.

<sup>b</sup>Hurtt et al. (2006) includes wood harvest and shifting cultivation.

<sup>c</sup>SAGE cropland data, HYDE pasture data and Hurtt et al. wood harvest and shifting cultivation.

Table 2. Average annual emissions of carbon from global<sup>a</sup> land-use change (PgC yr<sup>-1</sup>)

1980–1989	1990–1999	Data source	Reference
0.6	0.9	Satellite (AVHRR)	DeFries et al. (2002)
2.0	2.2	2000FRA	Houghton (2003)
–	1.1	Satellite (Landsat)	Achard et al. (2004)
1.5	1.6	2005FRA	Houghton (this study)
1.5	1.1	HYDE3.0	Strassmann et al. (2008)
1.0	1.1	HYDE-Hurtt	Shevliakova et al. (2009)
1.4	1.3	SAGE-Hurtt	Shevliakova et al. (2009)
0.7	1.1	SAGE-HYDE	Pongratz et al. (2009)
	1.5	GFED <sup>b</sup>	van der Werf et al. (2009)

<sup>a</sup>The values from DeFries et al. (2002), Achard et al. (2004) and van der Werf et al. (2009) are estimates for the tropics only.

<sup>b</sup>Global Fire Emissions Database. The estimate includes emissions from peat fires in Southeast Asia.

Table 3. Sources of data and models used in analyses of land use and land-use change

Attribute	Houghton (this study)	Strassmann et al. (2008)	Pongratz et al. (2009)	Shevliakova et al. (2009)	Shevliakova et al. (2009)
Cropland	Houghton	HYDE3.0	HYDE	HYDE	SAGE
Pasture	Houghton	HYDE3.0	Pongratz	HYDE	HYDE
Shifting cultivation	Houghton			Hurt et al. (2006)	Hurt et al. (2006)
Wood harvest	Houghton			Hurt et al. (2006)	Hurt et al. (2006)
Fire management	U.S. only				
Biomass	Assigned <sup>a</sup>	Modelled	Modelled	Modelled	Modelled
Model	Bookkeeping	LPJ	JSBACH	LM3V	LM3V

<sup>a</sup>The biomass of undisturbed ecosystems is assigned or specified. The biomass of managed systems is modelled (e.g. forest biomass is reduced as a result of harvest; it is increased as a result of regrowth).

for a review of flux estimates from tropical deforestation). The most noticeable feature in Fig. 2 is the gradually upward trend in net annual emissions, at least until ~1950. The next most noticeable feature is the variation among estimates. The range of annual estimates generally varies between about  $\pm 0.2$  and  $\pm 0.4$  PgC yr<sup>-1</sup> of the mean.

Reasons for differences among estimates, both long- and short-term, may be grouped into four categories, discussed later: (1) processes and activities included in individual analyses, (2) rates of change in land use, (3) carbon density (MgC ha<sup>-1</sup>) and (4) fate of affected land and carbon stocks. Although the use of different models may be said to contribute to the variability of flux estimates, they do so largely through affecting categories 3 and 4.

### 3.1. Processes and activities included in individual analyses

All of the analyses shown in Fig. 2 include the expansion (and contraction) of croplands and pastures (Table 3). An earlier analysis (McGuire et al., 2001) (not shown) included only changes in croplands and, thus, that estimate of 0.8 PgC yr<sup>-1</sup> for the 1990s presumably underestimated emissions.

Only three of the five analyses included wood harvest and shifting cultivation (Houghton, this study; and the HYDE and SAGE/HYDE analyses from Shevliakova et al., 2009). Including those activities increased the net emissions from those based only on cropland and pasture expansion by 32–35%, globally (Shevliakova et al., 2009) and 28% for the tropics (Houghton, this study). Not surprisingly, total emissions calculated by Shevliakova et al. (2009), were 22–42% higher than those calculated by Strassmann et al. (2008) and Pongratz et al. (2009), who did not include wood harvest or shifting cultivation (Table 3).

Although the emissions of carbon from fires associated with the conversion of natural ecosystems to managed ones were included in all analyses, a few analyses included other aspects of fire management (Table 3). Houghton et al. (1999) included the suppression of wildfires in the U.S. Fire suppression began in ~1920 and thereafter increased the sink of carbon in recovering forests. Interestingly, including the natural fire cycle in the

analysis reduced the calculated net emissions of carbon because the average forest biomass was less as a result of the fires and, hence, less carbon was released when forests were converted to agricultural lands.

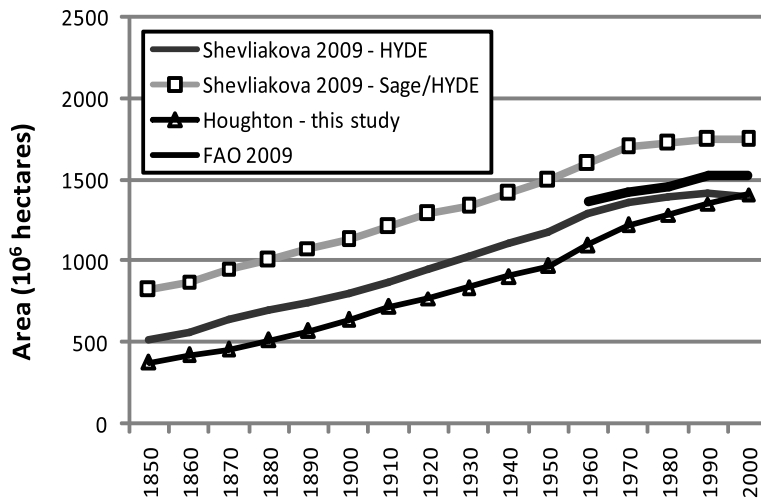
The emissions of carbon associated with the draining and burning of peatlands in Southeast Asia (Page et al., 2002; Hooijer et al., 2009) have not yet been included in global analyses of land-use change, but Achard et al. (2004) and van der Werf et al. (2008, 2009b) calculated that peat fires associated with deforestation contributed another 0.1 and 0.3 PgC yr<sup>-1</sup>, respectively, to recent emissions from land-use change.

### 3.2. Rates of land conversion

*3.2.1. Rates over the last centuries.* Clearly the rate of conversion of natural ecosystems to croplands and pastures is critical for estimating annual carbon emissions, and three quasi-independent estimates of land-use change have been constructed. The first global assessment was by Houghton et al. (1983). They assembled from national handbooks and international surveys rates of change in the area of cropland and pasture (Fig. 3) and rates of wood harvest for 10 world regions. They defined the changes in carbon density (vegetation and soil) that followed land conversion and wood harvest for two to six types of ecosystems in each region. And they used a bookkeeping model to calculate the annual sources and sinks associated with each type of land use in each region. The model tracked per hectare changes in vegetation, soil, wood products removed from sites of management and wood residues left on site. In the years since 1983, Houghton and colleagues have continued to refine the data used in the analyses; the results presented here are based on data more spatially detailed than those used in the 1983 study. Houghton's most recent estimates of the emissions of carbon from land use and land-use change are included in the global analyses of Canadell et al. (2007) and Le Quéré et al. (2009). The estimates and the data used to generate them are cited in this review as Houghton (this study).

Ramankutty and Foley (1998) constructed an estimate of change in global croplands at a much finer resolution (5 min resolution) than Houghton et al. (1983). Ramankutty and

## a. Croplands



## b. Pasture

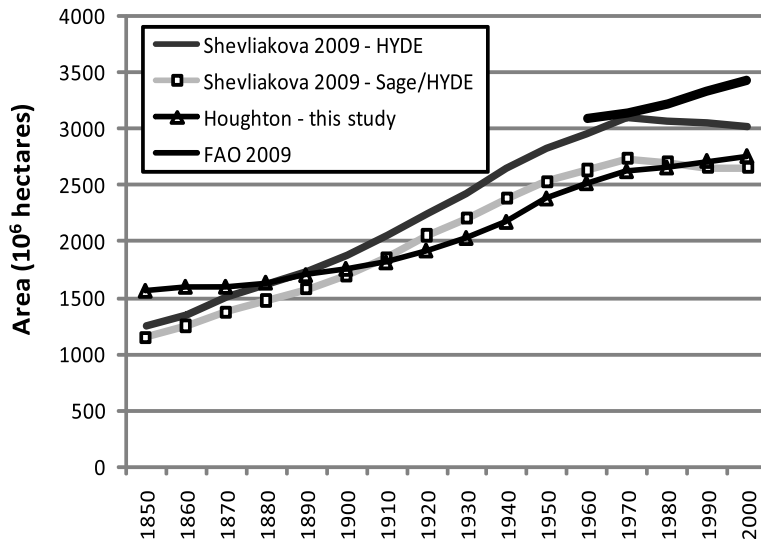


Fig. 3. Estimates of the global areas of (a) permanent croplands and (b) pastures.

Foley (1999) created annual maps of global cropland from 1700 to 1992 (often referred to as the SAGE data set). They started with the IGBP 1-km-resolution Global Land Cover Classification data set, calibrated its cover types with cropland data from the FAO (Ramankutty and Foley, 1998) and worked backward to 1700, assuming, in the absence of contrary data, that the 1992 distribution of croplands did not change location but only density (% cover). They accounted for historical deviations from this assumption with national and subnational data from historical cropland inventories, for example, the movement of croplands in North America from the eastern coast to the interior. Rates of cropland expansion were usually obtained from cropland inventories. Where detailed information was lacking, Ramankutty and Foley (1999) extrapolated backward us-

ing continental-scale cropland estimates from Houghton and Hackler (1995) and Richards (1990).

Klein Goldewijk (2001) created a similar set of maps (the HYDE data set), including both croplands and pastures (1700–1990) ( $0.5^\circ \times 0.5^\circ$  resolution) by assuming that croplands and pastures grew in proportion to, and in the same locations as, human population density. Differences between the SAGE and HYDE data sets were reviewed by Klein Goldewijk and Ramankutty (2004). The two data sets agreed best over North America and disagreed most over Latin America and Oceania. The original HYDE 2001 data set assigned a single land cover to each grid cell, while SAGE contained subgrid information. This difference has consequences for assigning carbon density to the lands converted to agriculture. An updated

version (HYDE3.0) now also contains subgrid information. The SAGE data set shows higher cropland areas throughout (Fig. 3), perhaps because the areas were calibrated in 1992 with a map of land cover (Ramankutty and Foley, 1998) rather than taken directly from reported cropland areas.

The three reconstructions are quasi-independent. They occasionally used data from each other, and they often used the same sources of information to determine rates of land-use change. For example, the land-use data compiled by Houghton et al. (1983) were subsequently reported by Richards (1990) and incorporated, in part, into the SAGE (Ramankutty and Foley, 1999) and HYDE (Klein Goldewijk, 2001) data sets. The SAGE and HYDE data sets have been used as the basis for several recent analyses but not necessarily in the same fashion. For example, Hurtt et al. (2006) created a SAGE/HYDE data set combining the cropland data from SAGE with the pasture data from HYDE. Pongratz et al. (2008) constructed an alternative time series for pasture, which was derived from the present-day distribution of pasture (Foley et al., 2003) and projected back in time, taking into account historical expansion of cropland onto pasture.

Hurtt et al. (2006) also advanced the global data sets by adding wood harvest and shifting cultivation (from Houghton's most recent analyses) to the SAGE and HYDE data sets. Adding these forms of management created secondary forests in addition to those created by agricultural abandonment. Hurtt et al. (2006) also extended the data sets to 2000.

Pongratz et al. (2008) extended the SAGE dataset backwards in time to cover the entire period since AD 800 using a population-based approach. In the course of this extension, they also revised the AD 1700–1992 SAGE data base (croplands) in West Africa, the Former Soviet Union, Australia and New Zealand. Combining their agricultural maps with maps of natural vegetation and defining specific allocation rules for cropland and for pasture (e.g. preferential allocation of pasture to natural grasslands), they created yet another time series of anthropogenic land-cover change. In a companion paper, Pongratz et al. (2009) used these land-cover changes with the JSBACH land surface model (Raddatz et al. 2007) to calculate carbon sources and sinks. They did not include shifting cultivation or wood harvest, and thus their estimated emissions from land-use change are lower than estimates that did include these activities (Table 3). The net emissions calculated by Pongratz et al. (2009) are also lower than estimates based on the HYDE and SAGE data because the alternative pasture data set allowed cropland to expand onto pasture.

Strassmann et al. (2008) used an updated version of HYDE, the HYDE3.0 data base, to calculate emissions of carbon with the Lund-Postdam-Jena Dynamic Global Vegetation Model (LPJ DGVM) (Sitch et al., 2003). Their analysis did not include shifting cultivation or wood harvest. The LPJ model, which represents natural vegetation as a mixture of plant function types, may overestimate emissions because pasture must expand into

the average biomass of this mixture rather than into the grassland portion, as is assumed to have occurred most often.

Shevliakova et al. (2009) used the maps created by Hurtt et al. (2006) to calculate net emissions of carbon from land use and land-use change using the LM3V land model, which combines a dynamic global vegetation model with a land surface model. Like the analysis by Houghton (this study), Shevliakova et al. (2009) did include shifting cultivation and wood harvest. The LM3V model, like LPJ, does not allow pastures to be converted selectively from natural grasslands in cells with mixed plant types.

*3.2.2. Rates over the last decades.* As mentioned earlier, knowing the recent trend in carbon emissions from land use and land-use change is particularly important for evaluating whether the airborne fraction is changing. Unfortunately, the five analyses in Fig. 2 suggest as many trends. Furthermore, 'trends' vary with the time interval considered, often alternating sign. One of the primary differences among analyses are the rates of growth in cropland and pasture areas (Fig. 3). The updated SAGE and HYDE data sets show lower rates of cropland and pasture expansion in the last decades than the FAO and Houghton.

Rates of deforestation are critical in determining trends in emissions, but trends in those rates are uncertain. The FAO (2006) reports that, globally, '... the areas of primary forest and modified natural forest are decreasing, while the areas of semi-natural forest and forest plantation are increasing. About 6 million hectares of primary forest have been lost or modified each year [between 1990 and 2005], and there is no indication that the rate of change is slowing down ...'.

In contrast, satellite-based measurements of deforestation in the two countries with the highest rates indicate recent declines. Rates have declined (since 2004) in the Brazilian Amazon to the lowest levels recorded since 1988 (INPE, 2009); and they declined in Indonesia between the 1990s and 2000–2005 (Hansen et al., 2009). However, a closer look is revealing. In Brazil, the decline since 2004 reverses an annual increase in the 7 years preceding 2004. And in Indonesia, despite the large decrease between 1990–2000 and 2000–2005, the 5 years in the 2000–2005 interval indicate a near-monotonic increase. There are clearly changes through time in the rates of tropical deforestation, but whether the changes define a trend is not at all clear. Systematic, accurate measurements of annual change in forest area are necessary but may not be sufficient to identify trends.

Houghton used data from the U.N.'s Forest Resources Assessments (FRAs) (FAO/UNEP, 1981; FAO, 1995, 2001, 2006) to infer a steady or increasing rate of tropical deforestation. According to data from the FAO, the recent rates of forest loss are higher than the net increases in agricultural land (Fig. 4), and this is the primary reason for Houghton's flux values being higher than other estimates during the 1990s. That is, Houghton (this study) used changes in forest area rather than changes in

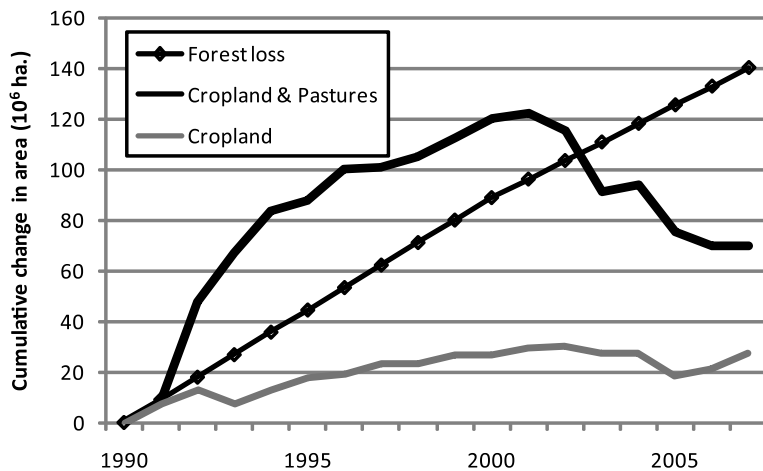


Fig. 4. Cumulative changes, since 1990, in the global areas of cropland, croplands and pastures combined and forests according to the FAO. Note that forest area is plotted negatively; that is, as cumulative forest loss. The data are from FAO (2009) (<http://faostat.fao.org/site/377/default.aspx#ancor>). In the early 1990s, agricultural lands were converted from both forests and non-forests; after 2000 forests were being lost more rapidly than agricultural lands were expanding. Much of these dynamics are driven by changes in pasture, which are not well documented.

cropland and pasture to calculate emissions. For the tropics, as a whole, the net loss of forest area was more than  $2\times$  greater than the net increase in agricultural lands.

The discrepancy between rates of agricultural expansion and forest loss raises the question of what the forests are becoming if not croplands or pasture. Explanations include the possibility that old agricultural lands, no-longer-fertile, are being abandoned yet not returning to forests, while at the same time forests are being converted to new agricultural lands to replace those abandoned. Forest area declines, but agricultural lands do not increase equivalently.

Another explanation is that forests are being converted to areas of shifting cultivation. The FAO considers the conversion of forests to shifting cultivation as deforestation but recognizes only the cropping phase (and fallows 5 years or less) of shifting cultivation as part of permanent agriculture. Thus, deforestation increases croplands, but only temporarily. After 5 years, the fallows are counted as neither forest nor cropland. This is the hypothesis Houghton and Hackler (2006) assumed to define the rate of expansion of shifting cultivation in regions of Africa. If correct, the hypothesis suggests that changes in the area of croplands and pastures are not good surrogates for deforestation. Alone, they are not sufficient to account for the emissions of carbon associated with forest loss. All of the explanations are based on the assumption that the trends are accurate enough that the differences are, in fact, real.

It is difficult to evaluate how accurate the FAO statistics are. The FRAs base their estimates of deforestation on surveys supplied by individual countries. Rates of deforestation reported in one FRA are often revised in subsequent assessments 5 to 10 years later, suggesting that the more recent estimates are better than the earlier ones. Revisions go in both directions; sometimes they are substantial. Revisions (in 2005) to their 2000 estimate of tropical forest loss during the 1990s reduced the calculated net emissions from  $2.2 \text{ PgC yr}^{-1}$  (Houghton, 2003) to  $1.5 \text{ PgC yr}^{-1}$  (this study).

Actually, the major revision in the 2005 FRA was not in the rate of deforestation but in the area of plantations in India. A lower (revised) estimate of 2000 plantation area in the 2005 FRA indicated a higher (revised) area of natural forest and, thus, a lower rate of deforestation than indicated in the 2000 FRA. The revision was nearly  $2 \text{ million ha yr}^{-1}$ , or  $\sim 70\%$  of the deforestation rate for South and Southeast Asia. It is not clear whether the revision corrected an earlier error, or whether the definition of plantations changed.

Grainger (2008), noting that FAO estimates of total forest area apparently remain nearly constant inventory after inventory while rates of deforestation are on the order of  $10\text{--}13 \text{ million ha yr}^{-1}$ , suggests that the FAO data are unreliable. He also hypothesizes that new forests are returning (unrecorded natural reforestation) and offsetting the areas deforested. Evidence from individual case studies across the tropics (Hecht and Saatchi, 2007; Fukushima et al., 2008; Williams et al., 2008) support this hypothesis, but the argument that forest area is expanding at a rate high enough to balance deforestation seems unlikely. Analyses of change in forest area with satellites show much lower rates of regrowth than of deforestation (DeFries et al., 2002; Achard et al., 2004; Steininger et al., 2008), suggesting a third explanation for the apparent lack of change in tropical forest area: rates of deforestation (and reforestation) are better known than the absolute areas of forests, which are subject to changing definitions. Using successive estimates of total forest area has never been an accurate way for estimating changes in forest area (Allen and Barnes, 1985).

If the deforestation rates reported by the 2005 FRA are correct, deforestation is occurring more rapidly in the tropics than the expansion of permanent agriculture, and the net flux of carbon from land-use change is  $\sim 1.5 \text{ PgC yr}^{-1}$  (Table 2). On the other hand, if the FRA estimates of deforestation are overestimates, the emissions of carbon are closer to  $\sim 1 \text{ PgC yr}^{-1}$ . Including the emissions of carbon from the burning of peat associated with deforestation in Southeast Asia would increase the estimates to



1.8 and 1.3 PgC yr<sup>-1</sup>, respectively. At present, the uncertainty is not resolved.

Van der Werf et al. (2009a) have advanced a new method for calculating emissions of carbon from land-use change based on satellite observation of fires. An advantage of using fires is that estimates may be obtained annually, while estimates based on measured changes in forest area, or inventories, are at 5- to 10-year intervals. However, although fire is highly correlated with forest conversion in some regions (e.g. Langner et al., 2007), it may not be correlated in all regions or under all types of land-use conversions (Morton et al., 2008). More work is needed before fires, even those burning in tropical forests, can be used to estimate carbon emissions from land-use change. Harvest of wood and other management practices do not include burning, yet alter carbon stocks.

### 3.3. Carbon stocks per hectare

Knowing which ecosystems (e.g. forests or grasslands) are converted to croplands and pastures and, in particular, the carbon densities of those lands prior to clearing is as important in calculating carbon emissions as rates of land-use change. For the spatial data sets described earlier (Ramankutty and Foley, 1999; Klein Goldewijk, 2001), the ecosystems cleared can be estimated with maps or models of natural vegetation. However, for maps without subgrid information (e.g. HYDE 2001), average carbon densities are assigned, while the types of vegetation converted may not be of 'average' density. For maps with subgrid information, rules may be defined for allocating specific agricultural types to different natural vegetation types. For the non-spatial analyses (Houghton et al., 1983; Houghton, 2003), the ecosystems converted were determined from spatially coarse maps of agricultural lands and natural lands or, where such maps were lacking, from assumptions about which ecosystems were likely to have been converted. For either approach, average carbon stocks are assigned to each type of ecosystem.

*3.3.1. Measured carbon stocks.* There are two problems with assigning carbon stocks to ecosystems. First, for many parts of the world the mean biomass of forests is poorly known. Seven different maps of aboveground biomass for the Brazilian Amazon, for example, yielded estimates of mean biomass that varied by a factor of two and yielded distributions of biomass that placed high- and low-biomass forests in different regions (Houghton et al., 2001).

Secondly, carbon stocks vary, as a result of environmental heterogeneity as well as disturbance and recovery, almost as much within one vegetation type as they do across vegetation types, and the concern is that sites chosen for clearing are not random with respect to carbon stocks. Ecosystems with systematically small or large stocks may be selectively targeted. Analyses of deforestation using maps of high-resolution biomass suggest that deforestation is occurring in forests with smaller aboveground biomass than the average forests in the region. This is true for the

forests in the arc of deforestation in Brazil (Loarie et al., 2009) and for forests in Central Africa (Laporte et al., 2004). In Brazil, the lower stocks are environmentally explained; in Africa, they result from former use of the land for either logging or shifting cultivation. The distinction is important because the latter implies a release of carbon sometime in the past. The work of Loarie et al. (2008) is particularly relevant for this discussion because deforestation seems to have been moving over the last decade into denser forests, such that, even if rates of deforestation were constant, emissions would be increasing.

As rates of deforestation become better known through systematic use of medium resolution satellite data, uncertainties in aboveground biomass will dominate the uncertainty of flux estimates. At present, the two factors (rates of land-use change and carbon density) contribute about equally to the range of flux estimates (Houghton, 2005; Houghton et al., 2009). In fact, revisions to estimates of mean forest biomass in successive FRAs of the FAO are much greater than revisions to estimates of deforestation rates, suggesting that carbon stocks contribute a greater share of the uncertainty in flux estimates.

*3.3.2. Modelled carbon stocks.* An alternative to direct measurement of carbon density is modelling it, including both its variation across environmental gradients and its variation over time in response to disturbance and recovery. Most of the recent analyses of land-use change have modelled biomass and soil carbon densities, using different terrestrial models (Strassmann et al., 2008; Pongratz et al., 2009; Shevliakova et al., 2009) (Table 3). The differences among modelled estimates of carbon emissions from land-use change appear to be less dependent on the model used and more dependent on the types of land-use change and management included (Jain and Yang, 2005).

A possible exception to this agreement among models, as discussed earlier in the context of spatial data, is the discrepancy in emission estimates that results because some studies do (Pongratz et al., 2008, 2009) and others do not (Shevliakova et al., 2009) take into account the preferential allocation of pasture to natural grassland. Until the last few decades, humans grazed animals on grasslands, if available, before they would clear forest for pasture. This allocation rule, whether it is attributed to model or data, leads to lower, but more realistic, emissions.

### 3.4. Fate of carbon stocks after disturbance (legacies)

Finally, even if both rates of land-use change and carbon densities are known (or modelled correctly), there remains the challenge of determining the fate of carbon stocks following deforestation or harvest. Some of the carbon initially held on the sites cleared or harvested is released to the atmosphere immediately and some, gradually. Although the fractions released immediately and over time make little difference in the long term, they do affect year-to-year variation and decadal trends in emissions. The carbon accumulating in woody debris and wood products lessens the emissions in the year of disturbance but increases

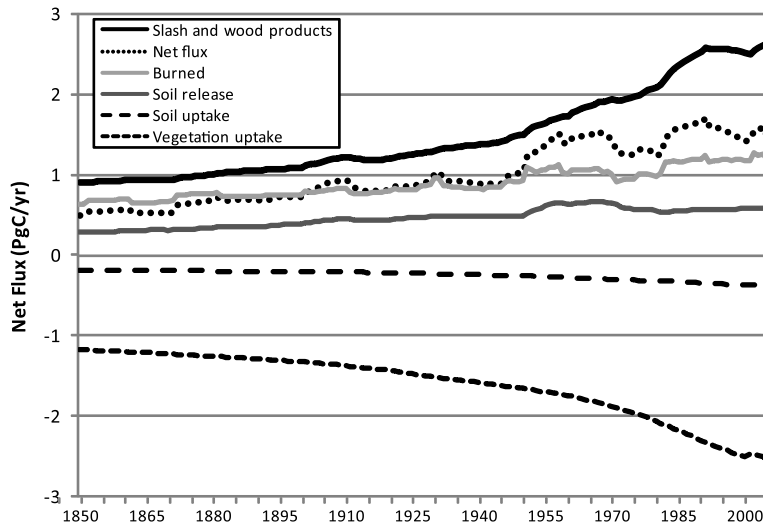


Fig. 5. Annual sources and sinks of carbon from global land use and land-use change, distinguishing between immediate and delayed fluxes. Immediate emissions occur at the time of disturbance (e.g. fires, fuelwood). Delayed emissions result from the decay of wood products, soil organic matter, and debris left from earlier disturbances. Delayed sinks result from the uptake of carbon in secondary or plantation forests established in previous years.

the emissions in subsequent years, just as the accumulation of secondary forests over time increases the carbon sink.

These legacies are important. Less than half of the carbon lost annually from deforestation in the Brazilian Amazon, for example, was calculated to have been released from the burning associated with deforestation (Houghton et al., 2000). Most of the emissions were from wood not burned and, thus, accumulated from earlier deforestation events. The percent burned is variable, however. A new study in the 'arc of deforestation' in Brazil reports a higher burning efficiency (65% of aboveground biomass) but also a higher rate of charcoal formation (6% of aboveground biomass) than earlier studies, presumably as a result of the drier conditions and greater number of small trees (Righi et al., 2009). Using decay rates obtained from the literature, Houghton (this study) found that delayed emissions in the tropics were approximately twice the magnitude of immediate emissions (Fig. 5). Essentially, 100% of the sinks were delayed, reflecting the generally longer time required for carbon accumulation (during recovery) than for carbon release (following disturbance).

Figure 5 also shows the annual uptake of carbon by the vegetation and soils of secondary lands, including the fallows of shifting cultivation. The total accumulation of carbon over the period 1850–2005 (288 PgC) was nearly twice the net emissions of 156 PgC. For the tropics alone, the average annual sink in secondary forests between 1990 and 2005 ( $1.5 \text{ PgC yr}^{-1}$ ) was of the same magnitude (opposite sign) as the net release from all changes in land use. Shevliakova et al. (2009) found an average annual sink of  $0.35\text{--}0.6 \text{ PgC yr}^{-1}$  in secondary tropical lands, 2.5–5 times smaller. Accounting for secondary forests does not explain why the net source reported by Shevliakova et al. (2009) was smaller than that reported by Houghton (this study). Instead, the major difference seems to be the rates of deforestation used in the two studies.

Another difference among analyses is the effect of cultivation on soil organic carbon. The emissions estimated by Pongratz et al. (2009) are lower than other estimates because their process model (JSBACH) caused carbon to accumulate in cropland soils (Reick et al., 2010) rather than to be lost. A 25–30% loss of organic carbon from the upper metre of soil as a result of cultivation has been found in a number of reviews (Schlesinger, 1986; Johnson, 1992; Davidson and Ackerman, 1993; Post and Kwon, 2000; Guo and Gifford, 2002; Murty et al., 2002). There is some variation about this average, but the loss is broadly robust across all ecosystems, despite the variety of soil types, cultivation practices and decomposition processes. The process model used by Shevliakova et al. (2009) reproduced the loss of soil carbon; they report that the carbon lost from soils accounted for  $\sim 37\%$  of the total emissions in both experiments. Houghton's estimate was lower:  $\sim 25\%$ , and the model used by Strassmann et al. (2008) was lower still,  $\sim 13\%$  of total emissions. These differences among estimates are attributed here to the use of different data and assumptions. They might also be described as resulting from different models.

Some of the organic carbon lost from the top metre of soil with cultivation may be transported downstream and deposited in the sediments of bottomlands, rivers, ponds or the coastal ocean. To the extent that soil carbon is not released to the atmosphere, but moves laterally, the emissions estimated by Houghton (this study) and Shevliakova et al. (2009) may be overestimated. A recent study estimated the net effect of erosion and deposition to be a net sink equivalent to about  $0.7 \text{ PgC yr}^{-1}$  (Berhe et al., 2007). If all of this flux is a steady-state flux related to farming, the sink of  $0.7 \text{ PgC yr}^{-1}$  helps explain a significant fraction of the residual terrestrial sink. If, in addition, the sink includes some of the observed loss of carbon from the top metre of soil, then the emissions of carbon to the atmosphere from land-use change have been overestimated. The export of alkalinity by

rivers (Raymond and Cole, 2003) is another example of a change in terrestrial carbon that results from land-use change but has not been counted in these analyses.

### 3.5. Synthesis

The general factors believed to account for differences among estimates are discussed earlier. Here, the individual estimates are compared in slightly more detail. For example, the estimate by Pongratz et al. (2009) is generally lower than the others, because they did not include wood harvest and shifting cultivation (which raised emissions by 32–35% in the analyses by Shevliakova et al., 2009), because their pasture areas and changes in them were lower, because they preferentially allocated cropland expansion to pastures where the two land uses overlapped in space, and because cultivated soils were a net sink for carbon rather than a net source.

Wood harvest and shifting cultivation were not included in the analyses by Strassmann et al. (2008), either, but none of the other factors that may have lowered the estimates of Pongratz et al. (2009) applied to Strassmann et al. (2008). On the contrary, not allowing croplands to come from pastures probably increased the emissions by Strassmann et al. (2008) and Shevliakova et al. (2009) relative to Pongratz et al. (2009) and Houghton (this study).

The two analyses by Shevliakova et al. (2009) (HYDE and SAGE/HYDE) are not independent, varying only in the historical expansion of croplands. The largest differences between Shevliakova et al. (2009) and Houghton (this study) result from different data on recent changes in the areas of cropland and pasture Fig. 3. The HYDE and SAGE estimates (Hurtt et al., 2006) are based on much lower rates of increase in agriculture than the rates used by Houghton (this study) or reported by the FAO. Houghton's estimates for cropland and pasture change were often based on data from the FAO, but the rates of change shown by FAO and Houghton are not identical, in part because of recent revisions in FAO estimates.

A more detailed intercomparison of these recent analyses might isolate the net emissions by region or by type of land use and land-use change, find the average carbon stocks assumed to have been affected, divide the net emissions into those from living vegetation, soil, wood products, and harvest residues, etc. to identify more precisely areas of major agreement and disagreement.

Such an intercomparison is beyond the scope of this review, but the net emissions, alone, allow for some interesting comparisons (Fig. 2). For example, before ~1950 the estimates all show generally increasing emissions. Although variation exists, trends are more consistent before ~1950 than after. It seems ironic, at first, that the estimates are most similar during the time when data are least available, and most dissimilar when real data exist. The resolution of the irony is probably that, when data are limited, investigators have relied on the same data and assumptions,

while, with abundant data, investigators choose different sources of information. The variability after ~1950 is not only among estimates but within individual estimates. The range of annual estimates generally varies between about  $\pm 0.2$  and  $\pm 0.4$  PgC yr<sup>-1</sup> of the mean. The close agreements in 1955, and to a lesser extent ~2000, are accidents; the years around them include the largest differences among estimates.

There are two challenges to estimating the net flux of carbon from land use and land-use change. One is measuring or documenting the changes known to affect carbon stocks (e.g. deforestation and wood harvest). Most of this review has been concerned with this challenge: how much agreement is there in recent estimates? Figure 2 suggests a range generally less than  $\pm 0.4$  PgC yr<sup>-1</sup> from the mean, and there is clearly room for improvement, especially over the last 50 years.

The second challenge is more difficult. It requires accounting for changes not yet known, perhaps not even identified. Agricultural, forestry, and fire management practices are examples of known activities. Including the emissions of carbon from peat drainage and burning in Southeast Asia, for example, would increase all recent estimates by 0.1–0.3 PgC yr<sup>-1</sup> (Achard et al., 2004; van der Werf et al., 2008, 2009b). Including the conversion of lands to settled or urban lands might also increase estimated emissions, while including erosional and depositional fluxes of carbon might decrease net emissions by 0.7 PgC yr<sup>-1</sup> (Berhe et al., 2007). What other management practices, so far overlooked, are altering terrestrial carbon stocks? How much of the residual terrestrial flux is an incomplete understanding of land use and land-use change? The answer may have to await a global analysis based on full-area and full-carbon accounting (Section 5).

## 4. Implications for the 'residual terrestrial carbon sink'

As noted earlier, the net flux of carbon from land-use change is not the net terrestrial flux, but it helps define the residual terrestrial sink, which is calculated by difference (the annual sources of carbon to the atmosphere from fossil fuels and land-use change minus the annual increase in the atmosphere and the annual sink in the oceans). The residual terrestrial sink has been increasing in proportion to total anthropogenic emissions (Canadell et al., 2007; Le Quéré et al., 2009). The mechanisms responsible for the residual are uncertain, yet important because different mechanisms have different potentials to affect future concentrations of CO<sub>2</sub> in the atmosphere.

Three general factors are thought to account for the residual terrestrial sink. Most explanations focus on environmentally induced changes in metabolism, driven, for example, by CO<sub>2</sub> fertilization of photosynthesis, higher rates of plant growth from deposition of fixed nitrogen or climate-related changes in temperature and moisture on growth and decay.

A second possibility is that disturbance regimes have changed, such that terrestrial ecosystems in recent decades have been recovering from past disturbances. Past disturbances may have loaded the landscape with numerous secondary forests, where the accumulations of carbon in growth exceed the emissions from decay. Support for such a shift comes from a global analysis of charcoal in soil profiles (Marlon et al., 2008). Using sedimentary charcoal records from six continents over the past two millennia, Marlon et al. (2008) found that global biomass burning rose sharply between 1750 and 1870 and then declined abruptly after 1870. The decline over the last ~140 years occurred despite higher global surface temperatures and increased population growth, presumably because of the intensification of land and fire management, worldwide. The decline in burning, by allowing disturbed forests to recover, may help explain the current terrestrial carbon sink, but would not imply its long-term persistence. Indeed, the most recent decades show increased areas burned in North American forests (Stocks et al., 2003; Kasischke and Turetsky, 2006; Westerling et al., 2006).

Finally, some fraction of the residual terrestrial flux of carbon may result from errors and omissions in the flux attributed to land-use change (or errors in the other terms of the carbon equation). Reducing the uncertainty of the net flux attributable to land-use change and management will indirectly provide a more accurate estimate of the residual sink.

## 5. Current estimates are not indicative of how well we *could* know the flux of carbon from land use and land-use change

It is important to recognize that the variability of estimates of annual emissions and the ambiguity of recent trends do not represent the precision or accuracy currently possible.

### 5.1. Present capabilities

A systematic evaluation of deforestation rates over the last 35+ years is possible using the archive of Landsat data that dates back to 1972. One would not have to cover the entire tropics but, instead, focus on those areas where deforestation has been greatest. If the FRAs are approximately correct, Brazil and Indonesia, together, account for about 60% of the carbon emissions from land-use change between 1990 and 2005 (Houghton, 2009), and that estimate does not include the emissions from peat drainage and fires associated with some of the deforestation in Southeast Asia (Hooijer et al., 2009). Random sampling (FAO 1996) and stratified random sampling, based on either active areas of deforestation identified with knowledge from environmental and forest experts in each region (Achard et al., 2002, 2004) or medium resolution satellite imagery, such as MODIS (Hansen et al., 2008), might also be used in lieu of wall-to-wall coverage of all forests. Proposals for the monitoring of tropical deforestation have received increased attention in recent years

(e.g. Mayaux et al., 2005; Achard et al., 2007; Steininger et al., 2009).

Satellite data are also being used to estimate above-ground biomass at high spatial resolution (Gibbs et al., 2007; Baccini et al., 2008; Goetz et al., 2009), so that actual, rather than mean, carbon densities might be assigned to the areas deforested. Scientists are constructing more direct algorithms for calculating aboveground biomass density from optical (MODIS), radar (ALOS/PALSAR and lidar (ICESAT) data calibrated with field measurements.

### 5.2. Planned capabilities

New satellites are being designed for measurement of above-ground biomass from space. For example, the United States (NASA) is working to launch the DESDynI mission in ~2017 and Europe (ESA), the BIOMASS mission in a comparable time frame. Both missions have a goal of determining aboveground forest biomass at high spatial resolution (Bergen, 2006; Zebker et al., 2007; [www.cesbio.ups-tlse.fr/us/indexbiomass.html](http://www.cesbio.ups-tlse.fr/us/indexbiomass.html)).

A satellite that could measure the vertical structure of forest and woodland canopies with enough detail to obtain reliable estimates of aboveground carbon density would improve enormously the average values now being used to calculate emissions (Houghton et al., 2009). Belowground stocks of carbon would have to be modelled, but the major changes (aboveground) would be observed directly.

More fundamentally, if a satellite could make repeated measurements of aboveground biomass density at the same location, the net flux of carbon could be determined more directly with a different approach. The procedure of measuring changes in land use and then assigning carbon densities to observed changes in area could be replaced with an approach that 'simply' measured changes in aboveground carbon (Houghton and Goetz, 2008). The simplified approach, first, would be more comprehensive, allowing changes from both degradation and growth to be observed without requiring identification of land use; and second, would do away with the need for arbitrary definitions of forest and deforestation, which hamper international agreements. Emphasis would be on changes in carbon density. The drawback of such an approach is that it would not, by itself, permit observed changes to be attributed to land use or land-use change, as opposed to indirect or natural effects. Nevertheless, systematic use of existing and planned satellite data could greatly improve current estimates of the flux of CO<sub>2</sub> from land use and land-use change.

## 6. Summary

From 1850 to 2000, land use and land-use change released an estimated 108–188 PgC to the atmosphere (Table 1), or about 28–40% of total anthropogenic emissions of carbon (274 PgC from fossil fuels) (Strassmann et al., 2008). The upward trend in

emissions to ~1950 was obtained in each analysis. In contrast, the ambiguity since then precludes a clear indication of trend in the airborne fraction (Canadell et al., 2007; Le Quéré et al., 2009; Knorr, 2009). The net flux from land use and land-use change over the recent period 1950–2005 is estimated to have ranged between 0.8 and 1.6 PgC yr<sup>-1</sup>.

The range results from four factors, which are as follows:

1. The processes and activities included in the analyses computing the flux.
2. Uncertain rates of land-use change and changes in management.
3. Uncertain density of carbon stocks in the areas affected by management.
4. Uncertain fate of affected ecosystems and carbon stocks, for example, rates of forest growth and the partitioning of disturbed biomass among pools with rapid to slow release rates.

The fourth factor is less important in the long term, because total emissions are the same, just released over longer or shorter periods. For recent trends, however, it remains important. The first factor can be overcome with intercomparisons more detailed than provided in this review. The second and third factors can be improved with systematic use of both existing and anticipated data from satellites in combination with ground measurements. Improved estimates would help establish, more than any other improvement, whether the airborne fraction is changing. It is important to note that recent emissions trends in land use and land-use change are determined not only by trends in tropical deforestation, but by trends in land use outside the tropics, as well. It is dangerous to assume that the net flux of carbon from land use in temperate and boreal zones has remained nearly zero.

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