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Reconciling apparent inconsistencies in estimates of terrestrial CO_2 sources and sinks

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ABSTRACT

The magnitude and location of terrestrial carbon sources and sinks remains subject to large uncertainties. Estimates of terrestrial CO_2 fluxes from ground-based inventory measurements typically find less carbon uptake than inverse model calculations based on atmospheric CO_2 measurements, while a wide range of results have been obtained using models of different types. However, when full account is taken of the processes, pools, time scales and geographic areas being measured, the different approaches can be understood as complementary rather than inconsistent, and can provide insight as to the contribution of various processes to the terrestrial carbon budget. For example, quantitative differences between atmospheric inversion model estimates and forest inventory estimates in northern extratropical regions suggest that carbon fluxes to soils (often not accounted for in inventories), and into non-forest vegetation, may account for about half of the terrestrial uptake. A consensus of inventory and inverse methods indicates that, in the 1980s, northern extratropical land regions were a large net sink of carbon, and the tropics were approximately neutral (albeit with high uncertainty around the central estimate of zero net flux). The terrestrial flux in southern extratropical regions was small. Book-keeping model studies of the impacts of land-use change indicated a large source in the tropics and almost zero net flux for most northern extratropical regions; similar land use change impacts were also recently obtained using process-based models. The difference between book-keeping land-use change model studies and inversions or inventories was previously interpreted as a “missing” terrestrial carbon uptake. Land-use change studies do not account for environmental or many management effects (which are implicitly included in inventory and inversion methods). Process-based model studies have quantified the impacts of CO_2 fertilisation and climate change in addition to land use change, and found that these environmental effects are in the right order of magnitude to account for the “missing” terrestrial carbon uptake. Despite recent carbon losses due to fire and insect attack in Canada and Russia, the northern extratropical regions generally have been a net carbon sink, only partially due to land-use changes such as abandonment of agricultural land. In the tropics, inventory data and flux measurements in extant forests support the existence of an environmental or management sink that counterbalances the effect of deforestation. Woody encroachment in savannas may also be a significant (but as yet poorly quantified) cause of tropical carbon uptake.

1. Introduction

The global budget of CO_2 can be partitioned between terrestrial and ocean fluxes using simultaneous measurements of atmospheric CO_2 and O_2 (Keeling and Shertz, 1992; Bender et al., 1996; Keeling et al., 1996; Manning, 2001). The IPCC (Intergovernmental Panel on Climate Change) global budget based on this methodology (Table 1; Prentice et al., 2001) is broadly consistent with alternative estimates based on CO_2 and $\delta^{13}C$ measurements, and with ocean model

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Table 1. *The global carbon budget*

	IPCC[1]			Update	
	1980s	1990s		1980s	1990s
Atmospheric increase	3.3 ± 0.1	3.2 ± 0.1			
Emissions (fossil fuel, cement)	5.4 ± 0.3	6.3 ± 0.4			
Ocean–atmosphere flux	−1.9 ± 0.6	−1.7 ± 0.5	Ocean correction[4]	−1.8 ± 0.8	−2.1 ± 0.7
Land–atmosphere flux[2]	−0.2 ± 0.7	−1.4 ± 0.7		−0.3 ± 0.9	−1.0 ± 0.8
–Land-use change[3]	*1.7 (0.6 to 2.5)*	*Incomplete*	*This paper*	*0.9 to 2.8*	*1.4 to 3.0*
–Residual terrestrial sink	*−1.9 (−3.8 to 0.3)*	*Incomplete*		*−4.0 to –0.3*	*−4.8 to −1.6*

Positive values represent atmospheric increase (or ocean/land sources), negative numbers represent atmospheric decrease (ocean/land sinks).

[1] Prentice et al, 2001, IPCC Third Assessment Report.

[2] The net land atmosphere flux consists of emissions due to land-use change as estimated by models, and sinks due to other processes, calculated as a residual.

[3] The IPCC estimated range for the land use change flux is based on the full range of Houghton's book-keeping model approach (Houghton, 1999; Houghton et al., 1999; Houghton et al., 2000) and the CCMLP ecosystem model intercomparison (McGuire et al., 2001). In the update, the 1980s estimate is the full range of Houghton updated (Houghton, 2003) and CCMLP; while the 1990s flux is based on Houghton (2003) only as the CCMLP analysis only went up to 1995.

[4] Corrections based on the results of Bopp et al. (2002) for 1990–1996, interpolated to the whole 1990s by Le Quéré et al. (2003). This is similar to the results of Plattner et al. (2002) for ocean and land fluxes, respectively, of −1.7 ± 0.6 and −0.4 ± 0.7 in the 1980s and −2.4 ± 0.7 and −0.7 ± 0.8 in the 1990s.

results (Tans et al., 1993; Ciais et al., 1995; Battle et al., 1996; Trolier et al., 1996; Schimel et al., 1996; Rayner et al., 1999; Orr et al., 2001). The land–atmosphere flux was estimated by IPCC (Prentice et al., 2001) to have increased from −0.2 ± 0.7 PgC yr^{-1} in the 1980s to −1.4 ± 0.7 PgC yr^{-1} in the 1990s (negative signs denote loss from the atmosphere i.e. land uptake), with the early part of the 1990s a period of higher uptake compared to the later part (Prentice et al., 2001; Bousquet et al., 2000).

Recently, the IPCC budget has been corrected, based on the consideration of impacts of recent climate change on the outgassing of O_2 from the ocean. Warming has a direct effect on oxygen solubility that was considered in the IPCC budget; however, warming also leads to stratification of the ocean, reducing mixing and affecting biology. Various studies have estimated the total effect of warming to be 3 to 4 times higher than the solubility-only effects (Keeling & Garcia, 2002; Plattner et al., 2001; Bopp et al., 2002). Revised carbon budget estimates imply the ocean flux increased from the 1980s to the 1990s rather than decreased, a result more in line with other observational and ocean model estimates. Revised estimates presented in Table 1 are based on the estimates of Bopp et al. (2002) for the terrestrial flux of −0.3 ± 0.9 PgC yr^{-1} in the 1980s and −1.2 ± 0.9 PgC yr^{-1} for 1990 – 1996 (Bopp et al., 2002), which can be interpolated as a flux for the whole 1990s of −1.0 ± 0.8 PgC yr^{-1} (Le Quéré et al., 2003; this is similar to results from the analysis of Plattner et al., 2002). For comparison, estimates of the net terrestrial flux based on atmospheric CO_2 and $\delta^{13}C$ for the 1990s have ranged from −0.8 PgC yr^{-1} (Keeling and Piper, 2000) to −1.4 PgC yr^{-1} (updated calculation of Cias et al., 1995; Tans et al., 1989; and Trolier et al., 1996 as presented in Prentice et al., 2001).

The global net land–atmosphere flux is the sum of several poorly known fluxes generated by a variety of potential mechanisms including changes in land-use, more subtle changes in land management, disturbances such as fire and pest outbreaks, the fertilising effects of increasing atmospheric CO_2 concentration and reactive nitrogen deposition, and the effects of climate variability and change. The breakdown of the net land–atmosphere flux into these components is much more uncertain than the magnitude of the flux itself. It is particularly difficult to assess the impacts of individual mechanisms because of the potential for strong regional variations, and because in some cases they may be synergistic (e.g. CO_2 enrichment and N fertilisation; Lloyd and Farquhar, 1996; Oren et al., 2001) or antagonistic. Mechanistic uncertainties are compounded by controversy about the magnitude of recent growth enhancement (Spiecker et al., 1996; Caspersen et al., 2000; Oren et al., 2001; Joos et al., 2002), and the long-term effects of temperature change on carbon

Table 2. *Processes included in different methods of assessing regional and global terrestrial fluxes*

	"Top-down" atmospheric inversion models CO_2/O_2, $\delta^{13}C$	"Bottom-up" inventory	"Bottom-up" modelling approaches Book-keeping Houghton	Process models CCMLP
Land-use change	√ (*All land use changes*)	√ (*Primarily afforestation, reforestation, deforestation*)	√ (*Natural veg to cropland, forest to pasture, afforestation and harvest*[1]*, shifting cultivation*)	√ (*Natural veg to cropland*)
Land-management change	√	√	Limited[1]	×
Environmental change	√	√	×	√
Non-forest vegetation	√	×	√	√
Soils and products	√	Not usual	√	√
Process isolation	×	Limited	LUC	√

"Land-use change" = a change in cover type e.g. from forest to agriculture.

"Land management change" = a change in the way land is managed with no change in type of land cover, but a likely change in carbon density.

[1] Houghton's "land-use" change analysis included ongoing forest harvest and regrowth which could also be considered as "management." Due to regrowth, forest harvest did not make a large difference to the net flux results despite increasing rates of logging and harvest efficiency. For the USA only, Houghton additionally estimated the impacts of fire management on woody encroachment, and management of agricultural soils (low tillage).

losses from soils (Giardina and Ryan, 2000; Valentini et al., 2000; Janssens et al., 2001; Trumbore et al., 1996; Rustad et al., 2001; Luo et al., 2001). These uncertainties contribute to the divergence of model projections of terrestrial carbon fluxes under global change (Cramer et al., 2001; Prentice et al., 2001; Cox et al., 2000; Friedlingstein et al., 2001).

This paper briefly reviews four approaches to regional and/or mechanistic analysis of the global land-atmosphere flux, namely inverse modelling based on spatially distributed atmospheric CO_2 measurements, bottom-up inventory measurements, and two model approaches, a statistical or book-keeping approach and a process-based approach (Table 2). We compare estimates of global and regional terrestrial fluxes from all four approaches. We consider why the estimates are different, how the differences might be reduced, and what can be learned from these differences.

2. Methods for assessing the terrestrial carbon sink

2.1. *Atmospheric inverse modelling*

Regional fluxes of CO_2 from the land and oceans are reflected in the spatial and temporal patterns of CO_2 concentration in the atmosphere. The large-scale pattern of surface CO_2 fluxes that generated the observed concentration gradients can be estimated, albeit with sizeable uncertainties, by inversion of an atmospheric transport model. Prior knowledge of fossil fuel sources is needed. Because the inversion problem is underdetermined, prior estimates of regional land and ocean fluxes and their plausible uncertainty ranges are also required to constrain the results. Improvements in measurement calibration and an increase in spatial and temporal coverage of observations make this a potentially useful tool for estimating fluxes. Inverse modelling has the attraction that it implicitly estimates the total net flux, i.e. the flux generated by the sum of all mechanisms (natural and anthropogenic). A problem with the methodology is that, although there are now about 100 monitoring stations around the globe, they are not evenly distributed, and measurements over continents, particularly in the tropics, are few. The north–south partitioning of fluxes is reasonably well constrained due to the large concentration gradient in this direction (although partitioning between land and ocean fluxes remains difficult). However, there are still large uncertainties about the magnitude and location of net fluxes in the east–west direction because atmospheric mixing attenuates the east–west signal resulting in differences of only a few tenths of 1 ppm, an order of magnitude less than the north–south concentration gradient.

Intercomparisons of inversions (Heimann, 2001; Gurney et al., 2002) show a considerable spread of results at the regional scale. Differences in inversions can be due to the atmospheric transport model used, the spatial aggregation of the data (i.e. the number of regions considered), the temporal aggregation of the analysis (i.e. with/without analysis of the seasonal cycle), the set of observations considered (inclusion or exclusion of specific data points), and the prior assumptions of regional fluxes and their uncertainties. One sensitivity study (Peylin et al., 2002) used the same set of input data with three atmospheric transport models, three spatial aggregations and three temporal aggregations (monthly data + monthly inversion, annual data + annual inversion, monthly data + annual inversion). By altering these factors alone, the estimated carbon balance of North America during the 1980s ranged from an apparent source of 1.1 PgC yr^{-1} to an apparent sink of –0.9 PgC yr^{-1}. This wide uncertainty emphasises the caution needed in interpreting east–west gradients in concentration with too few CO_2 measurements.

2.2. *Inventory*

Direct measurements of changes in carbon stocks in vegetation and soils over large areas can be spatially aggregated to estimate regional fluxes (e.g. Dixon et al., 1994; UN-ECE/FAO, 2000; Goodale et al., 2002). Inventory methodologies, like atmospheric inversions, implicitly measure the sum of impacts due to all processes occurring at the measurement site such as changes in land use, management (stocking densities, etc.) and environmental conditions (CO_2, N and climate). Comparing affected and non-affected plots can indicate the impact due to a particular mechanism, but interpretation is often difficult. Inventory measurements provide a detailed assessment of changes in carbon stocks from which fluxes can be calculated, at a finer spatial scale than inverse model estimates. However, inventory data generally fall short of full carbon accounting: consideration of belowground biomass, soil carbon, litter and the fate of forest products is inconsistent; spatial and temporal heterogeneity is high, and not fully accounted for; and, to date, most inventories have been carried out in forests only.

The FAO (Food and Agriculture Organisation of the United Nations) has been compiling forest inventories since 1946, providing detailed data on carbon stocks. FAO recently synthesised inventory data in the Global Forest Resource Assessment (FAO, 2001) and calculated the impacts of forest changes on carbon flux in the Temperate and Boreal Forest Resource Assessment 2000 (UN-ECE/FAO, 2000). For the 2000 assessment, countries were requested to report aboveground and belowground live and dead biomass, but since the previous 1990 assessment only reported aboveground live biomass, belowground changes were not included in carbon flux results. Countries reported data for different years, but generally the period covered was from the mid-1980s to the mid-1990s.

A global inventory analysis compiled by Dixon et al. (1994) for the 1980s calculated fluxes from changes in above- and belowground biomass, soils and litter, supplementing available data with a book-keeping modelling approach based on that of Houghton et al. (1983, see later explanation) for tropical regions. A more recent analysis for Northern Hemisphere forests (Goodale et al., 2002) combined data from inventories (covering various periods, generally from the late 1980s to the early 1990s) with improved and more detailed conversion factors, and estimated changes in dead organic matter pools from a combination of inventory data and modelling. Goodale et al. (2002) also modelled changes in product pools based on harvest and conversion data, and residence times of products in use and in landfills. In addition to the studies mentioned above, many individual site and country studies exist, each differing somewhat in their methodology.

A further source of inventory data comes from the United Nations Framework Convention on Climate Change (UNFCCC, 2000). All Annex I (developed) countries are required to report greenhouse gas emissions from land-use change, forestry and agriculture according to IPCC (Intergovernmental Panel on Climate Change) guidelines. Interpretation of guidelines is variable, accounting methods differ, and not all countries report data on land use, therefore this data source is difficult to interpret. IPCC and FAO definitions and methodologies differ slightly as discussed in the IPCC Special Report on Land Use, Land Use Change and Forestry (IPCC, 2000).

2.3. *Flux measurements*

Eddy-covariance techniques are a unique data source for analysing temporal variability over a small ($\approx$1 km^2) region. The high time resolution ($<$1 h) permits elucidation of physiological processes, such as the dependence of gross primary production on light and the nature of physiological responses to environmental change (Baldocchi et al., 1988). Some preliminary studies have attempted to scale flux results up to regions (e.g. Valentini et al., 2000; Malhi and Grace, 2000). However, due to difficulties of scaling up to regional levels and decadal time-scales, regional flux extrapolations are not considered further in this analysis.

2.4. Bottom-up modelling

Approaches to modelling range from book-keeping models that track changes in plant and soil carbon stocks (Dixon et al., 1994; Houghton, 1999), to more complex process-based models that integrate knowledge of physiological and ecological processes to model the response of the system to environmental changes (Cramer et al., 2001; Schimel et al., 2000; McGuire et al., 2001).

Houghton's book-keeping model (e.g. Houghton et al., 1983; Houghton, 1999, 2003) considers the impacts of land-use change alone, based on reconstructed country/regional historical land use data from 1700 or 1850 to the present. Only those ecosystems directly affected by humans are considered: primarily conversion of natural vegetation to croplands, and forests to pastures (grazing lands), in addition to shifting cultivation, wood harvest and afforestation. Standard growth and decomposition curves are used to track the changes in live vegetation, dead organic matter and product pools. Harvested material is assumed to enter soil and product pools in prescribed proportions, with each pool having prescribed rates of turnover (1, 10 or 100 yr), thus current fluxes include a component of past land-use change. Impacts of environmental changes (climate, CO_2, N) on decomposition or growth are not considered in this approach.

The first multi- process-based model study to incorporate land-use change, and to examine the historical effect of land-use change and other processes on the global terrestrial carbon flux, was performed by the Carbon Cycle Model Linkage Project (CCMLP, McGuire et al., 2001). Four process models, incorporating a range of approaches, were used: HRBM (Esser et al., 1994), IBIS (Foley et al., 1996; Kucharik et al., 2000), LPJ (Sitch, 2000; Prentice et al., 2000) and TEM (Tian et al., 1999). Model experiments were carried out to determine the impacts of historical changes in land use, climate and CO_2. Each model was driven with the same land use, climate and atmospheric CO_2 concentration data, run on a 0.5° grid resolution from 1860 to 1992. The spatially explicit historical land use data compiled by Ramankutty and Foley (1999) was used to provide information on conversions between crops and natural vegetation. Conversions to pasture (grazing lands) or other land use/management changes were not considered. Documented changes in cropland areas were projected back in time spatially based on current cropland distribution. The type and distribution of the natural vegetation replaced was calculated by the two DGVMs (dynamic global vegetation models), LPJ and IBIS, and was prescribed by the other two models. The fate of cleared carbon in product pools was based on the estimates of Houghton et al. (1983), while growth and decomposition rates were calculated by the models and thus affected by environmental change.

Both the Houghton and CCMLP methodologies rely on land-use change estimates, which have high uncertainty. Historical data are sparse and must be reconstructed from different types of documentation. Current global land cover maps show poor agreement due to different definitions of cover types and inconsistent sources of data (DeFries and Townshend, 1994). Satellite imagery is a valuable tool for estimating land cover, and, despite problems with cloud cover and interpretation, mapping algorithms are steadily improving.

The fate of carbon in natural and managed systems (e.g. the effects of burning, harvesting and environmental change on decomposition and soil carbon dynamics) is a further area of uncertainty for both types of modelling. The movements of agricultural and wood products via trade have not yet been included; fluxes from these sources have been assumed to occur in the same location as their production. This could be a cause of error as, for example, the carbon displaced annually by global agricultural trade between countries may amount to 0.2 PgC yr^{-1} (Ciais et al., 2001).

3. Results

3.1. Recent flux comparisons (1980s)

Results (Fig. 1, Table 3) are presented principally for the 1980s as several of the key analyses were not complete for the 1990s; however, in some cases data were available only for the 1990s. Interannual variability in land and ocean fluxes is high, with atmospheric increase in CO_2 of individual years differing by as much as 3–4 Pg yr^{-1} within a decade, largely associated with interannual climate variability. This variability is imposed on longer-term trends and is assumed to be approximately averaged out on the decadal time scale. Definitions of geographic areas vary somewhat between analyses, but we have standardised them here as far as possible. Table 2 summarises the processes included in different methods.

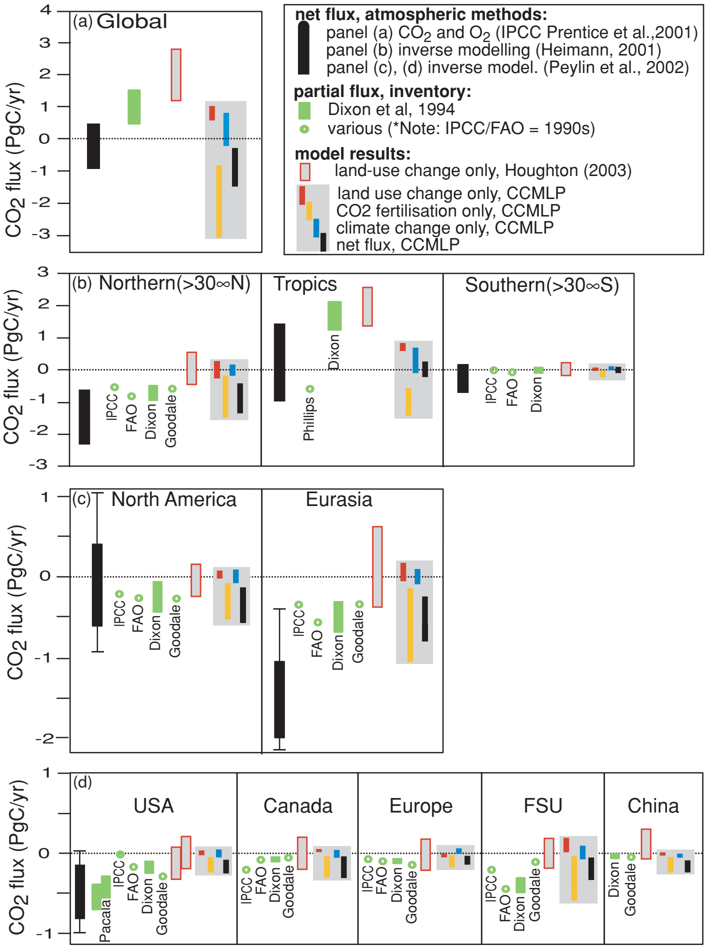

Fig. 1. Comparison of terrestrial CO_2 flux estimates from different methodologies during the 1980s. Positive numbers denote fluxes to the atmosphere; negative numbers denote uptake from the atmosphere. Not all estimates are for the 1980s as some data were only available for different time periods, but attempts have been made to use 1980s data as far as possible. For more information on data sources and time periods see Table 3 and text. For Houghton's model results in the USA, the right-hand bar represents land use change only the left-hand bar includes changes due to management that were calculated for the USA only (due to availability of data). For Pacala et al. (2001) USA, the right-hand bar represents inventory-based land-use/management, the left-hand bar includes other fluxes to estimate the total net flux.

3.1.1. Global analysis. Globally (Fig. 1a, Table 3) the net land–atmosphere flux based on CO_2 and O_2 analyses (Fig. 1a, black bar) was estimated as -0.2 ± 0.7 PgC yr^{-1} during the 1980s (Table 1, IPCC: Prentice et al., 2001) (negative values indicate atmospheric reduction or a land sink, positive values indicate atmospheric increase or a land source). The global forest inventory and land-use-based study of Dixon et al. (1994) (Fig. 1a, green bar) indicates a global source from forests due to land-use change (in all regions) and environmental/management impacts (extratropical regions only). Some of the difference between Dixon et al. (1994) and the atmosphere-based net budget could be due to sinks in non-forest lands and woody encroachment in the tropics.

Houghton's model using land-use change only (Houghton, 2003) (Fig. 1a, red and grey bar) finds a much larger source than Dixon et al. (1994). The difference points to possible contributions from sink processes that are captured in inventory measurements

Table 3. *Terrestrial fluxes of CO_2 ($PgC\ yr^{-1}$) estimated by different methodologies, regional/country breakdown*

PgC	IPCC[1] *emissions* 1990s	FAO[2] *inventory* 1980s–1990s live only	Dixon et al. (94)[3] *inventory* + *model* 1980s	Goodale et al. (2002)[4] *inventory* + *model* *Late 1980s/early 1990s*		Houghton[5] land use stats + model 1980s land use only	McGuire et al. (2001)[6] *process modelling* 1980s				Various[7] *atm. inversions* 1980s
				live only	live/dead/prod		Land use	Climate	CO_2	Total	
Europe	−0.08	−0.11	−0.09 to −0.12	−0.09	−0.14	−0.02 + 0.2	−0.05 to 0.00	−0.02 to +0.05	−0.18 to −0.03	−0.15 to −0.04	
Russia	−0.23	−0.43	–	+0.04	−0.11	–	+0.01 to +0.19	−0.06 to +0.12	−0.51 to −0.04	−0.30 to −0.04	
Russia + Other CIS = FSU[8]	–	−0.45	−0.30 to −0.50	–	–	+0.03 ± 0.2	+0.01 to +0.19	−0.07 to +0.10	−0.60 to −0.05	−0.35 to −0.07	
China	–	–	+0.02	−0.04	live only	+0.11 ± 0.2	−0.03 to +0.01	−0.05 to 0.00	−0.25 to −0.06	−0.25 to −0.10	
Japan	−0.03	−0.01	–	–	–	–	−0.01 to 0.00	0.00 to 0.00	−0.02 to 0.00	−0.02 to −0.01	
Others	–	–	–	−0.04	live only	–	+0.01 to +0.03	−0.01 to 0.00	−0.03 to −0.01	−0.03 to +0.02	Peylin et al.:
Eurasia total	**−0.34**	**−0.58**	**−0.49 ± 0.2**	**−0.13**	**−0.33**	**+0.12 ± 0.5**	**−0.05 to +0.18**	**−0.09 to +0.10**	**−1.07 to −0.15**	**−0.80 to −0.24**	**−2.3 to +0.42**
Canada	−0.21	−0.09	−0.08	+0.04	+0.04	+0.03 ± 0.2	+0.01 to +0.05	−0.06 to +0.04	−0.29 to −0.03	−0.32 to −0.03	Peylin et al.:
USA	−0.01	−0.17	−0.10 to −0.25	−0.11	−0.28	−0.12 ± 0.2	−0.03 to +0.03	−0.05 to +0.05	−0.24 to −0.05	−0.25 to −0.08	−1.02 to +0.03
North America total	**−0.21**	**−0.26**	**−0.26 ± 0.2**	**−0.07**	**−0.24**	**−0.09 ± 0.2**	**−0.02 to +0.07**	**−0.08 to +0.09**	**−0.53 to −0.08**	**−0.57 to −0.13**	**−0.86 to +1.14**
Northern extratropical total	**−0.55**	**−0.83**	**−0.74 ± 0.2**	**−0.21**	**−0.57**	**+0.03 ± 0.5**	**−0.06 to +0.26**	**−0.15 to +0.17**	**−1.61 to −0.23**	**−1.37 to −0.39**	Heimann: **−2.3 to −0.6**
Africa	–	–	+0.25 to +0.45	–	–	+0.30 ± 0.2	+0.08 to +0.22	+0.17 to +0.63	−0.49 to −0.23	+0.06 to +0.31	
South and Central America	–	–	+0.50 to +0.70	–	–	+0.77 ± 0.3	+0.26 to +0.39	−0.31 to −0.05	−0.74 to −0.22	−0.47 to −0.10	
Tropical Asia	–	–	+0.50 to +0.90	–	–	+0.88 ± 0.5	+0.12 to +0.33	−0.02 to +0.09	−0.27 to −0.08	−0.04 to +0.18	Heimann:
Tropical total	**–**	**–**	**+1.65 ± 0.4**	**–**	**–**	**+1.95 ± 0.6**	**+0.59 to +0.83**	**−0.12 to +0.66**	**−1.43 to −0.53**	**−0.19 to +0.26**	**−1.0 to +1.5**

Table 3. (cont'd)

PgC	IPCC[1] *emissions* 1990s	FAO[2] *inventory* 1980s–1990s live only	Dixon et al. (94)[3] *inventory + model* 1980s	Goodale et al. (2002)[4] *inventory + model* *Late 1980s/early 1990s*		Houghton[5] land use stats + model 1980s	McGuire et al. (2001)[6] *process modelling* 1980s				Various[7] *atm. inversions* 1980s
				live only	live/dead/prod	land use only	Land use	Climate	CO_2	Total	
Australia	+0.01	−0.04	trace	–	–						
New Zealand	<−0.01	<−0.01		–	–						
Southern extratropical total	**0.000**	**−0.04**	**trace**	**–**	**–**	**+0.01 ± 0.2**	**+0.01 to +0.07**	**−0.02 to +0.15**	**−0.23 to −0.05**	**−0.06 to +0.10**	Heimann: **−0.7 to +0.2**
Total global	**–**	**–**	**+0.9 ±0.4**	**–**	**–**	**+1.99 ± 0.8**	**+0.57 to +1.00**	**−0.24 to +0.79**	**-3.09 to −0.83**	**−1.47 to −0.29**	IPCC budget[9]: **−0.2 ± 0.7**

Positive values represent atmospheric increase (or ocean/land sources), negative numbers represent atmospheric decrease (ocean/land sinks).

[1] UNFCCC (2000). Official reporting of greenhouse gas fluxes by individual countries according to IPCC guidelines, Annexe 1 (developed) countries only. (i.e. Northern extratropical total missing China and some other countries).

[2] UN-ECE/FAO (2000). Temperate and Boreal Forest Resource Assessment calculated carbon flux from reported forest inventory data, aboveground changes in forest carbon stocks only. Other countries included in the Global Forest Resource Assessment (FAO, 2001) but carbon flux not calculated. Countries reported data for different years.

[3] Dixon et al. (1994). Range = uncertainty in analysis. Inventory analyses based largely on FAO data with some modelling for soils and litter pools, tropical data based on land-use change data with book-keeping model of Houghton due to lack of inventory data. For northern extratropical totals, means for countries were summed and an assumed maximum error bar of ±0.2 was used as in regional sums in original paper.

[4] Goodale et al. (2002). Data notes for live vegetation change: China - sequential inventories (Fang et al., 2001), specific conversion factors (Fang et al. 1998); Europe - (excluding woodlands) sequential FAO reports (Kuusela 1994, UN-ECE/FAO 2000), simple conversion factors (IPCC 1996); Coterminous US - (timberlands only) sequential inventories supplemented by age-class models (Birdsey and Heath, 1995, U.S. Government, 2000); Canada (Kurz and Apps 1999) and Russia (Nilsson et al. 2000, Shvidenko et al. 2000) were derived from syntheses of available inventory data, stand models, and information on the extent and dynamics of forest disturbances by fire, insects, and harvests. "Others" includes Japan, Baltic states, and CIS other than Russia (UN-ECE/FAO, 2000). Time period variable.

[5] Houghton (2003). range = uncertainty in analysis. "Africa" includes Houghton's "North Africa and Middle East." "Southern extratropical total" = Houghton's "Pacific Developed" which, in addition to Australia and New Zealand, includes Japan, N & S Korea and Taiwan (part of temperate Asia in other analyses), and Papua New Guinea and Oceana (part of "Tropical Asia") - but contribution from these countries is small. "China" includes Mongolia (part of temperate "others" in other analyses), contribution small.

[6] McGuire et al. (2001). range = range of model results. "Africa" includes North Africa and Middle East.

[7] Atmospheric inversion of Peylin et al. (2002) sensitivity study using three transport models, three spatial aggregations (numbers of regions) and three temporal aggregations (monthly.seasonal data/inversion), results for monthly data and seasonal inversion ignored for this table as authors consider this combination inappropriate (Peylin et al., 2002). In Fig. 3 the solid bar shows 1 standard deviation round the mean of the results, and the error bars show the full range (as given in this table). Heimann (2001) is an intercomparison of several inversion studies. The global IPCC budget (Prentice et al., 2001) based on CO_2/O_2 measurements is shown for comparison.

[8] Some analyses reported results for Russia only, while others reported results for Russia + the Commonwealth of Independent States (CIS), which collectively equal the Former Soviet Union (FSU).

[9] Note the IPCC budget has been revised due to corrections for temperature effects on ocean outgassing, see Table 1, the revised number for the 1980s is 0.3 ± 0.9 PgC yr^{-1}.

in extratropical regions (e.g. due to management, increasing CO_2 concentration, reactive N-deposition and climate), from soil and product emissions included in Houghton's analysis but not captured by the inventories (e.g. emissions from past land-use changes in slower turnover product and soil pools), or from differences in land-use change data used in different analyses.

The CCMLP model results (McGuire et al., 2001) find a global source due to land-use change (Fig. 1a, red bar) much smaller than that of Houghton. CCMLP additionally calculated a large sink due to CO_2 fertilisation (yellow bar), and a small source due to climate change (blue bar). Assuming a global NPP of around 60 PgC yr^{-1} (Saugier and Roy, 2001), the growth enhancement due to CO_2 fertilisation predicted by the models was about 3% of NPP for the 1980s. The total net flux estimated in the CCMLP analysis, including all processes (black bar: climate + CO_2 + land use), is in broad agreement with atmospheric analyses. The contribution of nitrogen deposition (not included in the CCMLP analysis) may be an additional sink ranging from –0.2 GtC yr^{-1} (Nadelhoffer et al., 1999) to as large as -1.31 to -1.81 GtC yr^{-1} globally in the 1980s (Holland et al., 1997). The effects of nitrogen deposition and increased atmospheric CO_2 on plants is synergistic, and has been estimated to account for a combined net uptake of -2.4 PgC yr^{-1} for 1990 (Lloyd, 1999).

3.1.2. Latitudinal breakdown. Northern extratropical flux (>30°N approx., Fig. 1b, Table 3): Inverse modelling results from an intercomparison analysis (Heimann, 2001) estimate a net terrestrial sink in the 1980s of -0.6 to -2.3 PgC yr^{-1} (Fig. 1b, black bar). Land-use change model studies, in contrast, find a zero net flux. CCMLP estimated an additional sink of -0.2 to -1.6 PgC yr^{-1} due to CO_2 fertilisation, while climate variations had no large net impact.

Inventory studies provide independent evidence of a net sink, and are in close agreement with each other (Dixon et al., 1994; UN-ECE/FAO 2000; UNFCCC, 2000; Goodale et al., 2002). Individual inventory studies indicate increasing growth rates and maximum size of mature forests (Spiecker et al., 1996), possibly due to changes in forest management (silvicutlural techniques, harvest methods, etc.), and environmental impacts (CO_2, N and climate). Local-scale flux studies also find sinks in mid-latitude forests (e.g. Valentini et al., 2000; Jarvis et al., 2001).

The total net flux in CCMLP and the inventory estimates are consistent with each other, but are at the smaller end of the range of atmospheric inversions. The difference between atmospheric inversion results and other (bottom-up) methods is an indication that perhaps only half of the net terrestrial flux is accounted for by forests (inventory estimates) or by processes included in the CCMLP models. Processes not considered in models include: fire suppression leading to woody encroachment (estimated to have resulted in a CO_2 sink of up to -0.17 PgC yr^{-1} in the USA during the 1980s, Houghton et al., 1999), recovery from past natural disturbance, sedimentation and spatial redistribution of carbon in products. The net export of agricultural products was estimated to result in a small sink of -0.1 PgC yr^{-1} north of 40°N, which is compensated by a release of the same magnitude south of this latitude (Ciais et al., 2001). A full analysis for woody products is not yet available, but Canada, for example, exports about two-thirds of its cumulative wood product pool (Apps et al., 1999). In addition, differences between the net flux simulated by process models and by the atmospheric inversions might be caused by background processes occurring within continental areas that are captured by the atmospheric inversions only, such as uptake of carbon during weathering processes on land and transport carbon from land areas to the ocean via rivers (approximately 0.8 PgC yr^{-1} globally, about half of which is from weathering processes) (Prentice et al., 2001).

Tropical flux (30°S to 30°N approx., Fig. 1b, Table 3, includes all of Africa and the Middle East for inventories/models): Tropical flux estimates are uncertain due to lack of spatial coverage of all types of data, high heterogeneity and rapid rates of change. Despite the large ranges of uncertainty, the differences between land-use change model studies (0.6 to 2.6 PgC yr^{-1}) and inverse model results (-1.0 to 1.5 PgC yr^{-1}) for the 1980s imply likely sinks in the tropics due to other processes. This inference is supported by inventory studies in mature tropical forests implying a sink of up to -0.6 PgC yr^{-1} in Latin America (Phillips et al., 1998), although there has been some controversy regarding this result (Clark, 2002; Phillips et al., 2002), and flux studies at tropical forest sites (Grace et al., 1995; Malhi and Grace, 2000).

The inventory results of Dixon et al. (1994) are quite similar in the tropics to those of Houghton (2003). This is to be expected, as Dixon et al. (1994) adopted Houghton's book-keeping methods (due to lack of inventory data for the tropics). Differences between the land-use change only results of Houghton and of CCMLP are most pronounced in the tropics, and are examined in more detail below. CCMLP results indicate climate change resulted in a small source of CO_2 in the tropics due to the effects of drought, high temperatures and fire (where included in the models), while CO_2 fertilisation produced a large sink, resulting in a total net flux around the mid-range of the atmospheric inversion results, fluctuating around zero. Additional sinks in other ecosystems currently neglected by the modelled land-use and forest inventory based calculations could account for large fluxes where non-forest lands are extensive and subject to a high degree of human influence, such as woody encroachment in African savannas.

Southern extratropical flux ($>30°$S approx., Fig. 1b, Table 3): Southern land areas are small compared to the tropics and northern latitudes, and so should not produce a strong atmospheric signal. Inventory studies find a net flux close to zero. Changes in the fire regime have caused woody encroachment in savannas/rangelands that is not accounted for in most forest inventories. A sink of -0.53 tC ha^{-1} yr^{-1}, or up to -0.04 PgC yr^{-1} for all of Queensland, has been estimated due to this phenomenon during the 1980s (Burrows et al., 2002).

3.1.3. Regional and country breakdowns: Northern extratropical zone. Greater data availability at northern extratropical latitudes makes more detailed analyses in this zone possible. However, there is still controversy regarding the contribution of different regions and countries to the net flux. Different processes are likely to be important in different regions: Inventory and model studies find a significant contribution to the recent northern sink from historical changes in land use such as abandonment of agricultural lands to forest in the USA, Europe and China over the last century (Fang et al., 2001; Pacala et al., 2001; Goodale et al., 2002); Canada and parts of Russia have recently suffered forest loss due to fire and insect attack (Kurz and Apps, 1999; Nilsson et al., 2000; Shvidenko and Nilsson, 2002); climate change benefits more northern regions due to an extended growing season but may adversely affect more southern regions due to increased drought and high temperatures; and N deposition is higher in Eurasia than North America (Holland, 1999).

Despite the different conditions in North America and Eurasia, a comparison of the inversion result of Peylin et al. (2002) for the period 1990–1994 found no large difference in the terrestrial sink of these two regions when the flux was considered on a per unit land area basis (Schimel et al., 2001). However, if we take the 1980s mean inversion results from the same analysis (Table 3, Peylin, personal communication), and divide these by the land area of North America (24.9×10^9 m^2) and Eurasia (42.3×10^9 m^2), the regional fluxes for this earlier time period are very different at –0.04 gC m^{-2} and -0.37 gC m^{-2}, respectively. The difference in the relative contributions of the continents between the 1980s and early 1990s may be an indication of high interannual variability in climate, affecting growth and disturbances (e.g. insect attack and fire in Canadian and Russian forests, also the early 1990s was an unusual period of anomalously high uptake). Much of the difference could also be data-driven, as the inclusion of measuring stations can have a large impact in implied fluxes, and the number of observing stations more than tripled over the 1980s (Gurney et al., 2002; Peylin et al., 2002). The large difference in the inversion fluxes for North America and Eurasia in the 1980s is in contrast to the smaller difference in the CCMLP modelled total net fluxes, and in the inventory analyses (Table 3, Fig. 1c), although the inventory and net model results generally lie within the very wide range of uncertainty of the regional inversion results.

Looking at regional results in more detail (Fig. 1d, Table 3) Canada and Europe both show net sinks. The inventory and model results in each of these regions are not very different, as changes are fairly well documented and have not been extensive in recent years. As more information has become available from Chinese inventories, updates have been carried out and inconsistencies reduced, with results implying a net sink (e.g. -0.01 PgC yr^{-1}: Fang et al., 2001). Uncertainties in Chinese land-use change data sets means differences persist in modelled results, partly due to classification of changing land use. Larger differences between inventory estimates for the Former Soviet Union reflect uncertainties in land-use change data, differences in conversion calculations, and also differences in the time periods covered (there can be large variations in fluxes form year to year) (Nilsson et al., 2000; Goodale et al., 2002; Shvidenko and Nilsson, 2002). Data reporting is also an issue, for example, the FAO data implies a larger sink than other inventory results apparently due to an error in Russian data reporting to the UN (Shvidenko and Nilsson, 2002). Despite these differences, results in the Former Soviet Union also show a small net sink.

More detailed analyses have been carried out for the USA, including estimates of fluxes due to changing agricultural management, fire suppression and other non-vegetation processes (sedimentation, river export,

Table 4. *USA terrestrial net sinks in the 1980s (PgC yr^{-1})*

	Houghton et al. (1999)	Houghton (2003)	Pacala et al. (2001)	
			Low	High
Forest/Woodland:				
Land-use change	−0.002	−0.002		
Management - harvest and regrowth	−0.024	−0.024		
Management - recovery from wildfire	0.063	0.063		
Management - fire supression western pines	0.052	0.026		
Forest total	*0.089*	*0.063*	*0.17*	*0.37*
Non-forest land:				
Cropland management (no till, etc.)	0.138	0.0	0.0	0.04
Woody encroachment (fire supp./grazing)	0.122	0.061	0.12	0.13
Non-forest land total	*0.260*	*0.061*	*0.12*	*0.17*
Management total	*0.351*	*0.126*	–	–
Land total	*0.349*	*0.124*	*0.29*	*0.54*
Other fluxes				
Sedimentation			0.01	0.04
Product (food/wood) export − import			0.04	0.09
River flux (export)			0.03	0.04
Other flux total			*0.08*	*0.17*
Total, all fluxes	**0.35±0.2**	**0.12±0.2**	**0.37**	**0.71**

Note: Net sinks rather than net flux so possitive numbers indicate terrestrial uptake.
"Land use change" = a change in cover type e.g. from forest to agriculture.
"Management change" = a change in the way land is managed with no change in type of land cover, but a likely change in carbon density.
In Houghton's results, "harvest and regrowth" and "recovery from wildfire" are part of the usual model results, the other catagories were calculated off-line. Recovery from wildfire was a large sink due to fire supression. Land use change consisted of a source of −0.092 PgC yr^{-1} from agricultural clearing and a sink of 0.090 PgC yr^{-1} from accumulation in recovering ecosystems. Since much of the change in agricultural areas is to or from forest areas, this has been included in the forest land use change category.

product export/import). Houghton's earlier estimate of fire suppression impact on woody encroachment based on published data (Houghton et al., 1999) was considered an upper bound and was halved for the most recent estimate (Houghton, 2003) presented in this paper (Table 4). The earlier estimate for cropland management was also considered too high and reduced to zero by Houghton (2003). Figure 1 shows two bars for Houghton's results, the left-hand bar represents land-use change only, and the right-hand bar includes management impacts listed in Table 4 (for more details see Houghton et al., 1999). Pacala et al. (2001) based their results (Table 4) on forest inventory analyses (incorporating land-use change, management and environmental effects), with additional fluxes estimated from the literature.

Considering both sets of estimates in more detail, Houghton's (2003) land-use change only flux (primarily from forests) consists of a source of 0.092 PgC yr^{-1} from agricultural clearing and a sink of 0.090 PgC yr^{-1} from accumulation in recovering ecosystems. Since much of the change in agricultural areas is to or from forest areas, this has been included in the forest land-use change category. Many discussions of the cause for the North American sink seen in the inversion model results for the 1980s is forest regrowth on abandoned agricultural land in the USA (e.g. Schimel et al, 2001), but the results of Houghton et al. (1999) indicate that while this sink was large in the 1950s and 1960s, it was small by the 1980s. Similarly, the CCMLP results did not find a large sink due to land use change in the USA in the 1980s (Table 3). Most of the Houghton USA sink is due to fire suppression (and in CCMLP it was due to CO_2 enhancement). Comparing model and inventory results, Houghton's (2003) total forest flux (including various management effects) represents only 10–20% of the Pacala et al. (2001) inventory-based total forest flux (that captures all management and environmental effects). These differences imply other management and environmental impacts on the carbon flux of extant forests could be very large. These implied sinks are in contrast to a recent study that did not find significant change in forest growth rates of extant forests due to environmental changes such as elevated CO_2, management changes, or any other change (Caspersen et al., 2000), although this result has been disputed (Joos et al., 2002).

Forests alone account for 50–70% of all vegetation fluxes in the US (Houghton, 2003; Pacala et al., 2001). Vegetation fluxes are only responsible for three-quarters of the total estimated flux, which additionally includes sedimentation and lateral transfers of carbon (Pacala et al., 2001). Once all fluxes are included, the total flux estimate of Pacala et al. is close to the mid-range of the atmospheric inversion estimate for the USA in the 1980s, although the inversion range is very large (Pacala et al., 2001, inversion data from Peylin et al., 2002 analysis, with the North America flux split according to modelled GPP). The CCMLP model results are not capturing the fluxes associated with management, or export of carbon (as products or in rivers), and thus find a smaller sink than the inversions and Pacala et al. (2001) (Fig. 1d).

3.2. *Historical fluxes*

Historical data on terrestrial fluxes are limited. Precise atmospheric CO_2 measurements began in the 1950s, and global networks have been established much more recently. Some land inventory measurements go back many years at certain sites, but extensive inventory coverage tends to be more recent. Thus historical analyses rely on model simulations with reconstructed land use and environmental data. Figure 2a shows the global terrestrial flux since 1900 as calculated by CCMLP (McGuire et al., 2001). All models show a similar pattern with a global net terrestrial source turning in to a net sink in the 1960s and increasing variability in more recent decades. Differences in magnitude of the flux may be partly due to differences in prescribed or simulated vegetation biomass. The model results are in approximate agreement with the global budget based on CO_2 and O_2 measurements, shown as grey boxes, including the increase in the net land sink from the 1980s to the 1990s.

Contributions from different causes of the net terrestrial sink are not yet adequately quantified. The CCMLP model results, broken down into component parts in Fig. 2b, suggest that the increasing net sink from the 1980s to the 1990s is partly due to a decline in the net land-use source (mainly decreasing deforestation in the tropics, and forest regrowth in North America and Eurasia), and partly due to other processes tending to increase carbon uptake (climate variability, which seems to have caused a temporary slowing of the atmospheric CO_2 increase in the early 1990s, and CO_2 fertilisation). The results of Houghton (2003) are shown in Fig. 2b for comparison with CCMLP land-use change emissions. The results are similar until the 1960s, when Houghton's land-use change emissions continue to rise while the CCMLP land-use change emissions decline. This divergence is particularly pronounced from 1980s onwards. Data in Table 3 and Fig. 1b indicate that the difference is mainly in the tropics. CCMLP found a decrease in land-use change emissions in the 1990s compared to the 1980s, whereas Houghton found both decades to be similar, albeit with emissions declining from a peak in 1990 over the rest of the decade. According to the FAO (2001), deforestation of natural forests increased between the 1980s and 1990s in tropical Africa and Asia, and decreased in Latin America. Plantation establishment reduced the net loss of forest area throughout the tropics.

3.3. *Differences in modelled land-use change fluxes*

The divergence of the CCMLP and Houghton land-use fluxes warrants further investigation. One potential reason for the difference is that CCMLP only considered changes in cropland areas, while Houghton also considered changes in pastures (grazing land), shifting cultivation and wood harvest. Figure 3 (top panel) shows the historical emissions of Houghton for croplands only as well as for all land use, compared with the CCMLP croplands only emissions (shaded area = range of all models). Houghton estimates carbon emissions due to cropland change only in the 1980s to be 61% of the total land use flux (croplands = 1.2 PgC yr^{-1}, total land use = 2.0 PgC yr^{-1}). If we scale the CCMLP results (0.6 to 1.0 PgC yr^{-1}) by the same proportion, the estimated total CCMLP land use flux would be 0.9 to 1.6 PgC yr^{-1}. The IPCC (Prentice et al., 2001) based their estimate of land-use change flux of 0.6 to 2.5 PgC yr^{-1} (Table 1) on the full range of both CCMLP and Houghton (2000; 1.7 $\pm$ 0.8 PgC yr^{-1}). Using the updated Houghton (2003) numbers (2.0 $\pm$ 0.8 PgC yr^{-1}) and the scaled CCMLP results brings the land-use change flux range to 0.9 to 2.8 PgC yr^{-1}. Considering the updated budget of Bopp

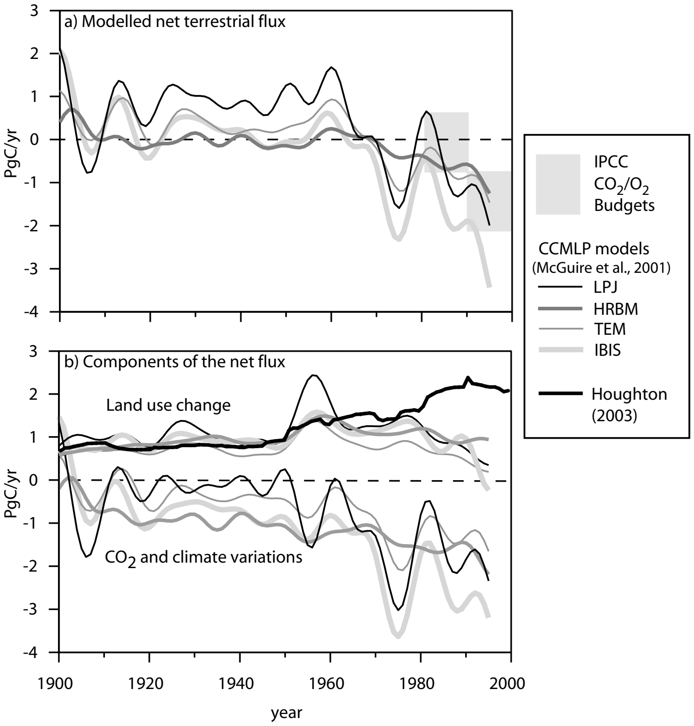

Fig. 2. Modelled global terrestrial CO$_2$ fluxes over the last century (from IPCC, Prentice et al., 2001). The modelled fluxes are from the CCMLP model intercomparison project (McGuire et al., 2001). Panel (a) shows the net terrestrial flux, and panel (b) breaks this down in to its component fluxes due to land use change (based on the data of Ramankutty and Foley, 1999) and due to changes in climate and CO$_2$ enhancement of vegetation growth. The results were smoothed using a 10-yr running mean to remove short-term variability. The peaks occur slightly earlier than the figures depicted in the paper by McGuire et al. (2001) due to an error in that paper that put the means at the end of each 10 yr interval. For comparison, grey boxes in panel (a) denote observational estimates of the net terrestrial flux according to the IPCC (Prentice et al., 2001). The thick black line in panel (b) represents the land use change results from the book-keeping model approach of Houghton (2003).

et al. (2002) and Le Quéré et al. (2003), this implies a residual terrestrial sink in the region of -4.0 to -0.3 PgC yr^{-1} (Table 1).

When considering results for cropland conversion only, the two modelling analyses are still quite different (Fig. 3, top panel). The CCMLP cropland emissions peaked in the late 1950s, while Houghton's estimates continued to increase through the 1980s and 1990s. The CCMLP emissions are greater than Houghton's until the mid 1960s, and are lower than Houghton in the 1980s. While the CCMLP emissions decreased from the 1960s to present, Houghton estimates increasing emissions from the 1960s to present. Much of the difference in emissions lies in the differences in the extent and timing of land cover change in the underlying data sets. Comparison of the rate of change of cropland area from Houghton and CCMLP (Fig. 3, bottom panel) shows that the land-use data sets are very different after the 1960s. (Agreement prior to 1960s does not imply higher data quality, but rather that the same data sources were used by Houghton and CCMLP). Preliminary analysis shows that the biggest differences lie in the tropics, and mainly arise from the use of different sources of data. For example, in tropical Africa, Houghton estimated cropland rate of change from the tropical deforestation rates of the FAO's Forest Resources Analysis (FAO, 2001), while CCMLP used the cropland areas of the FAOSTAT database (FAO, 1995).

Further differences in land-use change emissions may result from the modelling framework used. Comparing the relative timing in the rate of change of cropland with the resultant carbon emissions indicates differences in behaviour between the Houghton and

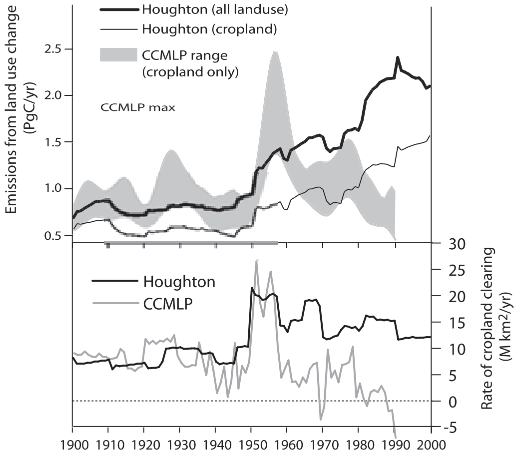

Fig. 3. Modelled land-use change emissions and rate of change of cropland area used to model cropland emissions. The top panel shows the modelled emissions due to land use change from two model exercises. For Houghton's (2003) book-keeping model approach, results are shown for emissions due to all land use conversions (bold line) and for cropland conversions only. The CCMLP model intercomparison (McGuire et al., 2001) only considered cropland conversions, and the grey shaded area represents the range of the four models included in CCMLP. The bottom panel shows the estimated rate of change in cropland area used to model emissions by Houghton (2003) and CCMLP (McGuire et al., 2001).

CCMLP approaches (Fig. 3): The CCMLP emissions closely follow the cropland rate of change (with approximately a 5-yr time lag); the Houghton emissions seem to have a long-term memory, wherein the emissions continue to increase after the 1960s even though the cropland rate of change stabilizes or decreases slightly (Fig. 3). Full analyses of the differences are ongoing, but some reasons have already emerged:

(1) *Differences in the vegetation types (forest versus grassland) cleared during cropland expansion*: CCMLP uses a spatially explicit cropland data set, and when croplands expand, they replace whichever "potential natural vegetation" is located in the grid cell, as calculated (IBIS, LPJ) or prescribed (HRBM, TEM) by the models. Therefore, CCMLP may assume conversion of grassland to cropland in places where Houghton may have assumed forest conversion. These different assumptions are especially likely in some tropical regions (e.g. Africa) where Houghton's results are based on deforestation statistics. Forest products and slash have slower turnover rates, so would result in a longer system memory, as well as larger eventual emissions.

(2) *Differences in the time-scales of soil carbon dynamics*: The CCMLP models borrow Houghton's approach in the consideration of the product fluxes, but they handle the ecosystem carbon dynamics independently.

4. Summary and conclusion

A review of four approaches to estimating the terrestrial carbon flux suggests that apparent inconsistencies in results can be understood in terms of the different sets of processes and pools considered by the different methods. When full account is taken of what is actually being measured (and that the time periods and geographic areas are consistent), the different approaches can be seen to be complementary rather than inconsistent, and considered together, they can be used to strengthen our understanding regarding the contribution of different processes to the terrestrial carbon budget.

Atmospheric inverse model and inventory methodologies both estimate the net flux due to many processes, but inventory results typically find smaller net sinks. In the northern extratropics the differences suggest that about half of the net terrestrial flux (sink) is in non-forest vegetation and belowground fluxes not included in the inventories. This is confirmed for the USA by the detailed study of Pacala et al. (2001). The "land-use only" estimates of Houghton (2003) and CCMLP (McGuire et al., 2001) are nearly neutral in northern extratropical regions, while the net estimates from inversion and inventory methods indicate a terrestrial sink. Thus, it is likely that environmental changes and changes in land management have contributed to the northern extratropical sink. A similar result is obtained when we look closer at North America and Eurasia, although the inversion results have much greater uncertainty when breaking down the flux along east–west concentration gradients. There is no evidence for a predominantly large terrestrial sink in North America compared to Eurasia; in fact, the evidence suggests that on a per unit land area basis the sink in Eurasia is higher (inversion models) or both are similar (process models). In the USA, the total net sink estimated by Pacala et al. (2001) is larger than that of the inventory and modelling methods, with 25% of the total due to sedimentation processes and lateral transfer of carbon, indicating a significant role for such processes in determining global continental carbon budgets. The various inventory and modelling budgets are in approximate agreement over the USA, Canada, Europe, FSU and China, and indicate small net sinks, partly due to historical land use changes such as abandonment of agricultural land to forest, and partly due to environmental and management impacts.

In the tropics, the "land-use only" estimates show a large source of carbon, while the inversion results indicate approximate neutrality. We infer the presence of a large terrestrial sink in extant natural or semi-natural ecosystems due to environmental change or land management. This inference has some support from inventories and flux measurements in extant forests. However, such estimates are subject to high uncertainty and it is currently not possible to account for the total size of the implied sink or the possible contribution of different processes.

Effects due to CO_2 and N fertilisation, and management effects in both forested and non-forested land, are still poorly documented but indications are that they are likely to have widespread importance. Such processes can plausibly account for much of the residual terrestrial flux (difference between the net flux and the land-use change emissions), or differences in the various methodologies for assessing the terrestrial flux, as model studies (McGuire et al., 2001; Holland et al., 1997) and detailed analyses in the USA (Pacala et al., 2001) have indicated. Consideration of a wider range of land types and processes, such as management, fire, nitrogen cycling and woody encroachment, should improve model results, reduce apparent inconsistencies with atmospheric data and improve understanding of terrestrial carbon cycling. It is especially important to take advantage of the full range of available data from ecological experiments and environmental monitoring at all scales to develop and evaluate models.

Atmospheric inversion estimates are expected to increase greatly in reliability and precision provided that current proposals for a denser network of ground measurement stations, tall towers and airborne and space-based CO_2 concentration determination go ahead. Better constraints on atmosphere–ocean fluxes would also be helpful. Inventory analyses are expected to become more standardised and more extensive with continuing efforts by the FAO, IPCC and international research and forestry groups. Inventory analyses are also likely to benefit greatly from increasing application of remote-sensing technology.

Current differences in land-use change model results can be largely attributed to the underlying datasets used to drive the models; thus, improvement in historical land-use change data are key to more accurate modelling of carbon sources and sinks. Work is underway to resolve differences in the land-use data sets, including consideration of pasture conversions in the CCMLP data sets, and integration with satellite measurements for recent land-use changes. New and improved data sources will provide an increasing challenge to modellers to establish the realism of model results for the present date and thus, we hope, to reduce the spread of model projections forced by scenarios of the future.

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