PERSPECTIVE

Gross CO_2 fluxes from land-use change: implications for reducing global emissions and increasing sinks



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The role of land use in the global carbon cycle involves both CO_2 sources (e.g., as forest land is converted to agricultural uses) and CO_2 sinks (as vegetation regrows following land disturbance). While land-use change contributions to the carbon cycle have been mainly evaluated using net emissions of CO_2, we estimated gross emissions and gross sinks of CO_2 from land-use change via global and regional simulations with a widely used carbon cycle model. Gross fluxes are large; for example, the gross CO_2 sources from land-use change amount to 4.3 PgC year^{-1} or more than 55% of emissions from fossil fuel combustion and cement manufacture. The airborne fraction is therefore estimated to be approximately 34% of total CO_2 emissions (i.e., fossil fuel plus land-use). Since land-use conversions and abandonment differ regionally, gross sources and sinks provide strong support for extensive land protection and land-use management strategies to reduce atmospheric CO_2.

In 1954, ecologist GE Hutchinson described CO_2 data of the Earth's atmosphere as being "wretchedly inadequate" [1]. In the half-century since, many thousands of scientists have studied the dynamics of the atmosphere's CO_2, motivated by the effects of increased CO_2 on plant photosynthesis, carbon cycling within the biosphere and climate change [2]. We now have a quantitative understanding and constrained estimates of three of the four major CO_2 fluxes of the contemporary global carbon cycle: fossil-fuel combustion emission of CO_2 to the atmosphere, CO_2 accumulation in the atmosphere, and CO_2 exchange between the oceans and the atmosphere [3,4]. Only estimates of CO_2 exchange between the land and the atmosphere might today be described by Hutchinson as "wretchedly inadequate". Scientists agree that land-atmosphere exchanges of CO_2 are large, and that **land-use change** makes these estimates highly uncertain.

Changes in land use not only affect CO_2 exchanges between land and atmosphere, they are important for carbon policy and management. Land protection from deforestation to minimize future emissions of CO_2 has gained wide international support [5,6,101], and economists argue that reductions in deforestation can be some of the most cost-effective approaches to GHG control [7,8]. While some scientists question whether reduced deforestation can appreciably decrease atmospheric CO_2 [9], the recent Copenhagen Accord prominently features land protection as a mechanism to provide multiple benefits [101], most especially diminished CO_2 emissions. Here, we examine net and gross CO_2 emissions from land-use change in an analysis that strongly supports extensive protection of the Earth's remaining **primary forests** and more sustainable management of land already in use, all to manage excess CO_2 in the atmosphere [8,10].

In the past, effects of land use on CO_2 have almost exclusively been evaluated as a net global source [3,9,11], a net source commonly estimated to be approximately 1.5 PgC year^{-1} (1.5 GtC year^{-1}). Owing to the burgeoning increases in fossil fuel emissions, today estimated to be approximately 7.7 PgC year^{-1} [3], this net source from land-use change has been shrinking on a relative basis. As a result, some scientists now question the benefits that can be derived from land protection [9]. No doubt, net global emissions are important to understanding

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Key terms

Land-use change: The clearing of lands for cultivation and pastures, the abandonment of these agricultural lands, harvests of wood, reforestation, afforestation and shifting cultivation.

Primary forests: Forests not significantly impacted by humanity, generally old in age.

the global carbon cycle; however, land uses are not uniform across the global landscape. In fact, across the world, the timing and carbon impacts of land-use change are diverse, even among regions and from one continent to another. For example, in some regions, ecosystems are losing carbon to the atmosphere owing to deforestation, burning, logging or conversion to cultivation. In other regions, carbon is accumulating from the atmosphere as ecosystems recover from land-use disturbances and as their vegetation and soils reaccumulate carbon in plant biomass and soil organic matter.

Here, we use the widely used land-use change model of Houghton [12–14] to estimate: gross CO_2 sources from the world's ecosystems that are losing carbon owing to deforestation, cultivation and logging; and gross CO_2 sinks in ecosystems that are gaining carbon owing to land-use affected revegetation and re-accruals of soil organic matter. The model is used to examine regional and global-scale shifts in land-atmosphere exchange of CO_2, as their CO_2 source and sink strengths evolve over decadal time scales. Global and regional carbon fluxes from changes in land use were estimated with the model, tracking carbon in living vegetation, dead plant material, wood products and soils for each hectare of land cultivated, harvested or reforested.

The model uses relatively coarse spatial and temporal resolution of changes in natural and human-affected ecosystems [12–14]. The model uses ten major regions for the world with two–six natural ecosystems per region. Spatial areas deforested before 1990 were obtained from various international and national statistics and, after 1990, were obtained from the UN Food and Agriculture Organization's Forest Resources Assessment [102]. Logging without cultivation rapidly affects aboveground carbon stocks but not that of soil carbon; with cultivation, 25% of soil carbon is assumed to be lost within 5 years. Rates of ecosystem-carbon losses and recoveries are varied among regions and ecosystems [12,13].

Overall carbon sinks at sea & on land

Prior to examining land-use effects on CO_2 exchange, we begin with the fundamentally important observation that, overall, contemporary ocean and land are substantial carbon sinks. Although fossil fuel emission of CO_2 has averaged 7.7 ± 0.4 PgC year^{-1} from 2000–2008 [3], the atmosphere is accumulating CO_2 at only 4.1 ± 0.1 PgC year^{-1}. The oceans and land take up the difference, approximately 3.6 PgC year^{-1} (Table 1). Since estimates of fossil fuel emission and atmosphere accumulation are tightly constrained [3], there is little question that without the sinks of Earth's ocean and land, the atmosphere would be increasing in CO_2 at nearly twice the rate it is today; for example, without the ocean and land sinks, the atmosphere would have approximately 500 ppm CO_2, compared with our contemporary atmosphere that is approaching 400 ppm. The data indicate that nearly 50% of the CO_2 from fossil fuel combustion is being absorbed by the ocean and land (Table 1).

The overall sink of 3.6 PgC year^{-1} can be partitioned between ocean and land because estimates of the oceanic CO_2 uptake are constrained at approximately 2.3 ± 0.4 PgC [3,4,15]. The overall CO_2 sink on land can then be estimated from the difference to be approximately 1.3 PgC year^{-1}. That the world's land surface may be absorbing more CO_2 than it releases is most impressive given the intensity of various land uses that are accelerating land-to-atmosphere releases of CO_2.

Land-use change sources & sinks of CO_2

A long-standing approach in ecosystem science evaluates how individual ecosystems such as forests, fields or water bodies gain or lose carbon, thus removing or adding CO_2 in the atmosphere [16–18]. Ecosystems lose

Table 1. The expanded global carbon budget accounting for anthropogenic CO_2 fluxes including gross and net land-use change fluxes for the first years of the 21st century (2000–2005 for gross sources and sinks, 2000–2008 for all other fluxes).

CO_2 sources and sinks	PgC year^{-1}	Ref.
Constrained sources and sinks		
Emissions from fossil fuels	+7.7 ± 0.04	[3]
Storage in the atmosphere	-4.1 ± 0.10	[3]
Ocean sink	-2.3 ± 0.4	[3]
Inferred net terrestrial sink		
Net terrestrial balance	-1.3	
Land-use affected ecosystem exchange		
Gross sources from land-use change	+4.3†	[13]
Gross sinks from land-use change	-2.8‡	[13]
Net source from land-use change	+1.5	[13]
Inferred net terrestrial sink		
Residual terrestrial sink	- 2.9	

†The new model indicates that of the CO_2 sources from land-use change in the tropics and temperate zone, nearly 70% of gross CO_2 emissions derive from the tropics (Figure 1).
‡Gross CO_2 sinks from land-use change are approximately half in the temperate zone and half in the tropics.

carbon and are sources of CO_2 to the atmosphere as a result of deforestation, cultivation and exploitive logging. Ecosystems are sinks for carbon by taking up atmospheric CO_2 during forest regrowth, after agricultural abandonment, or owing to improved agricultural and silvicultural practices that store carbon in soil and biomass.

At the beginning of the 21st century, more than half the Earth's land is cultivated, grazed or periodically logged, and these land uses have set individual ecosystems on contrasting trajectories of carbon loss or gain that persist for decades and even centuries [19]. The pace and strength of these gross gains or losses of carbon differ greatly among ecosystems, regions, and even among continents. To track the historic trajectories of land-use change as a source or sink of CO_2, we used Houghton's model to estimate gains and losses from ecosystems across the world as a whole, for the temperate zone and tropics, and for three tropical regions, in Africa, America and Asia [12–14].

Results demonstrate that land use-affected gross carbon fluxes are considerably larger than estimates of net global sources. Gross sources of CO_2 total 4.3 PgC year^{-1} from ecosystems influenced by deforestation, burning, harvesting of wood and cultivation for the years 2000–2005 (Table 1). Gross sinks of CO_2 affected by global land-use change are estimated to total approximately -2.8 PgC year^{-1} over the same time period, owing to afforestation and the regrowth of secondary forests and re-accrual of soil organic matter in the years and decades following logging, fire, agricultural land abandonment and agricultural improvements (Table 1). Land-use change is redistributing substantial amounts of carbon from ecosystems that are gross land-use sources of CO_2 to those that are sinks. These redistributions are hidden in the statistic of net emissions from land-use change, estimated to be 1.5 PgC year^{-1} (Table 1).

Key term

Secondary forests: Forests that are regrowing due to human disturbance.

In the 20th century, the largest gross sources of CO_2 from land-use change shifted dramatically from the temperate zone to the tropics (Figure 1). In the temperate zone, not only have gross CO_2 sources contracted, but gross sinks, which have historically been much lower than gross sources, have increased to match these decreasing sources (Figure 1). In the tropics, the story is fundamentally different. Gross sources of CO_2 due to tropical deforestation and agricultural development have greatly out-paced sinks throughout the late 20th century and into the 21st century. Gross CO_2 sources in the tropics are currently highest in South America and southern Asia rather than Africa. In the years 1990–2005, gross CO_2 sources from the three tropical regions average 1.5, 1.1 and 0.5 PgC year^{-1}, respectively. However, there is good indication that these patterns in the tropics are changing in recent decades, especially as gross sinks, that tend to lag sources, are intensifying (Figure 1).

The modeling indicates that net release of CO_2 from global land-use change has remained at approximately 1.5 PgC year^{-1} since the early 1960s (with a coefficient of variation among years of only 7.9%), in general agreement with widely cited estimates [3,9,11]. The model also demonstrates how this generally steady net global release of CO_2 entirely masks the large and increasing gross CO_2 sources in the tropics that are being counterbalanced by decreases in gross CO_2 sources in the temperate zone and the lagged but increasing gross CO_2 sinks in both the temperate zone and tropics (Figure 1).

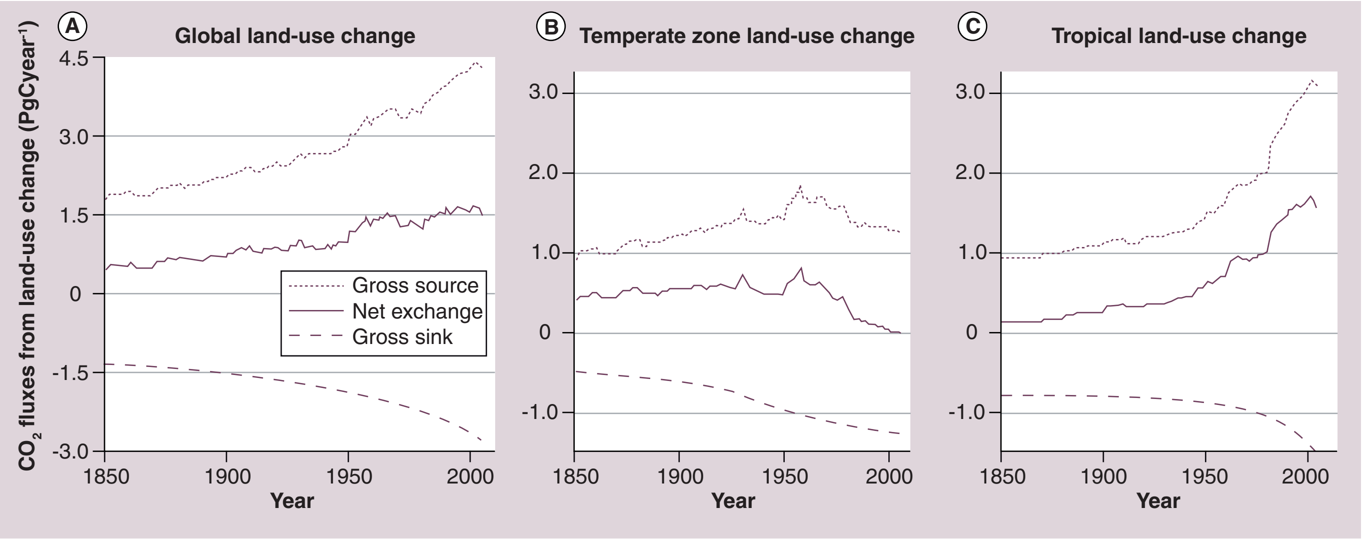

Figure 1. Historic development of land-use-affected sources and sinks of CO_2 across the globe and in the temperate zone and tropics, as estimated with the Houghton model [12–14].

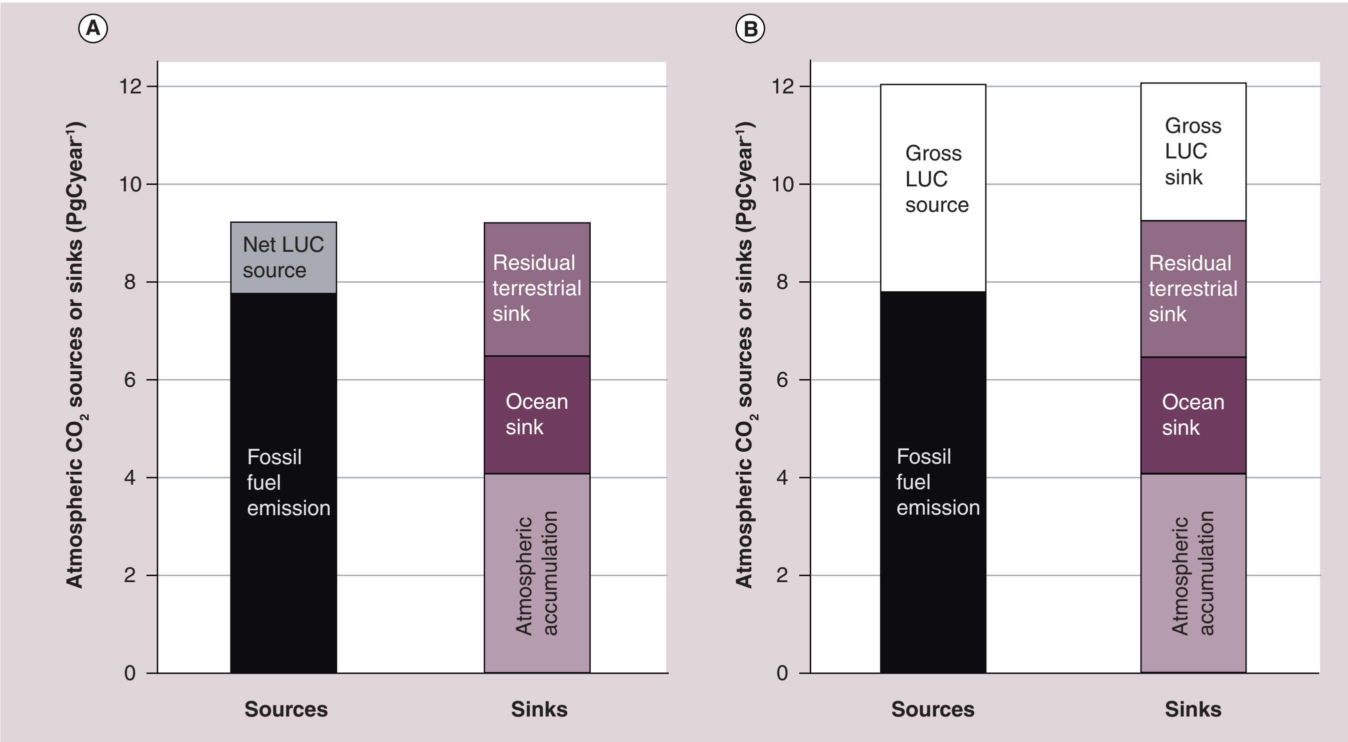

Figure 2. Anthropogenic CO_2 fluxes in the first decade of the 21st century (2000–2008 for all fluxes except gross land-use change sources and sinks, which are from 2000–2005) [3,13]**. (A)** The most common presentation of the global carbon cycle with land-use change presented as a net global source. **(B)** The expanded carbon cycle with land-use change of ecosystems that are a gross source of CO_2 presented separately from those that are gross sinks.

The 'expanded' global carbon budget

The expanded global carbon budget includes gross sources and sinks from land-use change in combination with fossil fuel emissions, the atmosphere's increase, and the ocean and land sinks **(Table 1 & Figure 2)**. Anthropogenic CO_2 emissions thus total approximately 12.0 PgC year^{-1}, 64% of which is from fossil fuel combustion and cement production and 36% of which is from gross emissions from land-use change **(Figure 2)**, on-going today mainly in the tropics **(Figure 1)**. Of the 12.0 PgC released to the atmosphere by human activities, CO_2 sinks on land or in the ocean account for approximately 47 and 19% of total emissions, respectively **(Figure 2)**. Approximately 34% of the 12.0 PgC of anthropic emissions are estimated to accumulate in the atmosphere **(Figure 2)**. This approach to CO_2 fluxes in the atmosphere suggests that the airborne fraction, which accounts for gross sources and sinks of CO_2 from land use-change, is much less than previous estimates: 34% rather than 45% from 2000 to 2008 [3]. This approach also indicates that these gross fluxes from land-use change may be sufficiently large to obscure trends in the airborne fraction that only accounts for fossil fuel emissions. There is well justified concern about whether the Earth's substantial sinks can keep pace with accelerating CO_2 emissions [3,11,20,21].

The land-based CO_2 flux that has greatest uncertainty, the residual terrestrial carbon sink, is estimated from the difference between all anthropogenic CO_2 sources (12.0 PgC) and all other known sinks (9.1 PgC), and amounts to approximately 2.9 PgC year^{-1} **(Table 1)**. The residual terrestrial sink is not a result of land-use change and hypothetically results from land-surface responses to variations in Earth's physical and chemical climate: primary forests that serve as sinks despite their age; erosion-sedimentation and terrestrial-to-aquatic transfers that accrue carbon in alluvial and wetland soils, freshwater lakes, streams and rivers; and fertilization of vegetation by CO_2 and atmospheric N pollutants [22–24]. The Earth's land sink accounts for an enormous 5.7 PgC year^{-1} when the gross sink affected by land-use is combined with the residual terrestrial sink **(Table 1 & Figure 2)**.

Opportunities for the land to store carbon

This expanded carbon budget and ecosystem analysis account for the dynamic series of ecosystem sources and sinks of CO_2 as these play out across different regions at differing rates. The expanded carbon budget can be used to guide policy and management over the coming decades; for example, the gross CO_2 sources and sinks illustrated in **Figures 1 & 2** help to substantiate land-based opportunities to diminish CO_2 emissions and promote CO_2 sinks. Establishing control over deforestation sources of CO_2 has been a main goal of programs such as reducing emissions from deforestation and forest degradation (REDD) and REDD-plus [5,6]. REDD-type programs could be far more ambitious than outlined in the past and aim to reduce the enormous gross source of 4.3 PgC year^{-1} currently released by land-use change **(Figure 2)**. Controlling these emissions will be difficult but the forests that are most vulnerable to deforestation can be identified and prioritized for protection. Such programs currently enjoy wide international support and, if effectively implemented over large areas, might also be justified by protecting a part of the large residual terrestrial sink as well **(Table 1 & Figure 2)** [22].

The expanded global carbon budget also underscores the importance of secondary-forest management, recently incorporated in programs such as REDD-plus [6]. Such management can become far more ambitious and can aim to increase gross sinks of -2.8 PgC year^{-1} that are attributed to land-use change. Currently, these efforts are conceived to promote secondary forests but could be considerably broadened to support improved management of agro-ecosystems as well. In cutover forest lands throughout the tropics and temperate zone: logging and deforestation can be more systematically followed by reforestation; forests can be restored on degraded lands; **timber-stand improvement** can be practiced on poorly stocked and high-graded forests; and agronomic management can include a goal of soil carbon storage [6,25,26]. Forest management offers an additional opportunity to increase land's carbon sink strength because solid wood products have long lifetimes subsequent to manufacture, on the order of decades to over a century. Wood can also displace steel, concrete, and fossil-energy sources [27,28], all making sustainable forest management potentially able to become an important force in combating excess CO_2 in the atmosphere [29–33].

The geographic scale, economics, politics and science make new initiatives for global land protection and improved land management extremely challenging [8,34–36]. The balance of land protection and management will differ among ecosystems and regions, owing to the balance of effects on land surface albedo and carbon cycling among other factors [26,37,38], but will depend on increasingly accurate estimates of land-use associated CO_2 sources and sinks. The sustainability of protected and managed ecosystems will need monitoring to assure multiple ecosystem functions [39,40], and research is needed to improve understanding of ecosystem and soil carbon dynamics on decadal time scales [19,41,42]. Nevertheless, history demonstrates that CO_2 emissions associated with land use can substantially increase or decrease across large regions on decadal time scales. Land use-associated emissions of CO_2 in the temperate zone, for example, decreased on average by 0.75 PgC year^{-1} throughout the latter half of the 20th century, owing both to reductions in gross sources and increases in gross sinks **(Figure 1)**. As we begin to manage the Earth's carbon cycle in the coming years, how can we not attempt to reduce gross CO_2 sources and increase gross sinks by protecting primary forests and improving land management?

> **Key term**
>
> **Timber-stand improvement:** Forestry practices with economic, conservation or restoration objectives aimed to modify species composition and forest-stand development.

Future perspective

The search to quantify and manage the global carbon cycle is like few other challenges undertaken by humanity. While some scientists question whether reduced deforestation and improved land management can appreciably decrease atmospheric CO_2 [9], that perspective considers land-use change from the perspective of its relatively low net CO_2 emission from land-use change. We used a widely applied land-use change model to estimate gross emissions of CO_2 from ecosystems emitting CO_2 due to land-use change and gross sinks from land-use affected ecosystems reaccumulating carbon. Other land-based models can be used to make similar estimates at a wide range of scales. In addition, remote sensing will be useful in this endeavor. Research and management can be aimed at predicting the most vulnerable natural ecosystems likely to be deforested or converted to unsustainable uses. Similarly, research and management can be aimed at improving management of working ecosystems to accumulate more carbon in biomass, soils, detritus and bio-products.

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Executive summary

- Of the 7.7 PgCO_2-C emitted each year by fossil fuel combustion, the atmosphere is gaining 4.1 PgC, whereas the ocean and land accumulate 3.6 PgC (data from 2000–2008).
- Land-use change across the entire world has released on a net annual basis approximately 1.5 PgC as CO_2 for the last several decades.
- Land-use change affects ecosystems that release CO_2 and other ecosystems that accumulate C and such fluxes amount to approximately 4.3 PgC of gross CO_2 releases and 2.8 PgC of gross sinks according to Houghton's land-use change model (data from 2000–2005).
- Gross fluxes of C from land-use change support the potential for land management improvements that can impact the global C budget; for example, protection for primary tropical forests to reduce future emissions, and improved management of land already in use or disturbed in the past to increase sinks.

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