The Carbon Cycle in Land and Water Systems

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The six chapters (Chapters 10-15) in Part III consider the current and future carbon balance of terrestrial and aquatic ecosystems in North America. Although the amount of carbon exchanged between these ecosystems and the atmosphere each year through photosynthesis and plant and microbial respiration is large, the net balance for all of the ecosystems combined is currently a net sink of 370-505 million tons of carbon (Mt C) per year[1]. This net sink offsets only about 20-30% of current fossil-fuel emissions from the region (1856 Mt C per year in 2003) (see Chapter 3 this report). The cause of this terrestrial carbon sink is uncertain. Although management has the potential for removing carbon from the atmosphere and storing it in vegetation and soil, most of the current sink is not the result of current management practices. Instead, most of it may be attributed to a combination of past management and the response of terrestrial ecosystems to environmental changes.

The large sink in the forests of Canada and the United States, for example, is, in some measure, the consequence of continued forest growth following agricultural abandonment that occurred in the past. This is partly the result of past and current management practices (*e.g.*, fire suppression), and partly the result of forest responses to a changing environment (climatic change, carbon dioxide [CO_2] fertilization, and the increased mobilization of nutrients). The relative importance of these broad factors in accounting for the current sink is unknown. Estimates vary from attributing nearly 100% of the sink in United States forests to regrowth (Caspersen *et al.*, 2000; Hurtt *et al.*, 2002) to attributing nearly all of it to CO_2 fertilization (Schimel *et al.*, 2000). The attribution question is critical because the current sink may be expected to increase in the future if the important mechanism is CO_2 fertilization, for example, but may be expected to decline if the important mechanism is forest regrowth (forests accumulate carbon more slowly as they age). Understanding the history of land use, management, and disturbance is critical because disturbance and recovery are major determinants of the net terrestrial carbon flux.

Land-use change and management have been, and will be, important in the carbon balance of other ecosystems besides forests. The expansion of cultivated lands in Canada and the United States in the 1800s released large amounts of carbon to the atmosphere (Houghton *et al.*, 1999), leaving those lands with the potential for recovery (*i.e.*, a future carbon sink), if managed properly. For example, recent changes in farming practice may have begun to recover the carbon that was lost decades ago. Recovery of carbon in soil, however, generally takes longer than its loss through cultivation. Grazing lands, although not directly affected by cultivation, have, nevertheless, been managed in the United States through fire suppression. The combined effects of grazing and fire suppression are believed to have promoted the invasion of woody vegetation, possibly a carbon sink at present. Wetlands are also a net carbon sink, but the magnitude of the sink was larger in the past than it is today, again, as a result of land-use change (draining of wetlands for agriculture and forestry). The only lands that seem to have escaped management are those lands overlying permafrost (perennially frozen ground), and they are clearly subject to change in the future as a result of global warming. Settled lands, by definition, are managed, and are dominated by fossil-fuel emissions. Nevertheless, the accumulation of carbon in urban and

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[1] The lower estimate is from this overview, the larger estimate from Chapter 3, with most of the difference attributable to uncertainty in the sink from woody encroachment. See Table III.1, footnote h, for discussion of this range.

suburban trees suggests a net sequestration of carbon in the biotic component of long-standing settled lands. Residential lands recently cleared from forests, on the other hand, are sources of carbon (Wienert and Hamburg, 2006).

From the perspective of carbon and climate, ecosystems are important if (1) they are currently large sources or sinks of carbon or (2) they have the potential to become large sources or sinks of carbon in the future through either management or environmental change, where "large" sources or sinks, in this context, are determined by the product of area (hectares) times flux per unit area (or flux density) (megagrams of carbon [Mg C] per hectare per year).

The largest carbon sink in North America (270 Mt C per year) is associated with forests (Chapter 11 this report) (Table III-1). The sink includes the carbon accumulating in wood products (*e.g.*, in increasing numbers of houses and landfills) as well as in the forests themselves. A sink is believed to exist in wetlands (Chapter 13 this report), including the wetlands overlying permafrost (Chapter 12 this report), although the magnitude of this sink is uncertain. More certain is the fact that the current sink is considerably smaller than it was before wetlands were drained for agriculture and forestry. The other important aspect of wetlands is that they hold more than half of the carbon in North America. Thus, despite the current net sink in these systems, their potential for future emissions is large.

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Although management has the potential to increase the carbon sequestered in agricultural (cultivated) lands, these lands today are nearly in balance with respect to carbon (Chapter 10 this report). The carbon lost to the atmosphere from cultivation of organic soils (soils dominated by organic matter) is approximately balanced by the carbon accumulated in mineral soils (soils consisting of more inorganic material, such as sand or clay). In the past, before cultivation, these soils held considerably more carbon than they do today, but 25-30% of that carbon was lost soon after the lands were initially cultivated. In large areas of grazing lands, there is the possibility that the invasion and spread of woody vegetation (woody encroachment) is responsible for a significant net carbon sink at present (Chapter 10 this report). The magnitude (and even sign) of this flux is uncertain, however, in part because some ecosystems lose carbon below-ground (soils) as they accumulate it aboveground (woody vegetation), and in part because the invasion and spread of exotic grasses into semi-arid lands of the western United States are increasing the frequency of fires, reversing woody encroachment, and releasing carbon (Bradley *et al.*, 2006).

The emissions of carbon from settled lands are largely considered in the chapters in Part II and in Chapter 14 of this report. Non-fossil carbon seems to be accumulating in trees in these lands, but the net changes in soil carbon are uncertain.

The only ecosystems that appear to release carbon to the atmosphere at present are the coastal waters. The estimated flux of carbon is close to zero (and difficult to determine) because the gross fluxes (from river transport, photosynthesis, and respiration) are large and variable in both space and time.

The average net fluxes of carbon expressed as Mg C per hectare per year in Table III-1 are for comparative purposes. They show the relative flux density for different types of ecosystems. These annual fluxes of carbon are rarely determined with direct measurements of flux, however, because of the extreme variability of fluxes in time and space, even within a single ecosystem type. Extrapolating from a few isolated measurements to an estimate for the whole region's flux is difficult. Rather, the net changes are more often based on differences in measured stocks over intervals of 10 years, or longer (see Chapter 3 this report), or are based on the large and rapid changes per hectare that are reasonably well documented for certain forms of management, such as the changes in carbon stocks that result from the conversion of forest to cultivated land. Thus, most of the flux estimates in Table III-1 are long-term and large-area estimates.

Nevertheless, average flux density is one factor important in determining an ecosystem's role as a net source or sink for carbon. The other important factor is area. Permafrost wetlands, for example, are currently a small net sink for carbon. They cover a large area, however, hold large stocks of carbon, and, thus, have the potential to become a significant net source of carbon if the permafrost thaws with global warming (Smith *et al.*, 2001; Smith *et al.*, 2005a; Osterkamp and Romanovsky, 1999; Osterkamp *et al.*, 2000). Forests clearly dominate the net uptake and storage of carbon in North America, although wetlands and settled lands have mean flux densities that are above average.

The two factors (flux density and area) demonstrate the level of management required to remove a significant amount of carbon from the atmosphere and keep it on land. Under current conditions, sequestration of 100 Mt C per year, for example (about 7% of fossil-fuel emissions from North America), requires nearly half the forest area (Table III-1). As discussed above, the cause of this sequestration is uncertain, but enhancing it through management over a few hundred million hectares would require considerable effort. Nevertheless, the cost (in \$/metric ton CO_2) may be low relative to other options for managing carbon. For example, forestry activities are estimated to have the potential to sequester 100-200 Mt C per year in the United States at prices ranging from less than $10/ton of CO_2 for improved forest management, to $15/ton for afforestation, to $30-50/ton for production of biofuels (Chapter 11 this report). Somewhat smaller sinks of 10-70 Mt C per year might be stored in agricultural soils at low to moderate costs ($3-30/ton CO_2) (Chapter 10 this report). The maximum amounts of carbon that might be accumulated in forests and agricultural soils are not known, thus, the number of years these rates of sequestration might be expected to continue is also unknown. It seems unlikely that the amount of carbon currently held in forests and agricultural lands could double. Changes in climate will also affect carbon storage, but the net effect of management and climate is uncertain.

Table III.1 Ecosystems in North America: their areas, net annual fluxes of carbon (negative values are sinks), and carbon stocks (including both vegetation and soils).

Type of ecosystem	Area (10^6 ha)	Current mean flux density (Mg C per ha per year)	Current flux (Mt C per year)	Carbon stocks (Mt C)	Mean carbon stocks (Mt C per ha)
Agriculture	231	0.0	0±15[a]	18,500	80
Grass, shrub and arid	558	–0.01	–6[b]	59,950	107
Forests	771	–0.35	–269[c]	171,500	222
Permafrost lands					
Peatlands	51	–0.13	–6.7	57,700	1130
Mineral soils[d]	517	–0.03	–14	98,780	191
Non-permafrost wetlands					
Peatlands	86	–0.12	–10	126,400	1470
Mineral soils	105	–0.21	–22.3	38,100	363
Estuarine	4.5	–2.3	–10.2	900	200
Settled lands[e]	104	–0.31	–32	~1,000	10
Coastal waters	384	0.05	19		
Sum	2427[f]	–0.15[g]	–370[h]	572,830[f]	
Total	2126[i]			480,000[j]	225[g]

a. Fossil-fuel inputs to crop management are not included. Some of the carbon sequestration is occurring on grasslands as well as croplands, but the inventories do not separate these fluxes. The near-zero flux is for Canada and the United States only. Including Mexican croplands would likely change the flux to a net source because croplands are expanding in Mexico, and the carbon in biomass and soil is released to the atmosphere as native ecosystems are cultivated.

b. Fossil-fuels are not included. The small net sink results from the Conservation Reserve Program in the United States. Including Mexico is likely to change the net sink to a source because forests are being converted to grazing lands. Neither woody encroachment nor woody elimination is included in this estimate of flux because the uncertainties are so large.

c. Includes an annual sink of 68 Mt C per year in wood products as well as a sink of 201 Mt C per year in forested ecosystems.

d. Includes zones with continuous, discontinuous, sporadic, and isolated permafrost; that is, not all of the lands are strictly over permafrost.

e. Urban trees only (does not include soil carbon). Note that this sink is accounted for as part of the forest sink in Chapter 3 (Table 3.1).

f. Sum does not include coastal waters. The summed area is larger than the total area (note i) because of double counting. For example, an estimated 75 × 10^6 hectares (ha) of permafrost lands in Canada are forested (and may be included in forest area as well as permafrost area), 26 x 10^6 ha of wetlands in the United States are forested, and 54 x 10^6 ha of wetlands are shrublands. In addition, an estimated 75 x 10^6 ha of other wooded lands are included as both forests and rangelands, and ~70 x 10^6 ha of grasslands and shrublands are counted also as non-permafrost lands within areas defined as sporadic or isolated permafrost (see note d).

g. Weighted average; does not include coastal waters.

h. Does not include coastal waters. The total annual sink of 370 Mt C is lower than the estimate of 505 Mt C presented in Chapter 3 (Table 3.1). The largest difference results from the flux of carbon attributed to woody encroachment. Chapter 3 includes a sink of 120 Mt C per year; Table III-1, above, presents a net flux of zero (see note b). Other differences between the two estimates include: (1) an additional sink in Table III-1 of 14 Mt C per year in permafrost mineral soils and (2) a sink of 25 Mt C per year in rivers and reservoirs that is included in Table 3.1 but not in Table III-1. In addition, there are small differences in the estimates for agricultural lands and grasslands.

i. Areas (10^6 ha) (*The Times Atlas of the World*, 1990)

Globe	North America	Canada	United States	Mexico
14,900	2,126	992	936	197

j. Total carbon stocks are reduced by the areas double counted (see note f).

Despite the limited nature of carbon uptake and storage in offsetting the global emissions of carbon from fossil fuels, local and regional activities may, nevertheless, offset local and regional emissions of fossil carbon. This offset, as well as other co-benefits, may be particularly successful in urban and suburban systems (Chapter 14 this report).

The effects and cost of managing aquatic systems are less clear. Increasing the area of wetlands, for example, would presumably increase the sequestration of carbon; but it would also increase emissions of methane (CH_4), countering the effect of carbon storage. Fertilization of coastal waters with iron has been proposed as a method for increasing oceanic uptake of CO_2, but neither the amount of carbon that might be sequestered nor the side effects are known (Chapter 15 this report).

A few studies have estimated the potential magnitudes of future carbon sinks as a result of management (Chapters 10, 11 this report). However, the contribution of management, as opposed to the environment, in today's sink is unclear (see Chapter 3 this report), and for the future, the relative roles of management and environmental change are even less clear. The two drivers might work together to enhance terrestrial carbon sinks, as seems to have been the case during recent decades (Prentice *et al.*, 2001) (Chapter 2 this report). On the other hand, they might work in opposing directions. A worst-case scenario, quite possible, is one in which management will become ineffective in the face of large natural sources of carbon not previously experienced in the modern world. In other words, while management is likely to be essential for sequestering carbon, it may not be sufficient to preserve the current terrestrial carbon sink over North America, let alone to offset fossil-fuel emissions.

At least one other observation about storing carbon in terrestrial and aquatic ecosystems should be mentioned. In contrast to the hundreds of millions of hectares that must be managed to sequester 100 Mt C annually, a few million hectares of forest fires can release an equivalent amount of carbon in a single year. This disparity in flux densities underscores the fact that a few million hectares are disturbed each year, while hundreds of millions of hectares are recovering from past disturbances. The natural fluxes of carbon are large in comparison to net fluxes. The observation is relevant for carbon management, because the cumulative effects of managing small net sinks to mitigate fossil-fuel emissions will have to be understood, analyzed, monitored, and evaluated in the context of larger, highly variable, and uncertain sources and sinks in the natural cycle.

The major challenge for future research is quantification of the mechanisms responsible for current (and future) fluxes of carbon. In particular, what are the relative effects of management (including land-use change), environmental change, and natural disturbance in determining sources and sinks of carbon for today and tomorrow? Will the current natural sinks continue, grow in magnitude, or reverse to become net sources? What is the role of soils in the current (and future) carbon balance (Davidson and Janssens, 2006)? What are the most cost-effective means of managing carbon?

Answering these questions will require two scales of measurement: (1) an expanded network of intensive research sites dedicated to understanding basic processes (*e.g.*, the effects of management and environmental effects on carbon stocks), and (2) extensive national-level networks of monitoring sites, through which uncertainties in carbon stocks (inventories) would be reduced and changes, directly measured. Elements of these measurements are underway, but the effort has not yet been adequate for resolving these questions.

KEY UNCERTAINTIES AND GAPS IN UNDERSTANDING THE CARBON CYCLE OF NORTH AMERICA

- As mentioned above, the net flux of carbon resulting from woody encroachment and its inverse, woody elimination, is highly uncertain. Even the sign of the flux is in question.
- Rivers, lakes, dams, and other inland waters are mentioned in Chapter 15 as being a source of carbon, but they are claimed elsewhere to be a sink (Chapter 3 this report). The sign of the net carbon flux attributable to erosion, transport, deposition, accumulation, and decomposition is uncertain (*e.g.*, Stallard, 1998; Lal, 2001; Smith *et al.*, 2005b).
- Several chapters cite studies that have attempted to quantify the potential for management to increase carbon sinks in the future, but no studies have yet attempted to estimate the potential future sources of carbon for North America as they have for the globe (*e.g.*, Friedlingstein *et al.*, 2006; Jones *et al.*, 2005). Global models that include the feedbacks between climatic change and the carbon cycle have all shown decreased carbon sinks over the next century. In North America, warming of wetlands and thawing of permafrost, in particular, are likely to increase emissions of carbon to the atmosphere, CH_4 as well as CO_2; and periods of unusually low rainfall, combined with warming trends, are likely to release carbon from the ecosystems of the Mountain West and the southwestern United States through increasing their vulnerability to wildfires and insect outbreaks (Potter *et al.*, 2003 and 2005).