PART III OVERVIEW

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 472-592 Mt C yr^{-1}, and offsets only about 25-30% of current fossil fuel emissions from the region (1856 Mt C yr^{-1} in 2003) (Chapter 3). If managed properly, these systems have the potential to become significantly larger sinks of carbon in the future; they may also become significant net sources of carbon if managed poorly or if the climate warms.

Much of the current North American carbon sink is the result of past changes in land use and management. The large sink in the forests of Canada and the United States, for example, is partly the result of continued forest growth following agricultural abandonment that occurred in the past, partly the result of current and past management practices (e.g., fire suppression), and partly the result of forest responses to a changing environment (climatic change, CO_2 fertilization, and the increased mobilization of nutrients). However, the relative importance of these three 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.*, 2002). 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 19th century 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. Grazing lands, although not directly affected by cultivation, were, nevertheless, 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 the second largest net carbon sink (after forests), 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, 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 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) (Mg C ha^{-1} yr^{-1}).

The largest carbon sink in North America (350 Mt C yr^{-1}) is associated with forests (Chapter 11) (Table 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), including the wetlands overlying permafrost (Chapter 12), 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 nearly two thirds of the carbon in North America. Thus, despite the current net sink in these systems, their potential for future emissions is large.

Table 1. Ecosystems in North America: their areas, net annual fluxes of carbon, and their potential for sources (+) or sinks (–) in the future

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). The carbon lost to the atmosphere from cultivation of organic soils is approximately balanced by the carbon accumulated in mineral soils. In the past, before cultivation, these soils held considerably more carbon than they do today, but about 25% 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). The magnitude (and even sign) of this flux is uncertain, however, in part because some ecosystems lose carbon belowground (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.*, in press).

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 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 ha^{-1} yr^{-1} in Table 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), 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 the Table 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 to potential to become a significant net source of carbon if the permafrost thaws with global warming (Smith *et al*,. 2005, Smith *et al.*, 2001, Osterkamp *et al.*, 1999, 2000). Forests clearly dominate the net sequestration 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 yr^{-1}, for example (~5% of fossil fuel emissions from North America), requires management over hundreds of millions of hectares (e.g., the area presently in agriculture or forests) (Table 1). Enhancement of this terrestrial carbon sink through management 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 yr^{-1} 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. Somewhat smaller sinks of 10–70 Mt C yr^{-1} might be sequestered in agricultural soils at low to moderate costs ($3–30/ton CO_2). The maximum amounts of carbon that might be accumulated in forests and agricultural soils are not known, and 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.

Despite the limited nature of carbon sequestration 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).

The effects and cost of managing aquatic systems are less clear. Increasing the area of wetlands, for example, would presumably sequester carbon; but it would also increase emissions of CH_4, countering the desired effect. Fertilization of coastal waters with iron has been proposed 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).

A few studies have estimated the potential magnitudes of future carbon sinks as a result of management (Chapters 10, 11). However, the contribution of management, as opposed to the environment, in today's sink is unclear (see Chapter 3), 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). 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 sequestering 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 cycling of carbon is large in comparison to net fluxes. The observation is relevant for carbon management, because the cumulative effects of small managed 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 today's and tomorrow's sources and sinks of carbon? 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). 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*., 2005).
- Several chapters cite studies that have attempted to quantify potential future carbon sinks in countries in North America, but no reference is made to estimates of future sources of carbon. Clearly, there are modeling studies that project large future carbon emissions, although these studies are largely global in scope (e.g., Cox *et al*., 2000; Jones *et al*., 2005). Are there no studies of future carbon sources and sinks for North America? Melting permafrost, in particular, is likely to increase emissions of carbon to the atmosphere, CH_4 as well as CO_2.
- The sum of land areas reported in these chapters is about 330 million ha larger than the area of North America (Table 1). The reason for this double-counting is unclear, but it implies a double counting of carbon stocks and, perhaps, current sinks, as well.

REFERENCES

Bradley, B. A., R. A. Houghton, J. F. Mustard, and S. P. Hamburg. Invasive grass reduces carbon stocks in shrublands of the Western United States *Global Change Biology*, in press.

Caspersen, J. P., S. W. Pacala, J. C. Jenkins, G. C. Hurtt, P. R. Moorcroft, and R. A. Birdsey. 2000. Contributions of land-use history to carbon accumulation in United States forests. *Science* **290**:1148–1151.

Cox, P. M., R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell. 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* **408**:184–187.

Davidson, E. A., and I. A. Janssens. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* **440**:165–173.

Houghton, R. A., J. L. Hackler, and K. T. Lawrence. 1999. The United States carbon budget: contributions from land-use change. *Science 285*:574–578.

Hurtt, G. C., S. W. Pacala, P. R. Moorcroft, J. Caspersen, E. Shevliakova, R. A. Houghton, and B. Moore III. 2002. Projecting the future of the United States carbon sink. *Proceedings of the National Academy of Sciences* **99**:1389–1394.

Jones, C., C. McConnell, K. Coleman, P. Cox, P. Falloon, D. Jenkinson, and D. Powlson. 2005. Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil. *Global Change Biology* **11**:154–166.

Lal, R. 2001. Fate of eroded soil carbon: emission or sequestration. *In*: Lal, R. (Ed.), *Soil Carbon Sequestration and the Greenhouse Effect*. Soil Science Society of America Special Publication, vol. 57. Madison, Wisconsin, pp. 173-181.

Osterkamp, T. E., and V. E. Romanovsky. 1999: Evidence for warming and thawing of discontinuous permafrost in Alaska. *Permafrost and Periglacial Processes*, 10(1):17–37.

Osterkamp, T. E., L. Viereck, Y. Shur, M. T. Jorgenson, C. Racine, A. Doyle, and R. D. Boone. 2000: Observations of thermokarst and its impact on boreal forests in Alaska, United States. *Arctic, Antarctic and Alpine Research*, **32**:303–315.

Prentice I. C., G. D. Farquhar, M. J. R. Fasham, M. L. Goulden, M. Heimann, V. J. Jaramillo, H. S. Kheshgi, C. Le Quéré, R. J. Scholes, and D. W. R. Wallace. 2001. The carbon cycle and atmospheric carbon dioxide. In: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, United States, pp. 183–237.

Schimel, D., J. Melillo, H. Tian, A. D. McGuire, D. Kicklighter, T. Kittel, N. Rosenbloom, S. Running, P. Thornton, D. Ojima, W. Parton, R. Kelly, M. Sykes, R. Neilson, and B. Rizzo. 2000. Contribution of increasing CO_2 and climate to carbon storage by ecosystems in the United States. *Science* **287**:2004–2006.

Smith, L.C., Y. Sheng, G.M. MacDonald, L.D. Hinzman, 2005: Disappearing Arctic Lakes, *Science*, 308, 1429.

Smith, S. L., M. M. Burgess, and F. M. Nixon. 2001: Response of activelayer and permafrost temperatures to warming during 1998 in the Mackenzie Delta, Northwest Territories and at Canadian Forces Station Alert and Baker Lake, Nunavut. *Geological Survey of Canada Current Research* 2001–E5, 8pp.

Smith, S.V., R.O. Sleezer, W.H. Renwick, and R.W. Buddemeier. 2005. Fates of eroded soil organic carbon: Mississippi Basin case study. *Ecological Applications* **15**:1929-1940.

Stallard, R.F. 1998. Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial. *Global Biogeochemical Cycles* **12**:231-257.

Wienert, A., and S.P. Hamburg. 2006. Carbon stock changes and greenhouse gas emissions from exurban land development in central New Hampshire. Master’s Thesis, Brown University, Providence, Rhode Island.

Table 1. Ecosystems in North America: their areas, net annual fluxes of carbon, and their potential for sources (+) or sinks (–) in the future

Type of ecosystem	Area (10^6 ha)	Current mean flux density (Mg C ha^{-1} yr^{-1})	Current flux (Mt C yr^{-1})	Carbon stocks (Mt C)	Future potential flux (Mt C yr^{-1})
Agriculture	231	0.0	0±15[1]	18,500	–(50 to100) to +??
Grass, shrub and arid	558	–0.01	–6[2]	59,950	–34
Forests	771	–0.45	–350[3]	171,475	–(100 to 200) to+??
Permafrost wetlands	621[4]	$^{-}$0.02	–14[5]	213,320	
Wetlands	246	–0.28	–70	220,000	
Settled lands	104	–0.31[6]	–32[6]	~1,000[6]	
Coastal waters	384	0.05	19		
Sum	2531[7]	–0.18[8]	–472[9]	684,245	
Total	2126[10.]				

1. Fossil fuel inputs to crop management are not included. Some of the C 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.
2. 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 (Bradley *et al.*, in press) is included in this estimate of flux because the uncertainties are so large.
3. Includes an annual sink of 67 Mt C yr^{-1} in wood products as well as a sink of 283 Mt C yr^{-1} in forested ecosystems.
4. Includes zones with isolated and sporadic permafrost.
5. This estimate is for peatlands (not mineral soils) in permafrost regions. The net flux for mineral soil permafrost areas is unknown. This estimate of flux may be high because it does not include the losses resulting from fires, but it may be low if mineral soils are also accumulating carbon in permafrost regions.
6. Urban trees only (does not include soil carbon).
7. Sum does not include coastal waters. The summed area is too high because an estimated 75×10^6 ha of permafrost peatlands in Canada are treed (and may be included in forest area as well as permafrost area). Nevertheless, another ~330×10^6 ha are double counted (United States forests on non-permafrost wetlands? Other wooded lands that are included as both forests and rangelands? Large areas of grasslands and shublands on non-permafrost lands within areas defined as sporadic or isolated permafrost? Inland waters?).
8. Weighted average; does not include coastal waters.
9. Does not include coastal waters. The total annual sink of 472 Mt C is lower than the estimate of 592 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 yr^{-1}; Table 1, above, presents a net flux of zero (see note 2). Other differences between the two estimates include: (1) an additional sink in Table 1 of 14 Mt C yr^{-1} in permafrost wetlands; (2) an additional sink in Table 1 of 32 Mt C yr^{-1} in settled lands; and (3) a sink of 25 Mt C yr^{-1} in rivers and reservoirs that is included in Table 3-1 but not in Table 1. In addition, there are small differences in the estimates for agricultural lands and grasslands.
10. 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