Chapter 3. The North American Carbon Budget
Past and Present

Coordinating Lead Author: Stephen Pacala[1]

Lead Authors: Richard Birdsey,[2] Scott Bridgham,[3] Richard T. Conant,[4] Kenneth Davis,[5] Burke Hales,[6] Richard Houghton,[7] J. C. Jenkins,[8] Mark Johnston,[9] Gregg Marland,[10] Keith Paustian,[4] and Steven C. Wofsy[11]

Contributing Authors: John Caspersen,[12] Robert Socolow,[13] and Richard S. J. Tol[14]

[1]Department of Ecology and Evolutionary Biology, Princeton University, [2]USDA Forest Service, [3]Center for Ecology and Evolutionary Biology, University of Oregon, [4]Natural Resource Ecology Laboratory, Colorado State University, [5]Department of Meteorology, The Pennsylvania State University, [6]College of Oceanic and Atmospheric Sciences, Oregon State University, [7]Woods Hole Research Center, [8]The Rubenstein School of Environment and Natural Resources, Gund Institute for Ecological Economics, University of Vermont, [9]Saskatchewan Research Council, [10]Department of Engineering, Physics and Mathematics, Mid Sweden University, [11]Atmospheric and Environmental Science (FAS), Harvard University, [12]Faculty of Forestry, University of Toronto, [13]Department of Mechanical and Aerospace Engineering and Princeton Environmental Institute, Princeton University, [14]Research Unit Sustainability and Global Change, Hamburg University

---

KEY FINDINGS

- Fossil fuel carbon emissions in the United States, Canada, and Mexico totaled 1856 Mt C yr^{-1} in 2003 This represents 27% of global fossil fuel emissions.
- Approximately 30% of North American fossil fuel emissions are offset by a natural sink of 592 Mt C yr^{-1} caused by a variety of factors, including forest regrowth, fire suppression, and agricultural soil conservation.
- North American carbon dioxide emissions from fossil fuel have increased at an average rate of approximately 1% per year for the last 30 years.
- The growth in emissions accompanies the historical growth in the industrial economy and Gross Domestic Product (GDP) of North America. However, at least in the United States and Canada the rate of emissions growth is less than the growth in GDP, reflecting a decrease in the carbon intensity of these economies.
- Historically the plants and soils of the United States and Canada were sources for atmospheric CO2, primarily as a consequence of the expansion of croplands into forests and grasslands. In recent

decades the terrestrial carbon balance of these regions have shifted from source to sink as forests recover from agricultural abandonment, fire suppression and reduced logging and, as a result, are accumulating carbons. In Mexico, emissions of carbon continue to increase from net deforestation.

- Fossil fuel emissions from North America are expected to continue to grow, but will also continue to grow more slowly than GDP.
- The future of the North American carbon sink is highly uncertain. The contribution of recovering forests to this sink is likely to decline as these forests mature, but we do not know how much of the sink is due to fertilization of the ecosystems by nitrogen in air pollution and by increasing CO2 concentrations in the atmosphere, nor do we understand the impact of tropospheric ozone or how the sink will change as the climate changes.
- The magnitude of the North American sink offers the possibility that significant mitigation of fossil fuel emissions could be accomplished by managing forests, rangelands, and croplands to increase the carbon stored in them. However, the range of uncertainty in these estimates is at least as large as the estimated values themselves.
- Current trends towards lower carbon intensity of U.S. and Canadian economies increase the likelihood that a portfolio of carbon management technologies will be able to reduce the 1% annual growth in fossil fuel emissions. This same portfolio might be insufficient if carbon emissions were to begin rising at the approximately 3% growth rate of GDP.

Fossil Fuel

Fossil fuel carbon emissions in the United States, Canada, and Mexico totaled 1856 Mt C yr^{-1} in 2003 and have increased at an average rate of approximately 1% per year for the last 30 years (United States = 1582, Canada = 164, Mexico = 110 Mt C yr^{-1}, see Fig. 3-1). This represents 27% of global emissions, from a continent with 7% of the global population, and 25% of global GDP (EIA, 2005).

Figure 3-1. Historical carbon emissions from fossil fuel in the United States, Canada, and Mexico. Data from the US Energy Information Administration (EIA 2005).

The United States is the world's largest emitter in absolute terms. Its per capita emissions of 5.4 t C yr^{-1} are among the largest in the world, but the carbon intensity of its economy (emissions per unit GDP) at 0.15 metric tons of emitted carbon per dollar of GDP is close to the world's average of 0.14 t C/$ (EIA, 2005). Total U.S. emissions have grown at close to the North American average rate of about 1.0% per year over the past 30 years, but U.S. per capita emissions have been roughly constant, while the carbon intensity of the U.S. economy has decreased at a rate of about 2% per year (see Figs. 3-1 to 3-5).

Absolute emissions grew at 1% per year even though per capita emissions were roughly constant simply because of population growth at an average rate of 1%. The constancy of U.S. per capita values masks faster than 1% growth in some sectors (e.g., transportation) that was balanced by slower growth in others (e.g., increased manufacturing energy efficiency) (Fig. 3-3, 3-4 and 3-5).

Historical decreases in U.S. carbon intensity began early in the 20th century and continue despite the approximate stabilization of per capita emissions (Fig. 3-2). Why has the U.S. carbon intensity declined? This question is the subject of the extensive literature on the so-called structural decomposition of the energy system and on the relationship between GDP and environment (i.e., Environmental Kuznets Curves; Grossman and Krueger, 1995; Selden and Song, 1994). See for example Greening *et al.* (1997, 1998), Casler and Rose (1998), Golove and Schipper (1998), Rothman (1998), Suri and Chapman (1998), Greening *et al.* (1999), Ang and Zhang (2000), Greening *et al.* (2001), Davis *et al.* (2002), Kahn (2003), Greening (2004), Lindmark (2004), Aldy (2005), and Lenzen *et al.* (2006).

Possible causes of the decline in U.S. carbon intensity include structural changes in the economy, technological improvements in energy efficiency, behavioral changes by consumers and producers, the growth of renewable and nuclear energy, and the displacement of oil consumption by gas, or coal by oil and gas (if we produce the same amount of energy from coal, oil, and gas, then the emissions from oil are only 80% of those from coal, and from gas only 75% of those from oil) (Casler and Rose, 1998; Ang and Zhang, 2000). The last two items on this list are not dominant causes because we observe that both primary energy consumption and carbon emissions grew at close to 1% per year over the past 30 years (EIA, 2005). At least in the United States, there has been no significant decarbonization of the energy system during this period. However, all of the other items on the list play a significant role. The economy has grown at an annual rate of 2.8% over the last three decades because of 3.6% growth in the service sector; manufacturing grew at only 1.5% per year (Fig. 3-4). Because the service sector has a much lower carbon intensity than manufacturing (a factor of 6.5 in 2002; compare Figs. 3-4 and 3-5), this faster growth of services reduces the country's carbon intensity. If all of the growth in the service sector had been in manufacturing from 1971 to 2001, then the emissions would have grown at 2% per year instead of 1%. So, structural change is at least one-half of the answer. Because the service sector is likely to continue to grow more rapidly than other sectors of the economy, we expect that carbon emissions will continue to grow more slowly than GDP. This is important because it implies that emissions growth is essentially decoupled from economic growth and speaks to the issue of our technological readiness to achieve an emissions target. For example, a portfolio of technologies able to convert the 1% annual growth in emissions into a 1% annual decline, might be insufficient if carbon emissions were to begin rising at the ~3% growth rate of GDP (Pacala and Socolow, 2004).

However, note that emissions from manufacturing are approximately constant despite 1.5% economic growth, while those of services grew at 2.1% despite 3.6% economic growth (Figs. 3-3 and 3-4). The decrease in the carbon intensity within these sectors is caused both by within-sector structural shifts (i.e., from heavy to light manufacturing) and by technological improvements (See Part II of this report). Emissions from the residential sector are growing at roughly the same rate as the population (Fig. 3-4; 30-year average of 1.0% per year), while emissions from transportation are growing faster than the population but slower than GDP (Fig. 3-4; 30-year average of 1.4% per year). The difference between the 3% growth rate of GDP and the 1.6% growth in emissions from transportation is not primarily due to technological improvement because carbon emissions per mile traveled have been level or increasing over the period (Chapter 7).

Figure 3-2. The historical relationship between U.S. per capita GDP and U.S. carbon intensity (green symbols, kg CO_2 emitted per 1995 dollar of GDP) and per capita carbon emissions (blue symbols, kg CO_2 per person). Each symbol shows a different year and each of the two time series progresses roughly chronologically from left (early) to right (late) and ends in 2002. *Source*: Maddison (2003), Marland *et al.* (2005). Thus, the red square farthest to the right shows U.S. per capita CO_2 emissions in 2002. The square second farthest to the right shows per capita emissions in 2001. The third farthest to the right shows 2000 and so on. Note that per capita emissions have been roughly constant over the last 30 years (squares corresponding to per capita GDP greater than approximately $16,000).

Figure 3-3. Historical U.S. GDP divided among the manufacturing, services and agricultural sectors. *Source*: Mitchell (1998) and WRI (2005).

Figure 3-4. Historical U.S. carbon emissions divided among the residential, commercial, industrial, and transportation sectors. *Source*: EIA (2005).

Carbon Sinks (see Tables 3-1and 3-2 for citations and data)

Approximately 30% of North American fossil fuel emissions are offset by a natural sink of 592 Mt C yr^{-1} caused by a variety of factors, including forest regrowth, fire suppression, and agricultural soil conservation. The sink currently absorbs 506 Mt C yr^{-1} in the United States and 134 Mt C yr^{-1} in Canada. Mexican ecosystems create a net source of 48 Mt C yr^{-1}. Rivers and international trade also export a net of 161 Mt C yr^{-1} that was captured from the atmosphere by the continent's ecosystems, and so North America absorbs 753 Mt C yr^{-1} of atmospheric CO_2 (753 = 592 + 161). Because most of these net exports will return to the atmosphere elsewhere within 1 year (e.g. carbon in exported grain will be eaten, metabolized, and exhaled as CO_2), the net North American sink is rightly thought of as 592 Mt C yr^{-1} even though the continent absorbs a net of 753 Mt C yr^{-1}. Moreover, coastal waters may be small net emitters to the atmosphere at the continental scale (19 Mt C yr^{-1}), but this flux is highly uncertain (see Chapter 15). The portion of the coastal flux caused by human activity is thought to be close to zero, and so coastal sea-air exchanges should also be excluded from the continental carbon sink.

As reported in Chapter 2, the United States is responsible for 27% of the global carbon sink and 86% of the North American sink. The reason for the disproportionate importance of U.S. sinks is probably the unique land use history of the country (summary in Appendix 3A). During European settlement, large amounts of carbon were released from the harvest of virgin forests and the plowing of virgin soils to create agricultural lands. The abandonment of many of the formerly agricultural lands in the east and the regrowth of forest is a unique event globally and is responsible for about one-half of the U.S. sink (Houghton *et al*., 2000). Most of the U.S. sink thus represents a one-time recapture of some of the carbon that was released to the atmosphere during settlement. In contrast, Mexican ecosystems, like those of many tropical nations, are still a net carbon source because of ongoing deforestation (Masera *et al*., 1997).

Table 3-1. Annual net carbon emissions (source = positive) or uptake (land sink = negative) of carbon in millions of tons.

Table 3-2. Annual net horizontal transfers of carbon in millions of tons.

Table 3-3. Carbon stocks in North America in billions of tons.

The non-fossil fluxes in Tables 3-1 and 3-2, are derived exclusively from inventory methods in which the total amount of carbon in a pool (i.e., living forest trees plus forest soils) is measured on two occasions. The difference between the two measurements shows if the pool is gaining (sink) or losing (source) carbon. Carbon inventories are straightforward in principle, but of uneven quality in practice. For example, we know the carbon in living trees in the United States relatively accurately because the U.S. Forest Service Forest Inventory program measures trees systematically in more than 200,000 locations. However, we must extrapolate from a few measurements of forest soils with models because there is no national inventory of carbon in forest soils.

Although the fluxes in Tables 3-1 and 3-2 represent the most recent published estimates, with most less than five years old, a few are older than ten years (see the citations at the bottom of each Table). Also, the time interval between inventories varies among the elements of the Tables, with most covering a five to ten year period. We report uncertainties using six categories: ***** = 95% certain that the actual value is within 10% of the estimate reported, **** = 95% certain that the estimate is within 25%, *** =

95% certain that the estimate is within 50%, ** = 95% certain that the estimate is within 100%, * = uncertainty > 100%.

In addition to inventory methods, it is also possible to estimate carbon sources and sinks by measuring carbon dioxide in the atmosphere. For example, if air exits the border of a continent with more CO_2 than it contained when it entered, then there must be a net source of CO_2 somewhere inside the continent. We do not include estimates obtained in this way because they are still highly uncertain at continental scales. Pacala *et al*. (2001) found that atmosphere- and inventory-based methods gave consistent estimates of U.S. ecosystem sources and sinks but that the range of uncertainty from the former was considerably larger than the range from the latter. For example, by far the largest published estimate for the North American carbon sink was produced by an analysis of atmospheric data by Fan *et al*. (1998) (-1700 Mt C yr^{-1}). The appropriate inventory-based estimate to compare this to is our –753 Mt C yr^{-1} of net absorption (atmospheric estimates include net horizontal exports by rivers and trade), and this number is well within the wide uncertainty limits in Fan *et al*. (1998). The allure of estimates from atmospheric data is that they do not risk missing critical uninventoried carbon pools. But, in practice, they are still far less accurate at continental scales than a careful inventory (Pacala *et al*., 2000). Using today's technology, it should be possible to complete a comprehensive inventory of the sink at national scales, with the same accuracy as the U.S. forest inventory currently achieves for above-ground carbon in forests (25%, Smith and Heath, 2005). Moreover, this inventory would provide disaggregated information about the sink's causes and geographic distribution. In contrast, estimates from atmospheric methods rely on the accuracy of atmospheric models, and estimates obtained from different models vary by 100% or more at the scale of the United States, Canada, or Mexico (Gurney *et al*., 2004). Nonetheless, extensions of the atmospheric sampling network should improve the accuracy of atmospheric methods and might allow them to achieve the accuracy of inventories at regional and whole-country scales. In addition, atmospheric methods will continue to provide an independent check on inventories to make sure that no large flux is missed, and atmospheric methods will remain the only viable method to assess inter-annual variation the continental flux of carbon.

The magnitude of the North American sink documented in Tables 3-1 and 3-2 offers the possibility that significant carbon mitigation could be accomplished by managing forests, rangelands, and croplands to increase the carbon stored in them. However, many of the estimates in Tables 3-1 and 3-2 are highly uncertain; for some the range of uncertainty is larger than the value reported. The largest contributors to the uncertainty in the U.S. sink are the amount of carbon stored on rangelands because of the encroachment of woody vegetation and the lack of comprehensive and continuous inventory of Alaskan lands. A carbon inventory of these lands would do more to constrain the size of the U.S. sink than would any other measurement program of similar cost. Also we still lack comprehensive U.S. inventories of carbon in soils, woody debris, wetlands, rivers, and reservoirs. Finally, we lack estimates of any kind for five significant components of the carbon budget in Canada and six in Mexico (see Table 3-1 and 3-2).

The cause and future of the North American carbon sink is also highly uncertain. Although we can document the accumulation of carbon in ecosystems and wood products, we do not know how much of the sink is due to fertilization of the ecosystems by the nitrogen in air pollution and by the added CO_2 in the atmosphere, we do not fully understand the impact of tropospheric ozone, nor do we understand precisely how the sink will change as the climate changes. Research is mixed about the importance of nitrogen and CO_2 fertilization (Casperson *et al*., 2000; Oren *et al*., 2001; Hungate *et al*., 2003; Luo 2006**;** Körner *et al*., 2005). If these factors are weak, then, all else equal, we expect the North American sink to decline over time as ecosystems complete their recovery from past exploitation (Hurtt *et al*., 2002). However, if these factors are strong, then the sink could grow in the future. Similarly, global warming is expected to lengthen the growing season in most parts of North America, which should increase the sink (but see Goetz et al. 2005). But warming is also expected to increase the rate of decomposition of dead organic matter, which should decrease the sink. The relative strength of these two factors is still difficult to predict. Experimental manipulations of climate, atmospheric CO_2, tropospheric ozone, and nitrogen, at the largest possible scale, will be required to reduce uncertainty about the future of the carbon sink.

In what follows, we provide additional detail about the elements in Tables 3-1 and 3-2.

Forests

Based on U.S. Forest Service inventories, forest ecosystem carbon stocks in the United States, excluding soil carbon, have increased since 1953. The rate of increase has recently slowed because of increasing harvest and declining growth in some areas with maturing forests. The current average annual increase in carbon in trees is 146 Mt C yr^{-1} (Smith and Heath, 2005, uncertainty ****) plus 23 Mt C yr^{-1} from urban and suburban trees (the midpoint of the range in Chapter 14, uncertainty ***). The total estimate of the carbon sink in forested ecosystems is –259 Mt C yr^{-1} and includes a sink of 90 Mt C yr^{-1} (uncertainty **) from the accumulation of nonliving carbon in the soil (-90-146-23 = –259) (Pacala *et al*., 2001; Goodale *et al*., 2002). Although the magnitude of the forest soil sink has always been uncertain, it is now possible to measure the total above-and below-ground sink in a few square kilometers by monitoring the atmospheric carbon dioxide that flows into and out of the site over the course of a year. Note that these spatially intensive methods appropriate for monitoring the sink over a few square kilometers are unrelated to the spatially extensive methods described above, which attempt to constrain the sink at continental scales. As described in Appendix 3B, these studies are producing data that so far confirm the estimates of inventories and show that most of the forest sink is above ground.

According to Canada's Greenhouse Gas Inventory (Environment Canada, 2005), managed forests in Canada (comprising 53% of the total forest area) sequestered 101 Mt C aboveground in 1990 (uncertainty ***). Since then, carbon sequestration has decreased gradually to 69 Mt C in 2003, as managed forests have recovered from past disturbances (Kurz and Apps, 1999, uncertainty ***). In addition, Goodale *et al*. (2002) estimate the sink of nonliving carbon belowground to be –30 Mt C yr^{-1} for the period 1990–1994 (uncertainty **).

The two published carbon inventories for Mexican forests (Masera *et al*., 1997 and Cairns *et al*., 2000) both report substantial losses of forest carbon, primarily because of deforestation in the tropical south. However, both of these studies rely on calculations of carbon loss from remote imagery, rather than direct measurements, and both report results for a period that ended more than 10 years ago. Thus, in addition to being highly uncertain, the estimates for Mexican forests in Table 3-1 are not recent.

Wood Products

Wood products create a carbon sink because they accumulate both in use (e.g., furniture, house frames, etc.) and in landfills. The wood products sink is estimated at –57 Mt C yr^{-1} in the United States (Skog and Nicholson, 1998) and –10 Mt C yr^{-1} in Canada (Goodale *et al*., 2002). We know of no estimates for Mexico.

Woody Encroachment

Woody encroachment is the invasion of woody plants into grasslands or the invasion of trees into shrublands. It is caused by a combination of fire suppression and grazing. Fire inside the United States has been reduced by more than 95% from the pre-settlement level of approximately 80 million hectares burned per year, and this favors shrubs and trees in competition with grasses (Houghton *et al*., 2000). Field studies show that woody encroachment both increases the amount of living plant carbon and decreases the amount of dead carbon in the soil (Guo and Gifford, 2002; Jackson *et al*., 2002). Although the gains and losses are of similar magnitude (Jackson *et al*., 2002), the losses occur within approximately a decade after the woody plants invade (Guo and Gifford, 2002), while the gains occur over a period of up to a century or more. Thus, the net source or sink depends on the distribution of times since woody plants invaded, and this is not known. Estimates for the size of the current U.S. woody encroachment sink (Kulshreshtha *et al*., 2000; Houghton and Hackler, 1999; and Hurtt *et al*., 2002) all rely on methods that do not account for the initial rapid loss of carbon from soil when grasslands were converted to shrublands or forest. The estimate of –120 Mt C yr^{-1} in Table 3-1 is from Kulshreshtha *et al*. (2000) but is similar to the estimates from the other two studies (–120 and –130 Mt C yr^{-1}). No estimates are currently available for Canada or Mexico. Note the error estimate of more than 100% in Table 3-1. A comprehensive set of measurements of woody encroachment would reduce the error in the national and continental carbon budgets more than any other inventory.

Agricultural Lands

Soils in croplands and grazing lands have been historically depleted of carbon by humans and their animals, especially if the land was converted from forest to non-forest use. Harvest or consumption by animals reduces the input of organic matter to the soil, while tillage and manure inputs increase the rate of decomposition. Changes in cropland management, such as the adoption of no-till agriculture (see Chapter 10), have reversed the losses of carbon on some croplands, but the losses continue on the remaining lands. The net is an approximate carbon balance for agricultural soils in Canada and estimates for the United States ranging from a small source of 2Mt C yr^{-1} to small sink of -6 Mt C yr^{-1}.

Wetlands

Peatlands are wetlands that have accumulated deep soil carbon deposits because plant productivity has exceeded decomposition over thousands of years. Thus, wetlands form the largest carbon pool of any North American ecosystem (Table 3-3). If drained for development, this soil carbon pool is rapidly lost. Canada's extensive frozen and unfrozen wetlands create a net sink of between –19 and –20 Mt C yr^{-1} (see Chapters 12 and 13), but drainage of U.S. peatlands have created a net source of 5 Mt C yr^{-1}. The very large pool of peat in northern wetlands is vulnerable to climate change and could add more than 100 ppm to the atmosphere (1 ppm ≈ 2.1 Gt C) during this century if released because of global warming (see the model result in Cox *et al.*, 2000 for an example).

The carbon sink due to sedimentation in wetlands is between 0 and –21 Mt C yr^{-1} in Canada and between 0 and –112 Mt C yr^{-1} in the United States (see Chapter 13). Another important priority for research is to better constrain carbon sequestration due to sedimentation in wetlands, lakes, reservoirs, and rivers.

The focus on this chapter is on carbon dioxide; we do not include estimates for other greenhouse gases. However, wetlands are naturally an important source of methane (CH_4). Methane emissions effectively cancel out the positive benefits of any carbon storage as peat in Canada and make U.S. wetlands a source of warming on a decadal time scale (Chapter 13). Moreover, if wetlands become warmer and remain wet with future climate change, they have the potential to emit large amounts of methane. This is probably the single most important consideration, and unknown, in the role of wetlands and future climate change.

Rivers and Reservoirs

Organic sediments accumulate in artificial lakes and in alluvium (deposited by streams and rivers), and colluvium (deposited by wind or gravity) and represent a carbon sink. Pacala *et al*. (2001) extended an analysis of reservoir sedimentation (Stallard, 1998) to an inventory of the 68,000 reservoirs in the United States and also estimated net carbon burial in alluvium and colluvium. Table 3-1 includes the midpoint of their estimated range of 10 to 40 Mt C yr^{-1} in the coterminous United States. This analysis has also recently been repeated and produced an estimate of 17 Mt C yr^{-1} (E. Sundquist, personal communication). We know of no similar analysis for Canada or Mexico.

Exports Minus Imports of Wood and Agricultural Products

The United States imports 14 Mt C yr^{-1} more wood products than it exports and exports 30–50 Mt C yr^{-1} more agricultural products than it imports (Pacala *et al*., 2001). The large imbalance in agricultural products is primarily because of exported grains and oil seeds. Canada and Mexico are net wood exporters, with Canada at –74 Mt C yr^{-1} (Environment Canada, 2005) and Mexico at –1 Mt C yr^{-1} (Masera *et al*., 1997). We know of no analysis of the Canadian or Mexican export-import balance for agricultural products.

River Export

Rivers in the coterminous United States were estimated to export 30–40 Mt C yr^{-1} to the oceans in the form of dissolved and particulate organic carbon and inorganic carbon derived from the atmosphere (Pacala *et al*., 2001). An additional 12–20 Mt C yr^{-1} of inorganic carbon is also exported by rivers but is derived from carbonate minerals. We know of no corresponding estimates for Alaska, Canada, or Mexico.

Coastal Waters

Chapter 15 summarizes the complexity and large uncertainty of the sea-air flux of CO_2 in North American coastal waters. It is important to understand that the source in Mexican coastal waters is not caused by humans and would have been present in pre-industrial times. It is simply the result of the purely physical upwelling of carbon-rich deep waters and is a natural part of the oceanic carbon cycle. It is not yet known how much of the absorption of carbon by U.S. and Canadian coastal waters is natural and how much is caused by nutrient additions to the coastal zone by humans. Accordingly, it is essentially impossible to currently assess the potential or costs for carbon management in coastal waters of North America.

CONCLUDING SUMMARY

Fossil fuel emissions currently dominate the net carbon balance in the United States, Canada, and Mexico (Fig. 3-1, Tables 3-1, 3-2). U.S. fossil fuel consumption currently emits 1582 Mt C yr^{-1} to the atmosphere. This is partially balanced by a flow of 506 Mt C yr^{-1} from the atmosphere to land caused by net ecosystem sinks in the United States. Canadian fossil consumption transfers 164 Mt C yr^{-1} to the atmosphere, but net ecological sinks capture 134 Mt C yr^{-1}. Mexican fossil emissions of 110 Mt C yr^{-1} are supplemented by a net ecosystem source of 48 Mt C yr^{-1} from tropical deforestation. Each of the three countries has always been a net source of carbon dioxide emissions to the atmosphere for the past three centuries (Houghton *et al*., 1999, 2000; Houghton and Hackler, 2000; Hurtt *et al*., 2002).

CHAPTER 3 REFERENCES

Aldy, J.E., 2005: An environmental kuznets curve analysis of US state level carbon dioxide emissions. *Journal of Environment and Development*, **14(1)**, 58–72.

Ang, B.W. and F.Q. Zhang, 2000: A survey of index decomposition analysis in energy and environmental studies. *Energy*, **25**, 1149–1176.

Archard, F., H.D. Eva, H.-J. Stibig, P. Mayaux, J. Gallego, T. Richards, and J.-P. Malingreau, 2002: Determination of deforestation rates of the world's humid tropical forests. *Science*, **297**, 999–1002.

Baldocchi, D., E. Falge, L.H. Gu, R. Olson, D. Hollinger, S. Running, P. Anthoni, C. Bernhofer, K. Davis, R. Evans, J. Fuentes, A. Goldstein, G. Katul, B. Law, X.H. Lee, Y. Malhi, T. Meyers, W. Munger, W. Oechel, K.T. Paw U, K. Pilegaard, H.P. Schmid, R. Valentini, S. Verma, T. Vesala, K. Wilson, and S. Wofsy, 2001: FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, *Bull. Am. Meteorol. Soc.*, **82**, 2415–2434.

Barford, C.C., S.C. Wofsy, M.L. Goulden, J.W. Munger, E.H. Pyle, S.P. Urbanski, L. Hutyra, S.R. Saleska, D. Fitzjarrald, and K. Moore, 2001: Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest. *Science*, **294**, 1688–1691.

Birdsey, R.A. and L.S. Heath, 1995: Carbon changes in U.S. forests. In: *Productivity of America's Forests and Climate Change* [Joyce, L.A. (ed.)]. General Technical Report RM-GTR-271, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 56–70.

Birdsey, R.A. and G.M. Lewis, 2003: Current and historical trends in use, management, and disturbance of U.S. forestlands. In: *The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect* [Kimble, J.M., L.S. Heath, and R. A. Birdsey (eds.)]. CRC Press LLC, New York, NY, pp. 15–33.

Bradley, B.A., R.A. Houghton, J.F. Mustard, and S.P. Hamburg, 2006: Invasive grass reduces carbon stocks in shrublands of the Western U.S. (in press).

Cairns, M.A., P.K. Haggerty, R. Alvarez, B.H.J. De Jong, and I. Olmsted, 2000: Tropical Mexico's recent land-use change: a region's contribution to the global carbon cycle. *Ecological Applications*, **10(5)**, 1426–1441.

Canadell, J.G., H.A. Mooney, D.D. Baldocchi, J.A. Berry, J.R. Ehleringer, C.B. Field, S.T. Gower, D.Y. Hollinger, J.E. Hunt, R.B. Jackson, S.W. Running, G.R. Shaver, W. Steffen, S.E. Trumbore, R. Valentini, B.Y. Bond, 2000: Carbon metabolism of the terrestrial biosphere: a multi-technique approach for improved understanding. *Ecosystems*, **3**, 115–130.

Casler, S.D. and A.Z. Rose, 1998: Carbon dioxide emissions in the US economy. *Environmental and Resource Economics*, **11(3–4)**, 349–363.

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 U.S. forests. *Science*, **290**, 1148–1151.

Cook, B.D., K.J. Davis, W. Wang, A. Desai, B.W. Berger, R.M. Teclaw, J.G. Martin, P.V. Bolstad, P.S. Bakwin, C. Yi, and W. Heilman, 2004: Carbon exchange and venting anomalies in an upland deciduous forest in northern Wisconsin, USA. *Agricultural and Forest Meteorology*, **126**, 271–295.

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.

Curtis, P.S., P.J. Hanson, P. Bolstad, C. Barford, J.C. Randolph, H.P. Schmid, and K.B. Wilson, 2002: Biometric and eddy-covariance based estimates of annual carbon storage in five eastern North American deciduous forests. *Agricultural and Forest Meteorology*, **113**, 3–19.

Davis, W.B., A.H. Sanstad, and J.G. Koomey, 2002: Contributions of weather and fuel mix to recent declines in US energy and carbon intensity. *Energy Economics*, **25**, 375–396.

Defries, R.S., R.A. Houghton, M.C. Hansen, C.B. Field, D. Skole, and J. Townshend, 2002: Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. *Proceedings of the National Academy of Sciences of the United States of America*, **99(22)**, 14256–14261.

Ehman, J.L., H.P. Schmid, C.S.B. Grimmond, J.C. Randolph, P.J. Hanson, C.A. Wayson, and F.D. Cropley, 2002: An initial intercomparison of micrometeorological and ecological inventory estimates of carbon exchange in a mid-latitude deciduous forest. *Global Change Biology*, **8**, 575–589.

EIA (Energy Information Administration), 2005: *Historical Data Overview*. U.S. Department of Energy. Available at http://www.eia.doe.gov/overview_hd.html; ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/ggrpt/057304.pdf

Environment Canada, 2005: *Canada's Greenhouse Gas Inventory 1990–2003: Initial Submission*. Greenhouse Gas Division, Environment Canada, Ottawa, Ontario, Canada. Available at http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/2761.php

Fan, S.-M., M. Gloor, J. Mahlman, S. Pacala, J. Sarmiento, T. Takahashi, and P. Tans, 1998: Atmospheric and oceanic CO_2 data and models imply a large terrestrial carbon sink in North America. *Science*, **282**, 442–446.

Goetz, S.J., A. Bunn, G. Fiske, and R.A. Houghton. 2005. Satellite observed photosynthetic trends across boreal North America associated with climate and fire disturbance. *Proceedings National Academy of Science* **102**:13521-13525.

Golove, W.H. and L.J. Schipper, 1998: Long-term trends in us manufacturing energy consumption and carbon dioxide emissions. *Energy*, **21(7/8)**, 683–692.

Goodale, C.L., M.J. Apps, R.A. Birdsey, C.B. Field, L.S. Heath, R.A. Houghton, J.C. Jenkins, G.H. Kohlmaier, W. Kurz, S. Liu, G.J. Nabuurs, S. Nilsson, and A.Z. Shvidenko, 2002: Forest carbon sinks in the northern hemisphere. *Ecological Applications*, **12(3)**, 891–899.

Gough, C.M., P.S. Curtis, J.G. Vogel, H.P. Schmid, and H.B. Su: Annual carbon storage from 1999 to 2003 in a Northern hardwood forest assessed using eddy-covariance and biometric methods. *Agricultural and Forest Meteorology* (in review).

Greening, L.A., W.B. Davis, L. Schipper, and M. Khrushch. 1997: Comparison of six decomposition methods: application to aggregate energy intensity for manufacturing in 10 OECD countries. *Energy Economics*, **19(3)**, 375–390.

Greening, L.A., W.B. Davis, and L. Schipper, 1998: Decomposition of aggregate carbon intensity for the manufacturing sector: comparison of declining trends from 10 OECD countries for the period 1971–1993. *Energy Economics*, **20(1)**, 43–65.

Greening, L.A., M. Ting, and W.B. Davis, 1999: Decomposition of aggregate carbon intensity for freight: trends from 10 OECD countries for the period 1971–1993. *Energy Economics*, **21(4)**, 331–361.

Greening, L.A., M. Ting, and T.J. Krackler, 2001: Effects of changes in residential end-uses on aggregate carbon intensity: comparison of 10 OECD countries for the period 1970 through 1993. *Energy Economics*, **23(2)**, 153–178.

Greening, L.A., 2004: Effects of human behavior on aggregate carbon intensity of personal transportation: comparison of 10 OECD countries for the period 1970–1993. *Energy Economics*, **26(1)**, 1–30.

Grossman, G.M. and A.B. Krueger, 1995: Economic growth and the environment. *Quarterly Journal of Economics*, **60(2)**, 353–375.

Guo, L.B. and R.M. Gifford, 2002: Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, **8(4)**, 345–360.

Gurney, K.R., R.M. Law, A.S. Denning, P.J. Rayner, B.C. Pak, D. Baker, P. Bousquet, L. Bruhwiler, Y.H. Chen, P. Ciais, I.Y. Fung, M. Heimann, J. John, T. Maki, S. Maksyutov, P. Peylin, M. Prather, and S. Taguchi, 2004: Transcom 3 inversion intercomparison: model mean results for the estimation of seasonal carbon sources and sinks. *Global Biogeochemical Cycles*, **18**, GB1010.

Horst, T.W. and J.C. Weil, 1994: How far is far enough? The fetch requirements for micrometeorological measurement of surface fluxes. *Journal of Atmospheric & Oceanic Technology*, **11**, 1018–1025.

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

Houghton, R.A. and J.L. Hackler, 2000: Changes in terrestrial carbon storage in the United States. 1. The roles of agriculture and forestry. *Global Ecology and Biogeography*, **9**, 125–144.

Houghton, R.A., J.L. Hackler, and K.T. Lawrence, 2000: Changes in terrestrial carbon storage in the United States. 2. The role of fire and fire management. *Global Ecology and Biogeography*, **9**, 145–170.

Houghton, R.A., 2003a: Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. *Tellus B*, **55(2)**, 378–390.

Houghton, R.A. 2003b: Why are estimates of the terrestrial carbon balance so different? *Global Change Biology*, **9(4)**, 500–509.

Hungate, B.A., J.S. Dukes, M.R. Shaw, Y. Luo, and C.B. Field, 2003: Nitrogen and climate change. *Science*, **302**, 1512–1513.

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 U.S. carbon sink. *Proceedings of the National Academy of Sciences of the United States of America*, **99**, 1389–1394.

Jackson, R.B., J.L. Banner, E.G. Jobbagy, W.T. Pockman, and D.H. Wall, 2002: Ecosystem carbon loss with woody plant invasion of grasslands. *Nature*, **418(6898)**, 623–626.

Kahn, M.E., 2003: The geography of US pollution intensive trade: evidence from 1958 to 1994. *Regional Science and Urban Economics*, **33**, 383–400.

Korner, C., R. Asshoff, O. Bignucolo, S. Hättenschwiler, S.G. Keel, S. Peláez-Riedl, S. Pepin, R.T.W. Siegwolf, and G. Zotz, 2005: Carbon flux and growth in mature deciduous forest trees exposed to elevated CO_2. *Science*, **309**, 1360–1362.

Kulshreshtha, S.N., B. Junkins, and R. Desjardins, 2000: Prioritizing greenhouse gas emission mitigation measures for agriculture. *Agricultural Systems*, **66(3)**, 145–166.

Kurz, W.A. and M.J. Apps, 1999: A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications*, **9**, 526–547.

Law, B.E., P.E. Thornton, J. Irvine, P.M. Anthoni, and S. Van Tuyl, 2001: Carbon storage and fluxes in ponderosa pine forests at different developmental stages. *Global Change Biology*, **7**, 755–777.

Lenzen, M., M. Wier, C. Cohen, H. Hayami, S. Pachauri, and R. Schaeffer, 2006: A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan. *Energy*, **31**, 181–207.

Lindmark, M., 2004: Patterns of historical CO_2 intensity transitions among high and low income countries. *Explorations in Economic History*, **41**, 426–447.

Luo, Y., D. Hui, and D. Zhang, 2006: Elevated carbon dioxide stimulates net accumulations of carbon and nitrogen in terrestrial ecosystems: a meta-analysis. *Ecology* (forthcoming in the 1st issue).

Masera, O.R., M.J. Ordonez, and R. Dirzo, 1997: Carbon emissions from Mexican forests: current situation and long-term scenarios. *Climate Change*, **35**, 265–295.

Maddison, A., 2003: *The World Economy: Historical Statistics*. OECD, Paris.

Marland, G., T.A. Boden, and R.J. Andres, 2005: Global, regional and national CO_2 emissions. In: *Trends: A Compendium of Data on Global Change*. Oak Ridge National Laboratory, Oak Ridge, TN. Available at http://cdiac.esd.ornl.gov/ trends/emis/em_cont.htm

Mitchell, B.R., 1998: *International Historical Statistics: The Americas, 1750–1993*. 4th Edition, Stockton Press, New York, NY.

Oren, R., D.S. Ellsworth, K.H. Johnsen, N. Phillips, B.E. Ewers, C. Maier, K.V.R. Schäfer, H. McCarthy, G. Hendrey, S.G. McNulty, and G.G. Katul, 2001: Soil fertility limits carbon sequestration by forest ecosystems in a CO_2-enriched atmosphere. *Nature*, **411**, 469–478.

Pacala, S.W., G.C. Hurtt, R.A. Houghton, R.A. Birdsey, L. Heath, E.T. Sundquist, R.F. Stallard, D. Baker, P. Peylin, P. Moorcroft, J. Caspersen, E. Shevliakova, M.E. Harmon, S.-M. Fan, J.L. Sarmiento, C. Goodale, C.B. Field, M. Gloor, and D. Schimel, 2001: Consistent land- and atmosphere-based U.S. carbon sink estimates. *Science*, **292(5525)**, 2316–2320.

Pacala, S.W. and R.H. Socolow, 2004: Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science*, **305(5686)**, 968–972.

Ramaswamy, V., O. Boucher, J. Haigh, D. Hauglustaine, J. Haywood, G. Myhre, T. Nakajima, G. Y. Shi, and S. Solomon, 2001: Radiative forcing of climate change. In: *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton J.T., 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, pp. 349–416.

Rothman, D.S., 1998: Environmental Kuznets curves—real progress or passing the buck: a case for consumption-based approaches. *Ecological Economics*, **25**, 177–194.

Selden, T.M. and D. Song, 1994: Environmental quality and development—is there a kuznets curve for air pollution emissions? *Journal of Environmental Economics and Management*, **27**, 147–162.

Skog, K.E. and G.A. Nicholson, 1998: Carbon cycling through wood products: the role of wood and paper products in carbon sequestration. *Forest Products Journal*, **48**, 75–83. Available at http://www.fpl.fs.fed.us/documnts/pdf1998/skog98a.pdf

Skog, K.E., K. Pingoud, and J.E. Smith, 2004: A method countries can use to estimate changes in carbon stored in harvested wood products and the uncertainty of such estimates. *Environmental Management*, **33** (**Supplement 1)**, S65–S73.

Smith, W.B., P.D. Miles, J.S. Vissage, and S.A. Pugh, 2004: *Forest Resources of the United States, 2002*. General Technical Report NC-241, U.S. Department of Agriculture, Forest Service, St. Paul, MN, 137 pp.

Smith, J.E. and L.S. Heath, 2005: Land use change and forestry and related sections (excerpted). In: *U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2003*. EPA 430-R-05-003. Available at http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2005.html

Stallard, R.F., 1998: Terrestrial sedimentation and the carbon cycle: coupling weathering and erosion to carbon burial. *Global Biogeochemical Cycles*, **12(2)**, 231.

Suri, V. and D. Chapman, 1998: Economic growth, trade and energy: implications for the environmental kuznets curve. *Ecological Economics*, **25(2)**, 195–208.

Verma, S.B., A. Dobermann, K.G. Cassman, D.T. Walters, J.M. Knops, T.J. Arkebauer, A.E. Suyker, G.G. Burba, B. Amos, H.S. Yang, D. Ginting, K.G. Hubbard, A.A. Gitelson, and E.A. Walter-Shea, 2005: Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. *Agricultural and Forest Meteorology*, **131**, 77–96.

Wofsy, S.C., M.L. Goulden, J.W. Munger, S.-M. Fan, P.S. Bakwin, B.C. Daube, S.L. Bassow, and F.A. Bazzaz. 1993: Net exchange of CO_2 in a mid-latitude forest. *Science*, **260**, 1314–1317.

WRI (World Resources Institute), 2005: *EarthTrends—The Environmental Information Portal*. Available at http://earthtrends.wri.org/

Table 3-1. Annual net emissions (source = positive) or uptake (land sink = negative) of carbon in millions of tons

Source (positive) or Sink (negative)	United States	Canada	Mexico	North America
Fossil source (positive)				
Fossil fuel[a] (oil, gas, coal)	1582[****] (681, 328, 573)	164[****] (75, 48, 40)	110[****] (71, 29, 11)	1857[****] (828, 405, 624)
Nonfossil carbon sink (negative) or source (positive)				
Forest	–259[b,***]	–99[c,***]	+52[d,**]	–306[***]
Wood products	–57[e,***]	–10[f,***]	ND	–67,***
Woody encroachment	–120[g,*]	ND	ND	–120[*]
Agricultural soils	–4[h,*]	–0[h]	–0[h]	–4[*]
Wetlands	–41[i,*]	–25[i,*]	–4[i,*]	–70[*]
Rivers and reservoirs	–25[j,**]	ND	ND	–25[*]
Total carbon source or sink	–506[***]	–134[**]	48[*]	–592[***]

Uncertainty:

*****(95% confidence within 10%)
****(95% confidence within 25%)
***(95% confidence within 50%)
**(95% confidence within 100%)
*(95% confidence bounds >100%)
ND = No data available

[a] http://www.eia.doe.gov/env/inlenv.htm

[b] Smith and Heath (2005) for above ground carbon, but including 23 Mt C/yr^{-1} for U.S. urban and suburban forests from Chapter 14, and Pacala *et al*. (2001) for below ground carbon.

[c] Environment Canada (2005)

[d] Masera *et al.* (1997)

[e] Skog *et al*. (2004), Skog and Nicholson (1998)

[f] Goodale *et al.* (2002)

[g] Kulshreshtha *et al*. (2000), Hurtt *et al*. (2002), Houghton and Hackler (1999).

[h] Chapter 10; Highly uncertain; Could range from -5 Mt C yr^{-1} to 5 Mt C yr^{-1}.

[i] Chapter 13

[j] Stallard, 1998; Pacala *et al*. (2001)

Table 3-2. Annual net horizontal transfers of carbon in millions of tons.

Net horizontal transfer: imports exceed exports = positive; exports exceed imports = negative	United States	Canada	Mexico	North America
Wood products	14[c,****]	–74[a,****]	–1[b,*]	–61[****]
Agriculture products	–65[d,***]	ND	ND	–65[***]
Rivers to ocean	–35[d,**]	ND	ND	–35[*]
Total net absorption (Total carbon source or sink in Table 3-1 plus exports)	–592[***]	–208[**]	47[*]	–753[**]
Net absorption (negative) or emission (positive) by coastal waters	ND	ND	ND	19[e,*]

Uncertainty:

*****(95% confidence within 10%)
****(95% confidence within 25%)
***(95% confidence within 50%)
**(95% confidence within 100%)
*(95% confidence bounds >100%)
ND = No data available
[a] Environment Canada (2005)
[b] Masera *et al.* (1997)
[c] Skog *et al*. (2004), Skog and Nicholson (1998)
[d] Pacala et al. (2001)
[e] Chapter 15

Table 3-3. Carbon stocks in North America in billions of tons

	United States	Canada	Mexico	North America
Forest	53[a,***]	85[a,***]	9[d,**]	147[***]
Cropland	14[b,****]	4[b,****]	1[b,**]	19[****]
Pasture	33[b,***]	12[b,***]	10[b,***]	55[***]
Wetlands	42[c,***]	152[c,***]	2[c,*]	196[***]
Total	142[***]	253[***]	22[**]	417[***]

Uncertainty:

*****(95% confidence within 10%)
****(95% confidence within 25%)
***(95% confidence within 50%)
**(95% confidence within 100%)
*(95% confidence bounds >100%)

[a] Goodale *et al*. (2002)
[b] Chapter 10
[c] Chapter 13
[d] Masera *et al*. (1997)

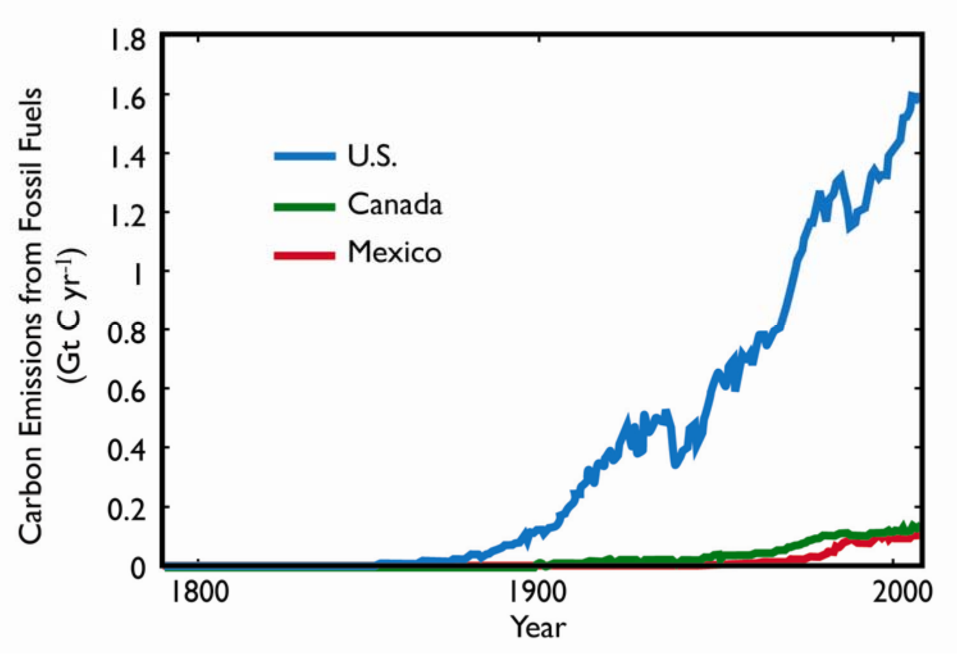

Fig. 3-1. Historical carbon emissions from fossil fuel in the United States, Canada, and Mexico. Data from the U.S. Energy Information Administration (EIA 2005).

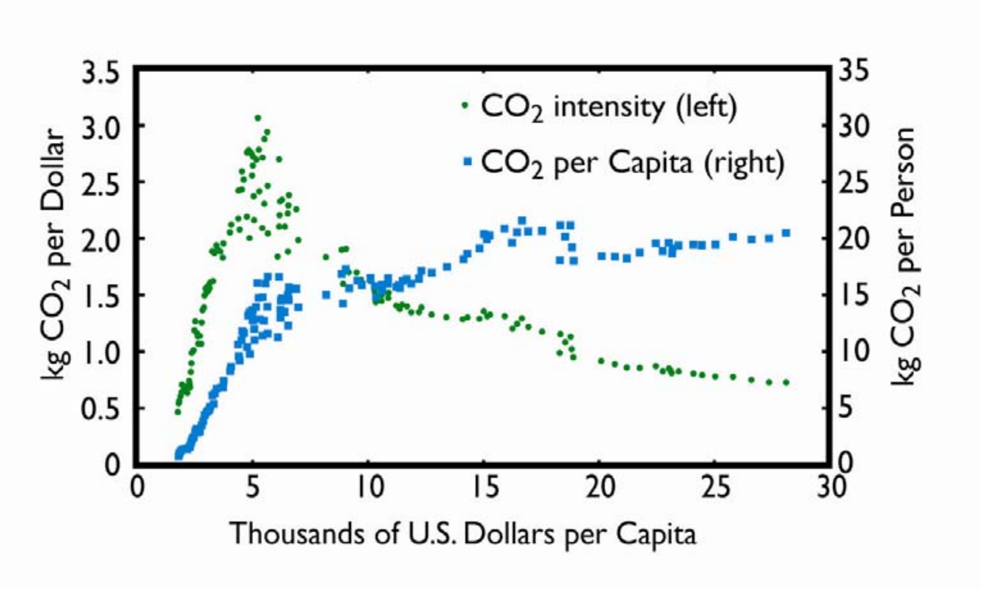

Fig. 3-2. The historical relationship between U.S. per capita GDP and U.S. carbon intensity (green symbols, kg CO_2 emitted per 1995 dollar of GDP) and per capita carbon emissions (blue symbols, kg CO_2 per person). Each symbol shows a different year and each of the two time series progresses roughly chronologically from left (early) to right (late) and ends in 2002. *Source*: Maddison (2003), Marland *et al*. (2005). Thus, the red square farthest to the right shows U.S. per capita CO_2 emissions in 2002. The square second farthest to the right shows per capita emissions in 2001. The third farthest to the right shows 2000, and so on. Note that per capita emissions have been roughly constant over the last 30 years (squares corresponding to per capita GDP greater than approximately $16,000).

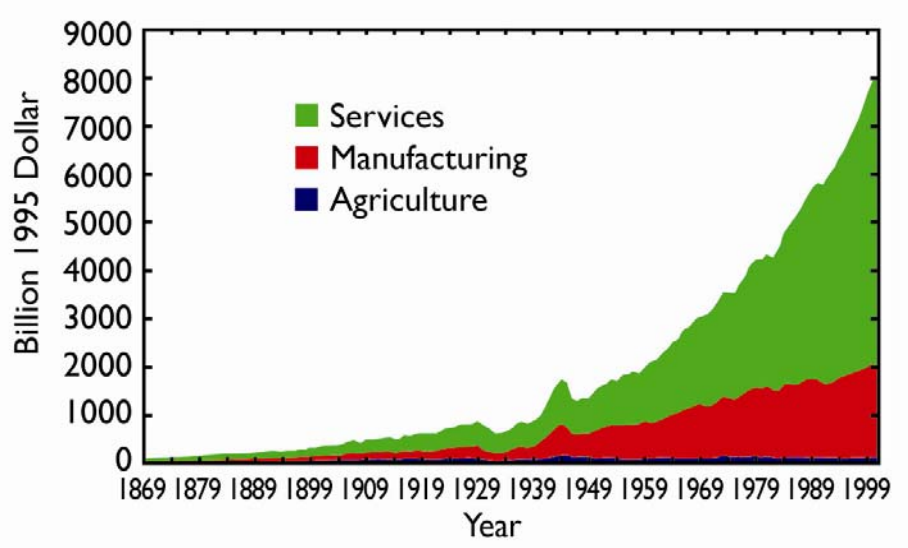

Figure 3-3. Historical U.S. GDP divided among the manufacturing, services, and agricultural sectors.

Source: Mitchell (1998), WRI (2005).

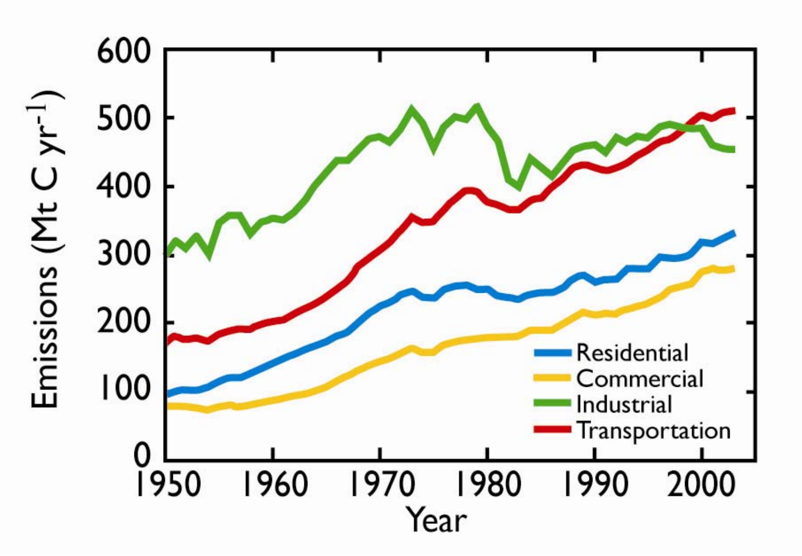

Figure 3-4. Historical U.S. carbon emissions divided among the residential, services, manufacturing, and transportation sectors. *Source*: EIA (2005).

[This page intentionally left blank]

Appendix 3A

Historical Overview of the Development of U.S., Canadian, and Mexican Ecosystem Sources and Sinks for Atmospheric Carbon

Although the lands of the New World were inhabited before the arrival of Europeans, the changes since arrival have been enormous, especially during the last two centuries. Peak U.S. emissions from land-use change occurred late in the 19th century, and the last few decades have experienced a carbon sink (Houghton *et al*., 1999; Hurtt *et al*., 2002). In Canada, peak emissions occurred nearly a century later than in the United States, and current data show that land-use change causes a net carbon sink (Environment Canada, 2005). In Mexico, the emissions of carbon continue to increase from net deforestation. All three countries may be in different stages of the same development pattern (see Fig. 3-2).

The largest changes in land use and the largest emissions of carbon came from the expansion of croplands. In addition to the carbon lost from trees, soils lose 25–30% of their initial carbon content (to a depth of 1 m) when cultivated. In the United States, croplands increased from about 0.25 million ha in 1700 to 236 million ha in 1990 (Houghton *et al*., 1999; Houghton and Hackler, 2000). The most rapid expansion (and the largest emissions) occurred between 1800 and 1900, and since 1920 there has been little net change in cropland area. Pastures expanded nearly as much, from 0.01 million to 231 million ha, most of the increase taking place between 1850 and 1950. As most pastures were derived from grasslands, the associated changes in carbon stocks were modest.

The total area of forests and woodlands in the United States declined as a result of agricultural expansion by 160 million ha (38%), but this net change obscures the dynamics of forest loss and recovery, especially in the eastern part of the United States. After 1920, forest areas increased by 14 million ha nationwide as farmlands continued to be abandoned in the northeast, southeast, and north central regions. Nevertheless, another 4 million ha of forest were lost in other regions, and the net recovery of 10 million ha offset only 6% of the net loss (Houghton and Hackler, 2000).

Between 1938 and 2002, the total area of forest land in the conterminous United States decreased slightly, by 3 million ha (Smith *et al*., 2004). This small change is the net result of much larger shifts among land-use classes (Birdsey and Lewis, 2003). Gains of forest land, primarily from cropland and pasture, were about 50 million ha for this period. Losses of forest land to cropland, pasture, and developed use were about 53 million ha for the same period. Gains of forest land were primarily in the

Eastern United States, whereas losses to cropland and pasture were predominantly in the South, and losses to developed use were spread around all regions of the United States.

In the United States, harvest of industrial wood (timber) generally followed the periods of major agricultural clearing in each region. In the last few decades, total volume harvested increased until a recent leveling took place (Smith *et al*., 2004). The volume harvested in the Pacific Coast and Rocky Mountain regions has declined sharply, whereas harvest in the South increased and in the North, stayed level. Fuel wood harvest peaked between 1860 and 1880, after which fossil fuels became the dominant type of fuel (Houghton and Hackler, 2000).

The arrival of Europeans reduced the area annually burned, but a federal program of fire protection was not established until early in the 20th century. Fire exclusion had begun earlier in California and in parts of the central, mountain and Pacific regions. However, neither the extent nor the timing of early fire exclusion is well known. After about 1920, the Cooperative Fire Protection Program gradually reduced the areas annually burned by wildfires (Houghton *et al*., 1999, 2000). The reduction in wildfires led to an increase in carbon storage in forests. How long this "recovery" will last is unclear. There is some evidence that fires are becoming more widespread, again, especially in Canada and the western United States. Fire exclusion and suppression are also thought to have led to woody encroachment, especially in the southwestern and western United States. The extent and rate of this process is poorly documented, however, and estimates of a carbon sink are very uncertain. Gains in carbon aboveground may be offset by losses belowground in some systems, and the spread of exotic annual grasses into semiarid deserts and shrublands may be converting the recent sink to a source (Bradley *et al*., in preparation).

The consequence of this land-use history is that U.S. forests, at present, are recovering from agricultural abandonment, fire suppression, and reduced logging (in some regions), and, as a result, are accumulating carbon (Birdsey and Heath, 1995; Houghton *et al*., 1999; Caspersen *et al*., 2000; Pacala *et al*., 2001). The magnitude of the sink is uncertain, and whether any of it has been enhanced by environmental change (CO_2 fertilization, nitrogen deposition, and changes in climate) is unclear. Understanding the mechanisms responsible for the current sink is important for predicting its future behavior (Hurtt *et al.,* 2002).

In the mid-1980s, Mexico lost approximately 668,000 ha of closed forests annually, about 75% of them tropical forests (Masera *et al*., 1997). Most deforestation was for pastures. Another 136,000 ha of forest suffered major perturbations, and the net flux of carbon from deforestation, logging, fires, degradation, and the establishment of plantations was 52.3 Mt C yr^{-1}, about 40% of the country's estimated annual emissions of carbon. A later study found the deforestation rate for tropical Mexico to be about 12% higher (1.9% per year) (Cairns *et al*., 2000).

REFERENCES FOR APPENDIX 3A

Birdsey, R.A. and L.S. Heath, 1995: Carbon changes in U.S. forests. In: *Productivity of America's Forests and Climate Change* [Joyce, L.A. (ed.)]. General Technical Report RM-GTR-271, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 56–70.

Birdsey, R.A. and G.M. Lewis, 2003: Current and historical trends in use, management, and disturbance of U.S. forestlands. In: *The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect* [Kimble, J.M., L.S. Heath, and R. A. Birdsey (eds.)]. CRC Press LLC, New York, NY, pp. 15–33.

Bradley, B.A., R.A. Houghton, J.F. Mustard, and S.P. Hamburg, 2006: Invasive grass reduces carbon stocks in shrublands of the Western U.S. (in press).

Cairns, M.A., P.K. Haggerty, R. Alvarez, B.H.J. De Jong, and I. Olmsted, 2000: Tropical Mexico's recent land-use change: a region's contribution to the global carbon cycle. *Ecological Applications*, **10(5)**, 1426–1441.

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 U.S. forests. *Science*, **290**, 1148–1151.

Environment Canada, 2005: *Canada's Greenhouse Gas Inventory 1990–2003: Initial Submission*. Greenhouse Gas Division, Environment Canada, Ottawa, Ontario, Canada. Available at http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/2761.php

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

Houghton, R.A. and J.L. Hackler, 2000: Changes in terrestrial carbon storage in the United States. 1. The roles of agriculture and forestry. *Global Ecology and Biogeography*, **9**, 125–144.

Houghton, R.A., J.L. Hackler, and K.T. Lawrence, 2000: Changes in terrestrial carbon storage in the United States. 2. The role of fire and fire management. *Global Ecology and Biogeography*, **9**, 145–170.

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 U.S. carbon sink. *Proceedings of the National Academy of Sciences of the United States of America*, **99**, 1389–1394.

Masera, O.R., M.J. Ordonez, and R. Dirzo, 1997: Carbon emissions from Mexican forests: current situation and long-term scenarios. *Climate Change*, **35**, 265–295.

Pacala, S.W., G.C. Hurtt, R.A. Houghton, R.A. Birdsey, L. Heath, E.T. Sundquist, R.F. Stallard, D. Baker, P. Peylin, P. Moorcroft, J. Caspersen, E. Shevliakova, M.E. Harmon, S.-M. Fan, J.L. Sarmiento, C. Goodale, C.B. Field, M. Gloor, and D. Schimel, 2001: Consistent land- and atmosphere-based U.S. carbon sink estimates. *Science*, **292(5525)**, 2316–2320.

Smith, W.B., P.D. Miles, J.S. Vissage, and S.A. Pugh, 2004: *Forest Resources of the United States, 2002*. General Technical Report NC-241, U.S. Department of Agriculture, Forest Service, St. Paul, MN, 137 pp.

[This page intentionally left blank]

Appendix 3B

Eddy-Covariance Measurements Now Confirm Estimates of Carbon Sinks from Forest Inventories

Long-term, tower-based, eddy-covariance measurements (e.g., Wofsy *et al*., 1993) represent an independent approach to measuring ecosystem-atmosphere CO_2 exchange. The method describes fluxes over areas of approximately 1 km^2 (Horst and Weil, 1994), measures hour-by-hour ecosystem carbon fluxes, and can be integrated over time scales of years. A network of more than 200 sites now exists globally (Baldocchi *et al*., 2001); more than 50 of these are in North America. None of these sites existed in 1990, so these represent a relatively new source of information about the terrestrial carbon cycle. An increasing number of these measurement sites include concurrent carbon inventory measurements.

Where eddy-covariance and inventory measurements are concurrent, the rates of accumulation or loss of biomass are often consistent to within several tens of g C m^{-2} yr^{-1} for a one-year sample (10 g C yr^{-1} is 5% of a typical net sink of 2 metric tons of carbon per hectare per year for an Eastern deciduous successional forest) . Published intercomparisons in North America exist for western coniferous forests (Law *et al*., 2001), agricultural sites (Verma *et al*., 2005), and eastern deciduous forests (Barford *et al*., 2001; Cook *et al*., 2004; Curtis *et al*., 2002; Ehmann *et al*., 2002; Gough *et al*., in review). Multiyear studies at two sites (Barford *et al*., 2001; Gough *et al*., in review) show that 5- to 10-year averages converge toward inventory measurements. Table 3B-1 from Barford *et al*. (2001) shows the results of nearly a decade of concurrent measurements in an eastern deciduous forest.

This concurrence between eddy-covariance flux measurements and ecosystem carbon inventories is relevant because it provides independent validation of the inventory measurements used to estimate long-term trends in carbon stocks. The eddy-covariance data are also valuable because the assembly of global eddy-covariance data provides independent support for net storage of carbon by many terrestrial ecosystems and the substantial year-to-year variability in this net sink. The existence of the eddy-covariance data also makes the sites suitable for co-locating mechanistic studies of inter-annual and shorter, time-scale processes governing the terrestrial carbon cycle. Chronosequences show trends consistent with inventory assessments of forest growth, and comparisons across space and plant functional types are beginning to show broad consistency. These results show a consistency across a mixture of observational methods with complementary characteristics, which should facilitate the development of an increasingly complete understanding of continental carbon dynamics (Canadell *et al*., 2000).

REFERENCES FOR APPENDIX 3B

Baldocchi, D., E. Falge, L.H. Gu, R. Olson, D. Hollinger, S. Running, P. Anthoni, C. Bernhofer, K. Davis, R. Evans, J. Fuentes, A. Goldstein, G. Katul, B. Law, X.H. Lee, Y. Malhi, T. Meyers, W. Munger, W. Oechel, K.T. Paw U, K. Pilegaard, H.P. Schmid, R. Valentini, S. Verma, T. Vesala, K. Wilson, and S. Wofsy, 2001: FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, *Bulletin of the American Meteorological Society*, **82**, 2415–2434.

Barford, C.C., S.C. Wofsy, M.L. Goulden, J.W. Munger, E.H. Pyle, S.P. Urbanski, L. Hutyra, S.R. Saleska, D. Fitzjarrald, and K. Moore, 2001: Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest. *Science*, **294**, 1688–1691.

Canadell, J.G., H.A. Mooney, D.D. Baldocchi, J.A. Berry, J.R. Ehleringer, C.B. Field, S.T. Gower, D.Y. Hollinger, J.E. Hunt, R.B. Jackson, S.W. Running, G.R. Shaver, W. Steffen, S.E. Trumbore, R. Valentini, B.Y. Bond, 2000: Carbon metabolism of the terrestrial biosphere: a multitechnique approach for improved understanding. *Ecosystems*, **3**, 115–130.

Cook, B.D., K.J. Davis, W. Wang, A. Desai, B.W. Berger, R.M. Teclaw, J.G. Martin, P.V. Bolstad, P.S. Bakwin, C. Yi, and W. Heilman, 2004: Carbon exchange and venting anomalies in an upland deciduous forest in northern Wisconsin, USA. *Agricultural and Forest Meteorology*, **126**, 271–295.

Curtis, P.S., P.J. Hanson, P. Bolstad, C. Barford, J.C. Randolph, H.P. Schmid, and K.B. Wilson, 2002: Biometric and eddy-covariance based estimates of annual carbon storage in five eastern North American deciduous forests. *Agricultural and Forest Meteorology*, **113**, 3–19.

Ehman, J.L., H.P. Schmid, C.S.B. Grimmond, J.C. Randolph, P.J. Hanson, C.A. Wayson, and F.D. Cropley, 2002: An initial intercomparison of micrometerological and ecological inventory estimates of carbon exchange in a mid-latitude deciduous forest. *Global Change Biology*, **8**, 575–589.

Gough, C.M., P.S. Curtis, J.G. Vogel, H.P. Schmid, and H.B. Su: Annual carbon storage from 1999 to 2003 in a Northern hardwood forest assessed using eddy-covariance and biometric methods. *Agricultural and Forest Meteorology* (in review).

Horst, T.W. and J.C. Weil, 1994: How far is far enough? The fetch requirements for micrometeorological measurement of surface fluxes. *Journal of Atmospheric and Oceanic Technology*, **11**, 1018–1025.

Law, B.E., P.E. Thornton, J. Irvine, P.M. Anthoni, and S. Van Tuyl, 2001: Carbon storage and fluxes in ponderosa pine forests at different developmental stages. *Global Change Biology*, **7**, 755–777.

Verma, S.B., A. Dobermann, K.G. Cassman, D.T. Walters, J.M. Knops, T.J. Arkebauer, A.E. Suyker, G.G. Burba, B. Amos, H.S. Yang, D. Ginting, K.G. Hubbard, A.A. Gitelson, and E.A. Walter-Shea, 2005: Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. *Agricultural and Forest Meteorology*, **131**, 77–96.

Wofsy, S.C., M.L. Goulden, J.W. Munger, S.-M. Fan, P.S. Bakwin, B.C. Daube, S.L. Bassow, and F.A. Bazzaz. 1993: Net exchange of CO_2 in a mid-latitude forest. *Science*, **260**, 1314–1317.

Table 3B-1. Carbon budget for Harvard Forest from forest inventory and eddy-covariance flux measurements, 1993–2001. *Source*: Barford *et al.* (2001), Table 1. Numbers in parentheses give the ranges of the 95% confidence intervals.

Component	Change in carbon stock or flux (g C m^{-2} yr^{-1})	Totals
Change in live biomass		
A. Aboveground		
1. Growth	1.4 (±0.2)	
2. Mortality	–0.6 (±0.6)	
B. Belowground (estimated)		
1. Growth	0.3	
2. Mortality	–0.1	
Subtotal		1.0 (±0.2)
Change in dead wood		
A. Mortality		
1. Aboveground	0.6 (±0.6)	
2. Belowground	0.1	
B. Respiration	–0.3 (±0.3)	
Subtotal		0.4 (±0.3)
Change in soil carbon (net)		0.2 (±0.1)
Sum of carbon budget figures		1.6 (±0.4)
Sum of eddy-covariance flux measurements		2.0 (±0.4)

[This page intentionally left blank]