Chapter 2. The Carbon Cycle of North America in a Global Context

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KEY FINDINGS

- Human activity over the last two centuries, including combustion of fossil fuel and clearing of forests, has led to a dramatic increase in the concentration of atmospheric carbon dioxide. Global atmospheric CO_2 concentrations have risen by 31% since 1850, and they are now higher than they have been for 420,000 years.
- North America is responsible for approximately 27% of the emissions produced globally by fossil-fuel combustion, with the United States accounting for 86% of the North American total.
- While emissions (a carbon source) dominate the carbon budget of North America, these emissions are partially offset by a smaller carbon sink (uptake of carbon). The sink is approximately 30% of the North American emissions, 9% of global emissions, and approximately 50% of the global terrestrial sink inferred from global budget analyses and atmospheric inversions. This sink is most likely caused by relatively young, growing forests which have re-colonized land formerly cleared of forests for agricultural use in past centuries.
- Global carbon dioxide emissions have increased for the last 30 years. In comparison, North American carbon dioxide emissions have increased at an average rate of approximately 1% per year for the last 30 years.
- While the future trajectory of carbon sinks in North America is uncertain (substantial climate change could convert current sinks into sources), it is clear that the carbon cycle of the next few decades will be dominated by the large sources from fossil-fuel emissions.
- Because North American carbon emissions are at least a quarter of global emissions, a reduction in North American emissions would have global consequences. North America has many opportunities for decreasing emissions, including changes to the energy system, increasing energy efficiency, investments in forest planting and agricultural soil management, biomass energy, and geological sequestration.

THE GLOBAL CYCLE

The modern global carbon cycle is a collection of many different kinds of processes, with diverse drivers and dynamics, that transfer carbon among major pools in rocks, fossil fuels, the atmosphere, the oceans, and plants and soils on land (Sabine *et al*., 2004b) (Fig. 2-1). During the last two centuries, human actions, especially the combustion of fossil fuel and the clearing of forests, have altered the global carbon cycle in important ways. Specifically, these actions have led to a rapid, dramatic increase in the concentration of carbon dioxide (CO_2) in the atmosphere (Fig. 2-2), changing the radiation balance of the Earth (Hansen *et al*., 2005), and most likely warming the planet (Mitchell *et al.*, 2001). The cause of the recent increase in atmospheric CO_2 is confirmed beyond a reasonable doubt (Prentice, 2001). This does not imply, however, that the other components of the carbon cycle have remained unchanged during this period. The background or unmanaged parts of the carbon cycle have, in fact, changed dramatically over the past two centuries. The consequence of these changes is that only about 48% ± 5% of the carbon dioxide emitted to the atmosphere from fossil-fuel combustion and forest clearing has remained there (Sabine *et al*., 2004b). In essence, human actions have received a large subsidy from the unmanaged parts of the carbon cycle. This subsidy has sequestered, or hidden from the atmosphere, approximately 240 ± 40 Gt of carbon. [Throughout this chapter, we will present the pools and fluxes in the carbon cycle in Gt C (1 Gt = 1 billion tons or 1×10^{15} g). The mass of CO_2 is greater than the mass of carbon by the ratio of their molecular weights, 44/12 or 3.67 times; 1 km^3 of coal contains approximately 1 Gt C.]

Figure 2-1. Schematic representation of the components of the carbon cycle.

Figure 2-2. Atmospheric CO_2 concentration from 1850 to 2005. The data prior to 1957 are from the Siple ice core (Friedli *et al*., 1986). The data since 1957 are from continuous atmospheric sampling at the Mauna Loa Observatory (Hawaii) (Keeling *et al*., 1976; Thoning *et al*., 1989).

The recent subsidy or sequestration of carbon by the unmanaged parts of the carbon cycle makes them critical for an accurate understanding of climate change. Future increases in carbon uptake in the unmanaged parts of the cycle could moderate the risks from climate change, while decreases or transitions from uptake to release could amplify the risks, perhaps dramatically.

In addition to its role in the climate, the carbon cycle intersects with a number of critical earth system processes. Because plant growth is essentially the removal of carbon dioxide from the air through photosynthesis, agriculture and forestry contribute important fluxes. Wildfire is a major release of carbon from plants and soils to the atmosphere (Sabine *et al*., 2004b). The increasing concentration of CO_2 in the atmosphere has already made the world's oceans more acid (Caldeira and Wickett, 2003). Future changes could dramatically alter the composition of ocean ecosystems (Orr *et al*., 2005).

The Background or Unmanaged Global Carbon Cycle

The modern background or unmanaged carbon cycle includes the processes that occur in the absence of human actions. These processes are, however, currently so altered by human influences on the carbon cycle that it is not appropriate to label them natural. This background or unmanaged part of the carbon cycle is dominated by two pairs of gigantic fluxes with annual uptake and release that are close to balanced (Sabine *et al*., 2004b) (Fig. 2-1). The first of these comprises the terrestrial carbon cycle: plant growth on land annually fixes about 100–200 Gt of atmospheric carbon, approximately 20 times the annual emission from fossil-fuel combustion, into carbohydrates. Respiration by land plants, animals, and microorganisms, which provides the energy for growth, activity, and reproduction, returns a slightly smaller amount to the atmosphere, with the difference burned in wildfires or stored as plant biomass or soil organic carbon. The second comprises the ocean carbon cycle: about 92 ± 5 Gt of atmospheric carbon dissolves annually in the oceans, and about 90 Gt moves from the oceans to the atmosphere. The rest remains in the ocean as a mix of dissolved CO_2, bicarbonate (HCO_3^-), carbonate ($CO_3^=$), and organic matter.

Before the beginning of the industrial revolution, carbon uptake and release through these two pairs of large fluxes were almost balanced, with carbon uptake on land of approximately 0.45 ± 0.1 Gt C yr^{-1} transferred to the oceans and released from the oceans to the atmosphere. As a consequence, the level of carbon dioxide in the atmosphere varied by less than 25 ppm in the 10,000 years prior to 1850 (Joos and Prentice, 2004). But atmospheric CO_2 was not always so stable. During the preceding 420,000 years, atmospheric CO_2 was 180–200 ppm during ice ages and approximately 275 ppm during interglacials (Petit *et al*., 1999). The lower ice-age concentrations in the atmosphere most likely reflect a transfer of carbon from the atmosphere to the oceans, possibly driven by changes in ocean circulation and sea-ice cover (Keeling and Stephens, 2001; Sigman and Boyle, 2000). Enhanced biological activity in the oceans, stimulated by increased delivery of iron-rich terrestrial dust, may have also contributed to this increased uptake (Martin, 1990).

In the distant past, the global carbon cycle was out of balance in a different way. Fossil fuels are the product of plant growth, especially in the period 354 to 290 million years ago, the Carboniferous. During this period, luxuriant plant growth and geological activity combined to bury a small fraction of each year's growth. Over millions of years, this gradual burial led to the accumulation of vast stocks of fossil fuel. The total accumulation of fossil fuels is uncertain, but probably in the range of 6000 ± 3000 Gt. It also led to a near doubling of atmospheric oxygen (Falkowski *et al*., 2005).

Anthropogenic Perturbations

Since the beginning of the industrial revolution, or about 1850, there has been a massive release of carbon from fossil-fuel combustion and deforestation. Cumulative carbon emissions from fossil-fuel combustion, natural gas flaring, and cement manufacture from 1850 through 2004 are just over 300 ± 30 Gt (Marland and Rotty, 1984; Andres *et al*., 1999). Land use change during this period, mostly from the clearing of forests, added another 160 ± 160 Gt (DeFries *et al*., 1999; Houghton, 1999). The rate of fossil-fuel consumption in any recent year would have required, for its production, more than 400 times the current global primary production (total plant growth) of the land and oceans combined (Dukes, 2003). This has led to a rapid increase in the concentration of CO_2 in the atmosphere since 1850, with atmospheric CO_2 rising by 31% (i.e., from 287 ppm to 377 ppm).

Together, the three major countries of North America (Canada, Mexico, and the United States) accounted, in 2003, for carbon emissions from fossil-fuel combustion of approximately 1.83 ± 0.2 Gt C, or about 27% of the global total. The United States, the world's largest emitter of carbon dioxide, was responsible for 86% of the North American total. Per capita emissions in 2003 were 5.4 ± 0.5 metric ton in the United States, 5.0 ± 0.55 metric ton in Canada, and 0.9 ± 0.1 metric ton in Mexico. Per capita emissions in the United States were nearly 5 times the world average, 2.5 times the per capita emissions for Western Europe, and more than 8 times the average for Asia and Oceania. The carbon intensity of the United States' economy, at 0.15 metric ton of emitted carbon per $1000 (in 1995 dollars) of GDP (measured as PPP or Purchasing Power Parity), in 2003 was close to the world's average of 0.14 tC/$1000 [DOE EIA (U.S. Department of Energy, 2005)]. Canada's carbon intensity is somewhat higher at 0.19 tC/$1000, and Mexico's is somewhat lower at 0.12 tC/$1000. Rich countries with substantially lower carbon intensity include Japan, France, the United Kingdom, and Germany. Rich countries with higher carbon intensity include Australia and New Zealand [DOE EIA (U.S. Department of Energy, 2005)].

The world's largest countries, China and India, have total carbon emissions from fossil-fuel combustion and the flaring of natural gas that are substantially lower than those in the United States. The 2003 total for China was 61% of that in the United States, and the total for India was 18% that of the United States. Per capita emissions for China and India in 2003 were 14% and 5%, respectively, of the U.S. rate. Carbon intensity in both China and India is high. In 2003, carbon intensity in China was 4.6 times greater than that in the United States. The carbon intensity in India was 3.4 times that in the United States [DOE EIA (U.S. Department of Energy, 2005)].

Carbon emissions from North America have grown by about 1.0% per year for the last 30 years, substantially slower than the growth in GDP (Fig. 2-3). Slower growth in emissions than GDP characterizes many of the world's richest countries, including Canada and the United States. Since 1980, emissions growth has been only slightly slower than GDP growth in Mexico, a pattern typical of rapidly industrializing countries (Fig. 2-3). More rapid growth in GDP than in emissions can result from decreasing both the energy intensity of the economy (through, for example, more efficient manufacturing and increasing the role of the service sector) and the carbon intensity of the energy system (through, for example, replacing coal with natural gas in power plants or replacing fossil power plants with wind power plants) (Sathaye, 2004). It is not clear whether, in the absence of policy, historical trends in the energy intensity of GDP and the carbon intensity of the energy system will continue.

Figure 2-3. GDP in 2000 U.S. dollars vs fossil-fuel carbon emissions (Mt C yr^{-1}). Data from EIA (2005). Each arrow shows the sequence from 1980 to 2003 for a country. Note that carbon emissions per unit GDP decelerate as a country gains wealth. The lines in the figure show the slopes associated with the different ratios of GDP and emissions growth (the y-intercept of the dotted and dashed lines are not informative and were chosen only to keep from obscuring the arrows).

ASSESSING GLOBAL AND REGIONAL CARBON BUDGETS

Changes in the carbon content of the oceans and plants and soils on land can be evaluated with at least five different approaches—flux measurements, inventories, inverse estimates based on atmospheric CO_2, process models, and calculation as a residual. The first method, direct measurement of carbon flux, is well developed for measurements over the spatial scale of up to 1 km^2, using the eddy flux technique (Wofsy *et al*., 1993; Baldocchi and Valentini, 2004). Although eddy flux measurements are now collected at more than 100 networked sites, spatial scaling presents formidable challenges. To date, estimates of continental-scale fluxes based on eddy flux must be regarded as preliminary.

Inventories, based on measuring trees on land (Birdsey and Heath, 1995) or carbon in water samples (Takahashi *et al*., 2002; Sabine *et al*., 2004a), can provide useful constraints on changes in the size of carbon pools, though their utility for quantifying short-term changes is limited. Inventories were the foundation of the recent conclusion that 118 Gt of anthropogenic carbon has entered the oceans (Sabine *et al*., 2004a) and that forests in the midlatitudes of the Northern Hemisphere sequestered 0.6 to 0.7 Gt C yr^{-1} in the 1990s (Goodale *et al*., 2002). Changes in the atmospheric inventory of O_2 (Keeling *et al*., 1996) and ^{13}C in CO_2 (Siegenthaler and Oeschger, 1987) provide a basis for partitioning CO_2 flux into land and ocean components.

Process models and inverse estimates based on atmospheric CO_2 (or CO_2 in combination with ^{13}C or O_2) also provide useful constraints on carbon stocks and fluxes. Process models build from understanding the underlying principles of atmosphere/ocean or atmosphere/ecosystem carbon exchange to make estimates over scales of space and time that are relevant to the global carbon cycle. For the oceans, calibration against observations with passive tracers (Matsumoto *et al*., 2004) (^{14}C and chlorofluorocarbons) tends to nudge a wide range of models toward similar results. Sophisticated models with detailed treatment of the ocean circulation, chemistry, and biology all reach about the same estimate for the current ocean carbon sink, 1.5 to 1.8 Gt C yr^{-1} (Greenblatt and Sarmiento, 2004). Models of the land carbon cycle take a variety of approaches. They differ substantially in the data used as constraints, in the processes simulated, and in the level of detail (Cramer *et al*., 1999; Cramer *et al*., 2001). Models that take advantage of satellite data have the potential for comprehensive coverage at high spatial resolution (Running *et al*., 2004), but only over the time domain with available satellite data. Flux components related to human activities, for example deforestation, have been modeled based on historical land use (Houghton, 1999). At present, model estimates are uncertain enough that they are often used most effectively in concert with other kinds of estimates (e.g., Peylin *et al*., 2005).

Inverse estimates based on atmospheric gases (CO_2, ^{13}C in CO_2, or O_2) infer surface fluxes based on the spatial pattern of atmospheric concentration, coupled with information on atmospheric transport (Newsam and Enting, 1988). The atmospheric concentration of CO_2 is now measured with high precision at approximately 100 sites worldwide (Masarie and Tans, 1995). The ^{13}C in CO_2 and O_2 are measured at far fewer sites. The basic approach is a linear Bayesian inversion (Tarantola, 1987; Enting, 2002), with many variations in the time scale of the analysis, the number of regions used, and the transport model. Inversions have more power to resolve year-to-year differences than mean fluxes (Rodenbeck *et al*., 2003; Baker *et al*., 2006). Limitations in the accuracy of atmospheric inversions come from the limited density of concentration measurements, especially in the tropics, uncertainty in the transport, and errors in the inversion process (Baker *et al*., 2006). Recent studies that use a number of sets of CO_2 monitoring stations (Rodenbeck *et al*., 2003), models (Gurney *et al*., 2003; Law *et al*., 2003; Gurney *et al*., 2004; Baker *et al*., 2006), temporal scales, and spatial regions (Pacala *et al*., 2001), highlight the sources of the uncertainties and appropriate steps for managing them.

A final approach to assessing large-scale CO_2 fluxes is solving as a residual. At the global scale, the net flux to or from the land is often calculated as the residual left after accounting for fossil emissions, atmospheric increase, and ocean uptake (Siegenthaler and Oeschger, 1987). Increasingly, the need to treat the land as a residual is receding, as the other methods improve. Still, the existence of constraints at the level of the overall budget injects an important connection with reality.

RECENT DYNAMICS OF THE UNMANAGED CARBON CYCLE

Of the approximately 460 ± 100 Gt carbon added to the atmosphere by human actions since 1850, only about 180 ± 5 Gt remain. The "missing carbon" was stored, at least temporarily, in the oceans and in ecosystems on land. Based on a recent ocean inventory, 118 ± 19 Gt of the missing carbon is now in the oceans (Sabine *et al*., 2004a). This leaves about 100 Gt that must be stored on land. Identifying the processes responsible for the uptake on land, their spatial distribution, and their likely future trajectory has been one of the major goals of carbon cycle science over the last decade.

Much of the recent research on the global carbon cycle has focused on annual fluxes and their spatial and temporal variation. The temporal and spatial patterns of carbon flux provide a pathway to understanding the underlying mechanisms. Based on several different approaches, carbon uptake by the oceans averaged 1.7 ± 0.3 Gt C yr^{-1} for the period from 1992–1996 (Gloor *et al*., 2003; Matear and McNeil, 2003; Matsumoto *et al*., 2004; Takahashi *et al*., 2002; Gurney *et al*., 2003). The total anthropogenic flux is this amount, plus 0.45 Gt yr^{-1} of preindustrial outgasing, for a total of 2.2 ± 0.4 Gt yr^{-1}. This rate represents an integral over large areas that are gaining carbon and the tropics, which are losing carbon (Fig. 2-4). Interannual variability in the ocean sink for CO_2, though substantial (Greenblatt and Sarmiento, 2004), is much smaller than interannual variability on the land (Baker *et al*., 2006).

Figure 2-4. The spatial distribution of ocean CO_2 exchange from 1992–1996 for several regions and measurement approaches. Tak99 and Tak02 are from (Takahashi *et al*., 2002) ΔpCO_2 estimates, T3L1 and T3L2 are from (Gurney *et al*., 2003; Gurney *et al*., 2004), Fwd is from predictive ocean models, JI is from the ocean atmosphere ocean inversions of (Jacobson *et al*., 2006). The far right column is the sum of the individual ocean basins toward the left [from (Jacobson *et al*., 2006)].

On land in the 1990s, carbon releases from land-use change were more than balanced by ecosystem uptake, leading to a net sink on land (without accounting for fossil-fuel emissions) of approximately 1.1 Gt C yr^{-1} (Schimel *et al*., 2001; Sabine *et al*., 2004b). The dominant sources of recent interannual variation in the net land flux were El Niño and the eruption of Mt. Pinatubo in 1991 (Bousquet *et al*., 2000; Rodenbeck *et al*., 2003; Baker *et al*., 2006), with most of the year-to-year variation in the tropics (Fig. 2-5). Fire likely plays a large role in this variability (van der Werf *et al*., 2004).

Figure 2-5. The 13-model mean CO_2 flux interannual variability (Gt C yr^{-1}) for several continents (solid lines) and ocean basins (dashed lines); (a) North Pacific and North America, (b) Atlantic north of 15ºN and Eurasia, (c) Australasia and Tropical Pacific, (d) Africa, and (e) South America (note the different scales for Africa and South America) (from Baker *et al*., 2006).

On a time scale of thousands of years, the ocean will be the sink for approximately 80% of the carbon released to the atmosphere by human activities (Joos and Prentice, 2004). The rate of CO_2 uptake by the oceans is, however, limited. CO_2 enters the oceans by dissolving in seawater. The rate of this process is determined by the concentration difference between the atmosphere and the surface waters and by an air-sea exchange coefficient related to wave action, wind, and turbulence (Le Quéré and Metzl, 2004). Because the surface waters represent a small volume with limited capacity to store CO_2, the major control on ocean uptake is at the level of moving carbon from the surface to intermediate and deep waters. Important contributions to this transport come from the large scale circulation of the oceans, especially the sinking of cold water in the Southern Ocean and, to a lesser extent, the North Atlantic.

On land, numerous processes contribute to carbon storage and carbon loss. Some of these are directly influenced through human actions (e.g., the planting of forests, conversion to no-till agriculture, or the burying of organic wastes in landfills). The human imprint on others is indirect. This category includes ecosystem responses to climate change (e.g., warming and changes in precipitation), changes in the composition of the atmosphere (e.g., increased CO_2 and increased tropospheric ozone), and delayed consequences of past actions (e.g., regrowth of forests after earlier harvesting). Early analyses of the global carbon budget (e.g., Bacastow and Keeling, 1973) typically assigned all of the net flux on land to a single mechanism, especially fertilization of plant growth by increased atmospheric CO_2. Recent evidence emphasizes the diversity of mechanisms.

The Carbon Cycle of North America

By most estimates, the land area of North America is currently a sink for carbon, in the absence of emissions from fossil-fuel combustion. This conclusion for the continental scale is based mainly on the results of atmospheric inversions. Several studies address the carbon balance of particular ecosystem types [e.g., forests (Goodale *et al*., 2002; Chen *et al*., 2003; Kurz and Apps, 1999)]. Pacala and colleagues (Pacala *et al*., 2001) used a combination of atmospheric and land-based techniques to estimate that the 48 contiguous U.S. states are currently a carbon sink of 0.3 to 0.6 Gt C yr^{-1}. Based on inversions using 13 atmospheric transport models, North America was a carbon sink of 0.97 Gt C yr^{-1} from 1991–2000 (Baker *et al*., 2006). Over the area of North America, this amounts to an annual carbon sink of 39.6 g C m^{-2} yr^{-1}, similar to the sink inferred for all northern lands (North America, Europe, Boreal Asia, and Temperate Asia) of 32.5 g C m^{-2} yr^{-1} (Baker *et al*., 2006).

Recent carbon storage in North America probably results from a number of different processes. Chen *et al*. (Chen *et al*., 2003) argue that Canadian forests are a small sink because processes tending to increase tree growth, including elevated atmospheric CO_2 and deposition of biologically available nitrogen, are more than compensating effects of recent disturbances. Kurz and Apps (Kurz and Apps, 1999) reach the opposite conclusion, that recent disturbances make Canadian forests a net carbon source. In the United States, forest regrowth is outpacing recent harvesting and disturbance (Birdsey and Heath, 1995). Some of this is a consequence of a profound historical shift in the location of United States agriculture.

Much of the Eastern United States was cleared for agriculture in the 18th century, only to be abandoned as agriculture moved to the Great Plains, the Southwest, and the West in the 19th and 20th centuries (Ramankutty and Foley, 1999). As a consequence, large areas once cleared for agriculture are currently regrowing forests (Caspersen *et al*., 2000). Increasing carbon in previously harvested forests has several drivers beyond the shift in agriculture, including changes in harvesting and management practices (Harmon *et al*., 1996; Goodale *et al*., 2002) and fire suppression (Calkin *et al*., 2005; Mouillot and Field, 2005). The processes sequestering carbon have been partially offset by processes that release stored carbon, including unusually high wildfire years [United States—(Mouillot and Field, 2005)], insect outbreaks [Canada—(Kurz and Apps, 1999)] , and storm damage [Europe—(Janssens *et al*., 2003)]. The heat wave and drought in Europe in the summer of 2003 led to a large loss of carbon, driven largely by decreased plant growth (Ciais *et al*., 2005).

Several other processes probably contribute to recent carbon sinks in the United States (Table 2-1), though they are difficult to quantify with confidence. These include the thickening of vegetation in woodland and shrubland areas, the burial of organic matter in lakes and reservoirs (Stallard, 1998), increases in the soil carbon in managed grassland and agricultural soils (Asner *et al*., 2003), and storage of carbon in durable products (e.g. houses and furniture) and waste in landfills (Pacala *et al*., 2001).

Table 2-1. Sinks of carbon for 1980--90 in the coterminous United States (Gt C yr^{-1}).

Some of the recent carbon storage in North America may be a consequence of increased atmospheric CO_2 (Schimel *et al*., 2000; Melillo *et al*., 2003), nitrogen deposition (Holland *et al*., 1997), or climate changes that have increased the length of the frost-free season in many locations (Myneni *et al*., 1997; Hicke *et al*., 2002). The evidence in support of the first two mechanisms comes from empirical and modeling studies. It is clear that plant growth in many terrestrial ecosystems is limited by either atmospheric CO_2 or biologically available nitrogen (Melillo *et al*., 2003). It is much less clear, however, that increased availability of either resource has led to carbon sequestration. Recent studies include many examples in which experimental treatment with elevated CO_2 leads to consistent increases in plant growth (e.g., Norby *et al*., 2005), but others in which elevated CO_2 has little effect on plant growth (Shaw *et al*., 2002), leads to an initial stimulation but limited long-term effects (Oren *et al*., 2001), or increases carbon losses as well as gains (Hungate, 1997; Schlesinger and Lichter, 2001). Evidence on the role of changes in the length of the growing season comes from field-based, satellite, and modeling studies (Myneni *et al*., 1997; Nemani *et al*., 2003). Recent evidence indicates that negative effects of dry summers can offset much or all of the effects of earlier springs (Angert *et al*., 2005).

To the extent that current carbon sink in North America reflects the regrowth of previously harvested forest, it is a one-time phenomenon and not a permanent feature of the carbon cycle. Similarly, a sink from effective fire suppression in the second half of the 20th century may have already saturated or even reversed, as large accumulations of highly flammable fuels amplify the challenge of current and future fire management. Sinks from CO_2 fertilization (Hungate *et al*., 2003), increased nitrogen deposition, and altered management of agricultural lands (Smith, 2004) could continue for some time, but they too will eventually saturate (Gruber *et al*., 2004).

Very little of the current carbon sink in North America is a consequence of deliberate action to sequester carbon. Some is a collateral benefit of steps to improve land management, for increasing soil fertility, improving wildlife habitat, etc. Much of the current sink is unintentional, a consequence of historical changes in technologies and preferences in agriculture, transportation, and urban design.

CARBON CYCLE OF THE FUTURE

The future trajectory of carbon sinks in North America is very uncertain. Several trends will play a role in determining the sign and magnitude of future changes. One important controller is the magnitude of future climate changes. If the climate warms significantly, much of the United States could experience a decrease in plant growth and an increase in the risk of wildfire (Bachelet *et al*., 2003), especially if the warming is not associated with substantial increases in precipitation. Exactly this pattern—substantial warming with little or no change in precipitation—characterizes North America in many of the newer climate simulations (Rousteenoja *et al*., 2003). If North American ecosystems are sensitive to elevated CO_2, nitrogen deposition, or warming, plant growth could increase (Schimel *et al*., 2000). The empirical literature on CO_2 and nitrogen deposition is mixed, with some reports of substantial growth enhancement (Norby *et al*., 2005) and others reporting small or modest effects (Oren *et al*., 2001; Shaw *et al*., 2002; Heath *et al*., 2005).

Overall, the carbon budget of North America is dominated by carbon releases from the combustion of fossil fuels. Currently, as much as 50% of this may be offset by carbon uptake in plants and soils (Baker *et al*., 2006). Most of this uptake appears to be a rebound, as natural and managed ecosystems recover from past disturbances. Little evidence supports the idea that these ecosystem sinks will increase in the future. Substantial climate change could convert current sinks into sources (Gruber *et al*., 2004).

In the future, trends in the North American energy economy may intersect with trends in the natural carbon cycle. A large-scale investment in afforestation could offset substantial future emissions (Graham, 2003). Costs of this kind of effort would, however, include the loss of the new forested area from its previous uses, including grazing or agriculture, plus the energy costs of managing the new forests, plus any increases in emissions of non-CO_2 greenhouse gases from the new forests. Large-scale investments in biomass energy would have similar costs but would result in offsetting emissions from fossil-fuel combustion, rather than sequestration (Giampietro *et al*., 1997). The relative costs and benefits of investments in afforestation and biomass energy will require careful analysis (Kirschbaum, 2003). Investments in other energy technologies, including wind and solar, will require some land area, but the impacts on the natural carbon cycle are unlikely to be significant or widespread (Hoffert *et al*., 2002; Pacala and Socolow, 2004).

Like the present, the carbon cycle of North America during the next several decades will be dominated by fossil emissions. Geological sequestration may become an increasingly important component of the budget sheet. Still, progress in controlling the net release to the atmosphere must be centered on the production and consumption of energy rather than the processes of the unmanaged carbon cycle. North America has many opportunities to decrease emissions (Hoffert *et al*., 2002; Caldeira *et al*., 2004; Pacala and Socolow, 2004). Many of these are in the area of increasing the efficiency of energy generation, the transportation system, building stocks, and manufacturing technologies. Others are in the area of replacing carbon-emitting energy technologies with nonemitting technologies, including solar, wind, biomass, and nuclear. Still others are in the area of sequestration, including both geological and biological components. Finally, there are many opportunities in conservation, in directing the economy and personal preferences away from carbon-intensive activities. Capitalizing on the opportunities in all four of these areas will require dedicated research, financial support, creativity, and an interested public (Raupach *et al*., 2004). Nothing about the status of the unmanaged carbon cycle provides a justification for decreasing the commitment to progress in all of these areas.

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Table 1. Sinks of carbon for 1980–90 in the coterminous United States (in Gt C yr^{-1}).

Category	Low	High	Land area 1980–90 (10^6 ha)	Houghton *et al.* (8)	Birdsey and Heath (12)
Forest trees	0.11	0.15	247–247	0.06 [a]	0.11
Other forest organic matter	0.03	0.15	247–247	– 0.01	0.18
Cropland soils	0.00	0.04	185–183	0.14	—
Nonforest, non-cropland (woody encroachment)	0.12 [b]	0.13 [b]	334–336 [c]	0.12	—
Wood products	0.03	0.07	—	0.03	0.03
Reservoirs, alluvium, colluvium	0.01	0.04	—	—	—
Exports minus imports of food, wood	0.04	0.09	—	—	—
Fixed in the United States but exported by rivers	0.03	0.04	—	—	—
"Apparent"[d] U.S. sink without woody encroachment	0.25	0.58	766	0.15–0.23 [e]	0.31
"Apparent"[d] U.S. sink including woody encroachment	0.37	0.71	766	0.15–0.35 [e]	—
Sink [f]	0.03	0.58	766	0.15–0.35 [e]	0.31

[a] Assumes that the 0.05 Gt C yr^{-1} estimated in (8) to be accumulating in western pine woodlands as a result of the suppression is assigned to forest instead of row 4.
[b] These numbers are not bounds, but rather the only two existing estimates.
[c] Total area for all lands other than forest and croplands. Possible woody encroachment because of fire suppression on up to about two-thirds of this land (10,16).
[d] By "apparent" sink, we mean the net flux from the atmosphere to the land that would be estimated in an inversion. It includes all terms in the table.
[e] Lower bound reflects uncertainty in the estimates for the effects of fire suppression.
[f] Excludes sinks caused by the export/import imbalance for food and wood products and river exports because these create corresponding sources outside the United States.
Source: Pacala *et al*. (2001)

Figure 2-1. Schematic representation of the components of the carbon cycle.

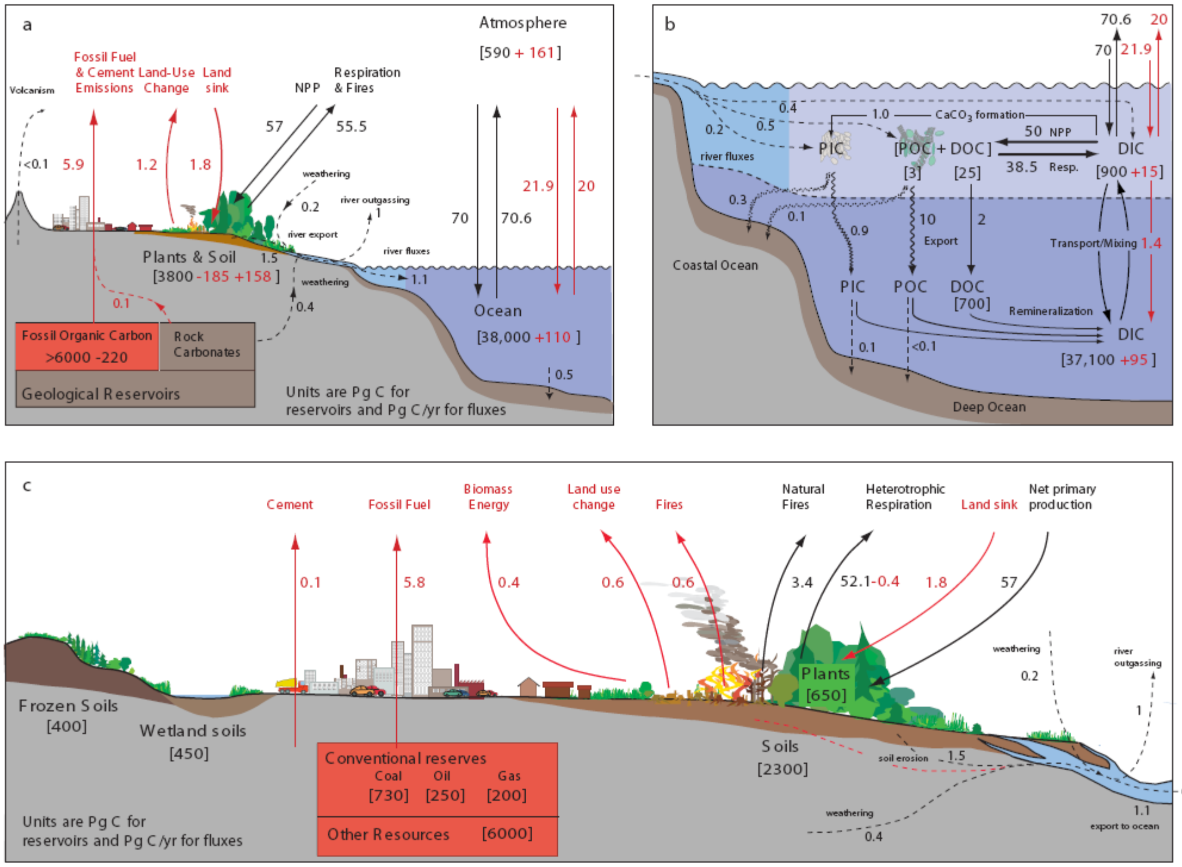
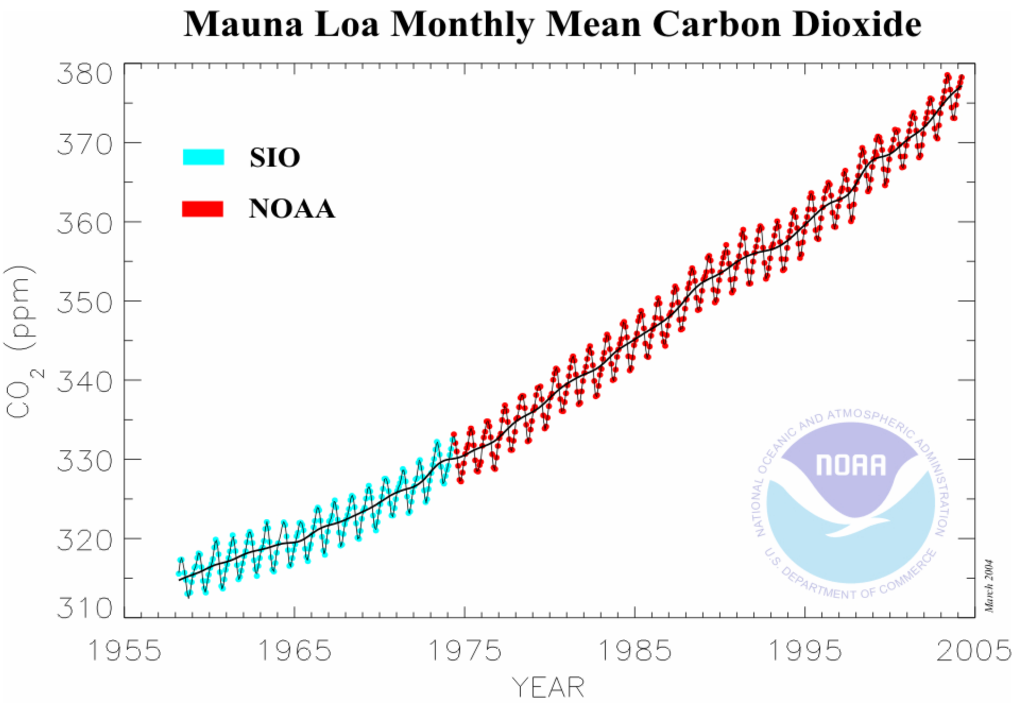


Fig. 2-2. Atmospheric CO_2 concentration from 1850 to 2005. The data prior to 1957 are from the Siple ice core (Friedli *et al*., 1986). The data since 1957 are from continuous atmospheric sampling at the Mauna Loa Observatory (Hawaii) (Keeling *et al*., 1976; Thoning *et al*., 1989).



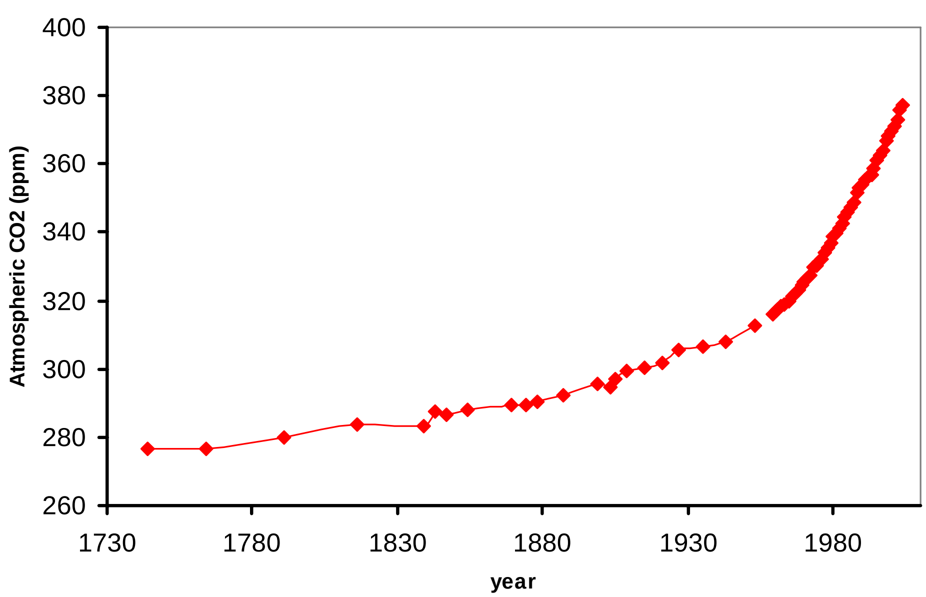


Figure 2-3. GDP in 2000 U.S. dollars vs fossil-fuel carbon emissions (Mt C yr^{-1}). Data from EIA (2005). Each arrow shows the sequence from 1980 to 2003 for a country. Note that carbon emissions per unit GDP decelerate as a country gains wealth. The lines in the figure show the slopes associated with the different ratios of GDP and emissions growth (the y-intercepts of the dotted and dashed lines are not informative and were chosen only to keep from obscuring the arrows).

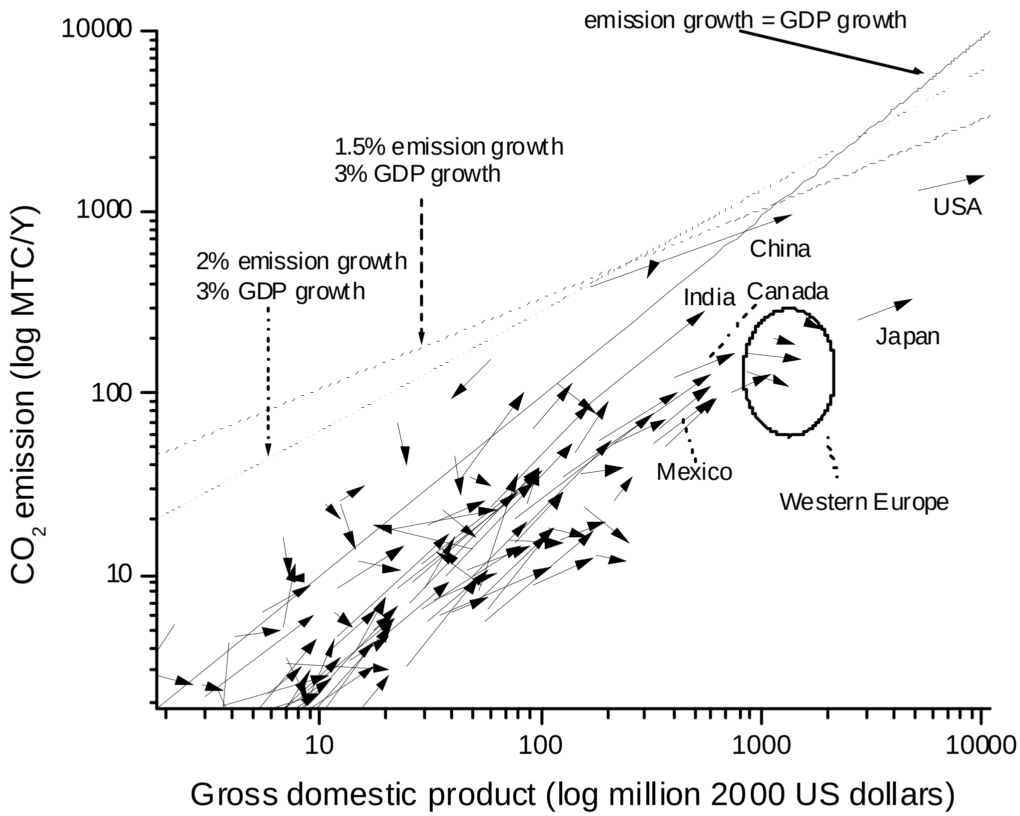


Figure 2-4. The spatial distribution of ocean CO_2 exchange from 1992–1996, for several regions and measurement approaches. Tak99 and Tak02 are from (Takahashi *et al.*, 2002) ΔpCO_2 estimates, T3L1 and T3L2 are from (Gurney *et al.*, 2003; Gurney *et al.*, 2004), Fwd is from predictive ocean models, JI is from the ocean atmosphere ocean inversions of (Jacobson *et al.*, 2006). The far right column is the sum of the individual ocean basins toward the left [from (Jacobson *et al.*, 2006)].

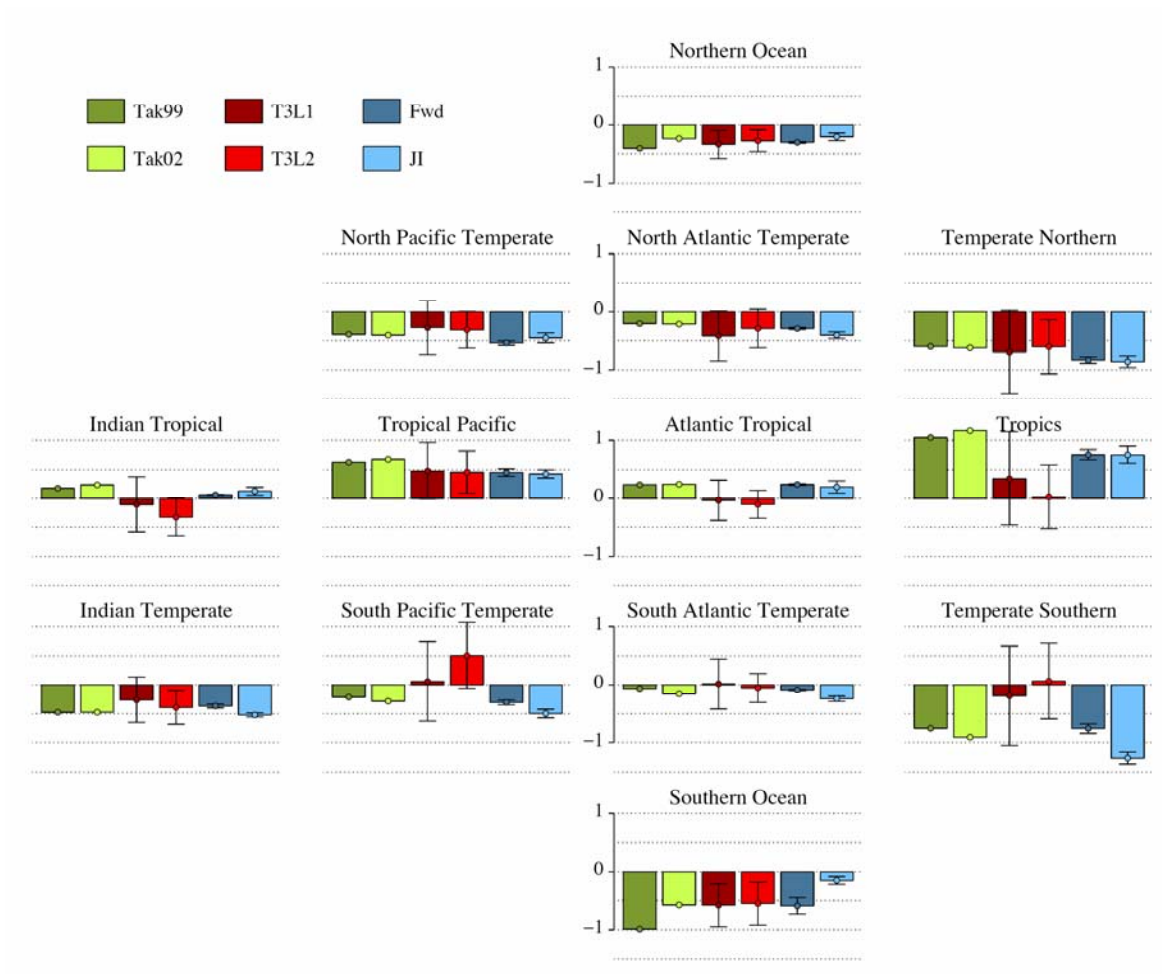


Figure 2-5. The 13-model mean CO_2 flux interannual variability (Gt C yr^{-1}) for several continents (solid lines) and ocean basins (dashed lines) (a) North Pacific and North America, (b) Atlantic north of 15ºN and Eurasia, (c) Australasia and Tropical Pacific, (d) Africa, and (e) South America (note the different scales for Africa and South America) [from (Baker *et al*., 2006)].