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The Carbon Cycle: Implications for Climate Change and Congress

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Peter Folger
Specialist in Energy Policy
Resources, Science, and Industry Division

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Summary

Carbon is stored in the atmosphere, in the oceans, in vegetation, and in soils on the land surface. Huge quantities of carbon are actively exchanged between the atmosphere and the other storage pools of carbon. The exchange, or flux, of carbon between the atmosphere, oceans, and land surface is called the carbon cycle. In sheer magnitude, human activities contribute a relatively small amount of carbon, primarily as carbon dioxide (CO_2), to the global carbon cycle. Burning fossil fuels, for example, adds less than 5% to the total amount of CO_2 released from the oceans and land surface to the atmosphere each year. If humans add only a small amount of CO_2 to the atmosphere each year, why is that contribution important to global climate change?

In short, the oceans, vegetation, and soils cannot consume carbon released from human activities quickly enough to stop CO_2 from accumulating in the atmosphere. Humans tap the huge pool of fossil carbon for energy, and affect the global carbon cycle by transferring fossil carbon — which took millions of years to accumulate — into the atmosphere over a relatively short time span. As a result, the atmosphere contains 100 parts per million more today (380 ppm vs 280 ppm) than prior to the beginning of the industrial revolution. As the CO_2 concentration grows it increases the *radiative forcing* (more incoming radiation energy than outgoing) of the atmosphere, warming the planet. In response, Congress is considering legislative strategies that would reduce U.S. emissions of CO_2, or increase the uptake of CO_2 from the atmosphere, or both.

Less than half of the total amount of CO_2 released from burning fossil fuels during the past 250 years has remained in the atmosphere because two huge reservoirs for carbon — the global oceans and the land surface — take up more carbon than they release. They are net *sinks* for carbon. If the oceans, vegetation, and soils did not accumulate as much carbon as they do today, then the concentration of CO_2 in the atmosphere would increase even more rapidly. A key issue to consider is whether these two sinks will continue to store carbon at the same rate over the next few decades. Will the sinks remove more, less, or the same amount of CO_2 released from fossil fuel combustion each year? Currently, most of the total global carbon sink is referred to as the *unmanaged*, or background, carbon cycle. Very little carbon is removed from the atmosphere and stored, or sequestered, by deliberate action.

Congress may opt to consider how land management practices, such as afforestation, conservation tillage, and other techniques, might increase the net flux of carbon from the atmosphere to the land surface. How the ocean sink could be managed to store more carbon is unclear. Iron fertilization and deep ocean injection of CO_2 are in an experimental stage, and their promise for long-term enhancement of carbon uptake by the oceans is not well understood. Congress may consider incorporating what is known about the carbon cycle into its legislative strategies, and may also evaluate whether the global carbon cycle is sufficiently well understood so that the consequences of long-term policies aimed at mitigating global climate change are fully appreciated.

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Introduction

Congress is considering several legislative strategies that would reduce U.S. emissions of greenhouse gases — primarily carbon dioxide (CO_2) — or increase uptake and storage of CO_2 from the atmosphere, or both. Both approaches are viewed by many as critical to forestalling global climate changed caused, in part, by the buildup of greenhouse gases in the atmosphere from human activities. Others point out that the human contribution of carbon to the atmosphere is a small fraction of the total quantity of carbon that cycles back and forth each year between the atmosphere and two huge carbon reservoirs: (1) the global oceans, and (2) the land surface of the entire planet. The exchange, or flux, of carbon between the atmosphere, oceans, and land surface is called the global carbon cycle.

An understanding of the details of the global carbon cycle has shifted from being of mainly academic interest to being of political interest. Policy makers are grappling with, for example, the importance of recognizing carbon sequestration by forests; or determining under a greenhouse gas cap what level of carbon emissions would limit the concentration of atmospheric CO_2 to a specific value; or understanding the magnitude and timing of ocean acidification and its impact on marine life. In sheer magnitude, human activities contribute a relatively small amount of carbon, primarily as CO_2, to the global carbon cycle. Fossil fuel combustion, for example, adds less than 5% to the total amount of carbon released from the oceans and land surface to the atmosphere each year. If humans add only a small amount of CO_2 to the atmosphere, why is that contribution important enough to influence global climate change?

This report explores the answer to that question and attempts to put the human contribution of carbon to the atmosphere into the larger context of the global carbon cycle. The report focuses almost entirely on CO_2, although methane (CH_4), black carbon, and organic carbon pollution are also part of the carbon cycle and have roles in human-induced climate change. Carbon dioxide, alone, is responsible for over half of the change in Earth's radiation balance, and methane for about an additional 20%.[1]

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[1] *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle.* Anthony W. King, Lisa Dilling, Gregory P. Zimmerman, David M. Fairman, Richard A. Houghton, Gregg Marland, Adam Z. Rose, and Thomas J. Wilbanks, eds., 2007. A report by the U.S. Climate Change Science Program (CCSP) and the Subcommittee on Global Change Research, Washington, DC; at

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Carbon Storage, Sources, and Sinks

Carbon is stored in the atmosphere, in the oceans, in vegetation, and in soils on the land surface. Carbon is actively exchanged (*fluxes*) between the atmosphere and the other storage pools, or stocks, of carbon. The atmosphere is also linked to fossil carbon in geological reservoirs — for example, oil, gas, and coal — via their extraction and combustion as fossil fuels.[2] Dissolved inorganic carbon in the ocean is the largest storage pool, followed in size by fossil carbon in geological reservoirs, and by the total amount of carbon contained in soils. The atmosphere itself contains nearly 800 billion metric tons of carbon[3] (or gigatonnes, GtC), which is more carbon than all of the Earth's living vegetation contains.[4] **Table 1** and **Figure 1** show the global amount of carbon held in storage in each pool that is linked to the atmosphere.

Carbon dioxide in the atmosphere has an average concentration around the globe of approximately 380 parts per million (ppm).[5] The atmosphere has a fairly uniform concentration of CO_2, although it shows minor variations (about 1%) by season — due to photosynthesis and respiration — and by latitude.[6] Carbon dioxide released from fossil fuel combustion mixes readily into the atmospheric carbon pool, where it undergoes exchanges with the ocean and land surface carbon pools. Thus, *where* fossil fuels are burned makes relatively little difference to the concentration of CO_2 in the atmosphere; emissions in any one region affect the concentration of CO_2 everywhere else in the atmosphere.[7]

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[1] (...continued)
[http://cdiac.ornl.gov/SOCCR/draft4.html]. (Hereafter referred to as SOCCR.) The SOCCR report is the fourth draft, and is not yet final. The Intergovernmental Panel on Climate Change, "Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change," *Climate Change 2007: the Physical Science Basis* (2007); at [http://ipcc-wg1.ucar.edu/wg1/wg1-report.html]. (Hereafter referred to as 2007 IPCC WG I Report.)

[2] Carbon in the Earth's crust is mainly in the form of carbonates, and is linked to the atmosphere by natural processes, such as erosion and weathering, and by metamorphism over geologic time scales. In contrast, the key source of fossil carbon for the purposes of this report are fossil fuels, which are now linked to the atmosphere almost entirely via human activities.

[3] One metric ton of carbon is equivalent to 3.67 metric tons of CO_2.

[4] William H. Schlesinger, *Biogeochemistry: an Analysis of Global Change (2nd Ed.)*, San Diego, CA: Academic Press, (1997), p. 360. Hereafter referred to as Schlesinger, 1997.

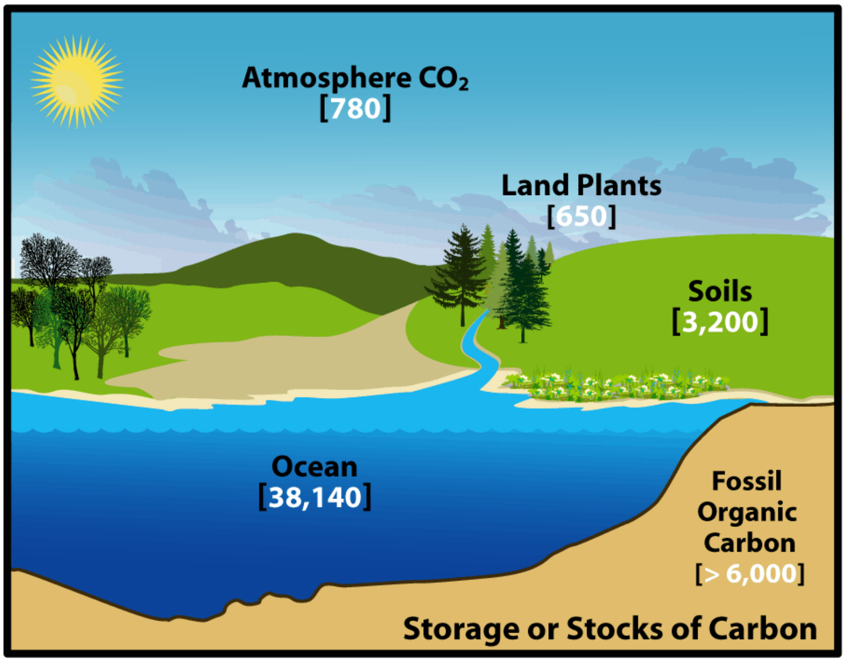
[5] World Data Centre for Greenhouse Gases (WDCGG), *WMO Greenhouse Gas Bulletin: The State of Greenhouse Gases in the Atmosphere Using Global Observations through 2005* (Geneva, 2006); at [http://gaw.kishou.go.jp/wdcgg.html].

[6] Schlesinger, 1997, p. 56.

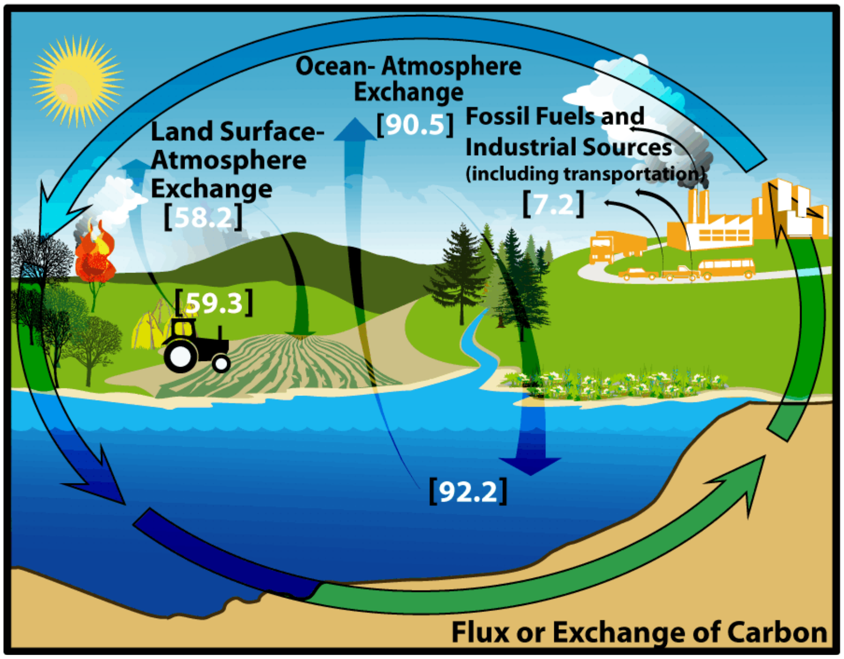
[7] Concentrations of CO_2 are slightly higher in the northern hemisphere compared to the southern hemisphere, by several parts per million, because most of the emissions of CO_2 from human activities are in the north.

Figure 1. (a) Storage or Stocks of Carbon (GtC); and (b) Annual Flux or Exchange of Carbon (GtC per year)

a.



b.



Sources: SOCCR; IPCC Working Group I Report, Table 7.1; Sabine et al., "Current Status and Past Trends of the Global Carbon Cycle," in C.B. Field and M.R. Raupach (eds.), *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World*, Washington, D.C.: Island Press (2004), pp. 17-44.
Note: Figure prepared by CRS.

The oceans, vegetation, and soils truly *exchange* carbon with the atmosphere constantly on daily and seasonal time cycles. In contrast, carbon from fossil fuels is *not* exchanged with the atmosphere, but is transferred in a one-way direction from geologic storage, at least at the human time scale.[8] Some of the CO_2 currently in the atmosphere may become fossil fuel someday, after it is captured by vegetation, buried under heat and pressure, and converted into coal, for example, but the process takes millions of years. How much of the fossil fuel carbon ends up in the atmosphere, instead of the oceans, vegetation, and soils, and over what time scale, is driving much of today's global warming debate.

How much carbon is stored in each pool — especially the atmospheric pool — is important in the global warming debate because as more CO_2 is added to the atmosphere, its heat-trapping capacity becomes greater.[9] Each storage pool — oceans, soils, and vegetation — is considered a *sink* for carbon because each pool takes up carbon from the atmosphere. Conversely, each storage pool is also a *source* of carbon for the atmosphere, because of the constant exchange or *flux* between the atmosphere and the storage pools. The pool of fossil carbon is only a source, not a sink, except over geologic time scales, as described above. How much carbon is transferred between the atmosphere and the sources and sinks is a topic of scientific scrutiny because the mechanisms are still not understood completely. Whether a storage pool is a net sink or a net source for carbon in the future depends very much on the balance of mechanisms assumed to drive its behavior, and how those mechanisms may change.[10]

Carbon Flux, or Exchange, with the Atmosphere

Over 90 billion tonnes (or 90 Gigatonnes of carbon, GtC) of carbon is exchanged each year between the atmosphere and the oceans, and close to 60 GtC is exchanged between the atmosphere and the land surface annually (**Table 1**).[11] Human activities — primarily land-use change and fossil fuel combustion — contribute less than 9 GtC to the atmosphere each year.[12] If the human contribution

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[8] An exception to this is the concept of direct carbon sequestration, or carbon capture and storage, whereby the geologic time scale cycle of carbon storage is "short circuited" by capturing CO_2 at its source — a fossil-fueled electricity generating plant for example — and injecting it underground into geologic reservoirs.

[9] See CRS Report RL33849, *Climate Change: Science and Policy Implications*, by Jane A. Leggett, for an explanation of the heat-trapping properties, or *radiative forcing*, of CO_2 and other greenhouse gases.

[10] Jorge L. Sarmiento and Nicolas Gruber, "Sinks for Anthropogenic Carbon," *Physics Today* (August, 2002), pp. 30-36.

[11] These massive exchanges of CO_2 between the atmosphere, oceans, and land surface result mostly from natural processes, such as photosynthesis, respiration, decay, and gas exchange between the ocean surface and the lower atmosphere.

[12] About 80% of human-related CO_2 emissions results from fossil fuel combustion, and 20% from land use change (primarily deforestation). Fossil fuel burning and cement production release approximately 7.2 GtC per year, land use change releases about 1.6 GtC per year

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of CO_2 is removed from the equation, then the average *net flux* — the amount of CO_2 released to the atmosphere versus the amount taken up by the oceans, soils, and vegetation — is close to zero. Most scientists conclude that for 10,000 years prior to 1750, the net flux was less than 0.1 GtC per year when averaged over decades.[13] That small value for net flux is reflected by the relatively stable concentration of CO_2 in the atmosphere — between 260 and 280 ppm — for the past 10,000 years prior to 1750.[14]

Table 1. Carbon Stocks in the Atmosphere, Ocean, and Land Surface, and Annual Carbon Fluxes

	Storage pool (or stock) in GtC		Annual flux (or exchange) *from* the atmosphere in GtC per year	Annual flux (or exchange) *to* the atmosphere in GtC per year	Net annual flux to the atmosphere in GtC per year
Atmosphere	780				
Ocean	38,140	Ocean-Atmosphere[b]	92.2	90.5	-1.7
Land Surface[a] (soils plus vegetation)	3,850	Land Surface-Atmosphere[c]	59.3	58.2	-1.1
Fossil Carbon (coal, gas oil, other)	>6,000	Fossil Carbon-Atmosphere	—	7.2	+7.2

Sources: SOCCR; IPCC Working Group I Report, Table 7.1; Sabine et al., “Current Status and Past Trends of the Global Carbon Cycle,” in C.B. Field and M.R. Raupach (eds.), *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World*, Washington, D.C.: Island Press (2004), pp. 17-44.
[a] The soil pool contains about 3,200 GtC, and the vegetation pool contains about 650 GtC.
[b] Gross fluxes between the ocean and atmosphere have considerable uncertainty, but the net flux is known to within +/-0.3 GtC per year (SOCCR, p. 2-3).
[c] The net flux between the land surface and the atmosphere is known to within +/-0.7 GtC per year (Jonathan A. Foley and Navin Ramankutty, “A Primer on the Terrestrial Carbon Cycle: What We Don’t Know But Should,” in C.B. Field and M.R. Raupach (eds.), *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World*, Washington, D.C.: Island Press (2004), p. 281.

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[12] (...continued)
(2007 IPCC Working Group I Report, pp. 501, 514-515).

[13] 2007 IPCC Working Group I Report, p. 514.

[14] Ice core data indicate that CO_2 concentrations ranged between 180 and 300 ppm over the past 650,000 years, and between 275 and 285 ppm from AD 1000 to AD 1750 (2007 IPCC Working Group I Report, p. 137 and p. 435). See also E.T. Sundquist and K. Visser, “The Geologic History of the Carbon Cycle,” in Heinrich D. Holland and Karl K. Turekian (eds.), *Treatise on Geochemistry*, Amsterdam, Netherlands: Elsevier Ltd. (2004), p. 443.

Currently the atmospheric concentration of CO_2 is almost 100 ppm higher than it was before 1750 because human activities are adding carbon to the atmosphere faster than the oceans, land vegetation, and soils can remove it. The relatively rapid addition of CO_2 to the atmosphere has tipped the balance between sources and sinks. Why is that occurring?

The short answer is timing. First, the oceans and land surface are taking up carbon released from human activities, but not as quickly as CO_2 is accumulating in the atmosphere. About 45% of the CO_2 released from fossil fuel combustion and land use activities during the 1990s has remained in the atmosphere, while the remainder has been taken up by the oceans, vegetation, or soils on the land surface.[15] Carbon dioxide is nonreactive[16] in the atmosphere and has a relatively long residence time, although eventually most of it will return to the ocean and land sinks. About 50% of a single pulse of CO_2 will be removed within 30 years, a further 30% removed in within a few centuries, and the remaining 20% may persist in the atmosphere for thousands of years.[17] As the CO_2 concentration grows it increases the *radiative forcing* of the atmosphere, warming the planet. Second, the oceans and land surface are acting at present as sinks for CO_2 emitted from fossil fuel combustion and deforestation, but as they accumulate more carbon the nature of the sinks may change. It is also likely that climate change itself — for example, higher temperatures, more intense hydrologic cycle — may alter the balance between sources and sinks, due to changes in the complicated feedback mechanisms between the atmosphere, oceans, and land surface.[18] How carbon sinks will behave in the future is currently a prominent question for both scientists and policy makers.

Land Surface-Atmosphere Flux. Most estimates of the carbon cycle indicate that the land surface (vegetation plus soils) accumulates more carbon per year than it emits to the atmosphere (**Figure 1** and **Table 1**).[19] The land surface thus acts as a net sink for CO_2 at present. Some policy makers advocate strategies for increasing the amount of CO_2 taken up and stored, or *sequestered*, by soils and plants, typically through agricultural or forestry practices.[20] How effective those strategies are likely to be depends, in part, on our understanding of the carbon cycle and the land-atmosphere flux.

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[15] IPCC Working Group I Report, pp. 514-515.

[16] As opposed to other greenhouse gases, such as methane (CH_4), which reacts with OH to produce water and CH_3; and nitrous oxide (NO_2), which is decomposed in the atmosphere by its reaction with ultraviolet light.

[17] IPCC Working Group I Report, p. 515.

[18] See CRS Report RL33849, *Climate Change: Science and Policy Implications*, by Jane A. Leggett, for more information on climate feedback mechanisms.

[19] IPCC Working Group I Report, p. 515.

[20] For more information on sequestration in the agricultural and forestry sectors, see CRS Report RL31432, *Carbon Sequestration in Forests*, by Ross W. Gorte, and CRS Report RL33898, *Climate Change: The Role of the U.S. Agriculture Sector*, by Renee Johnson.

The land use change component has the largest uncertainty of any component in the overall carbon cycle.[21] Most scientists agree, however, that in the past two decades *tropical deforestation* has been responsible for the largest share of CO_2 released to the atmosphere from land use changes.[22] Tropical deforestation and other land use changes may be responsible for releasing approximately 1.6 GtC per year to the atmosphere in the 1990s, and may be contributing similar amounts of carbon to the atmosphere today.[23] Even though deforestation releases more carbon than is captured by forest regrowth in some regions, net forest regrowth in other regions uptakes sufficient carbon so the land surface acts as a global net *sink* of approximately 1 GtC per year. By some estimates, even tropical lands, despite widespread deforestation, may be carbon-neutral or even net carbon sinks; tropical systems uptake substantial carbon to offset what is lost through deforestation.[24]

What used to be known as "the missing sink" component in the overall global carbon cycle is now understood to be that part of the terrestrial ecosystem responsible for the net uptake of carbon from the atmosphere to the land surface (especially high-latitude forests).[25] Scientists now prefer the term "residual land sink" to "missing sink" as it portrays the residual — or left over — part of the global carbon cycle calculation once the other components are accounted for (fossil fuel emissions, land-use emissions, atmospheric increase, and ocean uptake).[26] Precisely which mechanisms are responsible for the residual land sink are a topic of scientific controversy. One mechanism postulated for many years has been the fertilizing effect of increased atmospheric CO_2 concentrations on plant growth. Most models predict enhanced growth and carbon sequestration by plants in response to rising CO_2 levels; however, results of experiments have been mixed. Experiments show enhanced growth from increased CO_2 concentrations — at least initially — but nutrient availability and other limitations to growth are common. Long-term observations of biomass change and growth rates suggest that fertilization effects are too small to account for the residual land sink, at least in the United States.[27]

In North America, particularly the United States, the land-atmosphere flux is strongly tilted towards the land surface, where approximately 0.5 GtC per year is

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[21] IPCC Working Group I Report, p.518.

[22] IPCC Working Group I Report, p. 517.

[23] Ibid, Table 7.1.

[24] Ibid, p. 522. However, SOCCR (p. ES-6) notes that rates of forest clearing in the tropics, including Mexico, exceed rates of recovery and concludes that tropical regions dominated by rainforests or other forest types *are* a net source of carbon to the atmosphere.

[25] However, a recent study indicate that the northern latitude forests uptake less carbon than previously estimated, and tropical forests uptake more. See Britton B. Stephens et al., "Weak northern and strong tropical land carbon uptake from vertical profiles of atmospheric CO_2," *Science*, Vol. 316 (22 June 2007): pp. 1732-1735.

[26] SOCCR, p. 2-6.

[27] Sarmiento and Gruber (2002), p. 31.

accumulating in terrestrial sinks.[28] That amount constitutes a large fraction — possibly 25% — of the global terrestrial carbon sink.[29] According to some estimates, approximately 50% of the North American terrestrial carbon sink stems from regrowth of forests on abandoned U.S. farmland.[30] Woody encroachment — the increase in woody biomass occurring mainly on former grazing lands — is thought to be another potentially large terrestrial sink, possibly accounting for 20% of the net North American sink (although the actual number is highly uncertain).[31] Wood products (e.g. furniture, house frames, etc.), wetlands, and other smaller, poorly understood carbon sinks are responsible for accumulating the remaining carbon in North America.

Most of the North American terrestrial carbon sink, such as the forest regrowth component, is sometimes referred to as the *unmanaged*, or background, carbon cycle. Very little carbon is sequestered by deliberate action.[32] The future behavior of the unmanaged terrestrial carbon sink is another consideration for lawmakers. Whether the United States will continue its trajectory as a major terrestrial carbon sink is highly uncertain, and some evidence suggests that the terrestrial ecosystem sinks may not increase in size. Some current sinks may even become *sources* for carbon.[33]

Policy makers may also need to evaluate how management practices, such as afforestation, conservation tillage, and other techniques would increase the net flux of carbon from the atmosphere to the land surface.[34] How forests, rangelands, and croplands are managed in the future for carbon sequestration may become an important factor in the overall land-atmosphere flux.

Ocean-Atmosphere Flux. Similar to the land surface, the oceans today accumulate more carbon than they emit to the atmosphere each year, acting as a net sink of about 1.7 GtC per year (**Figure 1** and **Table 1**). If the land surface and oceans were not acting as net sinks, the CO_2 concentration in the atmosphere would be increasing at a faster rate than observed. More than the land surface, the oceans have a huge capacity to store carbon. Ultimately, the oceans could store more than 90% of all the carbon released to the atmosphere by human activities, but the process

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[28] SOCCR, p. ES-9. This includes fluxes to and from land vegetation and soils, and excludes emissions from fossil fuel combustion, cement manufacturing, and other industrial processes.

[29] Ibid, p. ES-5. However, SOCCR reports that the magnitude of the global terrestrial carbon sink is highly uncertain.

[30] Ibid.

[31] SOCCR, p. ES-9; IPCC Working Group I Report, p. 527.

[32] SOCCR, pp. 2-3, 2-8.

[33] Ibid, p. 2-9.

[34] For more information on agricultural and forestry practices and carbon management, see CRS Report RL34032, *Environmental Services Markets: Farm Bill Proposals*; CRS Report RL33898, *Climate Change: the Role of the U.S. Agricultural Sector*, by Renee Johnson; and CRS Report RL31432, *Carbon Sequestration in Forests*, by Ross W. Gorte.

takes thousands of years.[35] Policy makers may be more concerned about how CO_2 is accumulating in the oceans now, what its impact is on ocean chemistry and marine life (e.g. ocean acidification), and how its behavior as a net sink may change over the next few decades.

Carbon dioxide enters the oceans by dissolving into seawater at the ocean surface, at a rate controlled by the difference in CO_2 concentration between the atmosphere and the sea surface.[36] Because the surface waters of the ocean have a relatively small volume — and thus a limited capacity to store CO_2 — how much CO_2 is stored in the oceans over the time scale of decades depends on ocean mixing and the transport of CO_2 from the surface to intermediate and deep waters. Mixing between surface waters and deeper portions of the ocean is a sluggish process; for example, the oldest ocean water in the world — found in the North Pacific — has been out of contact with the ocean surface for about 1,000 years.[37] Thus the slow rate of ocean mixing, and slow transport of CO_2 from the surface to the ocean depths, is of possible concern to policymakers because it influences the effectiveness of the ocean sink for CO_2, and because CO_2 added to the surface waters of the ocean increases its acidity.

In addition to the vertical mixing of the ocean, large-scale circulation of the oceans around the globe is a critical component for determining the effectiveness of the ocean sink.[38] Surface waters carrying anthropogenic CO_2 descend into the ocean depths primarily in the North Atlantic and the Southern Oceans, part of the so-called oceanic "conveyor belt."[39] Some model simulations suggest that the Southern Ocean around Antarctica accounts for nearly half of the net air-sea flux of anthropogenic carbon.[40] From that region, a large portion of dissolved CO_2 is transported north towards the subtropics. Despite its importance as a CO_2 sink, the Southern Ocean is poorly understood, and at least one study suggests that its capacity for absorbing carbon may be weakening.[41]

As CO_2 is added to the surface of the ocean from the atmosphere, it increases the acidity of the sea surface waters, with possible impacts to the biological

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[35] CO_2 forms carbonic acid when dissolved in water. Over time, the solid calcium carbonate (CaCO3) on the seafloor will react with, or *neutralize,* much of the carbonic acid that entered the oceans as CO_2 from the atmosphere. See David Archer et al., "Dynamics of fossil fuel CO_2 neutralization by marine $CaCO_3$," *Global Biogeochemical Cycles* (June 1998), vol. 12, no. 2, pp. 259-276.

[36] SOCCR, p. 2-7. In addition to the relative difference in CO_2 concentration between atmosphere and ocean, the rate of CO_2 dissolution also depends on factors such as wave action, wind, and turbulence.

[37] Sarmiento and Gruber (2002), p. 31.

[38] SOCCR, p. 2-7.

[39] Sarmiento and Gruber (2002), p. 31.

[40] Ibid.

[41] Corinne Le Quere et al., "Saturation of the Southern Ocean CO_2 sink due to recent climate change," *Science, Vo. 316* (22 June, 2007): pp. 1735-1737.

production of organisms, such as corals. Corals, and calcifying phytoplankton and zooplankton, are susceptible to increased acidity as their ability to make shells in the water column is inhibited or possibly reversed, leading to dissolution.[42] Some reports indicate that sea surface pH has dropped by 0.1 pH units since the beginning of the industrial revolution.[43] One report suggests that pH levels could drop by 0.5 pH units by 2100, and suggests further that the magnitude of ocean acidification can be predicted with a high level of confidence.[44] The same report states, however, that research on the impacts of high concentrations of CO_2 on marine organisms is in its infancy.

The oceans appear to be a larger net sink for carbon than the land surface at present. As with the land surface, however, a consideration for policy makers is the future behavior of the ocean sink, particularly the Southern Ocean, given its importance to the net ocean-atmosphere CO_2 flux. In contrast to the terrestrial carbon sink, where management practices such as afforestation and conservation tillage may increase the amount of carbon uptake, it is unclear how the ocean carbon sink can be *managed* in a similar fashion. Some proposed techniques for increasing ocean sequestration of carbon, such as iron fertilization[45] and deep ocean injection of CO_2, are in an experimental phase and have unknown long-term environmental consequences.[46]

Conclusions

Huge amounts of carbon are exchanged between the atmosphere, the land surface, and the oceans each year. Humans are responsible for only a small fraction of the total exchange that, nonetheless, affects the global system by adding a large net flux of CO_2 to the atmosphere. Before the industrial revolution — and the large-scale combustion of fossil fuels, land-clearing and deforestation activities — the average net flux of CO_2 to the atmosphere hovered around zero for nearly 10,000 years. Because of the human contribution to the net flux, the amount of CO_2 in the atmosphere is now 100 ppm higher today than is has been for the past 10,000 years.

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[42] IPCC Working Group I Report, p. 529.

[43] Ibid. pH is measure of the concentration of hydrogen ions in solution. A lower pH means an increase in acidity, or a higher concentration of hydrogen ions.

[44] Ken Caldeira et al., "Ocean acidification due to increasing atmospheric carbon dioxide," *The Royal Society*, Policy Document 12/05 (June 2005), 60 pages; at [http://www.royalsoc.ac.uk/].

[45] The deliberate introduction of iron into the surface ocean to stimulate marine phytoplankton growth, which would increase carbon sequestration from the atmosphere via photosynthesis. The Southern Ocean, in particular, is deficient in iron as a nutrient such that the introduction of iron could stimulate phytoplankton growth. Several experiments have been conducted or are underway to further explore this process, for example, Stephane Blain, et al., "Effect of natural iron fertilization on carbon sequestration in the Southern Ocean," *Nature* (April 26, 2007), vol. 446, no. 7139, pp. 1070-1074.

[46] For more information about injection of CO_2 into the deep oceans, see CRS Report RL33801, *Direct Carbon Sequestration: Capturing and Storing CO_2*, by Peter Folger.

Congress is exploring legislative strategies that would alter the human component of the global carbon cycle. Strategies that limit emissions from fossil fuel combustion would reduce the current one-way transfer of fossil carbon to the atmosphere. What took millions of years to accumulate geologically is being released in only a few hundred years. Capturing CO_2 before it is released to the atmosphere and injecting it back into geological reservoirs — direct carbon sequestration — is one possible strategy to "short circuit" the geologic process and return the carbon underground over a human time scale. CO_2 injection into the subsurface has been used for decades to enhance recovery of oil; however, large-scale geologic sequestration of CO_2 for *storage* is currently in a pilot testing stage.

Less than half of the total amount of CO_2 released from burning fossil fuels over the past 250 years remains in the atmosphere, because two huge sinks for carbon — the global oceans and the land surface — take up more carbon than they release at present. Congress is exploring if and how management practices, such as afforestation, conservation tillage, and other techniques, might increase the net flux of carbon from the atmosphere to land surface. How the ocean sink could be managed to store more carbon is unclear. Iron fertilization and deep ocean injection of CO_2 are in an experimental stage, and their promise for long-term enhancement of carbon uptake by the oceans is not well understood.

Also of possible concern to Congress is how the ocean and land surface sinks will behave over the coming decades and longer, and whether they will continue to uptake more carbon than they release. For example, carbon emissions may be capped so as to keep atmospheric CO_2 concentrations below a prescribed level at some future date, but changes in the magnitude, or even the direction, of the ocean or land-surface sinks may affect whether those target concentrations can be achieved. Congress may wish to incorporate what is known about the carbon cycle into its legislative strategies. Congress may also wish to evaluate whether the global carbon cycle is sufficiently well understood that the consequences of long-term policies aimed at mitigating global climate change are fully appreciated.