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SUMMARY

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Large quantities of carbon are actively exchanged between the atmosphere and the other carbon storage pools, including the oceans, vegetation, and soils on the land surface. The exchange, or flux, of carbon among the atmosphere, oceans, and land surface is called the *global carbon cycle*. Comparatively, human activities contribute a relatively small amount of carbon, primarily to atmospheric carbon dioxide (CO_2), to the entire global carbon cycle. Despite this relatively small contribution to the atmospheric carbon, the resulting perturbation to the carbon cycle is increasingly recognized as a main factor driving climate change over the past 50 years.

If humans add only a small amount of CO_2 to the atmosphere each year, why is that contribution important to climate change? The answer is that some of the CO_2 released to the atmosphere by human activities is not transferred to oceans, vegetation, and soils quickly enough to prevent CO_2 concentrations in the atmosphere from increasing over time. Human activities are transferring fossil carbon—which took millions of years to accumulate—from a large, long-term carbon storage pool into the atmosphere over a relatively short time span, thereby affecting the global carbon cycle. As a result, the atmosphere contains approximately 46% more CO_2 today than prior to the beginning of the Industrial Revolution. As the CO_2 concentration of the atmosphere increases, the degree to which the atmosphere traps incoming radiation from the sun increases, which in turn contributes to further warming of the planet.

The increase in atmospheric CO_2 concentration is mitigated to some extent by two relatively large (as compared to the atmosphere) reservoirs of carbon—the global oceans and the land surface. The global oceans and the land surface are considered net *sinks* for carbon because they currently take up more carbon than they release. 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 (e.g., carbon capture and sequestration). If the oceans, vegetation, and soils did not act as sinks, then the concentration of CO_2 in the atmosphere would increase even more rapidly than has been observed.

The behavior and components of the global carbon cycle can be influenced by congressional policy decisions. Legislation introduced in the 117th Congress includes the climate policy goal of achieving net-zero CO_2 emissions—where emissions of CO_2 are balanced by removals from the atmosphere. Achieving this policy goal depends, in part, on the behavior of components of the global carbon cycle, specifically the land and ocean sinks, and on human activities influencing the cycle. Policy options to achieve net-zero CO_2 emissions will require changes in the carbon cycle that may include reductions in emissions from fossil fuel combustion and land-use change, increasing the uptake of CO_2 by land surface and ocean carbon sinks, and increasing the capacity for removal and long-term storage of CO_2 from the atmosphere by technical means.

Large uncertainties exist in the future behavior of important components of the global carbon cycle, including the levels of emissions of CO_2 to the atmosphere, and future levels of uptake or release of CO_2 from the land surface and oceans.

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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)—and/or increase uptake and storage of CO_2 from the atmosphere. Both approaches are viewed by many observers as critical to forestalling global climate change 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 naturally back and forth each year between the atmosphere and two large carbon reservoirs: the global oceans and the planet's land surface. A key question is how CO_2 emissions from human activities are changing the global carbon cycle—the exchange, or flux, of carbon between the atmosphere, oceans, and land surface—and how the changes affect the rate of CO_2 buildup in the atmosphere.[1]

There is a scientific consensus that human disturbances, or perturbations, to the carbon cycle are a main factor driving climate change over the past 50 years.[2] For the period 0-1850 CE, the global carbon cycle was roughly in balance, and the concentration of CO_2 in the atmosphere was fairly constant at approximately 280 parts per million (ppm).[3] Human activities, namely the burning of fossil fuels, deforestation, and other land-use activities, have significantly altered the carbon cycle. As a result, atmospheric concentrations of CO_2 are now greater than 400 ppm, having increased by over 46% since the Industrial Revolution.[4]

An understanding of the global carbon cycle has shifted from being of mainly academic interest to being also of policy interest. Policymakers are grappling with, for example, how the United States could achieve a state of net-zero CO_2 emissions, in which emissions to the atmosphere are balanced by removals. This is likely to require the implementation of human methods of carbon dioxide removal (CDR)[5] and would depend inherently on continued uptake of carbon by the oceans and land surface. Yet how much CO_2 forests or farmland are capable of taking up in the future, and for how long, is not clear. How the oceans and the land surface carbon reservoirs will behave in the future—how much CO_2 they will take up or release and at what rate—are topics of active scientific inquiry.

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[1] The buildup of CO_2 in the atmosphere is also changing the chemistry of the ocean's surface waters, a phenomenon known as *ocean acidification*, which could harm aquatic life. For more information, see CRS Report R43185, *Ocean Acidification*, by Harold F. Upton and Peter Folger.

[2] The Fourth National Climate Assessment (NCA4) of the U.S. Global Change Research Program addresses human causation of climate change. "This assessment concludes, based on extensive evidence, that it is extremely likely that human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century. For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence." Carbon dioxide is recognized as the greenhouse gas with the greatest influence on climate. See also Intergovernmental Panel on Climate Change (IPCC), "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021, p. 7 (hereinafter IPCC AR6 WGI SPM 2021).

[3] IPCC, "Chapter 2: Changing State of the Climate System" in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021, p. 300 (hereinafter 2021 IPCC Working Group I Report).

[4] U.S. Global Change Research Program, *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*, 2018, p. 24 (hereinafter SOCCR2). See also NOAA, "Climate Change: Atmospheric Carbon Dioxide," https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide; and IPCC AR6 WGI SPM 2021, p. 4.

[5] U.S. Global Change Research Program (USGRP), *Climate Science Special Report: Fourth National Climate Assessment*, Volume I, 2017, p. 399.

The scientific understanding of the carbon cycle is integral to many aspects of the current congressional debate over how to mitigate climate change. This report puts the human contribution of carbon to the atmosphere into the larger context of the global carbon cycle.[6] More than half of the human-caused increase in the earth's radiation balance is due to CO_2, the primary focus of this report.[7] According to the Intergovernmental Panel on Climate Change (IPCC), CO_2 is the most important greenhouse gas released to the atmosphere from human activities.[8]

Carbon Storage, Sources, and Sinks

The atmosphere, oceans, vegetation, and soils on the land surface all store carbon (**Figure 1, panel (a)**). Geological reservoirs also store carbon in a variety of forms, including fossil fuels, such as oil, gas, and coal.[9] A portion of these fossil fuel reservoirs are considered recoverable reserves.[10] Of these reservoirs (or pools), dissolved inorganic carbon in the ocean is the largest, followed in size by fossil carbon in geological reservoirs, and by the total amount of carbon contained in soils[11] (**Figure 1, panel (a); Table 1**). The total carbon stored in the live plant biomass of the earth is less[12] than the 870 billion metric tons of carbon[13] (870 GtC)[14] present in the atmosphere. Carbon contained in the oceans, vegetation, and soils on the land surface is linked to the atmosphere through natural processes such as photosynthesis, respiration, decomposition, and gas exchange. In contrast, carbon in fossil fuels is linked to the atmosphere through the extraction and combustion of fossil fuels.

The nearly constant concentration of CO_2 in the atmosphere has small annual and latitudinal fluctuations (approximately 1%), caused by photosynthesis and respiration.[15] Carbon dioxide released from fossil fuel combustion mixes into the atmospheric carbon pool, where it undergoes exchanges with the ocean and land surface carbon pools. Thus, *where* fossil fuels are burned

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[6] This report updates CRS Report RL34059, *The Carbon Cycle: Implications for Climate Change and Congress*, by Peter Folger (available to congressional clients upon request). This report draws on language, discussion, and information that appeared in the earlier report while adding new language, information, and analysis on the science and the legislative context of the carbon cycle.

[7] SOCCR2, p. 44. See also U.S. Global Change Research Program, *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle, U.S. Science Program Synthesis and Assessment Product 2.2*, 2007, p. 2 (hereinafter SOCCR).

[8] Methane, black carbon, and organic carbon pollution are also part of the carbon cycle and have roles in human-induced climate change. Methane probably accounts for about an additional 16% of the change in the earth's radiation balance.

[9] The earth stores carbon mainly as carbonate minerals. Carbonate minerals are linked to the atmosphere by natural processes, such as erosion and weathering, and by metamorphism over geologic timescales.

[10] Not all coal, natural gas, and oil fossil fuel resources present in the earth's crust are recoverable. The subset portion of those resources that have been verified and could be economically recovered are known as *reserves*.

[11] Rattan Lal, "Managing Soils and Ecosystems for Mitigating Anthropogenic Carbon Emissions and Advancing Global Food Security," *BioScience*, vol. 60 (2010), p. 708 (hereinafter Lal 2010). Also see Mojtaba Fakhraee et al., "A Largely Invariant Marine Dissolved Organic Carbon Reservoir across Earth's History," *Proceedings of the National Academy of Sciences*, vol. 118, no. 40 (2021).

[12] Lal 2010, p. 708. See also William H. Schlesinger, *Biogeochemistry: An Analysis of Global Change*, 2nd ed (San Diego: Academic Press, 1997), p. 360 (hereinafter Schlesinger 1997).

[13] IPCC, "Global Carbon and Other Biogeochemical Cycles and Feedbacks" in 2021 IPCC Working Group I Report, 2021, p. 700.

[14] One metric ton of carbon is equivalent to 3.67 metric tons of CO_2. A metric ton (or tonne) is 2,204.6 pounds. One billion metric tons of carbon is 1 gigatonne, or GtC.

[15] Schlesinger 1997, p. 56. Larger fluctuations by season occur in the Northern Hemisphere.

makes relatively little difference to the average concentration of CO_2 in the global atmosphere; emissions in any one region affect the concentration of CO_2 globally.[16]

The oceans, vegetation, and soils *exchange* carbon with the atmosphere constantly on daily and seasonal time cycles (see **Figure 1, panel (b)**). 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 within the timescale of human history. An understanding of the dynamics of the carbon cycle—and the ways in which human-sourced carbon emissions are apportioned among the atmosphere, oceans, vegetation, and soils—can inform and support deliberations on whether to take action to ameliorate global warming and what type of action that might be.

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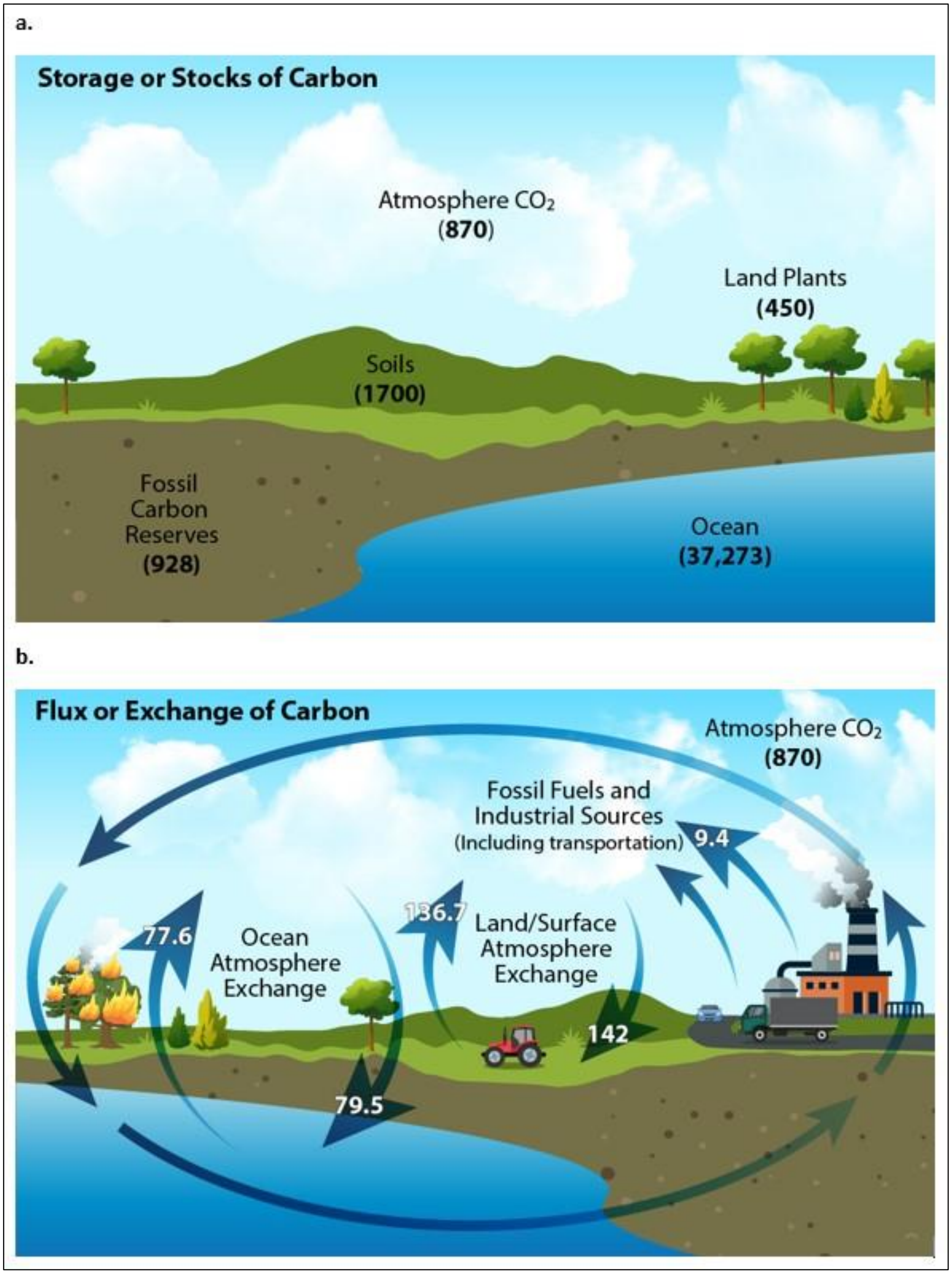
[16] Concentrations of CO_2 are slightly higher in the Northern Hemisphere compared to the Southern Hemisphere, by several parts per million, because most of the emissions of CO_2 from human activities are in the north.

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



Source: IPCC, "Global Carbon and Other Biogeochemical Cycles and Feedbacks" in 2021 IPCC Working Group I Report, 2021, p. 700.

Notes: Figure prepared by CRS. One GtC refers to 1 billion metric tons of carbon.

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

Storage pool	GtC	Annual flux (GtC/yr) *from* the atmosphere	Annual flux (GtC/yr) *to* the atmosphere	Net to the atmosphere (GtC/yr)
Atmosphere	870	—	—	—
Ocean	37,273	79.5	77.6	-1.9
Land surface (soils plus vegetation)	2,150	142	136.7	-5.3
Fossil carbon reserves (coal, gas, oil, other)	928	—	—	+9.4

Source: IPCC, "Global Carbon and Other Biogeochemical Cycles and Feedbacks" in 2021 IPCC Working Group I Report, 2021, p. 700.

Notes: There is some uncertainty associated with each of the estimated values in the table. Determining the values for carbon stocks and fluxes among stocks is an area of active, ongoing scientific research.

The amount of carbon stored in the atmospheric pool is important because as more CO_2 is added to the atmosphere, its heat-trapping capacity becomes greater.[17] Each storage pool—oceans, soils, and vegetation—is considered a *sink* for carbon because each pool takes up carbon from the atmosphere. For example, vegetation in the Northern Hemisphere is a sink for atmospheric carbon during the spring and summer months, due to the process of photosynthesis. In the fall and winter it is a source for atmospheric carbon because the process of respiration returns carbon to the atmosphere from the vegetation pool. In contrast to the oceans, soils, and vegetation, the pool of fossil carbon is only a source, not a sink, except over geologic timescales.

Carbon Flux, or Exchange, with the Atmosphere

Over 77 GtC is exchanged each year between the atmosphere and the oceans, and over 136 GtC is exchanged between the atmosphere and the land surface annually (see **Table 1**).[18] Human activities—primarily land-use change (e.g., deforestation) and burning of fossil fuels—contribute less than 12 GtC to the atmosphere each year.[19] If the human contribution of CO_2 is subtracted from the global carbon cycle, 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, a balanced state of natural net-zero CO_2 emissions. Research indicates that the average decadal net flux was less than 0.1 GtC per year for about 10,000 years leading up to 1750.[20] That small value

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[17] See CRS Report RL33849, *Climate Change: Science and Policy Implications*, by Jane A. Leggett (available to congressional clients upon request), for an explanation of the heat-trapping properties, or *radiative forcing*, of CO_2 and other greenhouse gases.

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

[19] Land-use change (mainly deforestation) accounts for approximately 15% of human-related CO_2 emissions, while fossil fuel combustion accounts for approximately 85% of such emissions. See 2021 IPCC Working Group I Report, p. 700. See also IPCC, *Climate Change 2007: The Physical Science Basis—Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007, pp. 514-515 (hereinafter 2007 IPCC Working Group I Report). Fossil fuel burning and industrial activities release about 9.4 GtC per year; land-use change releases about 1.6 GtC per year (2021 IPCC Working Group I Report, p. 700).

[20] 2007 IPCC Working Group I Report, p. 514.

for net flux is reflected by the relatively stable concentration of CO_2 in the atmosphere—between 260 ppm and 280 ppm—for about the 10,000 years prior to 1750.[21]

How Fast Carbon Is Exchanged

Currently the atmospheric concentration of CO_2 is approximately 130 ppm higher than it was before 1750 (410 ppm versus 280 ppm), primarily 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 so that even though the oceans and the land surface take up more CO_2 per year, on average, than they release, atmospheric concentrations of CO_2 continue to rise (see **Table 1**). During the 1990s 55% of CO_2 emissions from land-use activities and fossil fuel combustion were taken up by the oceans, vegetation, or soils on the land surface, with 45% persisting in the atmosphere,[22] a trend that was also confirmed for the period 2010-2019.[23] CO_2 is nonreactive in the atmosphere and has a relatively long residence time, although eventually most of it will return to the ocean and land sinks.[24] When a pulse[25] of CO_2 is added to the atmosphere, in 30 years about half will be withdrawn; thereafter, removal proceeds more slowly, with centuries required to remove an additional 30% and millennia before the final 20% is removed.[26] If CO_2 emissions continue or increase, however, adding to the cumulative CO_2 emissions since the start of the Industrial Revolution, atmospheric concentrations of CO_2 will also continue to rise. This will increase *radiative forcing*, the degree to which the atmosphere traps incoming radiation from the sun. There is a scientific consensus that there is an almost linear relationship between global temperature increases and such cumulative human-caused emissions of CO_2,[27] and a likely result is a continued warming of the planet.

At present the oceans and land surface are acting as sinks for CO_2 emitted from fossil fuel combustion, deforestation, and other human sources, but as they accumulate more carbon the capacity of the sinks—and the rate at which they accumulate carbon—may change. It is also likely that climate change itself (e.g., higher temperatures, a more intense hydrologic cycle[28]) may alter the balance between sources and sinks due to changes in the complicated feedback mechanisms among the atmosphere, oceans, and land surface.[29] How carbon sinks will behave in the future is a prominent question for both scientists and policymakers.

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[21] IPCC, *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, 2001, p. 203.

[22] 2007 IPCC Working Group I Report, pp. 514-515.

[23] IPCC, "Global Carbon and Other Biogeochemical Cycles and Feedbacks" in 2021 IPCC Working Group I Report, 2021, p. 676.

[24] That is, it does not react with other chemicals in the atmosphere. This contrasts with other greenhouse gases, such as methane (CH_4), which reacts with the hydroxyl ion (OH^-) to produce water and a methyl group (CH_3); and nitrous oxide (N_2O), which is decomposed to nitric oxide (NO) in the atmosphere by its reaction with ultraviolet light.

[25] In this context, a pulse of CO_2 is an addition of this gas to the atmosphere, where the definition of *pulse* is "a variation, characterized by a rise, limited duration, and decline of a quantity whose value normally is constant" in *Webster's New World Dictionary of the English Language, Second College Edition* (New York: Simon and Schuster, 1980).

[26] 2007 IPCC Working Group I Report, p. 514.

[27] IPCC, "Summary for Policy Makers," in 2021 IPCC Working Group I Report, 2021, p. 28.

[28] The *hydrologic cycle* is defined as "the sequence of conditions through which water passes from vapor in the atmosphere through precipitation upon land or water surfaces and ultimately back into the atmosphere as a result of evaporation and transpiration." See "hydrologic cycle" in Merriam-Webster.com Dictionary, Merriam-Webster, https://www.merriam-webster.com/dictionary/hydrologic%20cycle.

[29] See CRS Report RL34266, *Climate Change: Science Highlights*, by Jane Leggett (available to congressional clients

Land Surface-Atmosphere Flux

The IPCC estimates of the carbon cycle indicate that the land surface (vegetation plus soils) accumulates approximately 5.3 GtC more carbon per year than it emits to the atmosphere[30] (see **Figure 1, panel (b);** and **Table 1**). Recent research indicates that during the past 60 years, the land surface sink for CO_2 has increased,[31] as the growth rate of atmospheric CO_2 has increased, among other factors.[32] That means that the land surface acts as a net sink for CO_2 at present. Some policymakers advocate strategies for increasing the amount of CO_2 taken up and stored, or *sequestered*, by soils and plants, typically through land-use change, such as agricultural or forestry practices.[33] How effective these land-use practices will be for large-scale and long-term carbon sequestration is not clear.

There are large uncertainties associated with the land-use component of the global carbon cycle, although these uncertainties have been reduced.[34] There is uncertainty regarding which environmental factors are foremost in influencing the behavior of the land surface sink.[35] Studies combining satellite land cover change with biomass data suggest that tropical deforestation has been responsible for the largest share of CO_2 released to the atmosphere from land-use changes.[36] Tropical deforestation and other land-use changes released approximately 3.6 GtC per year to the atmosphere in the 1990s and approximately 3.8 GtC per year for the period 2011-2020.[37] Even though deforestation emits more carbon than is taken up by forest growth within some regions,[38] net forest regrowth takes up sufficient carbon such that the land surface acts as a global net sink.

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upon request), for more information on climate feedbacks.

[30] IPCC, "Global Carbon and Other Biogeochemical Cycles and Feedbacks" in 2021 IPCC Working Group I Report, 2021, p. 700.

[31] IPCC, "Global Carbon and Other Biogeochemical Cycles and Feedbacks" in 2021 IPCC Working Group I Report, 2021, p. 694.

[32] Pierre Friedlingstein et al., "Global Carbon Budget 2021," *Earth System Science Data*, vol. 14, no. 4 (2022), p. 1917 (hereinafter Friedlingstein 2022).

[33] For more information on sequestration in the agricultural and forestry sectors, see CRS Report R46312, *Forest Carbon Primer*, by Katie Hoover and Anne A. Riddle; CRS Report R46313, *U.S. Forest Carbon Data: In Brief*, by Katie Hoover and Anne A. Riddle; CRS In Focus IF11693, *Agricultural Soils and Climate Change Mitigation*, by Genevieve K. Croft; and CRS In Focus IF11404, *Greenhouse Gas Emissions and Sinks in U.S. Agriculture*, by Genevieve K. Croft.

[34] IPCC, "Carbon and Other Biogeochemical Cycles" in *Climate Change 2013: The Physical Science Basis—Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2013, p. 490.

[35] D.N. Huntzinger et al., "Uncertainty in the Response of Terrestrial Carbon Sink to Environmental Drivers Undermines Carbon-Climate Feedback Predictions," *Scientific Reports*, vol. 7, no. 1 (2017), p. 4765. See also Simone Fatichi et al., "Modelling Carbon Sources and Sinks in Terrestrial Vegetation," *New Phytologist*, vol. 221, no. 2 (2019), p. 652.

[36] Veronique De Sy et al., "Tropical Deforestation Drivers and Associated Carbon Emission Factors Derived from Remote Sensing Data," *Environmental Research Letters*, vol. 14, no. 9 (2019). See also IPCC, *Climate Change 2013: The Physical Science Basis—Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2013, p. 50.

[37] Friedlingstein 2022.

[38] William H. Schlesinger and Emily S. Bernhardt, *Biogeochemistry: An Analysis of Global Change*, 4th ed. (Academic Press, an imprint of Elsevier, 2020), p. 458.

Ocean-Atmosphere Flux

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. Like the land surface, the oceans today accumulate more carbon than they emit to the atmosphere each year, acting as a net sink of about 1.9 GtC per year.[39] (See **Figure 1, panel (b);** and **Table 1**.) The oceans have a much larger capacity to store carbon than the land surface. Ultimately, over the course of millennia, the oceans could take up all but about 7% of carbon emitted to the atmosphere from fossil fuel combustion and land-use change.[40] Policymakers are likely more concerned about CO_2 accumulating in the oceans now and its behavior as a net sink over the next few decades. Also, the additional CO_2 is increasing the acidity of the ocean's surface water, which may affect marine life.[41]

Uptake of CO_2 by the ocean occurs in stages. First, CO_2 dissolves in ocean water at the surface.[42] Higher CO_2 concentrations increase the rate of this reaction. Once dissolved, the CO_2 may be taken up biologically through phytoplanktonic photosynthesis, or chemically through the formation of calcium carbonate.

The quantity of uptake of CO_2 by the ocean is determined by a number of factors, some of which are affected by increases or decreases in the concentration of atmospheric CO_2, and by global temperature. CO_2, which diffuses into the ocean, reacts with water to form carbonic acid, which then reacts with calcium to form calcium carbonate.[43] This allows the ocean to absorb more CO_2 than is simply dissolved in the water. This chemical ability of the ocean to absorb CO_2 is known as the *buffering capacity*.

These uptake processes take place in the surface layers of the ocean, a small component of the ocean's total volume.[44] This surface water is moved into the ocean's depths by a slow process of mixing whereby it may be a millennium before the water returns to the surface.[45] The vertical mixing of the ocean, by the ocean waters' extensive movement around the globe, is a critical component of the ocean sink.[46]

This extensive mixing of the ocean, due to overturning circulation by the large ocean "conveyor belt" currents such as the Atlantic Meridional Overturning Current (AMOC), brings absorbed atmospheric carbon into the deep ocean, where it is sequestered from the atmosphere for long periods of time.[47] The scale and speed of this circulation contribute to the effectiveness of the

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[39] IPCC, "Global Carbon and Other Biogeochemical Cycles and Feedbacks" in 2021 IPCC Working Group I Report, 2021, p. 700.

[40] CO_2 forms carbonic acid when dissolved in water. Over time, the solid calcium carbonate ($CaCO_3$) on the seafloor will react with, or neutralize, much of the carbonic acid that entered the oceans as CO_2 from the atmosphere. See D. Archer et al., "Dynamics of Fossil Fuel CO_2 Neutralization by Marine $CaCO_3$," *Global Biogeochemical Cycles*, vol. 12, no. 2 (1998), p. 259.

[41] CRS Report R40143, *Ocean Acidification*, by Harold F. Upton and Peter Folger.

[42] SOCCR, p. 26. Turbulence, wave action, and wind also influence the rate at which CO_2 dissolves in seawater. SOCCR, p. 26.

[43] American Chemical Society, "Ocean Chemistry," https://www.acs.org/content/acs/en/climatescience/oceansicerocks/oceanchemistry.html.

[44] SOCCR, p. 26.

[45] Jorge L. Sarmiento and Nicolas Gruber, "Sinks for Anthropogenic Carbon," *Physics Today*, vol. 55, no. 8 (2002), p. 30 (hereinafter Sarmiento and Gruber 2002).

[46] SOCCR, p. 26.

[47] Sarminento and Gruber, 2002.

ocean sink. The North Atlantic and near Antarctica are sites of the downward movement of frigid, dense, carbon-rich surface water into the deep ocean.[48]

Recent research has shown that increases in atmospheric CO_2 due to human activity have started to affect the buffering capacity of the ocean, although there is no scientific consensus that this has changed the uptake of CO_2 by the ocean.

Some researchers have raised concerns that continued increases in atmospheric CO_2 and global temperatures could decrease the ocean's capacity to absorb CO_2 in the later part of this century. For example, increasing concentrations of atmospheric CO_2 reduce the buffering capacity of the ocean, which could lead to a decrease in CO_2 absorption by the ocean. In addition, CO_2 is less soluble in water at higher temperatures, and increased temperatures could also contribute to decreased ocean CO_2 uptake. If overturning circulation or mixing of ocean water were to decrease during this time,[49] a smaller quantity of carbon initially absorbed by surface water would be transported to the deep ocean. Ocean uptake of CO_2 could decrease for these reasons; however, models indicate that these changes are more likely to occur under future scenarios of higher CO_2 emissions.

The Carbon Budget Imbalance

The global carbon budget is the accounting of the carbon added to the global carbon cycle by human activity, often measured since the start of the Industrial Revolution (defined as the year 1750 CE). The global carbon budget includes CO_2 emissions from fossil fuel use (E_{FOS}); CO_2 emissions from land use change (E_{LUC}); the increased CO_2 concentration in the atmosphere (G_{ATM}); the removal of CO_2 from the atmosphere by the ocean sink (S_{OCEAN}); and removal of CO_2 from the atmosphere by the land-use sink (S_{LAND}). In the global carbon cycle, these quantities balance and sum to zero. However, our knowledge of the pools and fluxes of carbon in the global carbon cycle is imperfect, and when the estimates of these quantities do not sum to zero, there is a carbon budget imbalance (B_{IM}) with the following equation:[50]

$$B_{\mathrm{IM}} = E_{\mathrm{FOS}} + E_{\mathrm{LUC}} - (G_{\mathrm{ATM}} + S_{\mathrm{OCEAN}} + S_{\mathrm{LAND}})$$

In the past, this imbalance was referred to as the "missing carbon" and was thought to be largely due to the difficulty of measuring the uptake of carbon by terrestrial ecosystems—for example, in the Northern Hemisphere.[51] However, the average imbalance from recent calculations is now about 3% of emissions. This small percentage of imbalance (individual years sometimes differ) in the global carbon cycle suggests the partitioning of emissions among the components of the carbon cycle almost completely accounts for carbon in the global carbon budget.[52] These low values for the carbon budget imbalance support increased confidence in the scientific understanding of the global carbon cycle. As a recent scientific journal article on the global carbon budget noted, "Therefore, the near-zero mean and trend in the budget imbalance is seen as

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[48] Sarmiento and Gruber 2002; see also SOCCR, p. 26.

[49] See CRS Report R47021, *Federal Involvement in Ocean-Based Research and Development*, by Caitlin Keating-Bitonti, pp. 23, 28. As the planet warms, there is an increase in glacial melt and an increase in the addition of fresh water to the North Atlantic. This addition decreases the salinity and the density of the water, making it less heavy with less of a tendency to sink. The sinking of water in the North Atlantic is the driver of the AMOC, and a decrease in density slows the rate of the AMOC, reducing its capacity to carry absorbed atmospheric carbon to the deep ocean.

[50] Friedlingstein 2022.

[51] Britton B. Stephens et al., "Weak Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of Atmospheric CO2," *Science*, vol. 316 (2007), p. 1732.

[52] Friedlingstein 2022.

evidence of a coherent community understanding of the emissions and their partitioning on those timescales."[53]

It is not currently possible to attribute, with certainty, the source of the discrepancy producing these imbalances. Uncertainties in the measurements of the ocean and land surface sinks have been suggested, but a scientific consensus on the source of the imbalance has not been reached.

Policy Implications

The behavior of the global carbon cycle can be affected by the policy decisions and legislative actions of Congress. Assessing policy options in the context of the broader carbon cycle summarized above may be useful to project the potential effects of, and interactions among, various options. The vast array of policy choices that can affect GHG emissions and uptake may be direct and intentional, or indirect and collateral in their impact on other policy objectives.

There is a scientific consensus that in order to reduce the risk of increasing impacts of climate change, it is necessary to stabilize global temperatures, and that reaching a state of net-zero CO_2 emissions is necessary to achieve this stabilization.[54] *Net zero* means that emissions of CO_2 are balanced by removals of CO_2 and there is no net addition of CO_2 to the atmosphere, a situation that existed before the start of the Industrial Revolution. There have been legislative proposals introduced during the 117th Congress aimed at achieving net-zero CO_2 emissions domestically.[55] Additionally, having the United States achieve net-zero CO_2 emissions by 2050 is a stated climate policy goal of the Biden Administration.[56]

Any of the policy options to achieve net-zero CO_2 will require changes to the carbon cycle. These changes may include the following:

- Reducing emissions of CO_2 from fossil fuels and land-use change.
    - Techniques for reducing CO_2 emissions from fossil fuel use and land-use change are well understood and span a range of approaches, including energy efficiency and use of renewable energy sources to reduce emissions from fossil fuels, and maintaining indigenous forests and reducing deforestation to mitigate emissions from land-use change.
- Increasing the uptake of CO_2 by the land surface through management.
    - Techniques for doing so are well understood and include increasing forested land and changing cultivation practices to increase soil carbon.
- Increasing the uptake of CO_2 by the oceans.[57]
    - Techniques for doing so are not developed, are the subject of ongoing research, and have given rise to concerns about their feasibility and potential environmental impacts.
- Increasing the capacity for removal and long-term storage of CO_2 from the atmosphere.

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[53] Friedlingstein 2022.

[54] IPCC AR6 WGI SPM 2021, p. 28.

[55] H.R. 1512, H.R. 5179.

[56] Executive Order 14008, "Tackling the Climate Crisis at Home and Abroad," 86 *Federal Register* 7619 ("Sec. 201. Policy ... put the United States on a path to achieve net-zero emissions, economy-wide, by no later than 2050").

[57] CRS Report R47172, *Geoengineering: Ocean Iron Fertilization*, by Caitlin Keating-Bitonti.

- Techniques to develop additional carbon dioxide removal (CDR) capacity through technologies such as direct air capture (DAC)—essentially the development of an additional human-created carbon sink that removes CO_2 from the atmosphere for long-term sequestration—are under development and have not been demonstrated at scale.

The success of policies in achieving net zero is dependent, in part, on the behavior of the carbon cycle, specifically on the behavior of the land and ocean sinks. If the sink capacity of the ocean or the land carbon pools were to decrease, then achieving net zero would potentially require greater levels of emissions reductions, greater levels of CDR capacity, or a combination of the two. Such levels might not be necessary if the sink capacity of the ocean and the land continue to increase. The ongoing scientific effort to understand and anticipate the behavior of the global carbon cycle, now and in the future, can help to inform congressional deliberations on these and other climate policies.

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