15. Biogeochemical Cycles

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Key messages

1. **Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.**
2. **In total, land in the U.S. absorbs CO_2 equivalent to approximately 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink, absorbing 7% to 24% of annual U.S. fossil fuel emissions, with a best estimate of 16%. The effect of this carbon "storage" partially offsets warming from emissions of CO_2 and other greenhouse gases.**
3. **Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.**

Introduction

Biogeochemical cycles involve the fluxes of chemical elements among different parts of the Earth: from living to non-living, from atmosphere to land to sea, and from soils to plants. They are called "cycles" because matter is always conserved and because elements move to and from major pools via a variety of two-way fluxes, although some elements are stored in locations or in forms that are differentially accessible to living things. Human activities have mobilized Earth elements and accelerated their cycles – for example, more than doubling the amount of reactive nitrogen that has been added to the biosphere since pre-industrial times.[1,2] Reactive nitrogen is any nitrogen compound that is biologically, chemically, or radiatively active, like nitrous oxide and ammonia, but not nitrogen gas (N_2). Global-scale alterations of biogeochemical cycles are occurring, from human activities both in the U.S. and elsewhere, with impacts and implications now and into the future. Global carbon dioxide emissions are the most significant driver of human-caused climate change. But human-accelerated cycles of other elements, especially nitrogen, phosphorus, and sulfur, also influence climate. These elements can affect climate directly or act as indirect factors that alter the carbon cycle, amplifying or reducing the impacts of climate change.

Climate change is having, and will continue to have, impacts on biogeochemical cycles, which will alter future impacts on climate and affect our capacity to cope with coupled changes in climate, biogeochemistry, and other factors.

Human-induced Changes

Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.

The human mobilization of carbon, nitrogen, and phosphorus from the Earth's crust and atmosphere into the environment has increased 36, 9, and 13 times, respectively, over pre-industrial times.[3,4] Fossil-fuel burning, land-cover change, cement production, and the extraction and production of fertilizer to support agriculture are major causes of these increases.[5] Carbon dioxide (CO_2) is the most abundant of the heat-trapping greenhouse gases that are increasing due to human activities, and its production dominates atmospheric forcing of global climate change.[6] However, methane (CH_4) and nitrous oxide (N_2O) have higher greenhouse-warming potential per molecule than CO_2, and both are also increasing in the atmosphere. In the U.S. and Europe, sulfur emissions have declined over the past three decades, especially since the mid-1990s, because of efforts to reduce air pollution.[7] Changes in biogeochemical cycles of carbon, nitrogen, phosphorus, and other elements – and the coupling of those cycles – can influence climate. In turn, this can change atmospheric composition in other ways that affect how the planet absorbs and reflects sunlight (for example, by creating small particles known as aerosols that can reflect sunlight).

State of the Carbon Cycle

The U.S. was the world's largest producer of human-caused CO_2 emissions from 1950 until 2007, when it was surpassed by China. U.S. emissions account for approximately 85% of North American emissions of CO_2[8] and 18% of global emissions.[9,10] Ecosystems represent potential "sinks" for CO_2, which are places where carbon can be stored over the short or long term (see "U.S. Carbon Sink" box). At the continental scale, there has been a large and relatively consistent increase in forest carbon stocks over the last two decades,[11] due to recovery from past forest harvest, net increases in forest area, improved forest management regimes, and faster growth driven by climate or fertilization by CO_2 and nitrogen.[8,12] The largest rates of disturbance and "regrowth sinks" are in southeastern, south central, and Pacific northwestern regions.[12] However, emissions of CO_2 from human activities in the U.S. continue to increase and exceed ecosystem CO_2 uptake by more than three times. As a result, North America remains a net source of CO_2 into the atmosphere[8] by a substantial margin.

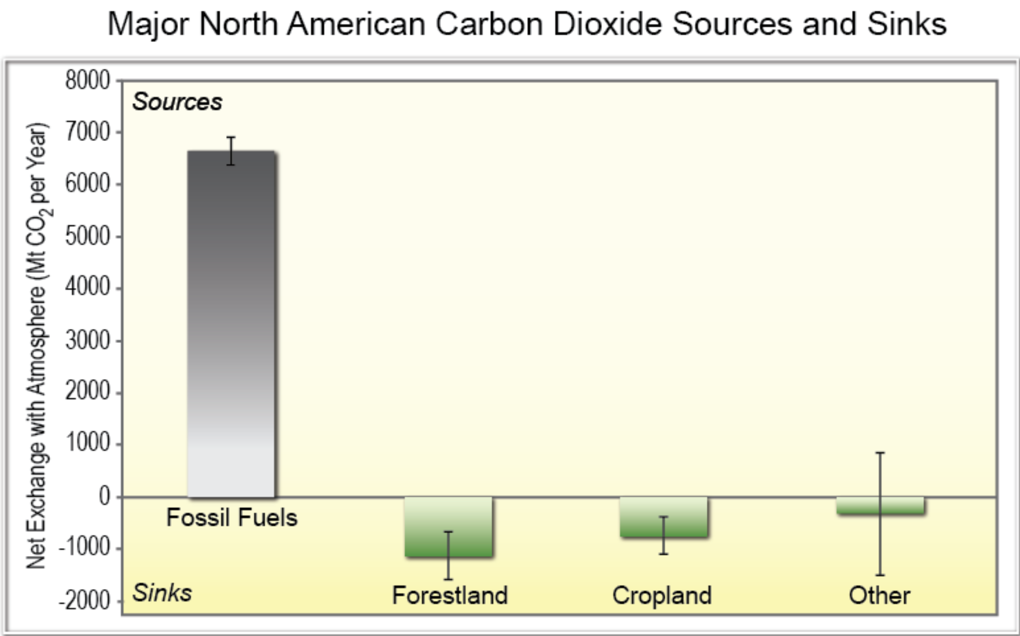

Figure 15.1: Major North American Carbon Dioxide Sources and Sinks

Caption: The release of carbon dioxide from fossil fuel burning in North America (shown here for 2010) vastly exceeds the amount that is taken up and temporarily stored in forests, crops, and other ecosystems (shown here is the annual average for 2000-2006). (Figure source: King et al. 2012[8]).

Sources and fates of reactive nitrogen

The nitrogen cycle has been dramatically altered by human activity, especially by the use of nitrogen fertilizers, which have increased agricultural production over the past half century.[1,2] Although fertilizer nitrogen inputs have begun to level off in the U.S. since 1980,[13] human-caused reactive nitrogen inputs are now at least five times greater than those from natural sources.[14,15,16,17] At least some of the added nitrogen is converted to nitrous oxide (N_2O), which adds to the greenhouse effect in Earth's atmosphere.

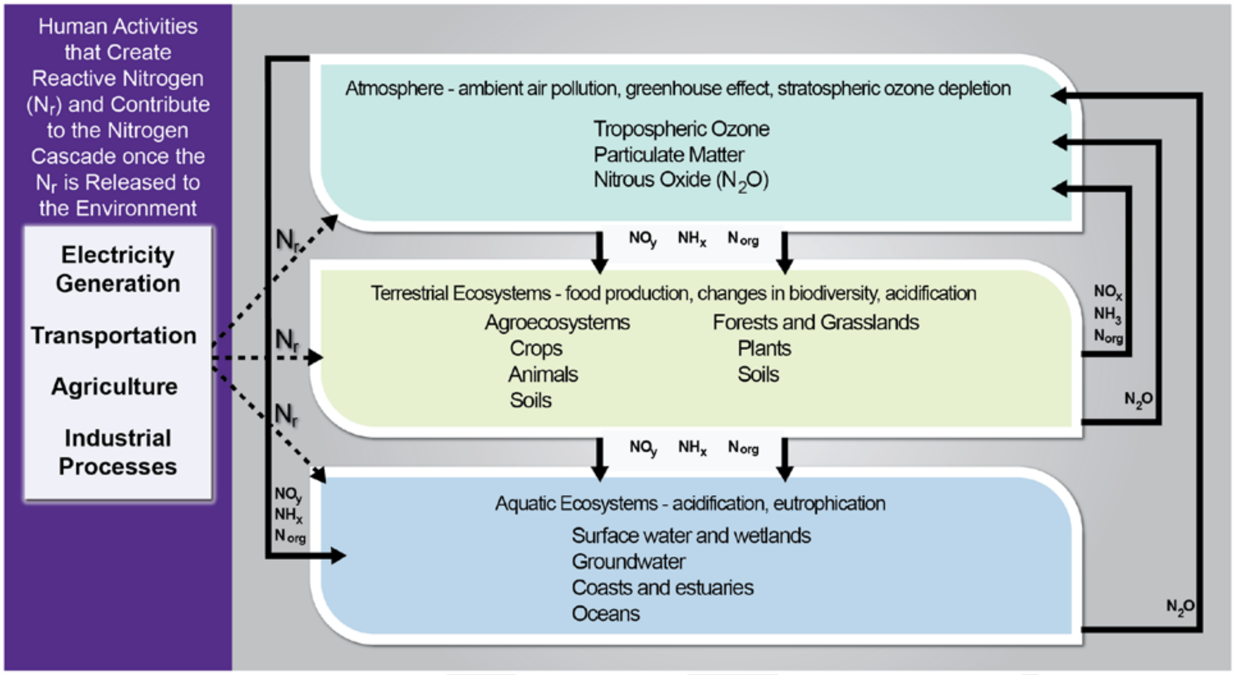

Figure 15.2: Human Activities that Form Reactive Nitrogen and Resulting Consequences in Environmental Reservoirs

Caption: Once created, a molecule of reactive nitrogen has a cascading impact on people and ecosystems as it contributes to a number of environmental issues. Molecular terms represent oxidized forms of nitrogen primarily from fossil fuel combustion (such as nitrogen oxides, NO_x), reduced forms of nitrogen primarily from agriculture (such as ammonia, NH_3), and organic forms of nitrogen (N_{org}) from various processes. NO_y is all nitrogen-containing atmospheric gases that have both nitrogen and oxygen, other than nitrous oxide (N_2O). NH_x is the sum of ammonia (NH_3) and ammonium (NH_4). (Figure source: adapted from EPA 2011;[14] Galloway et al. 2003;[18] with input from USDA. USDA contributors were Adam Chambers and Margaret Walsh).

An important characteristic of reactive nitrogen is its legacy. Once created, it can, in sequence, travel throughout the environment (for example, from land to rivers to coasts, sometimes via the atmosphere), contributing to environmental problems such as the formation of coastal low-oxygen “dead zones” in marine ecosystems in summer. These problems persist until the reactive nitrogen is either captured and stored in a long-term pool, like the mineral layers of soil or deep ocean sediments, or converted back to nitrogen gas.[18,19] The nitrogen cycle affects atmospheric concentrations of the three most important human-caused greenhouse gases: carbon dioxide, methane, and nitrous oxide. Increased available nitrogen stimulates the uptake of carbon dioxide by plants, the release of methane from wetland soils, and the production of nitrous oxide by soil microbes.

Phosphorus and other elements

The phosphorus cycle has been greatly transformed in the U.S.,[20] primarily from the use of phosphorus fertilizers in agriculture. Phosphorus has no direct effects on climate, but does have an indirect effect: increasing carbon sinks by fertilizing plants. Emissions of sulfur, as sulfur dioxide, can reduce the growth of plants and stimulate the leaching of soil nutrients needed by plants.[21]

Carbon Sinks

In total, land in the U.S. absorbs CO_2 equivalent to approximately 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink, absorbing 7% to 24% of annual U.S. fossil fuel emissions, with a best estimate of 16%. The effect of this carbon "storage" partially offsets warming from emissions of CO_2 and other greenhouse gases.

Considering the entire atmospheric CO_2 budget, the temporary net storage on land is small compared to the sources: more CO_2 is emitted than can be taken up (see "U.S. Carbon Sink" box).[8,22,23,24] Other elements and compounds affect that balance by direct and indirect means (for example, nitrogen stimulates carbon uptake [direct] and nitrogen decreases the soil methane sink [indirect]). The net effect on Earth's energy balance from changes in major biogeochemical cycles (carbon, nitrogen, sulfur, and phosphorus) depends upon processes that directly affect how the planet absorbs or reflects sunlight, as well as those that indirectly affect concentrations of greenhouse gases in the atmosphere.

Carbon

In addition to the CO_2 effects described above, other carbon-containing compounds affect climate change, such as methane and volatile organic compounds (VOCs). As the most abundant non-CO_2 greenhouse gas, methane is 20 to 30 times more potent than CO_2 over a century timescale. It accounted for 9% of all human-caused greenhouse gas emissions in the United States in 2011,[9] and its atmospheric concentration today is more than twice that of pre-industrial times.[25,26] Methane has an atmospheric lifetime of about 10 years before it is oxidized to CO_2, but it has about 25 times the global warming potential of CO_2. An increase in methane concentration in the industrial era has contributed to warming in many ways.[27]

Methane also has direct and indirect effects on climate because of its influences on atmospheric chemistry. Increases in atmospheric methane and VOCs are expected to deplete concentrations of hydroxyl radicals, causing methane to persist in the atmosphere and exert its warming effect for longer periods.[26,28] The hydroxyl radical is the most important "cleaning agent" of the troposphere (the active weather layer extending up to about 5 to 10 miles above the ground), where it is formed by a complex series of reactions involving ozone and ultraviolet light.[4]

Nitrogen and Phosphorus

The climate effects of an altered nitrogen cycle are substantial and complex.[5,29,30,31,32] Carbon dioxide, methane, and nitrous oxide contribute most of the human-caused increase in climate forcing, and the nitrogen cycle affects atmospheric concentrations of all three gases. Nitrogen cycling processes regulate ozone (O_3) concentrations in the troposphere and stratosphere, and produce atmospheric aerosols, all of which have additional direct effects on climate. Excess reactive nitrogen also has multiple indirect effects that simultaneously amplify and mitigate changes in climate. Changes in ozone and organic aerosols are short-lived, whereas changes in carbon dioxide and nitrous oxide have persistent impacts on the atmosphere.

The strongest direct effect of an altered nitrogen cycle is through emissions of nitrous oxide (N_2O), a long-lived and potent greenhouse gas that is increasing steadily in the atmosphere.[26,27] Globally, agriculture has accounted for most of the atmospheric rise in N_2O.[33,34] Roughly 60% of agricultural N_2O derives from elevated soil emissions resulting from the use of nitrogen fertilizer. Animal waste treatment accounts for about 30%, and the remaining 10% comes from crop-residue burning.[35] The U.S. reflects this global trend: around 75% to 80% of U.S. human-caused N_2O emissions are due to agricultural activities, with the majority being emissions from fertilized soil. The remaining 20% is derived from a variety of industrial and energy sectors.[36,37] While N_2O currently accounts for about 6% of human-caused warming,[27] its long lifetime in the atmosphere and rising concentrations will increase N_2O-based climate forcing over a 100-year time scale.[34,38,39]

Excess reactive nitrogen indirectly exacerbates changes in climate by several mechanisms. Emissions of nitrogen oxides (NO_x) increase the production of tropospheric ozone, which is a greenhouse gas.[40] Elevated tropospheric ozone may reduce CO_2 uptake by plants and thereby reduce the terrestrial CO_2 sink.[41] Nitrogen deposition to ecosystems can also stimulate the release of nitrous oxide and methane and decrease methane uptake by soil microbes.[42]

However, excess reactive nitrogen also mitigates changes in greenhouse gas concentrations and climate through several intersecting pathways. Over short time scales, NO_x and ammonia emissions lead to the formation of atmospheric aerosols, which cool the climate by scattering or absorbing incoming radiation and by affecting cloud cover.[27,43] In addition, the presence of NO_x in the lower atmosphere increases the formation of sulfate and organic aerosols.[44] At longer time scales, NO_x can increase rates of methane oxidation, thereby reducing the lifetime of this important greenhouse gas.

One of the dominant effects of reactive nitrogen on climate stems from how it interacts with ecosystem carbon capture and storage, and thus, the carbon sink. As mentioned previously, addition of reactive nitrogen to natural ecosystems can increase carbon storage as long as other factors are not limiting plant growth, such as water and nutrient availability.[45] Nitrogen deposition from human sources is estimated to contribute to a global net carbon sink in land ecosystems of 917 to 1,830 million metric tons (1,010 to 2,020 million tons) of CO_2 per year. These are model-based estimates, as comprehensive, observationally-based estimates at large spatial scales are hindered by the limited number of field experiments. This net land sink represents two components: 1) an increase in vegetation growth as nitrogen limitation is alleviated by human-caused nitrogen deposition, and 2) a contribution from the influence of increased reactive nitrogen availability on decomposition. While the former generally increases with increased reactive nitrogen, the net effect on decomposition in soils is not clear. The net effect on total ecosystem carbon storage was an average of 37 metric tons (41 tons) of carbon stored per metric ton of nitrogen added in forests in the U.S. and Europe.[46]

When all direct and indirect links between reactive nitrogen and climate in the U.S. are added up, a recent estimate suggests a modest reduction in the rate of warming in the near term (next several decades), but a progressive switch to greater net warming over a 100-year timescale.[29,30] That switch is due to a reduction in nitrogen oxide (NO_x) emissions, which provide modest cooling effects, a reduction in the nitrogen-stimulated CO_2 storage in forests, and a rising importance of agricultural nitrous oxide emissions. Current policies tend to reinforce this switch. For example, policies that reduce nitrogen oxide and sulfur oxide emissions have large public health benefits, but also reduce the indirect climate mitigation co-benefits by reducing carbon storage and aerosol formation.

Changes in the phosphorus cycle have no direct effects on climate, but phosphorus availability constrains plant and microbial activity in a wide variety of land- and water-based ecosystems.[47,48] Changes in phosphorus availability due to human activity can therefore have indirect impacts on climate and the emissions of greenhouse gases in a variety of ways. For example, in land-based ecosystems, phosphorus availability can limit both CO_2 storage and decomposition[47,49] as well as the rate of nitrogen accumulation.[50] In turn, higher nitrogen inputs can alter phosphorus cycling via changes in the production and activity of enzymes that release phosphorus from decaying organic matter,[51] creating another mechanism by which rising nitrogen inputs can stimulate carbon uptake.

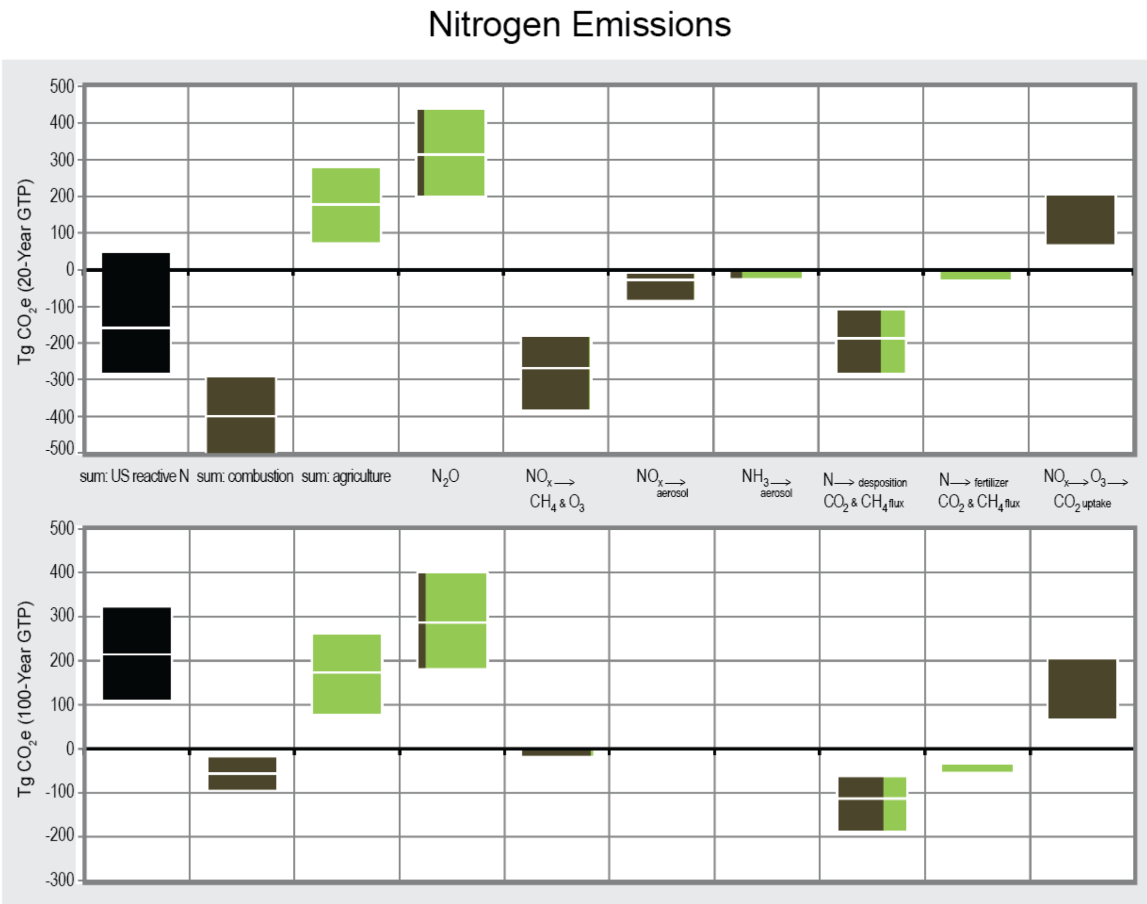

Figure 15.3: Nitrogen Emissions

Caption: Figure shows how climate change will affect U.S. reactive nitrogen emissions, in Teragrams (Tg) CO_2 equivalent, on a 20-year (top) and 100-year (bottom) global temperature potential basis. Positive values on the vertical axis depict warming; negative values reflect cooling. The height of the bar denotes the range of uncertainty, and the white line denotes the best estimate. The relative contribution of combustion (dark brown) and agriculture (green) is denoted by the color shading. (Figure source: adapted from Pinder et al. 2012[29]).

Other Effects: Sulfate Aerosols

In addition to the aerosol effects from nitrogen mentioned above, there are both direct and indirect effects on climate from other aerosol sources. Components of the sulfur cycle exert a cooling effect, through the formation of sulfate aerosols created from the oxidation of sulfur dioxide (SO_2) emissions.[27] In the U.S., the dominant source of sulfur dioxide is coal combustion. Sulfur dioxide emissions rose until 1980, but have since decreased by more than 50% following a series of air-quality regulations and incentives focused on improving human health and the environment, as well as reductions in the delivered price of low-sulfur coal.[52] That decrease in emissions has had a marked effect on U.S. climate forcing: between 1970 and 1990, sulfate aerosols caused cooling, primarily over the eastern U.S., but since 1990, further reductions in sulfur dioxide emissions have reduced the cooling effect of sulfate aerosols by half or more.[43] Continued declines in sulfate aerosol cooling are projected for the future,[43] particularly if coal continues to be replaced by natural gas (which contains far fewer sulfur impurities) for electricity generation. Here, as with nitrogen oxide emissions, the environmental and socioeconomic trade-offs are important to recognize: lower sulfur dioxide and nitrogen oxide emissions remove some climate cooling agents, but improve ecosystem health and save lives.[17,32,53]

Three low-concentration industrial gases are particularly potent for trapping heat: nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6), and trifluoromethyl sulfur pentafluoride (SF_5CF_3). None currently makes a major contribution to climate forcing, but since their emissions are increasing and their effects last for millennia, continued monitoring is important.

Impacts and Options

Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.

Climate change alters key aspects of biogeochemical cycling, creating the potential for feedbacks that alter both warming and cooling processes into the future. For example, as soils warm, the rate of decomposition will increase, adding more CO_2 to the atmosphere. In addition, both climate and biogeochemistry interact strongly with environmental and ecological concerns, such as biodiversity loss, freshwater and marine eutrophication (unintended fertilization of aquatic ecosystems that leads to water quality problems), air pollution, human health, food security, and water resources. Many of the latter connections are addressed in other sections of this assessment, but we summarize some of them here because consideration of mitigation and adaptation options for changes in climate and biogeochemistry often requires this broader context.

BOX 1. Many Factors Combine to Affect Biogeochemical Cycles

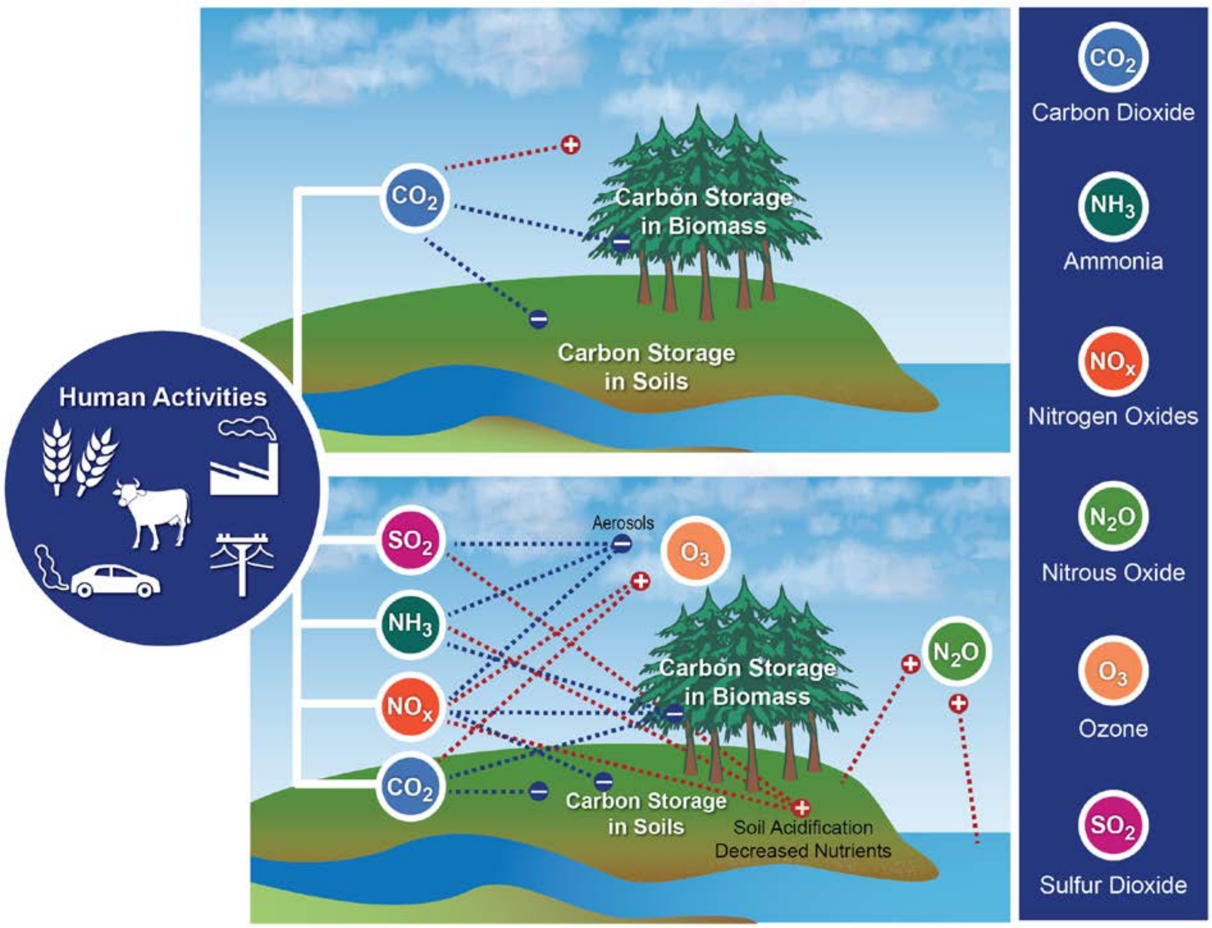

Figure 15.4

Caption: Top panel shows the impact of the alteration of the carbon cycle alone on radiative forcing. The bottom panel shows the impacts of the alteration of carbon, nitrogen, and sulfur cycles on radiative forcing. SO_2 and NH_3 increase aerosols and decrease radiative forcing. NH_3 is likely to increase plant biomass, and consequently decrease forcing. NO_x is likely to increase the formation of tropospheric ozone (O_3) and increase radiative forcing. Ozone has a negative effect on plant growth/biomass, which might increase radiative forcing. CO_2 and NH_3 act synergistically to increase plant growth, and therefore decrease radiative forcing. SO_2 is likely to reduce plant growth, perhaps through the leaching of soil nutrients, and consequently increase radiative forcing. NO_x is likely to reduce plant growth directly and through the leaching of soil nutrients, therefore increasing radiative forcing. However, it could act as a fertilizer that would have the opposite effect.

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Climate-Biogeochemistry Feedbacks

Both rising temperatures and changes in water availability can alter climate-relevant biogeochemical processes. For example, as summarized above, nitrogen deposition drives temperate forest carbon storage both by increasing plant growth and by slowing organic-matter decomposition.[54] Higher temperatures will counteract soil carbon storage by increasing decomposition rates and subsequent emission of CO_2 via microbial respiration. However, that same increase in decomposition accelerates the release of reactive nitrogen (and phosphorus) from organic matter, which in turn can fuel additional plant growth.[45] Temperature also has direct effects on net primary productivity (the total amount of CO_2 stored by a plant through photosynthesis minus the amount released through respiration). The combined effects on ecosystem carbon storage will depend on the extent to which nutrients constrain both net primary productivity and decomposition, on the extent of warming, and on whether any simultaneous changes in water availability occur.[55]

Similarly, natural methane sources are sensitive to variations in climate; ice core records show a strong correlation between methane concentrations and warmer, wetter conditions.[56] Thawing permafrost in polar regions is of particular concern because it stores large amounts of methane that could potentially be released to the atmosphere.

Biogeochemistry, Climate, and Interactions with Other Factors

Societal options for addressing links between climate and biogeochemical cycles must often be informed by connections to a broader context of global environmental changes. For example, both climate change and nitrogen deposition can reduce biodiversity in water- and land-based ecosystems. The greatest combined risks are expected to occur where critical loads are exceeded.[57,58] A critical load is defined as the input rate of a pollutant below which no detrimental ecological effects occur over the long-term according to present knowledge.[58] Although biodiversity is often shown to decline when nitrogen deposition is high due to fossil fuel combustion and agricultural emissions,[58,59] the compounding effects of multiple stressors are difficult to predict. Warming and changes in water availability have been shown to interact with nitrogen in additive or synergistic ways to exacerbate biodiversity loss.[60] Unfortunately, very few multi-factorial studies have been done to address this gap.

Human induced acceleration of the nitrogen and phosphorus cycles already causes widespread freshwater and marine eutrophication,[61,62] a problem that is expected to worsen under a warming climate.[62,63] Without efforts to reduce future climate change and to slow the acceleration of biogeochemical cycles, existing climate changes will combine with increasing inputs of nitrogen and phosphorus into freshwater and estuarine ecosystems. This combination of changes is projected to have substantial negative effects on water quality, human health, inland and coastal fisheries, and greenhouse gas emissions.[19,62]

Similar concerns – and opportunities for the simultaneous reduction of multiple environmental problems (known as "co-benefits") – exist in the realms of air pollution, human health, and food security. For example, methane, volatile organic compounds, and nitrogen oxide emissions all contribute to the formation of tropospheric ozone, which is a greenhouse gas and has negative consequences for human health and crop and forest productivity.[38,64,65] Rates of ozone formation are accelerated by higher temperatures, creating a reinforcing cycle between rising temperatures and continued human alteration of the nitrogen and carbon cycles.[66] Rising temperatures also work against some of the benefits of air pollution control.[65] Some changes will trade gains in one arena for declines in others. For example, lowered NO_x, NH_x, and SO_x emissions remove cooling agents from the atmosphere, but improve air quality.[17,32] Recent analyses suggest that targeting reductions in compounds like methane and black carbon aerosols that have both climate and air-pollution consequences can achieve significant improvements in not only the rate of climate change, but also in human health.[32] Finally, reductions in excess nitrogen and phosphorus from agricultural and industrial activities can potentially reduce the rate and impacts of climate change, while simultaneously addressing concerns in biodiversity, water quality, food security, and human health.[67]

BOX 2. Estimating the U.S. Carbon Sink

Any natural or engineered process that temporarily or permanently removes and stores carbon dioxide (CO_2) from the atmosphere is considered a carbon "sink." Temporary (10 to 100 years) CO_2 sinks at the global scale include absorption by plants as they photosynthesize, as well as CO_2 dissolution into the ocean. Forest biomass and soils in North America offer large temporary carbon sinks in the global carbon budget; however, the spatial distribution, longevity, and mechanisms controlling these sinks are less certain.[68] Understanding these processes is critical for predicting how ecosystem carbon sinks will change in the future, and potentially for managing the carbon sink as a mitigation strategy for climate change.

Both inventory (measurement) and modeling techniques have been used to estimate land-based carbon sinks at a range of scales in both time and space. For inventory methods, carbon stocks are measured at a location at two points in time, and the amount of carbon stored or lost can be estimated over the intervening time period. This method is widely used to estimate the amount of carbon stored in forests in the United States over timescales of years to decades. Terrestrial biosphere models estimate carbon sinks by modeling a suite of processes that control carbon cycling dynamics, such as photosynthesis (CO_2 uptake by plants) and respiration (CO_2 release by plants, animals, and microorganisms in soil and water). Field-based data and/or remotely sensed data are used as inputs, and also to validate these models. Estimates of the land-based carbon sink can vary depending on the data inputs and how different processes are modeled.[23] Atmospheric inverse models use information about atmospheric CO_2 concentrations and atmospheric transport (like air currents) to estimate the terrestrial carbon sink.[69] This approach can provide detailed information about carbon sinks over time. However, because atmospheric CO_2 is well-mixed and monitoring sites are widely dispersed, these models estimate fluxes over large areas and it is difficult to identify processes responsible for the sink from these data.[23] Recent estimates using atmospheric inverse models show that global land and ocean carbon sinks are stable or even increasing globally.[70]

The U.S. Environmental Protection Agency (EPA) conducts an annual inventory of U.S. greenhouse gas emissions and sinks as part of the nation's commitments under the Framework Convention on Climate Change. Estimates are based on inventory studies and models validated with field-based data (such as the CENTURY model) in accordance with the Intergovernmental Panel on Climate Change best practices.[71] An additional comprehensive assessment, The First State of the Carbon Cycle Report (SOCCR), provides estimates for carbon sources and sinks in the U.S. and North America around 2003.[68] This assessment also utilized inventory and field-based terrestrial biosphere models, and incorporated additional land sinks not explicitly included in EPA assessments.

Data from these assessments suggest that the U.S. carbon sink has been variable over the last two decades, but still absorbs and stores a small fraction of CO_2 emissions. The forest sink comprises the largest fraction of the total land sink in the U.S., annually absorbing 7% to 24% (with a best estimate of 16%) of fossil fuel CO_2 emissions during the last two decades. Because the U.S. Forest Service has conducted detailed forest carbon inventory studies, the uncertainty surrounding the estimate for the forest sink is lower than for most other components (see Pacala et al. 2007, Table 2[24]). The role of lakes, reservoirs, and rivers in the carbon budget, in particular, has been difficult to quantify and is rarely included in national budgets.[72] The IPCC guidelines for estimating greenhouse gas sources or sinks from lakes, reservoirs, or rivers are included in the "wetlands" category, but only for lands converted to wetlands. These ecosystems are not included in the Environmental Protection Agency's estimates of the total land sink. Rivers and reservoirs were estimated to be a sink in the State of the Carbon Cycle analysis,[24] but recent studies suggest that inland waters may actually be an important source of CO_2 to the atmosphere.[73] It is important to note that these two methods use different datasets, different models, and different methodologies to estimate land-based carbon sinks in the United States. In particular, we note that the EPA Inventory, consistent with IPCC Guidelines for national inventories, includes only carbon sinks designated as human-caused, while the SOCCR analysis does not make this distinction.

Land Area	**C sink (Tg C/y) (95% CI)**	**Method**
Forest	-256 (+/- 50%)	inventory, modeled
Wood products	-57 (+/- 50%)	inventory
Woody encroachment	-120 (+/- >100%)	inventory
Agricultural soils	-8 (+/- 50%)	modeled
Wetlands	-23 (+/- >100%)	inventory
Rivers and reservoirs	-25 (+/- 100%)	inventory
Net Land Sink	**-489 (**+/- 50%)	inventory

Table 15.1: Ecosystem Carbon Sinks

Caption: Carbon (C) sinks and uncertainty estimated by Pacala et al. for the first State of the Carbon Cycle Report.[24] Forests take up the highest percentage of carbon of all land-based carbon sinks. Due to a number of factors, there are high degrees of uncertainty in carbon sink estimates.

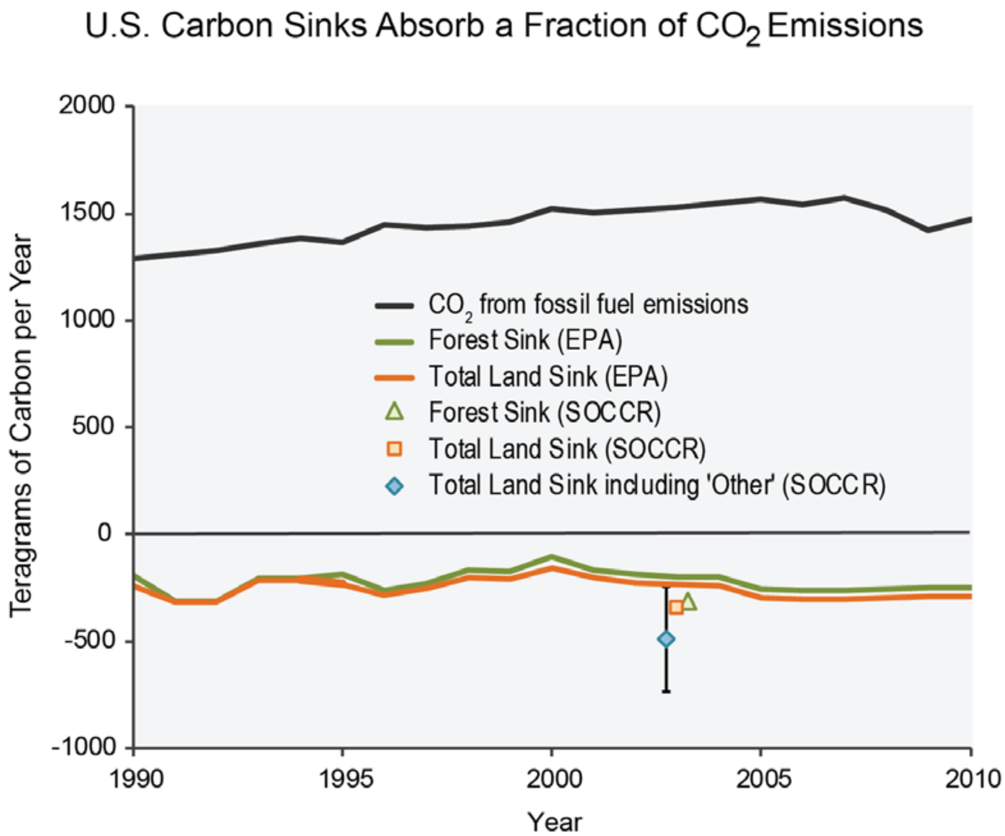

Figure 15.5: U.S. Carbon Sinks Absorb a Fraction of CO_2 Emissions

Caption: Figure shows growth in fossil fuel CO_2 emissions (black line) and forest and total land carbon sinks in the U.S. from 1990–2010 (green and orange lines; EPA 2012) and for 2003 (symbols) from the first State of the Carbon Cycle Report (2007). Carbon emissions are significantly higher than the total land sink's capacity to absorb and store them. (Data from EPA 2012 and CCSP 2007[22,68]).

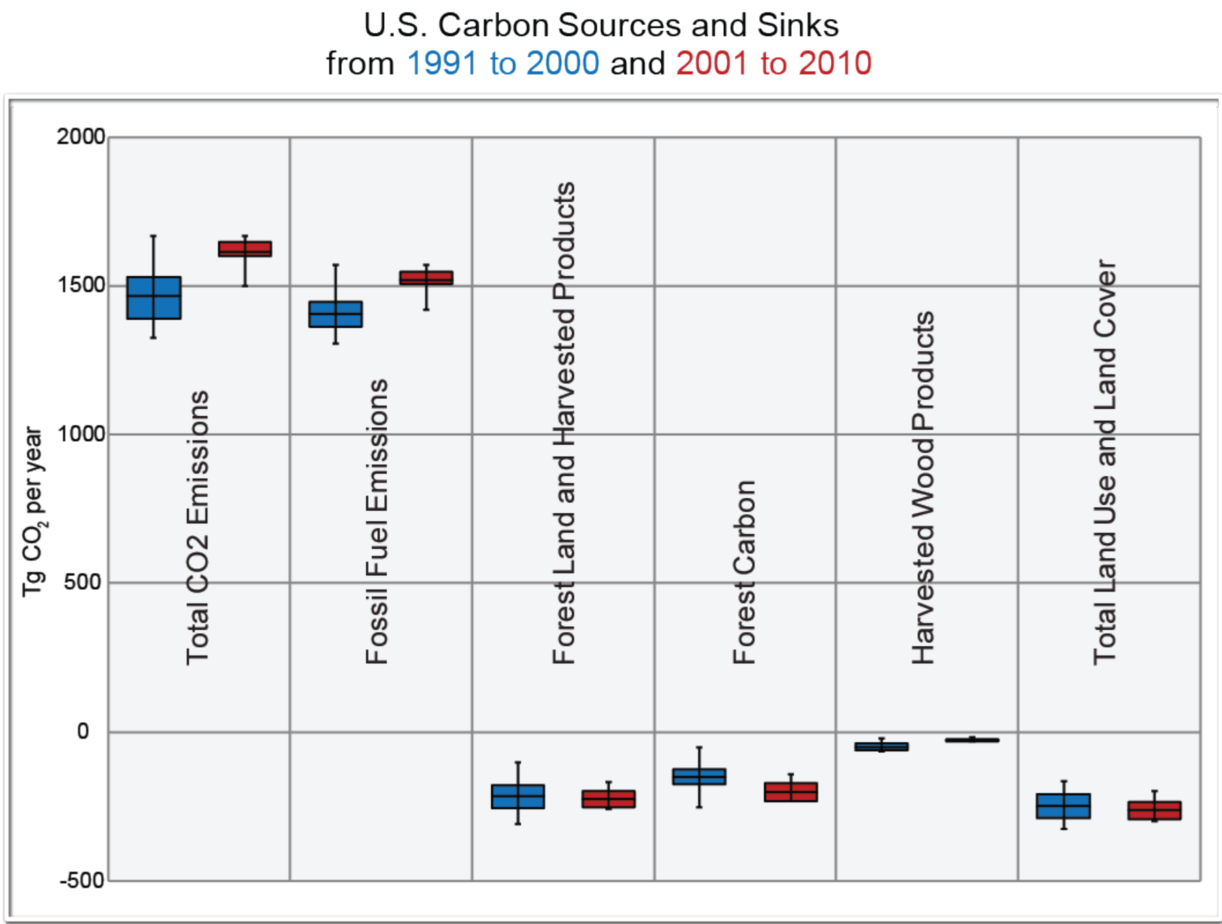

Figure 15.6: U.S. Carbon Sources and Sinks from 1991 to 2000 and 2001 to 2010

Caption: Changes in CO_2 emissions and land-based sinks in two recent decades, showing among-year variation (lines: minimum and maximum estimates among years; boxes: 25^{th} and 75^{th} quartiles; horizontal line: median). Total CO_2 emissions, as well as total CO_2 emissions from fossil fuels, have risen; land-based carbon sinks have increased slightly, but at a much slower pace. (Data from EPA 2012 and CCSP 2007[22,68]).

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Traceable Accounts

Chapter 15: Biogeochemical Cycles

Key Message Process: The key messages and supporting text summarize extensive evidence documented in two technical input reports submitted to the NCA: 1) a foundational report supported by the Departments of Energy and Agriculture: *Biogeochemical cycles and biogenic greenhouse gases from North American terrestrial ecosystems: A Technical Input Report for the National Climate Assessment*,[31] and 2) an external report: *The role of nitrogen in climate change and the impacts of nitrogen-climate interactions on terrestrial and aquatic ecosystems, agriculture, and human health in the United States: a Technical Report submitted to the U.S. National Climate Assessment*.[5] The latter report was supported by the International Nitrogen Initiative, a National Science Foundation grant, and the David and Lucille Packard Foundation.

Author meetings and workshops were held regularly for the foundational report,[31] including a workshop at the 2011 Soil Science Society of America meeting. A workshop held in July 2011 at the USGS John Wesley Powell Center for Analysis and Synthesis in Fort Collins, CO, focused on climate-nitrogen actions and was summarized in the second primary source.[5] An additional 15 technical input reports on various topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The entire author team for this chapter conducted its deliberations by teleconference from April to June, 2012, with three major meetings resulting in an outline and a set of key messages. The team came to expert consensus on all of the key messages based on their reading of the technical inputs, other published literature, and professional judgment. Several original key messages were later combined into a broader set of statements while retaining most of the original content of the chapter. Major revisions to the key messages, chapter, and these traceable accounts were approved by authors; further minor revisions were consistent with the messages intended by the authors.

Key message #1/3	**Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.**
Description of evidence base	The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[5,32] In particular, one report[5] focused on changes in the nitrogen cycle and was comprehensive. Original literature was consulted for changes in other biogeochemical cycles. The foundational report[31] updated several aspects of our understanding of the carbon balance in the United States. Publications have shown that human activities have altered biogeochemical cycles. A seminal paper comparing increases in the global fluxes of carbon (C), nitrogen (N), sulfur (S), and phosphorous (P) was published in 2000[3] and was recently updated.[4] Changes observed in the nitrogen cycle[1,18,19] show anthropogenic sources to be far greater than natural ones.[15,37,48] For phosphorus, the effect of added phosphorus on plants and microbes is well understood.[20,47,48] Extensive research shows that increases in CO_2 are the strongest human impact forcing climate change, mainly because the concentration of CO_2 is so much greater than that of other greenhouse gases.[3,6,8]

New information and remaining uncertainties	The sources of C, N, and P are from well-documented processes, such as fossil-fuel burning and fertilizer production and application. The flux from some processes is well known, while others have significant remaining uncertainties. Some new work has synthesized the assessment of global and national CO_2 emissions,[8] and categorized the major CO_2 sources and sinks.[5,31] Annual updates of

	CO_2 emissions and sink inventories are done by the EPA (e.g., [9]). Advances in the knowledge of the nitrogen cycle have quantified that human-caused reactive nitrogen inputs are now at least five times greater than natural inputs.[5,14,15]
Assessment of confidence based on evidence	**High** confidence. Evidence for human inputs of C, N, and P come from academic, government, and industry sources. The data show substantial agreement. The likelihood of continued dominance of CO_2 over other greenhouse gases as a driver of global climate change is also judged to be **high**, because its concentration is an order of magnitude higher and its rate of change is well known.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #2/3	**In total, land in the U.S. absorbs CO_2 equivalent to approximately 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink, absorbing 7% to 24% of annual U.S. fossil fuel emissions, with a best estimate of 16%. The effect of this carbon "storage" partially offsets warming from emissions of CO_2 and other greenhouse gases.**
Description of evidence base	The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[5,31] The "U.S. Carbon Sink" box relies on multiple sources of data that are described therein. Numerous studies of the North American and U.S. carbon sink have been published in reports and the scientific literature. Estimates of the percentage of fossil-fuel CO_2 emissions that are captured by forest, cropland, and other lands vary from a low of 7% to a high of about 24%, when the carbon storage is estimated from carbon inventories.[8,23,37] The forest sink has persisted in the U.S. as forests that were previously cut have regrown. Further studies show that carbon uptake can be increased to some extent by a fertilization effect with reactive nitrogen[45,46] and phosphorus,[47,48,49] both nutrients that can limit the rate of photosynthesis. The carbon sink due to nitrogen fertilization is projected to lessen in the future as controls on nitrogen emissions come into play.[29] While carbon uptake by ecosystems has a net cooling effect, trace gases emitted by ecosystems have a warming effect that can offset the cooling effect of the carbon sink.[27] The most important of these gases are methane and nitrous oxide (N_2O), the concentrations of which are projected to rise.[26,27,34,38,39]
New information and remaining uncertainties	The carbon sink estimates have very wide margins of error. The percent of U.S. CO_2 emissions that are stored in ecosystems depends on which years are used for emissions and whether inventories, ecosystem process models, atmospheric inverse models, or some combination of these techniques are used to estimate the sink size (see "Box 1: The U.S. Carbon Sink"). The inventories are continually updated (for example,[9]), but there is a lack of congruence on which of the three techniques is most reliable. A recent paper that uses atmospheric inverse modeling suggests that the global land and ocean carbon sinks are stable or increasing.[70] While known to be significant, continental-scale fluxes and sources of the greenhouse gases N_2O and CH_4 are based on limited data and are potentially subject to revision. Recent syntheses[29] evaluate the dynamics of these two important gases and project future changes. Uncertainties remain high.
Assessment of confidence based on evidence	We have **very high** confidence that the value of the forest carbon sink lies within the range given, 7% to 24% (with a best estimate of 16%) of annual U.S. greenhouse gas emissions. There is wide acceptance that forests and soils store carbon in North America, and that they will continue to do so into the near future. The exact value of the sink strength is very poorly constrained, however, and knowledge of the projected future sink is low. As forests age, their capacity to store carbon in living biomass will necessarily decrease,[11] but if other, unknown sinks are dominant, ecosystems may continue to be a carbon sink. We have **high** confidence that the combination of ecosystem carbon storage of human-caused greenhouse gas emissions and potential warming from other trace gases emitted by ecosystems will ultimately result in a net warming effect. This is

	based primarily on one recent synthesis,[29] which provides ranges for multiple factors and describes the effects of propagating uncertainties. However, the exact amount of warming or cooling produced by various gases is not yet well known, because of the interactions of multiple factors.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #3/3	**Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.**
Description of evidence base	The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[5,31] The climate–biogeochemical cycle link has been demonstrated through numerous studies on the effects of reactive nitrogen and phosphorus on forest carbon uptake and storage, and decomposition of organic matter;[45,54] temperature effects on ecosystem productivity;[55] and sensitivity of natural methane emissions to climate variation.[56] Where the nitrogen and phosphorus cycles are concerned, a number of publications have reported effects of excess loading on ecosystem processes[61,62] and have projected these effects to worsen.[62,63] Additionally, studies have reported the potential for future climate change and increasing nitrogen and phosphorus loadings to have an additive effect and the need for remediation.[19,62] The literature suggests that co-benefits are possible from addressing the environmental concerns of both nutrient loading and climate change.[5,32,65,66,67]
New information and remaining uncertainties	Scientists are still investigating the impact of nitrogen deposition on carbon uptake, and of sulfur and nitrogen aerosols on radiative forcing. Recent work has shown that more than just climate change aspects can benefit from addressing multiple environmental concerns (air/water quality, biodiversity, food security, human health, etc.)
Assessment of confidence based on evidence	**High**. We have a **high** degree of confidence that climate change will affect biogeochemical cycles through its effects on ecosystem structure and function (species composition and productivity). Similarly, there is **high** confidence that altered biogeochemical cycles will affect climate change, as for example in the increased rates of carbon storage in forests and soils that often accompany excess nitrogen deposition.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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