15. Interactions of Climate Change and Biogeochemical Cycles

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Key messages

1. **Human activities have increased CO_2 by more than 30% over background levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends are seen for phosphorus, sulfur, and other elements, and these changes have major consequences for biogeochemical cycles and climate change.**
2. **Net uptake of CO_2 by ecosystems of North America captures CO_2 mass equivalent to only a fraction of fossil-fuel CO_2 emissions, with forests accounting for most of the uptake (7-24%, with a best estimate of 13%). The cooling effect of this carbon "sink" partially offsets warming from emissions of other greenhouse gases.**
3. **Major biogeochemical cycles and climate change are inextricably linked, increasing the impacts of climate change on the one hand and providing a variety of ways to limit climate change on the other.**

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, from soils to plants. They are called "cycles" because matter is always conserved, 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 (Nr) that has been added to the biosphere since pre-industrial times (Galloway et al. 2008; Vitousek et al. 1997). (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 activities both in the U.S. and elsewhere, with impacts and implications now and into the future.

Global CO_2 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 act 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 society's capacity to cope with coupled changes in climate, biogeochemistry, and other factors.

Human-induced Changes

Human activities have increased CO_2 by more than 30% over background levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends are seen for phosphorus, sulfur, and other elements, and these changes have major consequences for biogeochemical cycles and climate change.

The human mobilization of carbon, nitrogen, sulfur, and phosphorus from the Earth's crust has increased 36, 9, 2, and 13 times, respectively, over pre-industrial times (Schlesinger and Bernhardt 2013). Fossil-fuel burning, land-cover change, cement production, and the extraction and production of fertilizer to support agriculture are major causes of these increases (Suddick and Davidson 2012). CO_2 is the most abundant of the greenhouse gases that are increasing due to human activities, and its production dominates atmospheric forcing of global climate change (IPCC 2007). However, methane (CH_4) and nitrous oxide (N_2O) have higher greenhouse capacity 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, in part because of clean-air legislation to reduce air pollution (Shannon 1999; Stern 2005). Changes in biogeochemical cycles of carbon, nitrogen, phosphorus, sulfur, 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 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 China surpassed the U.S. Emissions from the U.S. account for 85% of North American emissions of CO_2 (King et al. 2012). 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 (Woodbury et al. 2007), due to recovery of forests from past disturbances, net increases in forest area, and faster growth driven by climate or fertilization by CO_2 and nitrogen (King et al. 2012; Williams et al. 2012). 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 (King et al. 2012) by a substantial margin.

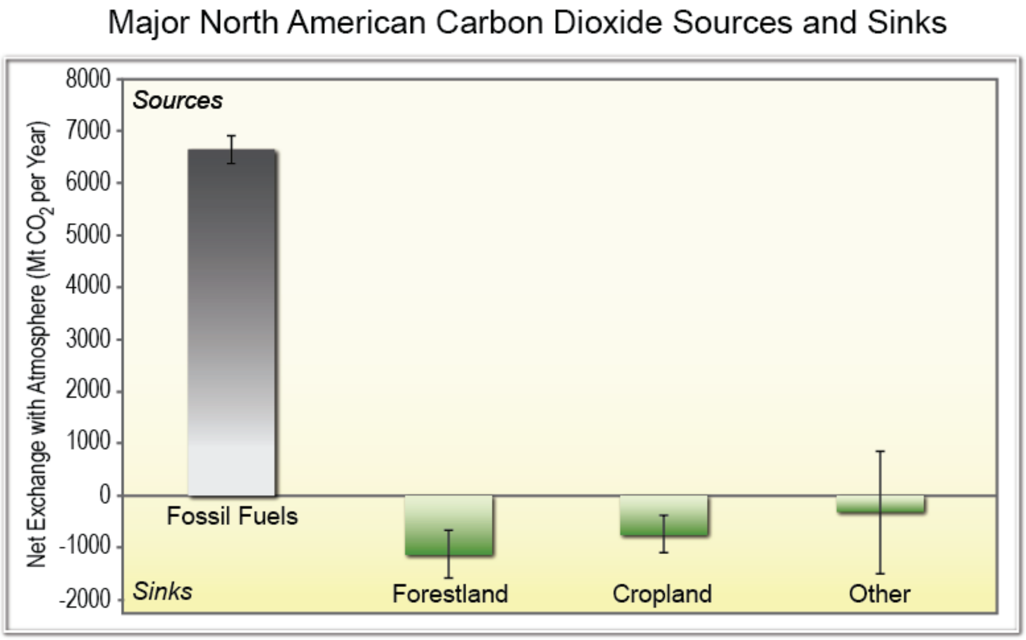

Figure 15.1: Major North American Carbon Dioxide Sources and Sinks

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 stored in forests, crops, and other ecosystems ("sinks"; shown here for 2000-2006). (Source: Post et al. 2012)

Sources and fates of reactive nitrogen

The nitrogen cycle has been dramatically altered by human activity, especially fertilization, which has increased agricultural production over the past half century (Galloway et al. 2008; Vitousek et al. 1997). Although fertilizer nitrogen inputs have begun to level off in the U.S. since 1980 (U. S. Geological Survey 2010), human-caused reactive nitrogen inputs are now five times greater than those from natural sources (EPA 2011a; Houlton et al. 2012; Suddick and Davidson 2012).

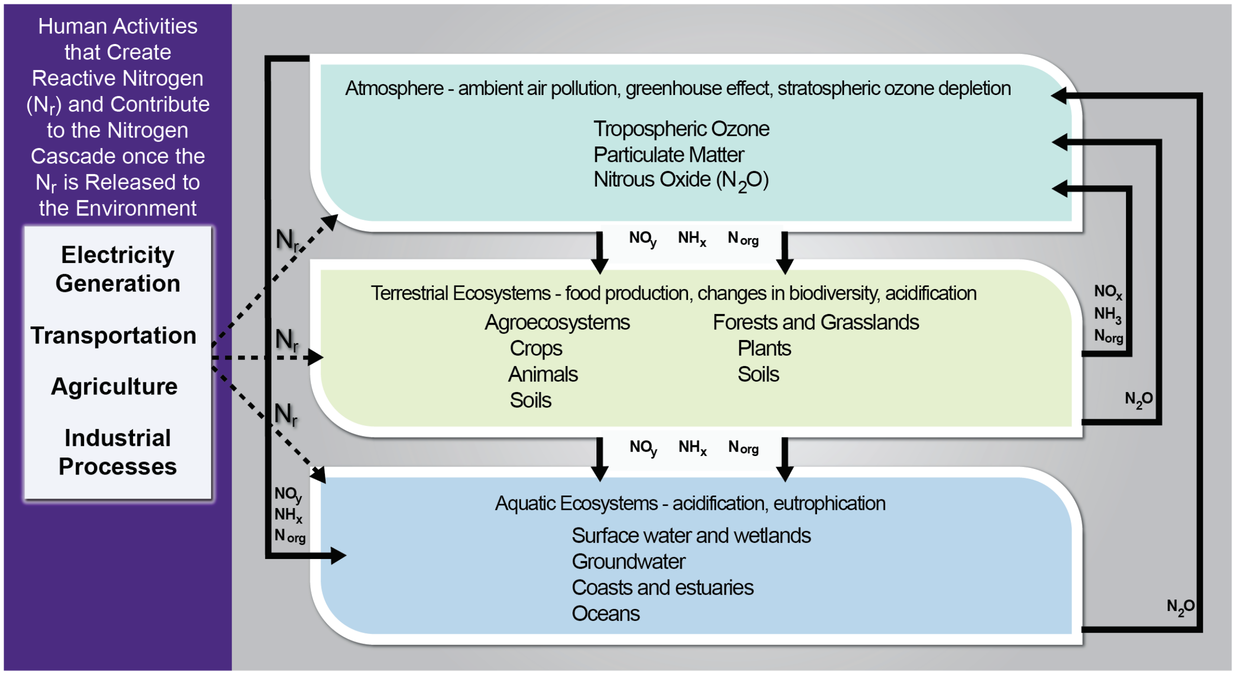

Figure 15.2: Human Activities that Form Reactive Nitrogen and Resulting Consequences in Environmental Reservoirs

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. (Figure adapted from EPA 2011a; Galloway et al. 2003, 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 (N_2) (Baron et al. 2012; Galloway et al. 2003). The nitrogen cycle affects atmospheric concentrations of the three most important human-caused greenhouse gases: carbon dioxide, methane, and nitrous oxide.

Phosphorus and other elements

In the U.S., the phosphorus cycle has been greatly transformed, (MacDonald et al. 2011; Smil 2000) primarily from the use of phosphorus in agriculture. Phosphorus has no direct effects on climate, but rather, an indirect effect: increasing carbon sinks by fertilization of plants.

Carbon Sinks

Net uptake of CO_2 by ecosystems of North America captures CO_2 mass equivalent to only a fraction of fossil-fuel CO_2 emissions, with forests accounting for most of the uptake (7-24%, with a best estimate of 13%). The cooling effect of this carbon "sink" partially offsets warming from emissions of other greenhouse gases.

Considering CO_2 concentration, the sink on land is small compared to the source: more CO_2 is emitted than can be taken up (EPA 2012; Hayes et al. 2012; King et al. 2012; Pacala et al. 2007) (see "U.S. Carbon Sink" box). Other elements and compounds affect that balance by direct and indirect means. The net effect on Earth's radiative 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 (like methane [CH_4] and volatile organic compounds [VOCs]). Methane is the most abundant non-CO_2 greenhouse gas, with atmospheric concentrations that are now more than twice those of pre-industrial times (Bousquet et al. 2006; Montzka et al. 2011).

Methane has direct radiative effects on climate because it traps heat, and indirect effects on climate because of its influences on atmospheric chemistry. An increase in methane concentration in the industrial era has contributed to warming in many ways (Forster et al. 2007). Increases in atmospheric methane, VOCs, and nitrogen oxides (NOx) are expected to deplete concentrations of hydroxyl radicals, causing methane to persist in the atmosphere and exert its warming effect for longer periods (Montzka et al. 2011; Prinn et al. 2005). The hydroxyl radical is the most important "cleaning agent" of the troposphere, where it is formed by a complex series of reactions involving ozone and ultraviolet light (Schlesinger and Bernhardt 2013).

Nitrogen and Phosphorus

The climate effects of an altered nitrogen cycle are substantial and complex (Pinder et al. 2012; Post et al. 2012; Suddick and Davidson 2012). CO_2, methane, and nitrous oxide contribute most of the anthropogenic (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.

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 (Forster et al. 2007; Montzka et al. 2011). Globally, agriculture has accounted for most of the atmospheric rise in N_2O (Matson et al. 1998; Robertson et al. 2000). Roughly 60% of agricultural N_2O derives from high soil emissions that are caused by nitrogen fertilizer use. Animal waste treatment and crop-residue burning account for about 30% and about 10%, respectively (Robertson 2004). 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 (Cavigelli et al. 2012; EPA 2011b). While N_2O currently accounts for about 6% of human-caused warming (Forster et al. 2007), its long lifetime in the atmosphere and rising concentrations will increase N_2O-based climate forcing over a 100-year time scale (Davidson 2012; Prinn 2004; Robertson and Vitousek 2009; Robertson et al. 2012).

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 (Derwent et al. 2008). Elevated tropospheric ozone may reduce CO_2 uptake by plants and thereby reduce the terrestrial CO_2 sink (Long et al. 2006; Sitch et al. 2007). Nitrogen deposition to ecosystems can also stimulate the release of nitrous oxide and methane and decrease methane uptake by soil microbes (Liu and Greaver 2009).

Excess reactive nitrogen 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 (Forster et al. 2007; Leibensperger et al. 2012). In addition, the presence of NO_x in the lower atmosphere increases the formation of sulfate and organic aerosols (Shindell et al. 2009). 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 (sequestration) and thus, the carbon sink. As mentioned previously, addition of reactive nitrogen to natural ecosystems can increase carbon sequestration as long as other factors are not limiting plant growth, such as water availability and other nutrients (Melillo et al. 2011). Nitrogen deposition from human sources is estimated to contribute to a global net carbon sink in land ecosystems of 917 million metric tons (1,010 million tons) to 1,830 million metric tons (2,020 million tons) of CO_2 per year. These are model-based estimates, as comprehensive, data-based estimates at large spatial scales are hindered by a limited number of field experiments. This net land sink represents two components: an increase in vegetation growth as nitrogen limitation is alleviated by anthropogenic nitrogen deposition; and a contribution from the influence of increased reactive nitrogen availability on decomposition. While the former is generally enhanced 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 (Butterbach-Bahl 2011).

When all direct and indirect links between reactive nitrogen and climate in the U.S. are added up, a recent estimate suggests a modest cooling effect in the near term, but a progressive switch to net warming over a 100-year timescale (Pinder et al. 2012). That switch is due to a reduction in the cooling effects of NO_x emissions, a reduction in nitrogen-stimulated CO_2 sequestration in forests (for example, Thomas et al. 2010), and a rising importance of agricultural nitrous oxide emissions.

Changes in the phosphorus cycle have no direct radiative effects on climate, but phosphorus availability constrains plant and microbial activity in a wide variety of land- and water-based ecosystems (Elser et al. 2007; Vitousek et al. 2010). 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 sequestration and decomposition (Cleveland and Townsend 2006; Elser et al. 2007) as well as the rate of nitrogen accumulation (Houlton et al. 2008).

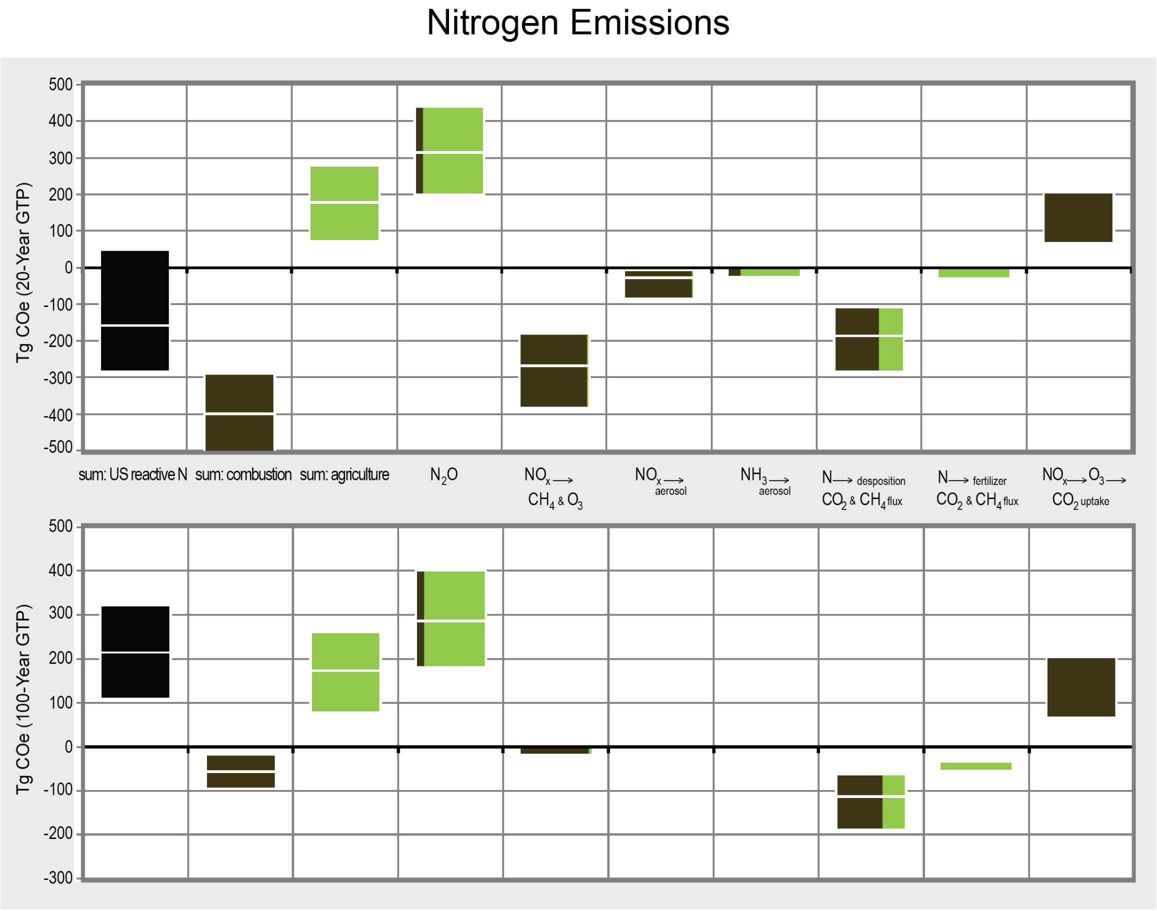

Figure 15.3: Nitrogen Emissions

Caption: Climate change will affect U.S. reactive nitrogen emissions, in Teragrams (Tg) CO_2 equivalents, on a 20-year (top) and 100-year (bottom) global temperature potential basis. The length of the bar denotes the range of uncertainty, and the white line denotes the best estimate. The relative contribution of combustion (brown) and agriculture (green) is denoted by the color shading. (Adapted from Pinder et al. 2012).

Other Effects: Sulfur 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 (Forster et al. 2007). In the U.S., the dominant source of sulfur dioxide is coal combustion. Sulfur dioxide emissions rose until 1980 but, following a series of air-quality regulations and incentives focused on improving human health, as well as reductions in the delivered price of low-sulfur coal, emissions decreased by more than 50% between 1980 and the present day (EPA 2010b). That decrease has had a marked effect on U.S. climate forcing: between 1970 and 1990, sulfate aerosols caused cooling, primarily over the eastern U.S. Since 1990, further reductions in sulfur dioxide emissions have reduced the cooling effect of sulfate aerosols by half or more (Leibensperger et al. 2012). Continued declines in sulfate aerosol cooling are projected for the future, though at a much smaller rate than during the previous three decades because of the emissions reductions already realized (Leibensperger et al. 2012). Here, as with NO_x emissions, the environmental and socio-economic trade-offs are important to recognize: lower sulfur dioxide and NO_x emissions remove some climate cooling agents, but improve ecosystem health and save lives (Shindell et al. 2012; Suddick and Davidson 2012).

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

Major biogeochemical cycles and climate change are inextricably linked, increasing the impacts of climate change on the one hand and providing a variety of ways to limit climate change on the other.

Climate change alters key aspects of biogeochemical cycling, creating the potential for feedbacks that alter both warming and cooling processes into the future. 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.

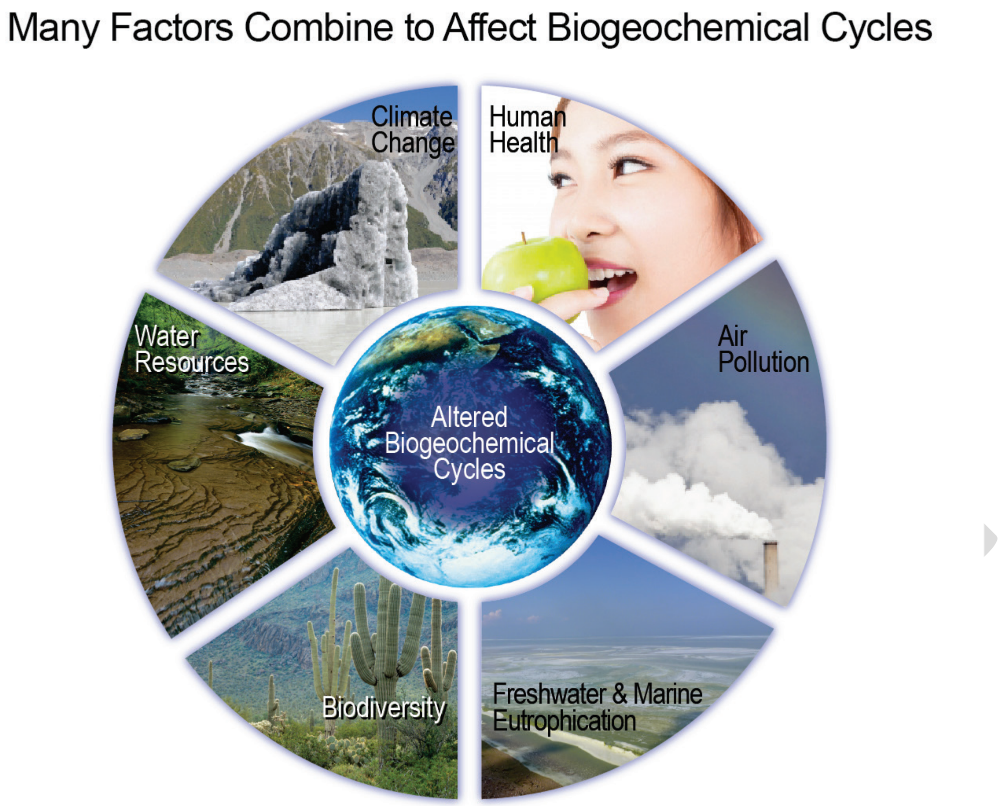

Figure 15.4: Many Factors Combine to Affect Biogeochemical Cycles

Caption: The interdependence of biogeochemical cycles, climate change, and other environmental stressors is shown in this illustration. Each section of this circle represents an important way that the planet's biological and chemical processes affect, and are affected by, other natural and human-caused changes. (Figure created by Nancy Grimm, Arizona State University)

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 (Janssens et al. 2010; Knorr et al. 2005). 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 (Melillo et al. 2011). Temperature also has direct effects on net primary productivity. 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 (Dijkstra et al. 2012; Schimel et al. 2001; Wu et al. 2011).

Similarly, natural methane sources are sensitive to variations in climate; ice core records show a strong correlation between methane concentrations and warmer, wetter conditions (Loulergue et al. 2008). Large potential sources of methane in high-latitude regions from permafrost thawing are of particular concern.

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 (Baron 2006; Pardo et al. 2011). (A Critical Load is defined as the input of a pollutant below which no detrimental ecological effects occur over the long-term according to present knowledge.) (Pardo et al. 2011) Although biodiversity is often shown to decline when nitrogen deposition is high (Bobbink et al. 2010; Pardo et al. 2011), the compounding effects of multiple stressors are difficult to predict. Unfortunately, very few multi-factorial studies have been done to address this gap.

Human acceleration of the nitrogen and phosphorus cycles already causes widespread freshwater and marine eutrophication (Carpenter 2008; Howarth et al. 2011; Smith and Schindler 2009), a problem that is expected to worsen under a warming climate (Howarth et al. 2011; Jeppesen et al. 2010; Rabalais et al. 2009). Without efforts to reduce future climate change and to slow the acceleration of biogeochemical cycles, existing climate changes will combine with increasing nitrogen and phosphorus loading to freshwater and estuarine ecosystems and are projected to have substantial additive or synergistic effects on water quality, human health, inland and coastal fisheries, and greenhouse gas emissions (Baron et al. 2012; Howarth et al. 2011).

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, VOC, and NO_x emissions all contribute to the formation of tropospheric ozone, which in turn is both a greenhouse gas and has negative consequences for human health and crop productivity (Chameides et al. 1994; Davidson 2012; Jacob and Winner 2009). Rates of ozone formation are accelerated by higher temperatures, creating synergies between rising temperatures and continued human alteration of the nitrogen and carbon cycles (Peel et al. 2012). Rising temperatures work against some of the benefits of air pollution control (Jacob and Winner 2009). 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 (Shindell et al. 2012; Suddick and Davidson 2012). Recent analyses suggest that targeting reductions in compounds like methane 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 (Shindell et al. 2012). Similarly, 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. (Townsend and Porder 2012).

BOX 1. 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." Important CO_2 sinks at the global scale include absorption by plants as they photosynthesize, as well as CO_2 dissolution into the ocean. North America represents a large carbon sink in the global carbon budget; however, the spatial distribution and mechanisms controlling this sink are less certain (King et al. 2007). Understanding these processes is critical for predicting how land-based carbon sinks will change in the future, and potentially for managing the carbon sink as a mitigation strategy.

Both inventory and modeling techniques have been used to estimate land-based carbon sinks at a range of temporal and spatial scales. 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 (Hayes et al. 2012). Atmospheric inverse models use information about atmospheric CO_2 concentrations and atmospheric transport (like air currents) to estimate the terrestrial carbon sink (Ciais et al. 2010; Gurney et al. 2002). 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 (Hayes et al. 2012). Recent estimates using atmospheric inverse models show that global land and ocean carbon sinks are stable or even increasing globally (Ballantyne et al. 2012).

The U.S. Environmental Protection Agency (U.S. 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 (IPCC) best practices (IPCC 2006). An additional comprehensive assessment, The First State of the Carbon Cycle Report, provides estimates for carbon sources and sinks in the U.S. and North America around 2003 (King et al. 2007). 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 13%) 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 (Table 2; Pacala et al. 2007). 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 (Cole et al. 2007). 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 (Pacala et al. 2007; Figure 2), but recent studies suggest that inland waters may actually be an important source of CO_2 to the atmosphere (Butman and Raymond 2011).

Carbon (C) sinks and uncertainty estimated by Pacala et al. (2007) for the first State of the Carbon Cycle Report.

Land Area	**C sink (Mt 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: Land-based Carbon Sinks

Caption: 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.

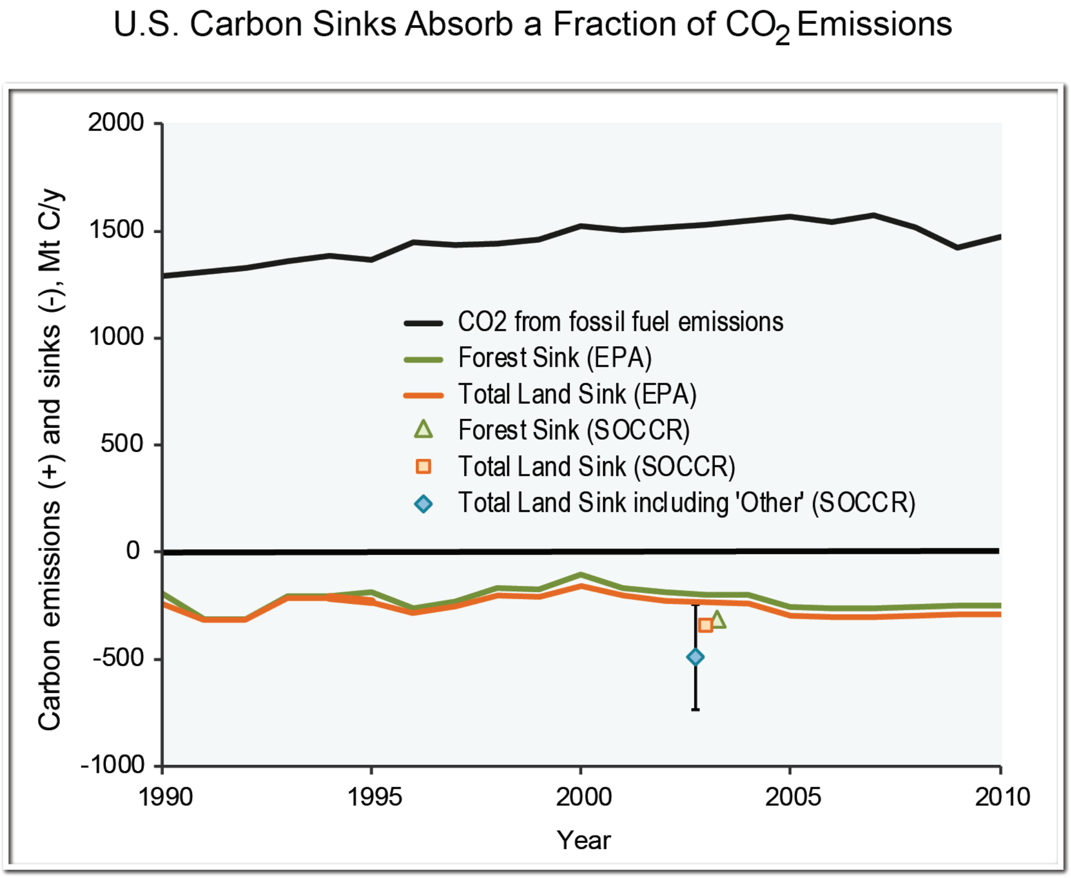

Figure 15.5: U.S. Carbon Sinks Absorb a Fraction of CO_2 Emissions

Caption: Chart 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 from the first State of the Carbon Cycle Report (SOCCR) (2007). Carbon emissions are significantly higher than the total land sink's capacity to absorb and store them.

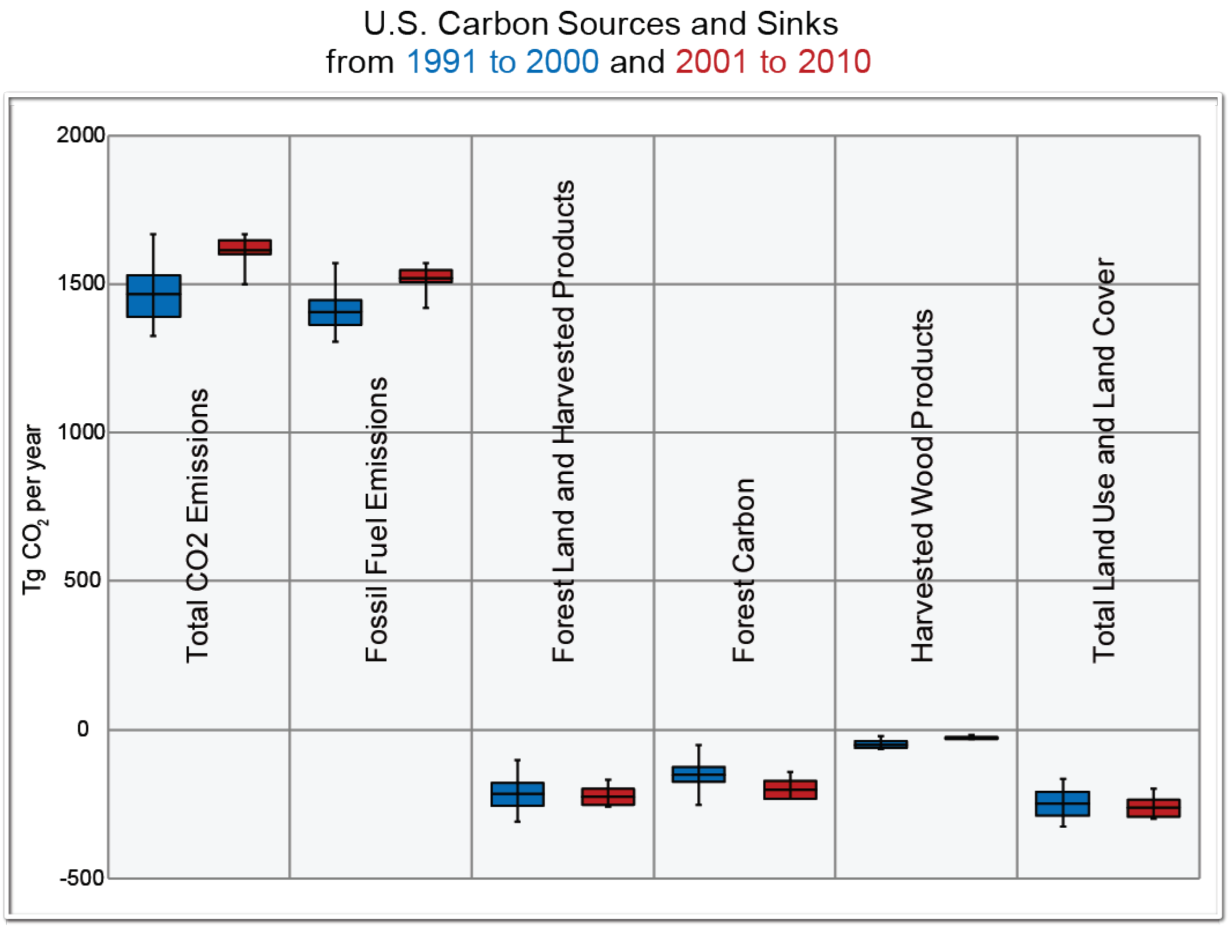

Figure 15.6: U.S. Carbon Sources and Sinks from 1991 to 2000 (blue) and 2001 to 2010 (red)

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: 25th and 75th 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).

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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 co-edited by W. Post and R. Venterea (2012): Biogeochemical cycles and biogenic greenhouse gases from North American terrestrial ecosystems: A Technical Input Report for the National Climate Assessment. Washington, DC. and supported by the Departments of Energy and Agriculture), and 2) an external report, Suddick, E. C. and E. A. Davidson, editors (2012): 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 US National Climate Assessment. North American Nitrogen Center of the International Nitrogen Initiative (NANC-INI), Woods Hole Research Center, Falmouth, MA), supported by the International Nitrogen Initiative, a National Science Foundation grant, and the U.S. Geological Survey. Author meetings and workshops were held regularly for the Post and Venterea (2012) report, 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 Suddick and Davidson (2012) report. Both reports are in review or in press as a series of papers in special issues of the journals *Frontier of Ecology and the Environment* and *Biogeochemistry*, respectively. 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 "Biogeochemistry" author team conducted its deliberations by teleconference from April to June, 2012, with three major meetings resulting in an outline and a set of key messages. All authors were in attendance for these teleconferences. 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 CO2 by more than 30% over background levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends are seen for phosphorus, sulfur, 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 (Shindell et al. 2012; Suddick and Davidson 2012).In particular, the Suddick and Davidson report focused on changes in the nitrogen cycle and was comprehensive. Original literature was consulted for changes in other biogeochemical cycles. The Post and Venterea (2012) report updated several aspects of our understanding of the carbon balance in the U.S. Publications have shown that human activities have altered biogeochemical cycles. A seminal paper comparing increases in the global fluxes of C, N, S, and P was published in 2000 and has yet to be updated specifically (Falkowski et al. 2000). However, changes observed in the nitrogen cycle (Baron et al. 2012; Galloway et al. 2003; Galloway et al. 2008; Vitousek et al. 1997) show anthropogenic sources to be far greater than natural ones (EPA 2011b; Houlton et al. 2012; Vitousek et al. 2010). For phosphorus, the effect of added phosphorus on plants and microbes is well understood (Elser et al. 2007; MacDonald et al. 2011; Smil 2000; Vitousek et al. 2010). Extensive research that shows increases in CO_2 to be the strongest anthropogenic climate-change force, mainly because its concentration is so much greater than other greenhouse gases (Falkowski et al. 2000; IPCC 2007; King et al. 2012).

New information and remaining uncertainties	Because the sources of C, N, S and P are from well-documented processes, such as fossil-fuel burning and fertilizer production and application, the uncertainties are small. Some new work has been synthesized for the assessment of the global and national CO_2 emissions (King et al. 2012), and categorizing the major sources and sinks (Post et al. 2012; Suddick and Davidson 2012). Annual updates of CO_2 emissions and sink inventories are done by the EPA (e.g., EPA 2012). Advances in the knowledge of the nitrogen cycle have quantified that human-caused reactive nitrogen inputs are now five times greater than natural inputs (EPA 2011a; Houlton et al. 2012; Suddick and Davidson 2012).
Assessment of confidence based on evidence	**Very high** confidence. Evidence for human inputs of C, N, S 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

Chapter 15: Biogeochemical Cycles

Key Message Process: See key message #1.

Key message #2/3	**Net uptake of CO2 by ecosystems of North America captures CO_2 mass equivalent to only a fraction of fossil-fuel CO2 emissions, with forests accounting for most of the uptake (7-24%, with a best estimate of 13%). The cooling effect of this carbon "sink" partially offsets warming from emissions of other greenhouse gases.**
Description of evidence base	The author team evaluated Technical Input reports (17) on biogeochemical cycles, including the two primary sources (Post et al. 2012; Suddick and Davidson 2012). The author team also contributed to a summary box on the carbon cycle (link), which is the source for the first part of this key message. The summary 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. The figure used in this chapter is from data in King et al. (2012). Estimates of the percentage of fossil-fuel CO_2 emissions that are captured by forest, cropland, and other lands vary from a low of 10% to a high of about 35%, when the carbon sink is estimated from carbon inventories (EPA 2011b; Hayes et al. 2012; King et al. 2012). Woodbury et al. (2007) show that 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 fertilizations effect with reactive nitrogen (Butterbach-Bahl 2011; Melillo et al. 2011) and phosphorus (Cleveland and Townsend 2006; Elser et al. 2007; Vitousek et al. 2010), 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 deposition come into play (Pinder et al. 2012; Thomas et al. 2010). 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 (Forster et al. 2007). The most important of these gases are methane and nitrous oxide (N_2O), the concentrations of which are projected to rise (Davidson 2012; Forster et al. 2007; Montzka et al. 2011; Prinn 2004; Robertson and Vitousek 2009; Robertson et al. 2012; Tian et al. 2012).
New information and remaining uncertainties	The carbon sink estimates have very wide margins of error, and the percentage sink 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 "U.S. Carbon Sink"box). The inventories are continually updated (for example, EPA 2012), 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 (Ballantyne et al. 2012). 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. The syntheses in Pinder et al. (2012) and Tian et al. (2012) 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 carbon sink lies within the range given. 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

	likely future sink is low. As forests age, their capacity to store carbon in living biomass will necessarily decrease (Woodbury et al. 2007), but if other, unknown sinks are dominant, ecosystems may continue to be a carbon sink. We have **high** confidence that the combination of carbon sink and potential offsets from other trace gases will ultimately result in a net warming effect. This is based primarily on the analysis of Pinder et al. (2012). However, the exact amount of warming or cooling produced by various gases is not yet well constrained, 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	**Major biogeochemical cycles and climate change are inextricably linked, increasing the impacts of climate change on the one hand and providing a variety of ways to limit climate change on the other.**
Description of evidence base	The author team evaluated Technical Input reports (17) on biogeochemical cycles, including the two primary sources (Post et al. 2012; Suddick and Davidson 2012). The climate–biogeochemical cycle link has been demonstrated through numerous studies on the effects of reactive nitrogen and phosphorus on forest carbon uptake, storage, and decomposition (Janssens et al. 2010; Knorr et al. 2005; Melillo et al. 2011), temperature effects on ecosystem productivity (Dijkstra et al. 2012; Schimel et al. 2001; Wu et al. 2011), and natural methane emission sensitivity to climate variation (Loulergue et al. 2008). Where the nitrogen and phosphorus cycles are concerned, a number of publications have reported effects of excess loading on ecosystem processes (Carpenter 2008; Howarth et al. 2011; Smith and Schindler 2009) and have projected these effects to worsen (Howarth et al. 2011; Jeppesen et al. 2010; Rabalais et al. 2009). Additionally, studies have reported the potential for the future climate change and increasing nitrogen and phosphorus loadings to have an additive effect and the need for remediation (Baron et al. 2012; Howarth et al. 2011). The literature suggests that co-benefits are possible from addressing these environmental concerns of nutrient loading and climate change (Jacob and Winner 2009; Peel et al. 2012; Shindell et al. 2012; Suddick and Davidson 2012; Townsend and Porder 2012).
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**. There is agreement that nitrogen deposition can stimulate carbon uptake in forests. The major questions concern the magnitude and the length of time that forests will provide this service.

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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