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

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Preface

This technical report is a product of the North American Nitrogen Center of the International Nitrogen Initiative (NANC-INI; http://nitrogennorthamerica.org/). The objective is to provide an in-depth analysis of the cross-cutting issue of climate-nitrogen interactions for consideration by the US National Climate Assessment Development Advisory Committee as they write their 2013 National Climate Assessment report.

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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

Chapter 1: EXECUTIVE SUMMARY

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Producing food, transportation, and energy for seven billion people has resulted in massive increases in use of synthetic nitrogen (N) fertilizers and in emissions of N as forms of air pollution. The global N cycle has become more severely altered by human activity than the global carbon (C) cycle. In its numerous chemical forms, reactive nitrogen (Nr) plays a critical role in all aspects of climate change considerations, including mitigation, adaptation, and impacts.

Mitigation: Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the most important anthropogenic greenhouse gases in terms of radiative forcing, and N cycling processes affect the atmospheric concentrations of all three gases. Hence, management of the N cycle will not only help mitigate emissions of the N-containing gas N_2O, but will also affect CO_2 and CH_4 in complex ways that are reviewed here. These include how N affects C sequestration in forests and soils, and how atmospheric CH_4 concentrations are affected by the chemistry of nitrogen oxides (NO_X) and ozone (O_3). While some of these N cycling processes have contrasting effects on the atmospheric burdens of greenhouse gases, including a possible net cooling effect on the time scale of a few decades, minimizing Nr releases to the environment would almost certainly help slow the rate of climate change over the long term (e.g., a century).

Adaptation: Understanding interactions of climate with the N cycle will be essential in situations where adaptation to climate change involves changes in energy and water use. Although considerable progress has been made in lowering NO_X emissions from energy, industry, and transportation sectors in the US, this progress could slow or reverse if energy use is increased for climate change adaption, such as additional air conditioning or pumping and treating water. Adaptations to increasing water scarcity may include greater consumptive use of surface and groundwaters, which will likely exacerbate problems of elevated nitrate (NO_3^-) concentrations in waters draining to rivers, lakes, groundwaters and estuaries, leading to eutrophication, costly drinking water treatments, or increased incidents of NO_3^--related disease. On the one hand, improvements in agricultural nutrient management (e.g., properly timed and appropriately balanced nutrient additions) can confer some adaptive capacity of crops to climatic variability, but on the other hand, increased climatic variability will also render the task of nutrient management more difficult. These are only a few examples reviewed in this report of climate-N interactions that would affect or be affected by climate change adaptation.

Impacts: Climate change will significantly alter N cycling processes, which will affect both terrestrial and aquatic ecosystems, as well as human health. Higher air temperatures will complicate air quality mitigation, because larger reductions in NO_X emissions will be needed to achieve the same reductions of O_3 pollution under higher temperatures, thus imposing further challenges to avoid harmful impacts of O_3 pollution on human health and crop productivity, also known as a "climate penalty." Changes in river flow, due to summer drought and extreme precipitation events, will affect the loading and processing of N within rivers and estuaries. Lower river flows may reduce the total flux of N entering coastal regions, but would also reduce rates of flushing of estuaries, whereas higher flows will accelerate loading of N from terrestrial to aquatic systems. In either case, more frequent blooms of harmful or nuisance algal species are possible. In addition, rising ambient temperatures will increase ammonia (NH_3) emissions throughout all phases of manure handling and will likely result in lower N use efficiency in livestock production systems and greater losses of Nr to the environment. Both climate change and N inputs from air pollution (i.e., N deposition) can provoke a loss of biodiversity in aquatic and terrestrial ecosystems, due to nutrient enrichment of native ecosystems which favors fast-growing, often non-native species. Less is known about the interactions of climate and N regarding biodiversity, but additive or synergistic effects are indicated. The impacts of climate-N interactions on C sequestration, agricultural productivity, aquatic ecosystems and water quality, biodiversity, and air pollution are analyzed in detail in the chapters of this report.

The climate-N interactions described in the following chapters are too numerous to list exhaustively in this executive summary, but a few of the highlights, organized by chapter topics, are listed here.

Alteration of N flows in the US (Chapter 2)

- Humans introduced about 29 Tg (10^{12}g) of newly formed Nr into the US in 2002 (the most recent year for which the most complete data are available; Figure 1.1). About 65% of N inputs were from agricultural sources (including synthetic N fertilizers and N fixation by legume crops), 20% from fossil fuel sources, and about 15% from industrial sources. Overall in the US, the amount of Nr produced by human activities was approximately five-times larger than all natural processes combined; while at the global scale, human activities produced approximately twice as much Nr as did natural processes (SAB 2011).

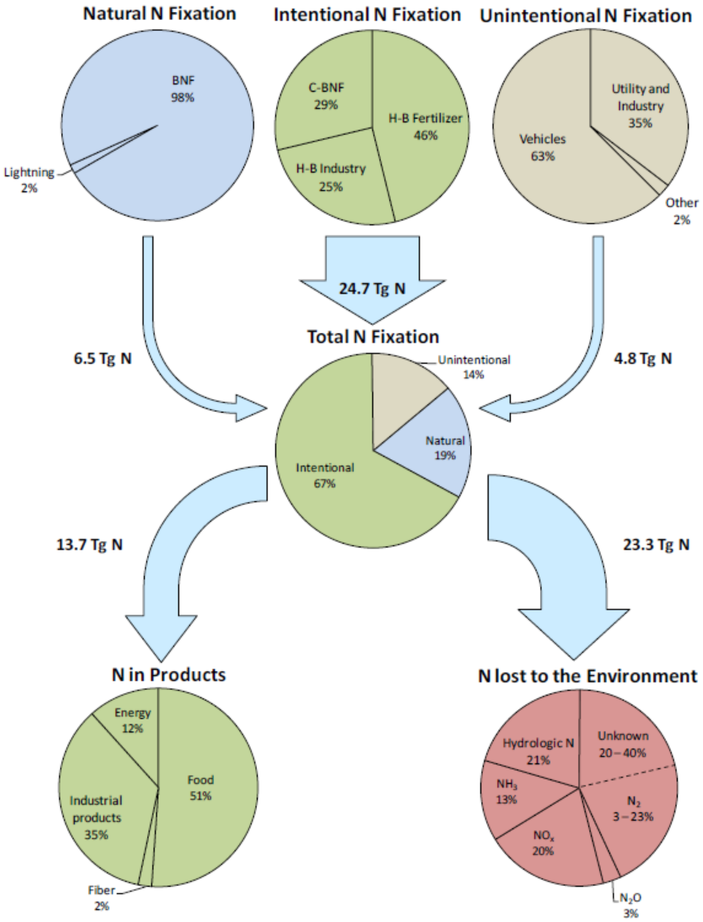

Figure 1.1: N fixation and fates of N in the US for 2007. "BNF" = Biological Nitrogen Fixation; "C-BNF" = Crop BNF; "H-B Fertilizer" = Haber-Bosch Fertilizer; "H-B Industry" = Haber-Bosch Industrial Products; (See also Figure 2.9, Section 2.2.5 in Chapter 2).

- Human activities have also greatly modified the amount of N that is released from the land to air and water resources. In terms of gaseous N releases, NH_3 and NO_X account for 31 % and 61 % respectively, of a combined flux of 9.3 Tg N/yr. Significant fractions of these N gases are re-deposited on US ecosystems downwind of sources. In contrast, the greenhouse gas N_2O is evenly mixed within the global atmosphere and accounted for approximately 8 % of all US gaseous Nr emissions (Houlton and Bai, 2009).

- Leaching of N to surface waters and groundwater has also increased substantially in the US and around the globe. Our 2002 US budget indicates that leaching to surface waters and groundwater was approximately 4-5 Tg N/yr. Approximately 14-45 % of N entering groundwater as NO_3^- derives from fertilizer and/or manure use and atmospheric deposition (Nolan et al., 2010; Puckett et al., 2011).

- On an annual basis, about 54% of Nr intentionally introduced into the US is converted to food, livestock feed, biofuel (energy), or industrial products; about 27 % o f Nr is released to the environment as various forms of air and water pollution, and an uncertain amount (3 - 21%) is converted to inert dinitrogen (N_2) gas. Considering only the agricultural sector, approximately 38% of agricultural N inputs (e.g., synthetic fertilizer and N fixation by leguminous crops) enter the annual food and livestock feed supply. Most of the N that reaches its intended target in consumable human food, animal feed, biofuels, and industrial products is eventually released to the environment as sewage, manure, and other waste products.

Radiative forcing (Chapter 3)

- Nitrogen cycling processes affect radiative forcing directly through emissions of N_2O, a greenhouse gas with long-term warming effects due to a mean residence time in the atmosphere of over 100 years. The US Environment Protection Agency (USEPA 2011) estimates that agricultural activities in the US are directly or indirectly responsible for emissions of about 0.48 million tons of $N_2O\text{-}N\ yr^{-1}$, which is about 80% of total anthropogenic US N_2O production (the remainder derives from energy and industrial sources), and is about 10% of the global N_2O emissions from agriculture.

- Emissions of NO_X indirectly affect radiative forcing through the effects on atmospheric concentrations of CH_4, O_3 and aerosol particulate matter (PM). These effects are complex and difficult to quantify (Rypdal et al. 2009, Penner et al. 2010, Myhre et al. 2011). However, they generally result in a cooling effect on time scales of days to decades, becoming insignificant on longer time scales (Boucher et al., 2009).

- Emissions of NO_X and NH_3 are chemically transformed and eventually deposited onto ecosystems with rain and snow and also as dry particles. This increases the availability of N to ecosystems, which can thus affect the sources and sinks of N_2O, CH_4, and CO_2, with the dominant effect being enhanced sequestration of C. The literature reviewed here reports a range of estimates of 20-70 kg C sequestered per kg N deposited onto forests, which are the dominant potential C sinks (Butterbachball et al., 2011; Thomas et al., 2010). Most of the sequestration occurs in aboveground forest biomass, with less consistency and lower rates reported for C sequestration in soils. The permanency of the forest biomass sink is uncertain, but data on forest product fates in the US indicate that only a small fraction of enhanced forest biomass C is sequestered in long-term harvest products or in unmanaged forests.

- The net effect of all of these N cycle processes on radiative forcing in the US is probably a modest cooling effect for a 20-year time frame (although the uncertainty of this estimate includes zero net effect), and a modest warming for a 100-year time frame (Figure 1.2).

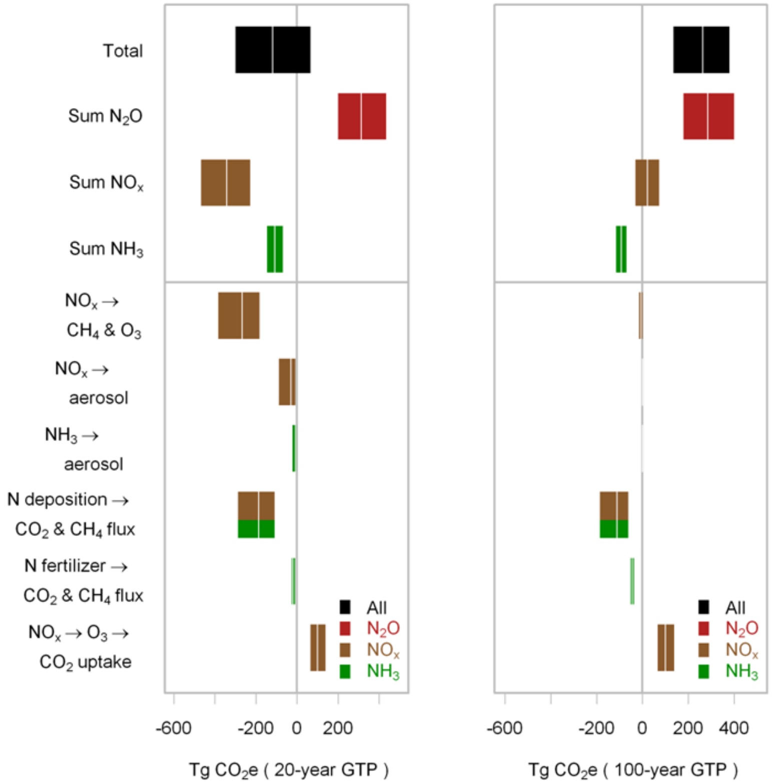

Figure 1.2: The climate change impacts of US reactive nitrogen emissions on a 20-year and 100-year global temperature potential (GTP) basis. (See also Figure 3.1, Section 3.4 in Chapter 3; redrawn from Pinder et al., in review).

Agriculture (Chapter 4)

- Climate-N interactions affect agricultural productivity in part through exposure of crops to elevated O_3. The O_3 production efficiency per unit NO_X emitted is high in rural areas. Furthermore, increases in temperature can also lead to higher rates of precursor emissions and O_3 formation. Based on large-scale experimental studies in the US (Heagle, 1989; Heck, 1989), the USEPA estimates that the yields of about one-third of US crops were reduced by 10% due to ambient O_3 concentrations in the 1980s (USEPA, 1996). Model simulations of O_3 used with these established concentration and yield response relationships predict larger effects for grain crops for 2000 and 2030 (Avnery et al., 2011a, b). More recent field studies have found similar or larger yield reductions at similar O_3 exposures in a variety of crops (Mills et al., 2007; Emberson et al., 2009).

- Increases in drought frequency and intensity from increasing temperatures will also adversely affect crop growth and yield, ultimately impacting nutrient use and uptake efficiency and facilitating unintentional N releases to the environment. Fertilizer N is usually applied at rates expected to produce historically maximum crop yields for a given location. Thus, environmental factors that reduce crop growth and yield, including both drought and excessive moisture, would increase Nr releases to water and air due to reduced crop uptake (Figure 1.3).

- Extreme wet cycles can also result in substantial releases of Nr to the environment, through greater transport of NO_3^- as excess water drains from fields, and through gaseous losses of N_2O promoted in wet soils. Nitrate leaching and N_2O production occur when large amounts of soil NO_3^- are present after fertilizer application, before the crop has started growing vigorously, and when the soils are wet (Davidson et al., 2012).

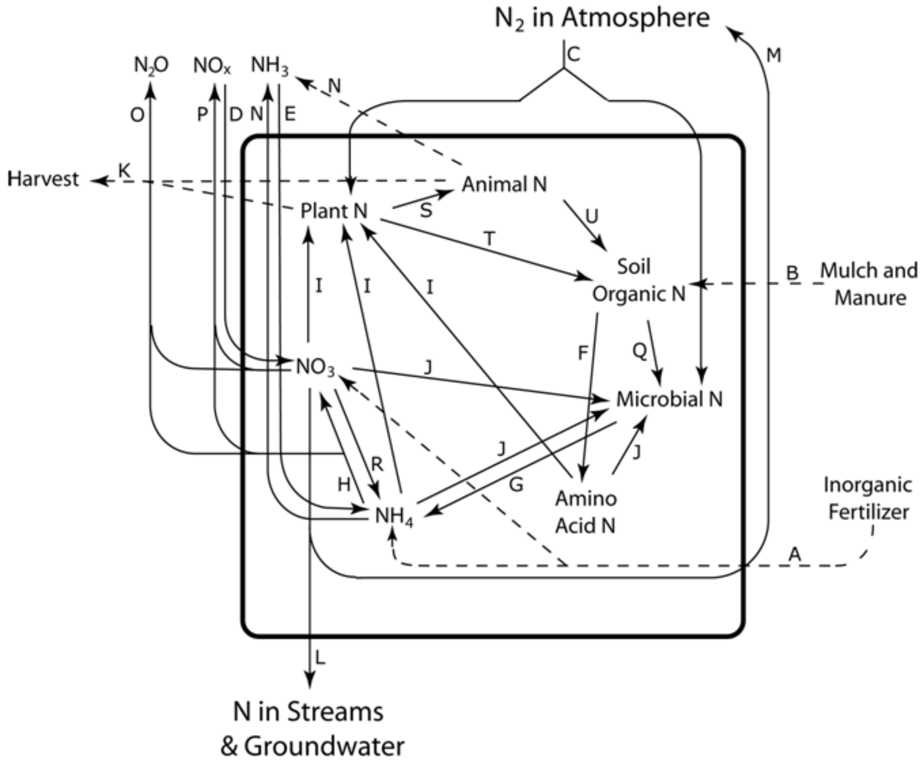

Figure 1.3: Pathways of N cycling in agricultural ecosystems. (See Figure 4.2, Section 4.0 in Chapter 4 for an explanation of the symbols A-T) From Robertson and Vitousek 2007.

- The presence of winter cover crops can reduce Nr losses through mechanisms of plant N uptake and reduced subsurface percolation. Cover crops in some locations have been documented to reduce both N_2O emissions and NO_3^- leaching compared with bare fallow systems (McSwiney et al., 2010).

- Rates of NH_3 emissions from livestock operations are also very sensitive to temperature (Montes et al., 2009), such that rising ambient temperatures will also increase this source of N loss throughout all phases of manure handling. Overall, the net effect of changes in the agricultural N cycle in response to higher temperature is likely a reduction in N use efficiency of animal systems, resulting in larger potential releases of Nr to the environment.

- Projected temperature changes will also directly and indirectly affect livestock production, primarily due to heat stress, which causes reduced feed intake, increased water intake, higher body temperatures, increased respiration, decreased activity, and hormonal and metabolic changes. These effects can lead to lower production, lower reproduction, and higher mortality (Nardone et al., 2010). As production is increased elsewhere to make up for this lost productivity, more N will be needed and Nr releases to the environment will increase. Under our current climate, heat stress is estimated to cause an annual economic loss of 1.7 to 2.4 billion dollars in the US livestock sector (St-Pierre et al., 2003).

- Applying the right source of fertilizer N at the right rate, time, and place is the core concept of mitigation strategies designed to increase crop N use efficiency and to reduce N_2O, NO_X, and NH_3 emissions. However, crop demand for nutrients is highly dependent upon climate and climatic variability, so improved nutrient use management will be increasingly challenging under climate change scenarios of more variable climatic patterns.

Aquatic ecosystems and resources (Chapter 5)

- Nearly all freshwaters and coastal zones of the US exhibit some degree of degradation from inputs of excess Nr. Two-thirds of US estuaries are degraded from N pollution, and effects include anoxia (no oxygen) and hypoxia (low oxygen), loss of critical habitat and biodiversity, and increased frequency of harmful algal blooms (Bricker et al. 2007, SAB 2011).

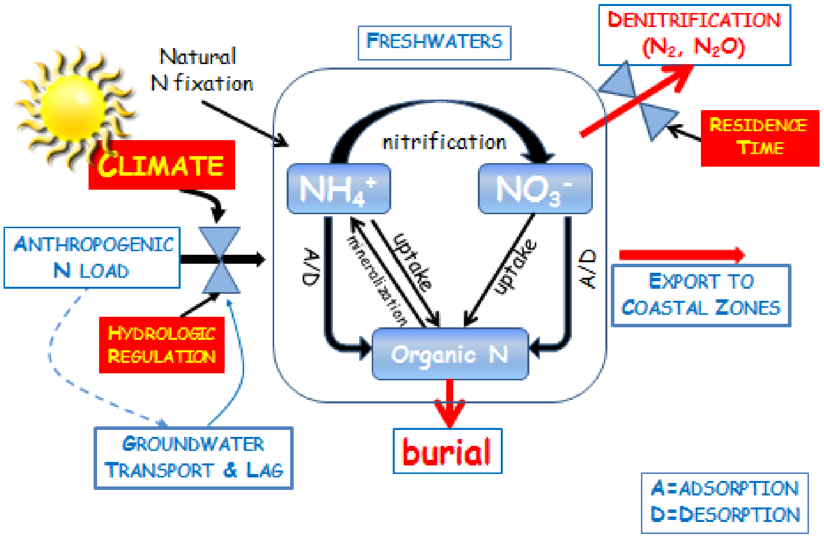

Figure 1.4: Conceptual model of N input, cycling and losses of Nr to inland waters. (See also Figure 5.1, Section 5.2.1 in Chapter 5).

- The loading of N from watersheds and atmospheric deposition has more than doubled the flux of N to estuaries and coastal oceans since the industrial and agricultural revolutions (Howarth et al. 2011a, Boyer and Howarth 2008).

- Inputs to river systems were estimated with the USGS SPARROW model to be 4.8 Tg N yr^{-1} in 2002 (SAB 2011, Alexander et al. 2008). North American riverine N export to the coastal zone, inlands and drylands was estimated at approximately 7.0 Tg N yr^{-1} (Boyer et al. 2006).

- Aquatic ecosystems are critically important denitrification hotspots where Nr can be returned to the atmosphere as un-reactive and harmless N_2. Denitrification rates per-unit-area are approximately ten-fold the per-unit-area denitrification rates in soils (Seitzinger et al. 2006). One estimate suggests 20% of global denitrification occurs in freshwaters (e.g., groundwaters, lakes, and rivers) (Seitzinger et al. 2006).

- The effect of climate change on N processing in fresh and coastal waters will be felt most strongly through changes to the hydrologic cycle (Figure 1.4). Alterations in the amount, timing, frequency, and intensity of precipitation will speed or slow runoff, thereby influencing both rates of Nr inputs to aquatic ecosystems and groundwater and the water residence times that affect Nr removal within aquatic systems. Both hydrologic manipulation by human-made infrastructure and climate change alter the landscape connectivity and hydrologic residence times that are essential for denitrification (Howarth et al. 2011b).

- The reliance of Americans on groundwater for drinking water is likely to increase under future climate change scenarios. In addition, there will likely be increases in costs for treating water to avoid exposure to NO_3^--related disease. At present, approximately 1.2 million Americans use private, shallow groundwater wells in areas with estimated NO_3^- concentrations between 5 and 10 mg L^{-1}, and about 0.5 million use groundwater in areas with estimated NO_3^-> 10 mg L^{-1} (Nolan and Hitt 2006). A recent study showed that the maximum NO_3^- contaminant level of 10 mg L^{-1} was exceeded in 22% of domestic wells in agricultural areas (Dubrovsky et al. 2010). Model results also suggest that deeper groundwater supplies may be contaminated in the future as NO_3^- in shallow groundwater migrates downward and is slow to respond to changes in management (Nolan and Hitt 2006, Exner et al. 2010, Howden et al. 2010). In addition to the well known NO_3^- related disease methemoglobinemia (blue baby syndrome), NO_3^- from drinking water contributes to the formation of N-nitroso compounds, which have been associated with cancer, diabetes, and adverse reproductive outcomes (Ward et al. 2005).

- Increasing numbers of studies show correlations between N enrichment in waters and pathogen abundance and diseases of both humans and wildlife (Johnson et al. 2010). Many mosquitoes that are carriers of diseases like malaria or West Nile Virus and other parasites associated with warm climates or seasons have increased breeding success in waters high in NO_3^- (Johnson et al. 2010). Occurrence of algal blooms, for which there is also a direct connection to nutrient enrichment and warm waters (Heisler et al. 2008), can cause disease such as swimmers itch, food poisoning, cancer, and paralysis (Johnson et al. 2010). Harmful algal blooms are responsible for massive fish kills and marine mammal kills (Morris 1999).

- Without mitigation, the concurrent impositions of climate change and the increasing load of Nr to freshwater and estuarine ecosystems will most likely have unprecedented additive or synergistic effects on water quality, aquatic biodiversity, human health, and fisheries.

Biodiversity (Chapter 6)

- The strongest drivers of biodiversity loss include habitat loss, overexploitation, invasive species, climate change, and pollution, including pollution from Nr (MEA 2005) (Figure 1.5). Nitrogen enrichment also impacts ecosystems and biodiversity by enhancing plant

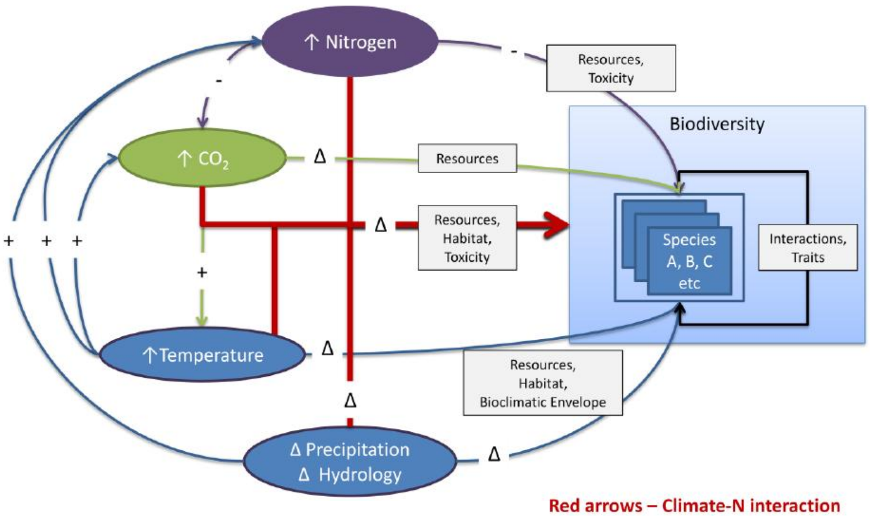

Figure 1.5: Direct and indirect effect of changing climate, N and CO_2 on biodiversity. (See also Figure 6.1, Chapter 6).

growth, which has been shown to favor fast-growing, sometimes invasive, species over native species adapted to low N conditions. Results from both empirical studies and modeling indicate that N and climate change can interact to drive losses in biodiversity greater than those caused by either stressor alone.

- For example, controlled experiments in California grassland have shown that increased N and CO_2, separately and in combination, significantly reduced forb diversity (Zavaleta et al. 2003). In arid ecosystems of southern California, elevated N deposition and changing precipitation patterns have promoted the conversion of native shrub communities to communities dominated by a few species of annual non-native grasses. A change in biodiversity can also affect ecosystem function, such as increasing fire risk where fuel accumulation was previously rare (Rao et al. 2010).

- Another example of climate-N interactions on biodiversity involves the combined effects of earlier snowmelt and increased N deposition. Earlier snowmelt in high elevation sites has caused earlier starts to the growing season, thus increasing the exposure of some plants to killing frosts (Inouye 2008). Deposition of N has been associated with greater frost sensitivity in conifer species (Perkins et al. 2000). The combination of more frequent frosts and greater plant sensitivity to those frosts can cause greater mortality of those species.

- Coastal ecosystem biodiversity can become more or less sensitive to N pollution due to climate-driven changes in water residence time, ocean currents, and stratification. For example, the New York Harbor estuary has experienced more occurrences of algal blooms and has become more eutrophic because summer water residence times have increased (less flushing) as a result of less winter snowpack in the Adirondack Mountains (Howarth et al. 1999). The St. Lawrence Estuary and Gulf of St. Lawrence have also become hypoxic in recent years, as their bottom waters now come more from the deep Atlantic water and less from the Labrador Current (Gilbert et al. 2005, Howarth et al. 2011a). Moreover, due to greater stratification, productivity in the Dead Zone area in the Gulf of Mexico has become co-limited by P, causing less N uptake, more Nr loss in coastal environments, and greater transport of Nr to deeper waters (Sylvan et al. 2006, Donner and Scavia 2007).

Air pollution and human health (Chapter 7)

- Nitrogen oxides, O_3, and fine particulate matter ($PM_{2.5}$) pollution related to atmospheric emissions of Nr and other pollutants can cause premature death and a variety of serious health effects (USEPA 2006; USEPA 2008; USEPA 2009). Recent studies have provided evidence that the adverse health consequences of

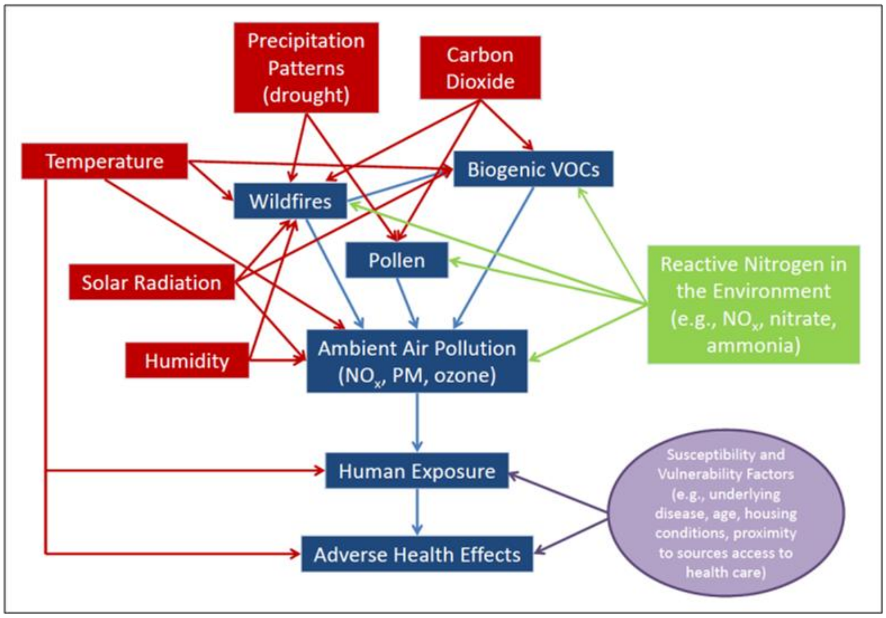

Figure 1.6: Interactions of climate change factors, Nr and their impact on air quality and human health. (See also Figure 7.1, Section 7.0 in Chapter 7).

ambient O_3 pollution increase when temperatures are higher (Jacob and Winner, 2009). Changes in temperature and precipitation patterns are projected to both lengthen the O_3 season and intensify high O_3 episodes in some areas. A longer O_3 season could result in O_3 exposure overlapping the spring and fall respiratory viral and asthma seasons. In addition, there is evidence that O_3 and other pollutants can enhance the susceptibility to and the severity of respiratory infections and increase sensitization to allergens (Chauhan and Johnson 2003; Ciencewicki and Jaspers 2007; Rusznak et al. 1996).

- Other climate-related changes may increase the atmospheric release of N-containing air pollution precursors and reactants by impacting wildfire regimes, emissions from soil, and volatile organic carbon (VOC) emissions from terrestrial ecosystems. Increases in climate-induced anthropogenic NO_x emissions are more likely during the summer, when extreme O_3 events are most common and when O_3 formation is most sensitive to NO_x emissions (e.g., Jacob 1999; Liao et al 2010; Weaver et al 2009).

- The impact of climate change on $PM_{2.5}$ levels is less clear than for O_3. While climate-induced severe air stagnation events can lead to increased pollutant levels, $PM_{2.5}$ formation is expected to decrease in areas where rainfall is expected to increase and/or become extended. Higher temperatures will also shift the thermodynamic equilibrium away from nitric acid combining with NH_3 to form the ammonium nitrate (NH_4NO_3) aerosol, leading to lower levels of that aerosol product (Stelson and Seinfeld, 1982, Dawson et al., 2007; Mahmud et al., 2010). Accordingly, the impact that climate change will have on $PM_{2.5}$ will likely vary regionally.

- Vulnerability to the joint impacts of N-related air pollutants and global climate change will reflect the non-uniform distribution of human exposures (Morello-Frosch et al. 2011). Furthermore, vulnerability to the impact of both air pollution and temperature is greater in the absence of air conditioning, which has been shown to prevent or reduce infiltration of many ambient air pollutants indoors as well as to affect vulnerability to heat waves. This vulnerability has been shown to covary with socioeconomic status, education, poverty and race, social isolation, age, and pre-existing diseases (e.g., diabetes; Reid et al. 2009).

- Although some components of air quality have been improving in the US and are expected to improve further as NO_X emissions decrease due to current control programs, air pollution may worsen even with future NO_X emissions reduction due to the “climate penalty” (Wu et al. 2008). In other words, the same amount of NO_X reduction may result in less O_3 mitigation in a warmer world.

In addition to analyzing these main points and others, each of the following chapters also provides a list of research needs for improved understanding of climate-N interactions.

Conclusions

Analysis of the drivers of climate change, adaptation options, and the severity of impacts requires in-depth understanding of many interactions between climate change and human alteration of the N cycle. Perturbations of both climate and the N cycle will cause multiple stressors to ecosystem function and human health that are likely to be additive or synergistic. Although our knowledge of those interactions is incomplete, we know a great deal about mitigation of climate change and mitigation of excess N in the environment. As with climate change, political and economic impediments often stand in the way of mitigating releases of excess N to the environment (Davidson et al., 2012). However, we demonstrate in this report that policies aimed at improving N-use efficiencies in agriculture and reducing emissions from transportation and energy sectors would have multiple interacting benefits for climate mitigation and for minimizing climate change impacts on crop productivity, air and water quality, biodiversity, and human health risks.

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