

# The role of nitrogen in climate change and the impacts of nitrogen–climate interactions in the United States: foreword to thematic issue

Emma C. Suddick · Penelope Whitney ·  
Alan R. Townsend · Eric A. Davidson

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**Abstract** Producing food, transportation, and energy for seven billion people has led to large and widespread increases in the use of synthetic nitrogen (N) fertilizers and fossil fuel combustion, resulting in a leakage of N into the environment as various forms of air and water pollution. The global N cycle is more severely altered by human activity than the global carbon (C) cycle, and reactive N dynamics affect all aspects of climate change considerations, including mitigation, adaptation, and impacts. In this special issue of *Biogeochemistry*, we present a review of the climate–nitrogen interactions based on a technical report for the United States National Climate Assessment presented as individual papers for terrestrial and aquatic ecosystems, agriculture and human health within the US. We provide a brief overview of each of the paper’s main points and conclusions is presented in this foreword summary.

**Keywords** Nitrogen · Climate change · Interactions · US

## Introduction

In the last 50 years, synthetic fertilizer production, widespread cultivation of leguminous crops, and a variety of industrial processes including fossil fuel use have greatly increased the release of reactive nitrogen (Nr) to the environment (Vitousek et al. 1997; Galloway et al. 2004, 2008). Globally, the N cycle is perhaps the most altered of the major biogeochemical cycles, with serious implications for human health, biodiversity, and air and water quality (Vitousek et al. 1997; Galloway et al. 2008; Townsend and Howarth 2010; Davidson et al. 2012). Moreover, Nr’s unwanted consequences can be further aggravated by climate change, and vice versa. Reactive nitrogen moves easily through the atmosphere, from air to water and to soil and back to plants, therefore, in its numerous chemical forms, Nr plays a critical role in all aspects of climate change considerations, including mitigation, adaptation, and impacts (Davidson et al. 2012).

The collection of papers within this *Biogeochemistry* special issue originated from a July 2011 workshop in Fort Collins, CO, at the US Geological Survey John Wesley Powell Center for Analysis and Synthesis. The central objective of the workshop was

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E. C. Suddick (✉) · E. A. Davidson  
The Woods Hole Research Center, 149 Woods  
Hole Road, Falmouth, MA 02450, USA  
e-mail: esuddick@whrc.org

P. Whitney  
Resource Media, 101 Montgomery St., Suite 2600,  
San Francisco, CA 94104, USA

A. R. Townsend  
Department of Ecology and Evolutionary Biology,  
University of Colorado, INSTAAR, 1560 30th St.,  
Boulder, CO 80303, USA

to provide in-depth analysis of climate–nitrogen interactions in both terrestrial and aquatic systems for consideration by the United States National Climate Assessment (US-NCA) for the 2013 National Climate Assessment report. The papers in this special issue reflect much of the workshop input to the US-NCA, and highlight some of the most important climate–N interactions in terrestrial, aquatic and agricultural systems, as well as those relevant to human health concerns.

### Mitigation

Nitrogen cycling affects atmospheric concentrations of the three most important anthropogenic greenhouse gases in terms of total current radiative forcing: carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). Therefore, mitigation of excess Nr would both reduce N<sub>2</sub>O emissions and affect CO<sub>2</sub> and CH<sub>4</sub> in complex ways (Pinder et al. this issue). These include how N affects C sequestration in forests and soils, and how atmospheric CH<sub>4</sub> concentrations are affected by the chemistry of nitrogen oxides (NO<sub>x</sub>) and ozone (O<sub>3</sub>) of which NO<sub>x</sub> is a precursor in the lower atmosphere. Several 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 (Pinder et al. 2012). However, most evidence suggests that minimizing Nr release to the environment would slow the rate of climate change over the next century (Townsend et al. 2012).

### Adaptation

Understanding how nitrogen cycling affects climate change is essential, especially as adaptation to climate change involves changes in energy and water use. Although considerable progress has been made in lowering nitrogen oxide (NO<sub>x</sub>) pollution from energy, industry, and transportation sectors in the US, this progress could slow or be reversed if energy use increases to adapt to climate change, such as to provide additional energy for air conditioning or to pump and treat water.

Adaptations to increasing water scarcity, which many regions will experience with climate change, may include greater use of surface and groundwater (Gleick 2003). This will likely exacerbate problems of

elevated nitrate (NO<sub>3</sub><sup>−</sup>) concentrations in waters draining to rivers, lakes, groundwater and estuaries, leading to eutrophication, costly drinking water treatments (Hoagland et al. 2002), or increased incidents of nitrate-related disease (Johnson et al. 2010). In agriculture, improvements in nutrient management such as proper timing and use of fertilizer will reduce N releases and could also provide some adaptive protection to crops from climate variability (Bruulsema et al. 2009). Yet unpredictable weather will also make efficient nutrient management more difficult for farmers and may worsen downstream and downwind problems: drought will cause a buildup of NO<sub>3</sub><sup>−</sup> in soils and estuaries, and flooding will cause fertilizer and manure that has been applied to crops to be released more rapidly downstream and into the atmosphere (Davidson et al. 2012).

### 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<sub>x</sub> emissions will be needed to achieve the same reductions of O<sub>3</sub> pollution under higher temperatures (Wu et al. 2008). Such a “climate penalty” will impose challenges to avoid harmful impacts of O<sub>3</sub> pollution on human health (Racherla and Adams 2009) and crop productivity (Mauzerall and Wang 2001). 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<sub>3</sub>) 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 (Rotz 2004; Montes et al. 2009; Hristov et al. 2011). 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 (Rao et al. 2010). Less is known about the interacting effects N and climate on biodiversity, but additive or synergistic effects are indicated (Porter et al. this issue). The impacts of climate–N interactions on carbon (C) sequestration, agricultural productivity, aquatic ecosystems and water quality, biodiversity, and air pollution are analyzed in detail in the individual papers of this special issue.

### Intentional versus unintentional N Use in the US

Using mass-balance principals and pre-existing data on long-term trends in Nr creation, Houlton et al. (this issue) examine Nr use efficiencies within the food, fiber, energy and industrial sectors of the continental US. Estimates show that human actions in the US have increased Nr inputs into the environment by at least ~5 times compared to pre-industrial conditions.

- Focusing on two time points (2002 and 2007, for which all major N flow data were available and no major changes in Nr were observed), humans introduced approximately 29 Tg ( $10^{12}$  g) of newly formed Nr into the US; with 24.7 Tg N intentionally occurring through the Haber–Bosch process to create N fertilizers and the cultivation of crops that biologically fix N (C-BNF). The remainder, approximately 15–20 % of the total, occurs from unintentional N fixation derived from vehicle use, fossil fuel combustion by stationary power plants, industrial boilers, and other similar processes. This is compared to the 6.5 Tg N year<sup>-1</sup> fixed naturally from lightning strikes (2 %) and biological nitrogen fixation (BNF; 98 %) (SAB 2011).
- On an annual basis, about 54 % (13.7 Tg N) of Nr intentionally introduced into the US is converted to food, livestock feed, biofuel (energy), or industrial products. 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, making it the dominant sink for intentional Nr in the US.
- For the US an estimated 2 % of intentional Nr escapes to the atmosphere as N<sub>2</sub>O, where it contributes to climate change (Pinder et al.

2012), and 12 % as NO<sub>x</sub> and NH<sub>3</sub> to the air where it contributes to poor air quality via tropospheric O<sub>3</sub> and particulate matter (Muller and Mendelsohn 2007). An uncertain fraction—from 3 to 21 %—of Nr is converted to N<sub>2</sub>, an effectively unreactive and stable form of N in the Earth system.

- Leaching of N to surface waters and groundwater has also increased substantially in the US and around the globe. Houlton et al. (this issue) estimate that approximately 13 % (4–5 Tg N) is released into the hydrosphere where it contributes to eutrophication (Diaz and Rosenberg 2008) and drinking water risks (Ward et al. 2005).

### Nitrogen's contribution to climate change: radiative forcing

A direct affect on global warming occurs through emissions of N<sub>2</sub>O, a greenhouse gas ~300 times more potent than CO<sub>2</sub>, with long-term warming effects because of its >100 year residence time in the atmosphere. Most of the increases in N<sub>2</sub>O come from fertilized agricultural soils and from livestock manure, about 0.48 million tons of N<sub>2</sub>O-N year<sup>-1</sup>, which is about 80 % of total anthropogenic US N<sub>2</sub>O production (the remainder derives from energy and industrial sources) (US-EPA 2011). Pinder et al. (this issue) review the climate change impact of Nr and N cycle process on radiative forcing in the US and calculate the global temperature potential (GTP) over a 20 year or 100 year time period.

- Overall, the effect of N cycling processes in the US on global warming is probably a modest cooling effect for a 20-year time frame, and a modest warming for a 100-year time frame. In short, combustion sources of Nr that are likely causing cooling are declining in the US due to enforcement of air pollution regulations for human health. In contrast, most agricultural sources of Nr cause long-term warming, especially N<sub>2</sub>O, and these are mostly unregulated and are increasing.
- Emissions of NO<sub>x</sub>, indirectly affect radiative forcing through the effects on atmospheric concentrations of CH<sub>4</sub>, O<sub>3</sub>, 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 net cooling effect on time scales of days to decades, becoming insignificant on longer time scales (Boucher et al. 2009).

- Emissions of  $\text{NO}_x$  and  $\text{NH}_3$  are chemically transformed and eventually deposited onto ecosystems via wet (e.g., rain or snow) and dry (e.g., wind) deposition. This increases the availability of N to ecosystems, which can affect the sources and sinks of  $\text{N}_2\text{O}$ ,  $\text{CH}_4$ , and  $\text{CO}_2$ , 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 (Butterbach-Bahl 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.

### Nitrogen–climate interactions and impacts

Climate change will almost certainly increase the release of Nr, which in turn will impact agriculture, land and aquatic ecosystems and human health. In each of these sectors, a changing climate and greater Nr release can then interact in a variety of ways, further complicating attempts to manage and maintain key ecosystem services.

#### Agriculture

Robertson et al. (this issue) review literature to understand N cycling and climate change-N interactions and the subsequent impact on agricultural systems. Climate change-N interactions affect agricultural productivity in part through exposure of crops to elevated  $\text{O}_3$ . These interactions will also result in greater emissions of Nr from livestock and cropping systems. Climate change impacts including drought, heat, and higher rainfall will hinder the ability of farmers to match crop needs with appropriate fertilizer applications, causing additional N releases to water

and air, especially if higher fertilizer rates are used to meet climate challenges on crop growth.

- Increases in temperature can lead to higher rates of precursor emissions and  $\text{O}_3$  formation. Based on large-scale experimental studies in the US (Heagle 1989; Heck 1989), higher  $\text{O}_3$  levels will decrease crop growth and yield in a variety of crops (Mills et al. 2007; Emberson et al. 2009). Model simulations of  $\text{O}_3$  used with these established concentration and yield response relationships predict larger effects for grain crops for 2000 and 2030 (Avnery et al. 2011a, b).
- Projected temperature changes will increase  $\text{NH}_3$  emissions throughout all phases of manure handling (Montes et al. 2009), likely hampering the efforts of livestock industries to improve N use efficiency and causing greater losses of Nr to the environment. 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 1.7–2.4 billion dollars in the US livestock sector (St-Pierre et al. 2003).
- Flooding and extreme precipitation can also cause major releases of Nr as excess water drains from fields and through gaseous losses of  $\text{N}_2\text{O}$  from wet soils. Increased  $\text{NO}_3^-$  flushed from agricultural systems due to irregular precipitation (Davidson et al. 2012) will pose greater risks to groundwater and drinking water safety.

#### Aquatic ecosystems and resources

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). For many US watersheds, the relative increase is far greater, sometimes exceeding an order of magnitude. A review of Nr inputs to various aquatic systems through literature sources and model outputs by Baron et al. (this issue), have shown that nearly all freshwaters and coastal zones in US are degraded by N pollution, including remote sources in alpine regions such as Rocky Mountain National Park

in Colorado. Inputs to river systems were estimated with the USGS SPARROW model to be 4.8 Tg N year<sup>-1</sup> 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 year<sup>-1</sup> (Boyer et al. 2006). Adverse effects range from eutrophication and acidification to human health risks, biodiversity loss, and economic costs to fisheries and tourism from the increased frequency of harmful algal blooms (Bricker et al. 2007; SAB 2011).

Aquatic ecosystems are critically important to N processing because of their ability to transform Nr into unreactive N<sub>2</sub> gas during denitrification (although some N<sub>2</sub>O is also produced). One estimate suggests one-fifth of global denitrification occurs in freshwater such as lakes and rivers (Seitzinger et al. 2006). 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 effect of climate change on N processing in fresh and coastal waters will be felt most strongly through precipitation changes. This will speed or slow runoff, thereby influencing the rate Nr is added to aquatic systems and groundwater, and the average time water resides in a body of water such as a reservoir, a process that aids N removal. Other impacts include:

- More extreme precipitation events will flush fertilizer or manure into streams or groundwater. Freshwater bodies such as lakes will have less time to process and reduce excess N before it travels further downstream or is transported into the atmosphere.
- Algal blooms, which are linked to nutrient enrichment and warm waters (Heisler et al. 2008), will occur more frequently. These have been linked to human health impacts, 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).
- 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<sub>3</sub><sup>-</sup> (Johnson et al. 2010).
- American reliance on groundwater for drinking water is expected to increase under future climate change scenarios. In addition, there will likely be increases in costs for treating drinking water to avoid exposure to NO<sub>3</sub><sup>-</sup>, which contributes to the formation of N-nitroso compounds associated with cancer, diabetes, and reproductive problems such as premature birth (Ward et al. 2005). At present, approximately 1.2 million Americans use private, shallow groundwater wells in areas with estimated NO<sub>3</sub><sup>-</sup> concentrations between 5 and 10 mg L<sup>-1</sup>, and about 0.5 million use groundwater in areas with estimated NO<sub>3</sub><sup>-</sup> > 10 mg L<sup>-1</sup> (Nolan and Hitt 2006). A recent study showed that the maximum NO<sub>3</sub><sup>-</sup> contaminant level of 10 mg L<sup>-1</sup> 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<sub>3</sub><sup>-</sup> 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).

## Biodiversity

Biodiversity loss is caused by loss of habitat, overexploitation, invasive species, climate change, and pollution, including N pollution (Millennium Ecosystem Assessment (MEA) 2005; Hooper et al. 2012). Porter et al. (this issue) review and show that the results from both empirical studies and modeling indicate N pollution coupled with climate change can drive species losses that are greater than those caused by either stressor alone; including favoring the growth of fast-growing non-native species that favor or can adapt to high levels of N.

- For example, controlled experiments in California grassland have shown that increased N and CO<sub>2</sub>, 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).



- Earlier snowmelt in high elevation sites has caused earlier starts to the growing season, increasing the exposure of some plants to killing frosts (Inouye 2008). Excess N deposition 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 die-off of those species.
- Some estuaries, such as the New York harbor estuary, have experienced more occurrences of algal blooms and become more eutrophic. In New York, this is due to less winter snowpack in the Adirondack Mountains, which has increased the amount of time water resides in the estuary over the summer and decreases N flushing (Howarth et al. 1999). In addition, 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 phosphorus (P), causing less N uptake, more N<sub>r</sub> loss in coastal environments, and greater transport of N<sub>r</sub> to deeper waters (Sylvan et al. 2006; Donner and Scavia 2007).
- result in O<sub>3</sub> exposure overlapping the spring and fall respiratory viral and asthma seasons. In addition, there is evidence that O<sub>3</sub> and other pollutants can enhance the susceptibility to and the severity of respiratory infections and increase sensitization to allergens (Chauhan et al. 2003; Ciencewicz and Jaspers 2007; Ruzsnaik 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<sub>x</sub> emissions are more likely during the summer, when extreme O<sub>3</sub> events are most common and when O<sub>3</sub> formation is most sensitive to NO<sub>x</sub> emissions (e.g., Jacob 1999; Liao et al. 2010; Weaver et al. 2009).
- The impact of climate change on PM<sub>2.5</sub> levels is less clear than for O<sub>3</sub>. While climate-induced severe air stagnation events can lead to increased pollutant levels, PM<sub>2.5</sub> 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<sub>3</sub> to form the ammonium nitrate (NH<sub>4</sub>NO<sub>3</sub>) 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<sub>2.5</sub> 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<sub>x</sub> emissions decrease due to

### Air pollution and human health

Nitrogen pollution plays an important role in air quality and the resulting impacts on human health (Peel et al. this issue). Emissions of N<sub>r</sub> released into the atmosphere from agriculture, industry, and urban areas contribute to high levels of fine particulate matter (PM<sub>2.5</sub>), ground-level O<sub>3</sub>, and NO<sub>x</sub> in the air we breathe and can cause premature death and a variety of serious health effects (US-EPA 2006, 2008, 2009). In addition, NO<sub>x</sub> is a key component of O<sub>3</sub> creation in the lower atmosphere, which affects air quality for both human health and crop productivity.

- Changes in temperature and precipitation patterns are projected to both lengthen the O<sub>3</sub> season and intensify high O<sub>3</sub> episodes in some areas. Recent studies have provided evidence that the adverse health consequences of ambient O<sub>3</sub> pollution increase when temperatures are higher (Jacob and Winner 2009). A longer O<sub>3</sub> season could

current control programs, in a warmer world, larger reductions in  $\text{NO}_x$  will be needed to achieve the same reductions of ozone due to the “climate penalty” (Wu et al. 2008). Air pollution may worsen even if current regulations continue to reduce  $\text{NO}_x$  emissions.

### Potential mitigation solutions

Reducing N pollution can be used as a lever to avert or slow impending climate impacts. 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 (Townsend et al. 2012). To date, the greatest success has been through the Clean Air Act enforcement, which has dramatically reduced industrial and transportation  $\text{NO}_x$  emissions from smokestack and combustion sources.

In addition, the opportunities for further reductions are greatest in agricultural systems, since its use of N is often inefficient. Applying current practices and technologies could reduce Nr pollution from farm and livestock operations by 30–50 % (Robertson and Vitousek 2009; Davidson et al. 2012). They include managing fertilizer timing, optimizing fertilizer use, and implementing wetlands, wood chip trenches, cover crops, and streamside vegetation to mitigate excess N released into the environment. While agriculture is the major source of N pollution in the US and worldwide, there is little national awareness of the connection between agricultural activities and human health that would spur effective regulatory action. Outside of N pollution hotspots like the Chesapeake Bay or Gulf of Mexico, which have borne economic costs to their fisheries, there has been little political will to improve agricultural management and reduce agricultural releases. As efforts to reduce N pollution are not as nationally politicized as the climate debate, focusing on reducing Nr from agriculture, with its co-benefits for reducing human health risks, could offer promise.

Emphasizing the damage costs of Nr on clean air, safe drinking water and fisheries could build the public will and support for funding federal agricultural

conservation programs to extensively reduce N releases. A recent EPA study by Compton et al. (2011) showed that the human health costs of  $\text{NO}_x$  releases are about \$23 per kilogram. Looking at coastal eutrophication, the cost of fisheries decline in the Gulf of Mexico is estimated to be \$56 per kilogram of excess Nr released. Most importantly, prevention costs were found to be far less than the total costs of the resulting pollution, with current efforts in Chesapeake Bay to prevent and reduce N loads into the Bay ranging from \$8 to \$15 per kilogram. Clearly, action is needed, as reducing Nr releases from all sectors will almost certainly help slow the rate of climate change over the next century.

Perturbations to 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 special issue of *Biogeochemistry* that policies aimed at improving national N use efficiencies (NUE) would: (i) benefit the US economy on the production side; (ii) reduce social damage costs; and (iii) help avoid some major climate change risks in the future.

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