Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions

James N. Galloway,†,‡ Alan R. Townsend,§ Jan Willem Erisman,∥ Mateeek Bekunda,¶ Zucong Cai,¶ John R. Freney,¶ Luiz A. Martinelli,¶ Sybil P. Seitzinger,¶ Mark A. Sutton¶

Humans continue to transform the global nitrogen cycle at a record pace, reflecting an increased combustion of fossil fuels, growing demand for nitrogen in agriculture and industry, and pervasive inefficiencies in its use. Much anthropogenic nitrogen is lost to air, water, and land to cause a cascade of environmental and human health problems. Simultaneously, food production in some parts of the world is nitrogen-deficient, highlighting inequities in the distribution of nitrogen-containing fertilizers. Optimizing the need for a key human resource while minimizing its negative consequences requires an integrated interdisciplinary approach and the development of strategies to decrease nitrogen-containing waste.

Our understanding of reactive nitrogen (Nr) (1) and the N cycle has shifted from how to promote food production to a realization that agricultural intensification damages environmental systems (2). Since 1970, world population has increased by 78% and reactive nitrogen creation has increased by 120%. In 1970, Delwiche stated, “The ingenuity that has been used to feed a growing world population will have to be matched quickly by an effort to keep the nitrogen cycle in reasonable balance” (3). Thirty-five years later, Dobermann and Cassman pointed out, “Failure to arrest the decrease in cereal crop area and to improve nitrogen use efficiency in the world’s most important agricultural systems will likely cause severe damage to environmental services at local, regional, and global scales due to a large increase in reactive N load in the environment (4).”

It is clear that an optimum has not been achieved. In some parts of the world,Nr has been used to create an excess of food and a growing prevalence of unhealthy diets, while also contributing to a host of environmental problems (2, 5–7). Yet, other world regions lack sufficient Nr to meet even the most basic caloric demands of hundreds of millions of people (8).

Major research and management challenges remain and are becoming ever more pressing as the creation and use of Nr continues to accelerate. Although diverse management strategies are necessary, they are also possible, and we believe a more favorable balance between the benefits and unwanted consequences of Nr can be achieved.

Continued Acceleration of Nr Creation

Nr creation continues to increase every year. It is dominated by agricultural activities, but fossil fuel energy plays an important role, and the growing prevalence of biofuels is adding a new and rapidly changing dimension. From 1860 to 1995, energy and food production increased steadily on both an absolute and per capita basis; Nr creation also increased from ~15 Tg N in 1860 to 156 Tg N in 1995. The change was enormous, and it increased further from 156 Tg N yr⁻¹ in 1995 to 187 Tg N yr⁻¹ in 2005, in large part because cereal production increased from 1897 to 2270 million tons (20%), and meat production increased from 207 to 260 million tons (26%) (9). These rising agricultural demands were sustained by a rise in Nr creation by the Haber-Bosch process from 100 Tg N yr⁻¹ to 121 Tg N yr⁻¹ (20%) (9). Cultivation-induced biological nitrogen fixation (C-BNF) occurs in several agricultural systems, with crop, pasture, and fodder legumes being the most important (10). The C-BNF estimate for 1995 was 31.5 Tg N (5) and, because of the increase in soybean and meat production over the past decade, we estimate that in 2005 C-BNF was 40 Tg N. There is substantial uncertainty in this value, and this is a critical area where more precise data are needed. In parallel, primary commercial energy production by coal, natural gas, and petroleum combustion increased from 8543 million tons of oil equivalents (mtoe) to 10,600 mtoe (24%), much of it in the developing world (11). However, decreases in NOx emissions in the developed world, among other reasons, led to a relatively constant global creation rate of Nr–NOx of ~25 Tg N yr⁻¹ from 1995 to 2000 (12), and we assume for the purpose of discussion that this value also holds for 2005.

Finally, an important but poorly understood aspect of N mobilization is industrial Nr use. NH₃ from the Haber-Bosch process is used as a raw material to create multiple products, including nylon, plastics, resins, glues, melamine, animal/fish/shrimp feed supplements, and explosives. In 2005, ~23 Tg N was used for chemical production (13), accounting for 20% of Haber-Bosch Nr, but little is known about the fate of Nr used in these industrial activities.

Nr Distribution Patterns Are Changing

In 2004, ~45 Tg N of the ~187 Tg N of Nr created was traded internationally (Fig. 1), and in the preceding decade, global trade of N commodities increased twice as fast as the rate of Nr creation. Unlike aquatic or atmospheric transport, where Nr is diluted to varying degrees, commerce typically results in injection of Nr to ecosystems in more concentrated doses. Although this has the potential to cause greater damage to a smaller region, it also allows the possibility of greater control over Nr release. However, the rise in international trade is posing new socioeconomic questions, such as who pays for environmental damage associated with Nr losses (14). Regions that consume N-containing products, such as meat and milk, may be far removed from regions that produce the commodity and thus do not have to bear the environmental cost of the production. For example, in 1910, The Netherlands used 13 k tonne of fertilizer N yr⁻¹ to produce food for its population of 6 million. In 1999, for the same agricultural area, 400 k tonne N yr⁻¹ fertilizer N was used, and the yields were enough to feed 32 million people, only half of whom lived in The Netherlands. The rest of the food, and the Nr it contained, was exported, whereas the Nr lost in the food-production process remained in the Dutch environment, causing increased groundwater pollution, ambient ammonia and particle emissions, and nitrogen deposition (15). Similarly, areas of Latin America are bearing the cost of land conversion for soy that is fueling rising meat consumption in Asia (14).

On a global basis, atmospheric transport and subsequent deposition has become the dominant Nr distribution process. It is estimated that in 1860, 34 Tg N yr⁻¹ of Nr was emitted as NOx and NH₃ and then deposited to the Earth’s surface as NOY and NHx; in 1995, it had increased to 100 Tg N yr⁻¹; by 2050, it is projected to be 200 Tg N yr⁻¹. N deposition to ecosystems in the absence of human influence is generally
reviews

~0.5 kg N ha\(^{-1}\) yr\(^{-1}\) or less (16). There are now large regions of the world where average N deposition rates exceed 10 kg N ha\(^{-1}\) yr\(^{-1}\), greater than an order of magnitude increase compared with natural rates. By 2050, this may double, with some regions reaching 50 kg N ha\(^{-1}\) yr\(^{-1}\) (5), and landscape-level inputs may be much larger, especially for forest ecosystems (17). These rates are well in excess of the critical loads that have detrimental impacts on receiving ecosystems (18) (Fig. 2). Critical loads for the open ocean have not been calculated, but Duce et al. (19) conclude that the increasing amounts of atmospheric anthropogenic N\(_r\) entering the ocean could increase annual new marine biological production by \(~3\%\) and increase the emission of N\(_2\)O to the atmosphere by \(\sim 1.6 \text{Tg N yr}^{-1}\).

Given the growing importance of the atmosphere in N\(_r\) distribution, it is critical to get a better understanding of emissions rates. There is a relatively good understanding of NO\(_x\) emissions from fossil fuel combustion, but less so from biomass burning and soil emissions. The largest uncertainties are in the NH\(_3\) emissions rates, from all sources, on all scales (17). There are also critical questions about the fate and impact of the N deposited to terrestrial, freshwater, and marine realms.

**Vexing Questions**

N\(_r\) creation is still accelerating, a trend unlikely to change in the near future. The additional anthropogenic N\(_r\) affects climate, the chemistry of the atmosphere, and the composition and function of terrestrial and aquatic ecosystems (2). Moreover, because a single molecule of reactive N can “cascade” through the environment, it can contribute to more than one of these environmental responses (20). Yet, we also know that N\(_r\) creation is essential to support a burgeoning human population (21) and that hundreds of millions of people still suffer from a “fertilizer deficit” (8). Finally, we know that environmental changes wrought by excess N\(_r\) can feed back to affect human health and welfare, both directly, for example through increased production of atmospheric particulate matter, and indirectly through impacts on food production (6). Thus, the grandest overall challenge posed by a changing N cycle is how to maximize the benefits of anthropogenic N\(_r\) while minimizing its unwanted consequences (see www.initrogen.org).

Although the role of N\(_r\) in multiple aspects of environmental change is undeniable, important research questions remain unresolved. We have identified five broad categories of questions that are priorities for future research.

*What is the ultimate fate of N\(_r\)?* Although data on the creation of anthropogenic N\(_r\) are relatively well constrained, those on its fate are uncertain. For example, in the mid-1990s, the fate of only 35% of N\(_r\) inputs to the terrestrial biosphere was relatively well known: 18% was exported to and denitrified in coastal ecosystems, 13% was deposited to the ocean via the marine atmosphere, and 4% was emitted as N\(_2\)O (5). Thus, the majority (65%) either accumulated in soils, vegetation, and groundwater or was denitrified to dinitrogen (N\(_2\)).

Even with these uncertainties, it is likely that denitrification is an important N\(_r\) sink. The first spatially explicit pattern of denitrification from soils to the coastal ocean suggested that more than 80% of denitrification is occurring in soils and freshwater systems (groundwater, rivers, lakes, and reservoirs). The bulk of the remainder (~15%) appears to occur in continental shelf sediments, thus indicating that rivers, although important sources to coastal systems, are typically small sources of N\(_r\) to the open ocean, even in heavily altered regions (22).

There is a growing database on N\(_r\) riverine fluxes, and several models are available that relate watershed characteristics to N\(_r\) flux (23, 24). Even with these advances, some of the largest uncertainties in measuring denitrification rates are in upland terrestrial systems, which seem to account for a considerable, but unknown, N\(_r\) “sink.” N\(_r\) inputs to these systems continue to rise, however, so the question is whether the fraction of N\(_r\) exported to the coasts will remain small or whether upland “sinks” will saturate to allow greater N\(_r\)-fueled coastal change.

Rising levels of atmospheric deposition also lend urgency to multiple questions about the fate of N\(_r\). Ultimately, the fate of N\(_r\) that enters terrestrial systems appears to be under strong climatic control (25), an interaction that helps explain regional differences in N export and that should be considered in forecasts of future N cycle dynamics. The fate and impacts of N\(_r\) are also often dependent on its chemical form,
further highlighting the need to better resolve changing inputs of oxidized versus reduced forms of Nr.

What are the net climate effects of increasing Nr? Nitrogen is both influenced by and affects climate; the net contributions of anthropogenic Nr to a changing climate remain widely debated (17, 26). Nr can directly increase radiative forcing in the troposphere, principally through the production of N_2O and tropospheric O_3, but atmospheric Nr can also have cooling effects (26), largely through tropospheric aerosols and stratospheric O_3 declines. Moreover, Nr has strong interactions with the carbon (C) cycle that can have global-scale effects on atmospheric carbon dioxide (CO_2) and methane (CH_4) (27, 28).

Elevated Nr deposition may stimulate plant growth in N-limited regions and cause substantial CO_2 uptake in Northern Hemisphere forests, although the size is controversial (see SOM text). N-driven C storage in nonforested or agricultural systems appears modest at best, and N-fueled increases in tropospheric O_3 can reduce C uptake in all systems (29). It remains a major research challenge to quantify all relevant N interactions sufficiently to estimate the net effect of Nr on climate forcing (17, 26).

How will tropical regions respond to rising Nr inputs? Much of our knowledge on N dynamics is from the temperate world, yet tropical regions will receive the most dramatic increases in Nr inputs over the next few decades [see, e.g., (30)]. Some tropical regions already experience elevated Nr deposition, acidic deposition, and aquatic eutrophication (31), both from urban development and from a combination of agricultural extensification and intensification. The tropospheric O_3 pose direct health threats to humans.

A Strategy for Now

There is compelling evidence that human alteration of the N cycle is negatively affecting human and ecosystem health. As demands for food and energy continue to increase, both the amount of Nr created and the magnitude of the consequences will also increase. Given the complexities of Nr use, its environmental mobility, and differences among regions, no single strategy will suffice (40).

How will biofuel development alter the N cycle? The rapid development of biofuels has created an entirely new link between human activities and the global N cycle, but the full suite of connections is not well resolved. Currently, much of the world’s biofuels are produced from corn in the United States or sugar cane in Brazil. U.S. corn covers nearly 29 million ha and is fertilized by an average of 160 kg N ha^{-1} yr^{-1}; Brazilian cane covers ~7 million ha and receives an average of 100 kg N ha^{-1} yr^{-1}. As with many intensive agricultural systems, N fertilizer use efficiency in Brazilian sugar cane is low: Only ~30% ends up in plant tissues (38). Thus, most of the applied N reaches the environment, and because the sugar cane area is predicted to double in Brazil by 2016, the biofuel industry will contribute to a rapidly changing tropical N cycle (38). Consequently, N-intensive biofuels could cancel out any CO_2 savings by contributing to both N_2O and tropospheric O_3 production (39). Second-generation biofuels will use more woody biomass from year-round crops and production forests and tend to have much higher conversion efficiencies. Although the full environmental consequences of these systems are also not well understood, their required N use should be smaller than that of current first-generation crops.
REVIEWS

We conclude by stressing two points. First, although reducing Nr creation and its unwanted impacts will be challenging, it is both possible and of critical importance. Second, not all management priorities are about reduction of Nr. Substantial and sustained intervention is also needed in regions that do not have sufficient Nr or other nutrients to sustain the population (8). In such regions, it will be important to seek ways to increase food production while minimizing nutrient loss and its subsequent environmental damages.

References and Notes

1. The term reactive nitrogen (Nr) as used in this paper includes all biologically active, photochemically reactive, and radiatively active N compounds in the atmosphere and biosphere of Earth. Thus, Nr includes inorganic reduced forms of N (e.g., NH₃ and NH₄⁺), inorganic oxidized forms (e.g., NOₓ, HNO₃, N₂O, and NO₃⁻), and organic compounds (e.g., urea, amines, and proteins), by contrast to unreactive N₂ gas.


42. United Nations Environment Programme and Woods Hole Research Center, Paris, Reactive Nitrogen in the Environment: Too Much or Too Little of a Good Thing (2007), Fig. 3.

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Supporting Online Material

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SOM Text

References

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Expansion of Discussion on Interactions of N and C in Terrestrial Ecosystems

The latest IPCC report (S1) undertook the most comprehensive assessment of Nr-climate interactions to date, but several critical components remain uncertain. The potential response of the C cycle offers a good example. Although earlier syntheses based on $^{15}$N additions (S2) and modeled extensions of N budgets had suggested only a modest effect of N deposition on net forest C uptake, a recent synthesis of eddy flux data from northern hemisphere forests concluded that elevated N deposition is creating a sizable C sink (S3). This finding is currently a matter of hot debate, as a major synthesis of European forest inventory data (S4) and a re-analysis of the Magnani et al. dataset (S5) both imply a C:N response that is an order of magnitude smaller than that claimed. In addition, even if an N-stimulated C sink is large, its future persistence is debatable, both because of progressive alleviation of N limitation, and because future increases in N deposition will be most pronounced in equatorial regions where N limitation is thought to be less widespread (S6).
Background Details on Use of Interventions to Decrease Nr Loss to Environment

This material expands on the four intervention points mentioned in the paper’s text and identified in Figure 3.

The first intervention point involves fossil fuel combustion. Using maximum feasible reductions, Nr creation during fossil fuel combustion can be decreased by about 30% of its current level (S7). The barriers to such a decrease are primarily financial, as the scientific, engineering and policy instruments are well developed. Utilizing this available technology, Nr creation from fossil fuel combustion would decrease from ~25 Tg N yr\(^{-1}\) to ~7 Tg N yr\(^{-1}\).

The second intervention point is to increase the N use efficiency (NUE) of crop production. Cassman and colleagues estimate that there will be a 38% increase in global cereal demand by 2025. Compared to continuation of current trends, they project that this demand can be met with a 30% decrease in N fertilizer application to cereals if the decline in cereal harvest area (-0.33% yr\(^{-1}\) over 20 years) is halted and the crop yield response to applied N is increased by 20% (S8). This ‘intervention’ would reduce the global Nr creation rate by ~15 Tg N yr\(^{-1}\).

Third, improving the genetic potential of the herd, animal feeding strategies and manure management would decrease N losses to the environment. It is estimated that improved animal feeding strategies in EU-27 could decrease by 2020 the total N excretion by ~13% and total N losses from animal manure by ~11%. A combination of
improved animal feeding and low-emission techniques could decrease by 2020 total N losses from animal manure in EU-27 by ~30%. Extending this to the world while considering the diversity in herd management, animal feeding and animal manure management, would result in a decrease of ~10-20 Tg lost to the environment (S9). Animal production systems are highly conducive to releasing Nr to the environment, so eating less meat would both substantially decrease Nr losses while having potential health benefits (S10)

The fourth intervention point involves sewage treatment. Each year, the global population produces ~20 Tg N in human waste of which <1% undergoes treatment that will convert it to N₂ (generally tertiary treatment). Even if only half of the 3.2 billion people who live in an urban environment had access to the required level of sewage treatment, this would result in 5 Tg N being converted to N₂.

Supplemental Material References


S6. P. A. Matson, W. H. McDowell, A. R. Townsend, P. M. Vitousek,


