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BEHIND THE PAPER

Reflections on 200 years of Nitrogen, 20 years later

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INTRODUCTION

In 1772, nitrogen was identified as a chemical element; in 1836, nitrogen was also discovered to be an essential element for growth, development, and reproduction of all living things (e.g., plants, animals, insects and microorganisms), but in 1852, certain reactive N compounds were discovered to be the causes of various environmental and public health problems (Galloway et al. 2013).

As the role of N as both a necessity and a problem expanded, so did the scientific literature. By 2000, about 80 papers were published each year using the term 'global nitrogen cycle'[1]. In order to enhance and organize this interest, the First International Nitrogen Conference (N-1998[2]) was held in The Netherlands in 1998. At the end of the conference, Jan Willem Erisman, one of the organizers, announced that Ellis Cowling and Jim Galloway would host the Second International Nitrogen Conference (N-2001[3]) in the USA during the fall of 2001. With the aid of a very helpful organizing committee, N-2001 was convened in Potomac MD in October of that year. In March 2002, a special issue of *Ambio* was published containing 18 overarching papers from the 2001 conference (Galloway et al. 2002). In 2002, Ms. Elizabeth Kessler was the editor-in-chief of *Ambio*, and she asked Cowling and Galloway to join her as guest editors.

It is now our privilege, nearly 20 years after the N-2001 Conference and publication of the *Ambio* special issue, to offer a few reflections on some of the major points made in the conference and the special issue.

[1] Web of Science, July 2020.

[2] https://www.sciencedirect.com/book/9780080432014/nitrogen-the-confer-n-s.

[3] https://digital.library.unt.edu/ark:/67531/metadc827720/.

CREATION OF REACTIVE FORMS OF NITROGEN

The increasing interest in nitrogen over the past two decades is a result of increased conversion of non-reactive N_2 into chemically, biologically, and radiatively active compounds (Nr, defined as all N molecules except N_2) and the subsequent negative impacts on human and environment health.

Each year more Nr is created. In 1990, 140 Tg Nr was created by human activities (Galloway and Cowling 2002). By 2010, 210 Tg N was created (Fowler et al. 2013). In 2020, we estimate that ~240 Tg N will be created—an increase of ~70% relative to 1990. Most of this increase is due to increased use of N fertilizer and increased legume cultivation to satisfy the increased demand for food for a growing global population and an increasing preference for animal protein. With respect to anthropogenic Nr creation, one piece of good news is that society has an almost inexhaustible supply of N via the Haber-Bosch process to produce food. Another piece of good news concerns Nr creation from fossil fuel combustion. Globally, NOx emissions from fossil fuel combustion reached their maximum in ~2000 and have significantly decreased from then, due to air pollution legislation and increased use of renewable energy sources. This is especially true for North America and Europe. Over the next several decades, NOx emissions are projected to continue to decrease in all regions of the world (Lamarque et al. 2010; Ciais et al. 2013).

Reflection: In 2002, creation of Nr was driven by both energy and food production. In 2020 and onward however, food production will become increasingly dominant as the primary source of new Nr.

Nr TRANSPORT AND DEPOSITION

Nr is distributed around the world by water, wind, and commerce. The increase in Nr creation automatically means that there will be more losses to waters and to the atmosphere. The fact that much of the newly created Nr is used in food production means that more commodity-N will be traded internationally (Lassaletta et al. 2014). As an example of the magnitude and extent of future atmospheric transport, Ciais et al. (2013) compared 2090s projected N deposition (two scenarios, Representative Concentration Pathways 2.6 & 8.5) to deposition in the 1990s (similar to Figure 4 in Galloway and Cowling 2002) (Fig. 1). In both scenarios, N deposition is projected to increase dramatically, underscoring the fact that while NOx from fossil fuel combustion is a pollutant, that is not needed and relatively easy to remove, NH_3 emissions from agriculture are driven by the need to provide more food for more and more people.

Reflection: Decreasing N loss from agriculture along the food production supply chain is a conundrum, a wicked problem or just plain hard to do – pick your favorite expression. Until very tight management of N from agricultural fields to sewage treatment plants is optimized, with substantial recycling, the world will continue to have heavy loadings of Nr to the environment.

NITROGEN CASCADE

Now for the bad news. It begins with the fact that ~85% of the N used to produce food is lost to the environment during the food production and consumption processes. The remainder is injected into the environment as human waste because the vast majority of human waste does not undergo advanced wastewater treatment, which enhances denitrification. Once in the environment, Nr contributes to numerous environmental negative impacts connected in time and space by the N Cascade. This concept was introduced by Galloway and Cowling (2002) and then more fully presented by Galloway et al. (2003) (Fig. 2). Simply stated, once the triple bond within the N_2 molecules is broken, the resulting Nr will cascade through environmental reservoirs contributing to negative impacts and will stay active until either converted to N_2 or stored in a long-term reservoir (e.g., long-living forest trees and ocean sediments).

The list of environmental issues and public health associated with the nitrogen cascade has not changed much in the last two decades, but their extent has. For example, groundwater is increasingly contaminated with nitrate (Ward et al. 2018). Hypoxic coastal waters have increased in number and geographical area (Diaz et al. 2019). The troposphere and stratosphere are increasingly burdened by N_2O. In the troposphere, N_2O is a greenhouse gas that contributes to global warming; in the stratosphere, N_2O is the primary destroyer of ozone (Ravishankara et al. 2009).

Reflection: There is a direct connection between Nr creation rate and environmental effects–the more the first increases, the greater the effects will be in scope and magnitude.

Nr MANAGEMENT

The concept of an international organization that focuses on the science and management of nitrogen had its initial beginnings at the First International Nitrogen Conference (N-1998) held in The Netherlands in 1998. The need for such an organization was further articulated at the Second International Nitrogen Conference (N-2001), in Maryland, USA three years later. The overwhelming view of the 400 participants was that some type of international program was required to optimize the benefits of nitrogen and minimize associated problems. In December 2002, the Scientific Committee on Problems of the Environment (SCOPE) agreed to be the founding sponsor of the International Nitrogen Initiative (INI) and in January 2003, and the International Geosphere-Biosphere Program (IGBP) agreed to co-sponsor INI. In March 2003, the formation of the INI[4] program was formally announced at the Annual Meeting of the American Association for the Advancement of Science, less than one year following the March 2002 *Ambio* publication.

One of the organizing principles of the INI was establishing regional centers, given that the issue of Nr management varies greatly by geographical region. The first five INI regional centers were established in 2004 in Africa[5], Asia, Europe[6], Latin America[7], and North America[8]. In 2012, the Asian center was subdivided into the East Asia[9] and South Asia[10] Nitrogen Centers. The INI recently established the Oceania Nitrogen Center. Each center has a director, a vice-director, and an executive committee with representatives from member countries.

Since its creation, INI has sponsored international conferences on a regular basis: China (N-2004[11]), Brazil (N-

[4] https://initrogen.org/.
[5] https://initrogen.org/africa.
[6] https://initrogen.org/europe.
[7] https://initrogen.org/latin-america.
[8] https://initrogen.org/north-america.
[9] https://initrogen.org/east-asia.
[10] https://initrogen.org/south-asia.
[11] http://www.ssa.ac.cn/n2004/.

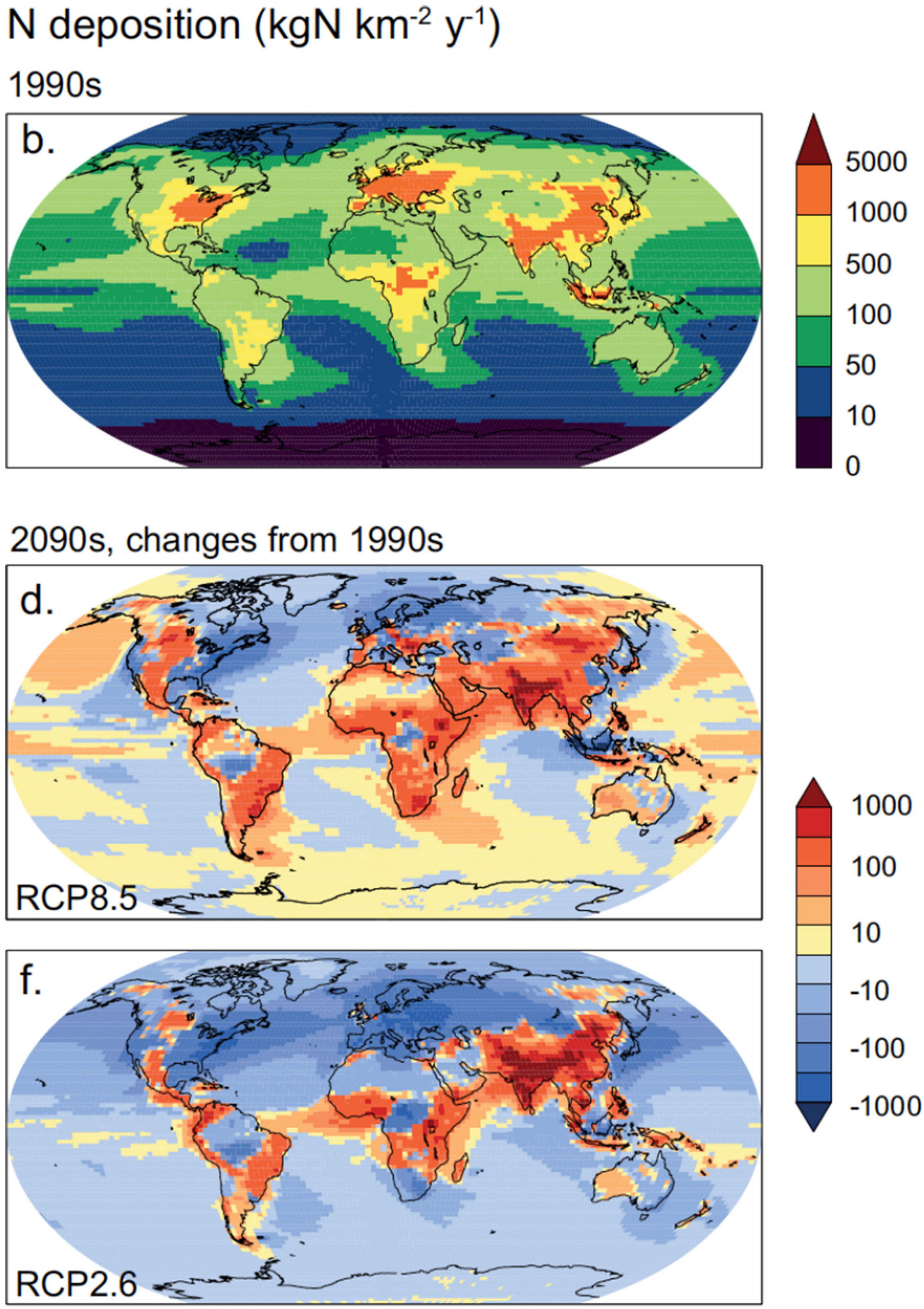

Fig. 1 Spatial variability of nitrogen atmospheric deposition in 1990s with projections to the 2090s (shown as difference relative to the 1990s), using the RCP2.6 and RCP8.5 scenarios, kgN km^{-2} $year^{-1}$, adapted from Lamarque et al. (2011) (Ciais et al. 2013)

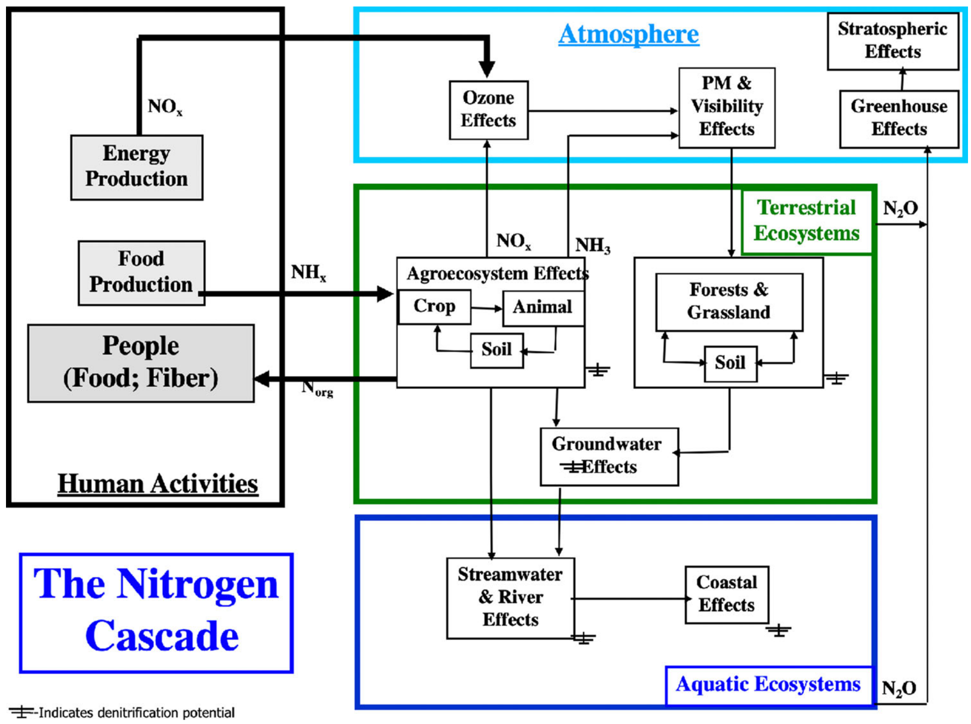

Fig. 2 Illustration of the nitrogen (N) cascade showing the sequential effects that a single atom of N can have in various reservoirs after it has been converted from a non-reactive to a reactive form. Abbreviations: GH, greenhouse effect; NH_3, ammonia; NO_3^-, nitrate; NOx, nitrogen oxide; N_2O, nitrous oxide; PM, particulate matter (Galloway et al. 2003)

2007), India (N-2010[12]), and Uganda (N-2013[13]) and Australia (N-2016[14]). In lieu of the postponed 8th INI conference in Germany due to COVID-19, a virtual (electronic) ‘curtain raiser’[15] event was held online on 4th May 2020 and follow up virtual conference will be held in spring 2021.

The successes of INI over its 17-year history have been in large part because it is an independent grass roots organization, which gives it great flexibility in addressing N-related global issues with their regional underpinnings, through INI’s regional hubs.

In addition, INI has called out the need for intergovernmental nitrogen assessment and management programs. It began with INI undertaking a project in 2016 titled “Improving Understanding of the Global Nitrogen Cycle towards the Establishment of an International Nitrogen Management System (INMS)”. A major achievement of INI through this project is a United Nations resolution on ‘sustainable nitrogen management’, which was adopted in the 4th UN environment assembly (2019). In addition, the INI has promoted the establishment of an Inter-convention Nitrogen Coordination Mechanism. The establishment of this group is currently in process.

Reflection: From its beginning in 2003 as a grass roots effort, INI has become very effective in not only promoting regionally based inquiry on a global scale, but also in setting the stage for multi-stakeholder engagement on issues critical to the management of N in the future as evidenced by formation of the International Nitrogen Management System.

THE NEXT TWENTY YEARS AND BEYOND

At the conclusion of Galloway and Cowling (2002), we posed several issues from science (e.g., fate of Nr created by people) and management (e.g., strategies for decreasing Nr creation by energy and food production processes) perspectives. We ended the paper with this statement: “These critical issues will require a new way of examining how people manage the environment and their use of resources” (including water, energy and food resources).

Now 20 years later, we can report that there have been important successes. There is certainly an increased focus on N-related issues. And there have been successes in decreasing the amount of Nr created by humans. As an example, due to purposeful action, NOx emissions from fossil fuel combustion have dropped significantly and are projected to do so even more in the coming decades (Ciais et al. 2013). Nevertheless, there are still major hurdles to overcome on the food production and consumption sides. So much so that it is improbable that the world will have a

[12] http://agriculture.columbia.edu/events/past-events/n2010-5th-international-nitrogen-conference/.

[13] https://initrogen.org/get-involved/events/6th-international-nitrogen-conference.

[14] http://www.ini2016.com/.

[15] https://ini2020.com/virtual-event/.

similar success with respect to decreasing the Nr created for food production. In this connection, there are two key words: people and protein. By 2050, the world population of people is estimated to be ∼9.8 billion, up from 7.8 billion in 2020. With respect to protein, on average, the per-capita protein consumption will likely increase, especially since 99% of the population growth from 2020 to 2050 is projected to occur in Asia and Africa[16] which currently have low protein consumption rates now relative to North America and Europe.

Reflection: We now know what needs to be done to maximize the benefits of Nr management (feeding the people of the world) while minimizing its negative environmental impacts through the nitrogen cascade. On the food production side, we know how to increase nitrogen use efficiency and decrease food waste. The challenge is to get this information to people together with the mechanisms to implement needed changes. On the food consumption side, if many more people were to follow the well-established nutritional guidelines for protein (e.g., WHO 2017*), the environmental losses of Nr would be decreased significantly. The challenge is to provide the educational framework to provide this information. Citizens in the more developed world have the opportunity to lead the way by example and knowledge.*

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[16] https://ourworldindata.org/future-population-growth.