Global Nitrogen in Sustainable Development: Four Challenges at the Interface of Science and Policy

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Definitions

Reactive nitrogen: Nitrogen contains chemical species that are readily converted to other compounds and are thus capable of cascading through the environment and impacting people and ecosystems. Reactive nitrogen compounds include nitrous oxide (N_2O), nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3), and ammonium (NH_4^+). Anthropogenic reactive nitrogen sources include industrial processes, the combustion of fossil fuels, and agriculture (cultivation of N-fixing legume crops and use of synthetic nitrogen fertilizers derived from the Haber-Bosch process).

Haber-Bosch process: A process that artificially fixes nitrogen to produce ammonia. The process was developed early in the twentieth century and industrialized for the manufacture of synthetic fertilizers. Since then, it has become one of the main sources of anthropogenic reactive nitrogen.

Human alteration of the nitrogen cycle: The modification of the natural biogeochemical cycle

by which nitrogen is converted into multiple chemical forms as it circulates among atmospheric, terrestrial, and marine ecosystems. Increases in the availability of reactive nitrogen through the cycle intensify the cascading effects on ecosystems, humans, and animals.

Green revolution: International process of agro-technological change initiated in the 1950s and 1960s to modernize agricultural practices, particularly in areas of the so-called Third World. Although originated for geopolitical purposes, the term is broadly used to describe technological improvements including in seeds, fertilizers, pesticides, irrigation, and other mechanization processes. The global increase in reactive nitrogen from the use of nitrogen fertilizers is a direct product of the Green Revolution.

Introduction: Global Nitrogen, Four Challenges

The increasing use of anthropogenic reactive nitrogen (N_r) derived from the industrialization of the Haber-Bosch process has been critical in feeding the increasing world population since the 1960s. However, the abundance of N_r has also impacted humans and ecosystems, altering the natural nitrogen cycle in unprecedented ways (Boyer and Howarth 2002; Galloway and Dowling 2002; Jenkinson 2001; Fowler et al. 2013; Vitousek et al. 1997; Erisman et al. 2013b). Accordingly, a major challenge for scientists and policymakers is

how to exploit the benefits of nitrogen, e.g., meeting food production demands, while limiting its negative impacts. Although it has received limited public attention, scientists and international organizations consider the global nitrogen challenge one of the most critical environmental issues of the twenty-first century, and a central element for the achievement of the 17 UN Sustainable Development Goals (SDGs).

The SDGs set in 2015 by the United Nations General Assembly represent one of the last chapters integrating the principles of sustainable development since the publication of the Brundtland Report in 1987. The SDGs form the most inclusive – and ambitious – agenda the UN has delivered to date. Seventeen goals encompassing 169 individual targets offer a leading international coordinating framework to address interconnected challenges regarding poverty, inequality, climate change, environmental degradation, peace, and justice. Although critiques have arisen on the scope and the lack of specificity of the targets (Stafford-Smith 2014), the SDGs represent a fundamental chapter in the history of sustainable development and a potential turning point for the place of nitrogen in the international policy arena.

This chapter examines four of the challenges associated to the global nitrogen problem across scientific communities and policy circles, which are interrelated: (1) Meeting global food demand while reducing nitrogen pollution; (2) Quantifying the nitrogen cascade: linking nitrogen forms, expert communities, and policy frameworks; (3) Externalities: assessing costs, benefits, and solutions; and (4) Institutional frameworks: designing effective knowledge governance systems. The chapter ends with the analysis of the role of the nitrogen challenge in sustainable development policy and future directions for the achievement of the SDGs.

Meeting Global Food Demand While Reducing Nitrogen Pollution

Although reactive nitrogen is a product of natural biogeochemical processes on earth, human activities have increased the rates at which nitrogen is

being added to the natural nitrogen cycle. Globally, about 75% of anthropogenic nitrogen fixation originates from the production and use of fertilizers derived from the industrialization of the Haber-Bosch process which converts non-reactive N_2 to reactive ammonia (NH_3), and 25% is from fossil fuel and biomass burning (in the form of nitrous oxide, N_2O) (Erisman et al. 2013a; Galloway et al. 2008; Fowler et al. 2013). In the early 1960s, global nitrogen use was heavily concentrated in the United States and Western Europe. Since then, hotspots of intensive fertilizer applications have expanded to include regions in Asia and Latin America (Sutton and Bleeker 2013; Potter et al. 2010; Swarbreck et al. 2019). While some nations in Northern Europe have reduced nitrogen intake, countries with emerging economies like Chile, Brazil, and India have maintained a steady increase (FAOSTAT 2016). Since 2000, new areas of increased use in East and South Asia have emerged (Lu and Tian 2017; Swarbreck et al. 2019). Projections show new zones of intensification through 2050 in South Asia, Latin America, and North and East Africa (Galloway and Dowling 2002; Sutton and Bleeker 2013; Galloway et al. 2008; Fowler et al. 2013).

The production of N_r through the Haber-Bosch process has been critical in feeding the exponentially increasing world population. By the end of the twentieth century, only half of the world population could have been fed using agriculture supplied using pre-synthetic fertilizers, and even then only with overwhelming vegetarian diets (Smil 2001). However, although anthropogenic N_r has been critical in food production, 80% of anthropogenic N_r produced as nutrient intake for global food production is lost into the environment, wasting energy for its production and causing a cascade of environmental effects (Sutton et al. 2013). Food waste, and the uneven distribution of food production and consumption in global food supply chains, are also key elements in the massive increase in N_r lost into the environment (Grizzetti et al. 2013).

Scientific knowledge on the human modification of the nitrogen cycle has significantly expanded (Galloway et al. 2013; Galloway et al. 2017; Keeney and Hatfield 2008). Although

nitrogen pollution has received limited public attention compared to biodiversity loss and climate change (Erisman et al. 2013a), international scientific communities and organizations, including the United Nations Environment Programme (UNEP), consider nitrogen pollution a leading socioecological concern for the twenty-first century (UNEP 2019a, b; Sutton et al. 2013). Nitrogen pollutes watersheds and coastal ecosystems, threatening drinking-water and causing eutrophication and hypoxia in marine ecosystems (Diaz and Rosenberg 2008). The loss of ecosystems services due to hypoxia in coastal ecosystems has been recently estimated worth \$170 billion annually (Sutton et al. 2019). Furthermore, nitrogen compounds threaten air quality and contribute to tropospheric (ground level) ozone pollution (WHO 2006) and climate change (Tubiello et al. 2013; IPCC 2014). Nitrous oxide (N_2O) is estimated to have a warming potential ~ 300 times that of carbon dioxide (100 year GWP) with a median lifetime in the atmosphere of 200 years (Sutton et al. 2019). In 2013, N_2O became the dominant cause of ozone depletion and the third greatest climate forcer (UNEP 2013). Furthermore, nitrogen oxides (NO_x) and ammonia (NH_3) are estimated to be a major threat to global biodiversity (Sutton et al. 2019).

A growing network of researchers and organizations has coined the concept of the “Global Nitrogen Challenge” to discuss the challenges of this conundrum and assess potential solutions. **The first challenge**, then, becomes one of increasing the efficiency of fertilizers to meet global food demand, while protecting the environment (Townsend and Palm 2009; Fixen and West 2002). The concept, broadly embraced by the scientific community during the last two decades, is a product of the accumulative efforts initiated in the 1960s to understand the positive and – later on – negative impacts of nitrogen in humans and the environment. More recently, intergovernmental organizations have adopted it as a critical socioenvironmental issue and a fundamental piece in the achievement of the SDGs (UNEP 2019a, b).

The global nitrogen challenge concept emphasizes that in order to face the nitrogen problem,

nations will require new technologies, management practices, and policies. Such a complex challenge has provided an effective umbrella term to incorporate various approaches, methods, and solutions. Research has expanded from understanding particular aspects of the nitrogen cycle and specific effects of N_r in the 1960s and 1970s, to exploring more efficient uses of nitrogen fertilizer and technologies in farming practices during the 1980s, to the assessment of integrated policies in the 1990s and 2000s. In this process, initial expert communities consisting of agricultural and environmental scientists (e.g., soil, plant nutrition, biochemistry specialists) have expanded to integrate a broader range of policy and social sciences scholars. This process has also opened the discussion to new research questions, including factors of behavioral change among farmers, consumers, and industries; and the need to develop approaches that consider, socioeconomic factors, global food chains, and institutional partnerships (Leach et al. 2016; Kanter et al. 2015, 2020; Houlton et al. 2019; Swarbreck et al. 2019; Zhang et al. 2015).

Figure 1 synthesizes three main areas of research on the global nitrogen challenge. It shows areas of concern on its socioecological effects (green), research on nitrogen use efficiency (NUE) and nitrogen-efficient technologies and managements practices (TMPs) (yellow), and agricultural and environmental policies (orange). The figure also outlines how researchers have raised questions about how these three dimensions interact, for instance: how pricing policies for TMPs, fertilizers, and crops (e.g., nitrogen taxes or subsidies to enhanced efficiency fertilizers) might affect rates of nitrogen application, efficiency, and loss; what the economic impacts of TMPs might be on farmers’ profits and on the fertilizer industry; and, how TMPs can effectively reduce the effects of nitrogen on human health and the environment.

Feeding a growing population while reducing nitrogen pollution requires developments in three major areas: (1) assessing socio-environmental degradation and reducing negative impacts, (2) developing new technologies and practices to reduce nitrogen loss and increase efficiency, and

Global Nitrogen in Sustainable Development: Four Challenges at the Interface of Science and Policy, Fig. 1 Global research on nitrogen science, policy, and technologies. (Adapted from San Martín (2017a). Based

on Erisman et al. (2013a), Galloway et al. (2014), Kanter et al. (2015), Robertson et al. (2013), Zhang et al. (2015), Mosier et al. (2004))

(3) designing responses that consider decisions and profits by major stakeholders, including farmers and fertilizer industries. Although research in each of these areas has grown, how each of these dimensions can effectively be incorporated in various agricultural systems and regulatory frameworks around the world is still a major challenge.

Quantifying the Nitrogen Cascade: Linking Nitrogen Forms, Expert Communities, and Policy Frameworks

The first International Nitrogen Conference (INI) took place in the Netherlands in 1998. The conference provided an opportunity for researchers and stakeholders from 30 countries to exchange knowledge on the many ways nitrogen pollutes environments at a local, regional, continental, and

global scale (Erisman et al. 1998). The meeting concluded that nitrogen was more complex than other pollutants – in contrast to carbon dioxide (CO_2), one atom of N_r can have a “cascade effect” and contribute to several environmental issues across the globe. It can contribute to urban smog, have direct effects on vegetation, contribute to acidification or eutrophication of water, and can contribute to the greenhouse effect through emission of N_2O (Erisman et al. 1998). Addressing this cascade effect required an integrated approach to both scientific research and abatement strategies. Participants in this first conference called for the need to (1) further synchronize activities among international bodies, (2) improve spatial and temporal emission inventories, and (3) support both research and abatement strategies in areas where the nitrogen issue had not been widely acknowledged by researchers and policymakers, such as the United States and Asia (Erisman et al. 1998).

In the following two decades, six additional International Nitrogen Conferences have taken place, in the USA (2001), China (2004), Brazil (2007), India (2010), Uganda (2013), and Australia (2016). The eighth conference, scheduled for Berlin, in May 2020, was postponed due to the COVID-19 pandemic and is expected to take place in 2021 (<https://ini2020.com>).

Since the inaugural meeting, scholars have widely used the concept of the “nitrogen cascade” to describe how a single atom of N_r can trigger a sequence of negative environmental impacts through time and space in ways that transcend traditional disciplinary, geographical, and political boundaries (Galloway 1998; Galloway et al. 2003). The concept marks the integration of various corpora of knowledge on nitrogen pollution accumulated since the 1960s (represented in the green area in Fig. 1). It also represents a turning point in the history of the scientific knowledge about the human transformation of the nitrogen cycle. Previous research and management strategies had mostly focused on the effects of N_r on a particular environmental media. The nitrogen cascade concept, however, called for the need to integrate the analysis of emission stocks and pollution across expert communities, regions, and ecosystems.

Despite these efforts, quantifying nitrogen flows and threats at a global scale is still one of the major challenges in nitrogen scholarship. Today nitrogen science combines a set of multiple disciplines and bodies of knowledge where expert communities mostly focus on distinct N_r forms (e.g., N_2O or NH_3) or their effects in specific human or environmental media (e.g., soil acidification or eutrophication of coastal ecosystems). The variability of N_r across time and space has created a set of highly specialized expert communities with distinct methods and metrics (Sutton 2011a). While assessing – and quantifying – certain phases of this biochemical process has been easier for some of these communities, others aspects of the cascade still remain unknown (Sutton 2011a). Today this *unequal* quantifications of nitrogen flows – as expression of the imbalanced scientific knowledge about the tradeoffs between different N_r forms and linked biogeochemical cycles – are considered

critical for (1) the further advancements of nitrogen science, and (2) the role of nitrogen science in the international policy arena (Sutton 2011a; INMS 2019).

1. Quantifying global N_r flows and threats:

There are different measurement tools for each nitrogen form. These distinct chemical species also interact differently with various biochemical processes. Therefore, it becomes a challenge for researchers to integrate the scientific understanding of all the different components and processes (Sutton 2011a).

In 2013, the Global Partnership on Nutrient Management (GPNM) – a multistakeholder association integrating the private sector, governments, and international organizations – and the International Nitrogen Initiative (INI) – a scientific organization formed following the World Summit on Sustainable Development in Johannesburg on 2002 (Mosier et al. 2004), and a major organizer of the International Nitrogen Conferences – published *Our Nutrient World: The Challenge to Produce More Food and Energy with Less Pollution*. The publication has become an authoritative assessment and one of the main sources for the United Nations Environment Assembly Resolution adopted in 2019 on Sustainable Nitrogen Management (UNEP 2019a).

Although the report estimated that 80% of anthropogenic N_r used as nutrient in food production is lost to the environment (Sutton et al. 2013), it also recognized that several discrepancies exist in the quantification of nutrient fluxes. According to the report, this is due to several reasons: (a) biogeochemical cycles are complex, and generally scientific fields and studies are only able to address part of the cycle; (b) although expert communities have grown in different regions around the world, data at global scale are still scarce, and except for the information that can be gathered by satellite images or global models, data coverage is not homogeneous across the globe; (c) strong regional differences exist in terms of environmental conditions, climate, and sources of N_r ; and (d) methodological approaches differ from study to

study (Sutton et al. 2013). The authors highlighted the need to recognize the inherent uncertainty in the quantification of nitrogen flows. This discrepancies among quantifications and methods expose that the nitrogen cascade, although a critical guiding concept in the recent history of the nitrogen challenge, as stated by Sutton (2011a) still represents “a purely conceptual framework.”

2. Linking science and policy frameworks:

Since the first discussions about the nitrogen cascade effect in the late 1990s, uncertainty in the quantification of nitrogen flows has been considered critical to the role of nitrogen science in the policy arena (Erisman et al. 1998). Since then, the fragmentation of nitrogen forms, scientific disciplines, and policy domains have become a fundamental issue for the establishment of international efforts (UNEP 2019b; Sutton 2011a).

At a national level, major policy instruments addressing nitrogen pollution in Europe have indeed followed the epistemic and chemical divisions rooted in nitrogen-related sciences. Policies have mostly addressed a particular N_r form and environmental media in which the pollution form occurs (e.g., drinking water, air pollution) (Oenema 2011). However, this fragmentation also responds to the usual fragmentation of policy portfolios in government agencies. For instance, administrative distinctions between agriculture and the environment in policy-making agencies (Sutton 2011a). This contributes to make the uncertainty of quantifications an even more complex issue in the policy arena.

At an international level, this challenge becomes even larger. Quantification gaps are main obstructions to the coordination between different institutions and governmental bodies (Sutton et al. 2013). Relevant instruments to address the nitrogen challenge are indeed divided in many regulatory bodies and inter-governmental organizations. For instance, biodiversity lost is overseen by the Convention on Biological Diversity (CBD); the pollution of water and marine ecosystems, by the Global Programme of Action for the Protection of the

Marine Environment from Land-based Activities (GPA), air pollution, by the Convention on Long-range Transboundary Air Pollution (LRTAP), while Climate Change and stratosphere depletion, by the United Nations Framework Convention on Climate Change (UNFCCC) and the Montreal Protocol (Sutton et al. 2016, 2019).

Furthermore, the multiplicity of N_r forms, effects, disciplines, and policies also translates into dissimilar challenges faced by farmers, industries, conservation managers, and other stakeholders. Researchers agree that divisions between nitrogen forms, science, and policies have contributed substantially to the barriers-to-change (Sutton et al. 2019). Although this fragmentation across nitrogen forms, quantifications, expert communities, and policies has received relatively limited attention in the research of the nitrogen challenge, key organizations such as INI and the UNEP have taken steps to address the issue. At the 2016 International Nitrogen Conference, the UNEP and INI with support from the Global Environmental Facility (GEF) launched the project “Towards the International Nitrogen Management System” (INMS). INMS was established as a global scientific platform bringing evidence to inform policies and the public on the multiple benefits and threats of N_r (Sutton et al. 2016). The organization defined four interconnected priority areas: (1) Tools and methods for understanding the nitrogen cycle; (2) Global and regional quantification of nitrogen use, flows, impacts, and benefits of improved practices; (3) Regional demonstrations and verifications; and (4) Awareness raising and knowledge sharing. The second priority tackles the need to link uneven quantifications of nitrogen flows and impacts, which is central to effectively address the third and fourth priorities (INMS 2019; Sutton et al. 2016). Quantifying flows and tradeoffs, benchmarking nitrogen indicators, and sharing common methodologies across the regions are also critical for the development of the first Global Nitrogen Assessment, one of INMS’s central goals (INMS 2019).

INMS emerged in a context of rising concerns about the place of nitrogen science in international policy and the challenges to provide evidence-based recommendations to diverse stakeholders, including intergovernmental organizations, industries, and the civil society. INMS also developed as a response to a highly fragmented nitrogen policy arena and the lack of an international convention on nitrogen pollution and management. Since then, the scientific community has widely understood that addressing the issue of quantifications is a major challenge to build a framework for nitrogen governance at a global scale. Along this process, scholars and organizations have agreed on the need to establish an international nitrogen convention allowing for further coordination between countries and multilateral environmental agreements (MEAs). In 2019, the UN Resolution on Sustainable Nitrogen Management conveyed the establishment of a Nitrogen Coordination Mechanism (UNEP 2019a). Soon after, the fourth meeting of the INMS endorsed the proposal and established further steps for its creation (INMS 2019). INMS is currently working with the UNEP to establish the “Inter-convention Nitrogen Co-ordination Mechanism” (INCOM) (Sutton et al. 2019). Under this new institutional infrastructure, INMS would provide scientific support, and INCOM would coordinate efforts across conventions and MEAs, including UNEP, UNFCCC, GPA, LRTAP, and CBD (Sutton et al. 2019).

So far, the multiple metrics and unequal distribution of quantified effects have had a relatively limited impact in the establishment of transnational organizations such as INI or INMS, or in the development of regional nitrogen assessments (e.g., in Europe, California, and India) (Abrol et al. 2017; EPA 2011; Tomich 2016; Sutton 2011b). However, the discussion about quantifications has omitted additional questions about the inequality of scientific and policy assessments at a global scale. Research institutions and scientific communities around the world have unequal access to resources, laboratories, and instruments. National science-policy interface frameworks

relevant for nitrogen management are sometimes inexistent (San Martín 2017a, b). In-depth studies of policy frameworks have mostly focused on the North Atlantic (Oenema 2011; Tomich 2016; Sutton 2011a). Regional assessments have mostly taken place in the United States, Europe, and among OECD members (Galloway et al. 2013; Sutton 2011b; Tomich 2016; EPA 2011; OECD 2018; SRU 2015), with the exception of the Indian Nitrogen Assessment (Abrol et al. 2017). Although efforts toward other regional assessments continue, there is a profound lack of understanding on how distinct nitrogen forms and scientific communities interact with policy frameworks in many regions around the world. As global shifts in nitrogen use advance, the disparity of global quantifications will have to face the lack of knowledge on the practices of scientific production and policymaking in these regions. Uneven quantifications of the nitrogen-cascade effects and tradeoffs remain a fundamental issue of science-policy interface in global nitrogen management and governance (San Martín 2020). As the process of institutionalization of the Global Nitrogen Challenge advances in the international policy arena, questions about imbalanced quantifications might provide a larger area of conflict for multilateral agreements. The **second challenge** thus is one of linking nitrogen forms, expert communities, and policy frameworks. Bridging efforts across these areas at an international scale will be fundamental to advance in global nitrogen governance.

Externalities: Assessing Costs, Benefits, and Solutions

Quantifying the mechanism by which N_r interacts with humans and biochemical processes has been translated by researchers in terms of developing an analysis of costs and benefits. Cost-benefit analysis is seen as a technical instrument that can assist the translation of expert knowledge on N_r fluxes into the arena of nitrogen management and policies (Sutton 2011a; Sutton et al. 2013; UNEP

2019b; van Grinsven et al. 2013). The use of cost-benefit analysis among researchers working on the global nitrogen challenge is especially fitting as nitrogen supplies and demands are governed by economic dynamics that are central to the global economy. Although the reduction of nitrogen pollution is a critical goal in international policy agenda, the acknowledgement that a healthy functioning of the economy depends on a stable flow of anthropogenic N_r is at the center of the coordination strategies with farmers, industries, and governments (Sutton 2011a).

However, contrary to large combustion sources of N_r , such as power plants and vehicle manufacturers, where transferring costs to consumers and technical mitigation strategies are comparatively easier to implement, agricultural sources of N_r represent a more complex issue. This is even more difficult when research on cultural factors shaping farmers' decisions and the socio-economic dimensions of nitrogen management are still poorly understood (Zhang et al. 2015).

As stated by Sutton and colleagues (Sutton 2011a; Sutton et al. 2013), farming practices as a source of pollution present a distinct set of challenges. First, there are many individual farmers around the world, with different farming practices and production processes, who operate in a somewhat open ecological system. From an environmental perspective, farms in many regions are production systems that are literally open to air, soil, and water, and where full control of environmental factors, biochemical processes, and the costs of the production process is practically impossible. Second, farmers are a social group, frequently characterized by scientists, scholars, and policy-makers as resistant to technical change. Social scientists are still a minority among nitrogen expert communities, and the fact that farmers' decisions and assumptions are at the final step in shaping farming practices seems usually forgotten in academic discussions. And third, while internalizing environmental costs is part of broader discussions on environmental policy, the global agricultural market is today a productive sector with high uncertainty on how any costs might be transferred to consumers at any scale.

Similarly, in monopolizing the quantification of tradeoffs or complex biochemical interactions, cost-benefit analysis reduces the more complex discussion on the multiple metrics that can better assess the distinct nature of biophysical process, societal priorities, or economic interests. For instance, Birch et al. (2011) in addressing the diversity of nitrogen forms and fluxes states that multiple metrics may be required to provide appropriate information on the flow of chemical species through ecosystems and the diverse impacts of those flows in individual ecosystems and on human health. The economic valuation of benefits and costs implies the construction of a rational and reasoned argument. However, it can also obstruct and confuse both political and technical discussions. Critiques about cost-benefit analysis from the history and sociology of science, and from the practice of social activism, have highlighted its technical limitations to solve problems that are in essence political or sociocultural (Porter 1994). For instance, in assessing the impacts of N_r in biodiversity loss or human health, cost-benefit analysis might fail to give expression to the complex value that conservation managers and local communities give to the entities that should be protected. Furthermore, for many farmers and citizens around the world, cost-benefit analysis can be considered a technocratic tool that blocks free democratic debate, which might bring down social support that could be critical for the implementation of certain policies. For instance, the violent protests that took place in the Netherlands during October 2018 are allegedly the first massive responses against policies aimed at reducing nitrogen pollution. As nitrogen becomes a pressing issue globally, both regulations and conflicts are expected to go on the rise. The Netherlands case showed that measurements, metrics, and quantifications of nitrogen emissions are not only negotiated within the scientific and policy-making communities. They are also contested in the public sphere. Nitrogen governance debates need to remember that assessments of costs and benefits are a social struggle as much as a struggle for the sphere of science-policy interface (San Martín 2020).

Finally, assessing costs and benefits requires a revision of standards. For much of the history of the global nitrogen challenge, NUE has become a central metric. Focusing on nitrogen responsiveness or reducing nitrogen loss have been later proposed as a more effective system to bridge farming practices around the world (Swarbreck et al. 2019; Sutton et al. 2019). Solving the nitrogen problem does not simply translate into applying less fertilizer or setting global standards of NUE rates. NUE varies among cropping systems, and it is highly variable considering environmental and climate conditions (Fixen and West 2002). The “4R” Nutrient Stewardship concept, for instance, calls to apply the Right source of nutrients at the Right rate, Right time, and Right place (IFA 2009). However, 4Rs vary regionally depending on cropping systems, soil types, climate-environmental conditions, and sociocultural and economic factors (Davidson et al. 2015; Zhang et al. 2015; Fixen and West 2002). While some regions have excessive nitrogen, such as Western Europe, China, and North America, others like those in Sub-Saharan Africa lack enough fertilizer (Fixen and West 2002; Stevens 2019). Policies have shown to be more effective when considering the heterogeneity of agricultural practices and the environment (Kaye-Blake et al. 2019). The **third challenge** is thus the development of cost-benefit assessments, nitrogen-use standards, and solutions that consider the variety of farming practices and socio-ecological actors at both local and global scales.

Institutional Frameworks: Designing Effective Knowledge Governance Systems

The increasing use of nitrogen fertilizers has been central to the process of agro-technological change known as the Green Revolution. From the perspective of the history of agriculture and technology, the Green Revolution is fundamentally a process of knowledge and technology transfer by which farmers learned and naturalized practices and uses of new agricultural technologies. The global N challenge – as a project that is a

product of the consequences of the Green Revolution and aims to correct its negative effects – is at the end an attempt to replicate the process and naturalize new farming practices, agricultural knowledge, and technologies (e.g., enhanced efficacy fertilizers) (San Martín 2017a).

The Green Revolution, as a set of international efforts to “modernize” agricultural practices, expanded agricultural development programs that were highly effective in providing access to experts and technologies for farmers around the world. In many regions, they created an active network of research centers, experimentation and demonstration stations, and both university and government-based extension programs that connected farmers and specialists in unprecedented ways (Perkins 1997; San Martín 2017a).

These programs radically increased nitrogen fertilizer consumption by establishing a functional institutional framework that provided the means for the exchange of knowledge and “site-specific science.” By 1980, many countries had acquired a cadre of trained agricultural scientists, many of whom had received advanced study in the United States and Europe. Plant breeders, soil scientists, plant nutrition experts, fertilizer chemists, hydrologists, and irrigation specialists worked in each country to find the crop varieties and fertilization rates that were suited to their locations (Perkins 1997). The United States and Europe played an important role providing training to these scientific networks. National governments and higher education institutions were fundamental in supporting university and government-based extension programs. Site specific research, experimentation, and demonstration stations provided farmers a close look at the benefits of nitrogen and increased fertilization rates (Perkins 1997; San Martín 2017a). Government subsidies and other means of state support for fertilizer access complemented these programs.

These institutional frameworks were effective in providing local and transnational channels for the development of nitrogen-management knowledge and the drastic change in agricultural practices in many areas around the world. Today, however, scholars agree that the lack of institutional partnerships and local extension programs is a significant

challenge to expanding better nitrogen management practices globally (Brownlie et al. 2015; Houlton et al. 2019; Stevens 2019; Davidson et al. 2015). As expert communities incorporate new questions regarding the local socioeconomic and political dimensions of the nitrogen challenge (Zhang et al. 2015; Davidson et al. 2015), the challenge will soon become the absence of institutional frameworks that can effectively produce change across the variety of farming practices. Although localized programs have shown good results, today they are mostly present in developed regions. For instance, Hellsten (2019) reports that education and advisory programs for farmers have been effective in reducing nitrogen pollution in northern Europe. Specific nitrogen-management programs with farmers have also reported positive results in the United States (Brownlie et al. 2015). However, university and government-based extension programs for farmers are still limited, especially in developing nations (Tabor 1995). In-depth analyses of relevant agricultural extension programs across regions are still needed in the scholarship of nitrogen solutions.

Additionally, extension programs were not the only factors increasing nitrogen consumption during the Green Revolution. Alliances between governments and the private sector were also critical (Kumar et al. 2017). Several researchers have pointed out the need to incorporate a full-chain approach, including farmers' decision making and the role of industries and business to the analysis of the global nitrogen challenge (Kanter et al. 2020; Brownlie et al. 2015). They agree that sustainably feeding the increasing world population will require new crop varieties, new areas of nitrogen research, and effective extension programs (Swarbreck et al. 2019). Further research on each of these aspects is still needed. Although an essential part of the nitrogen challenge, mechanisms that made the Green Revolution such an effective process are still mostly ignored among expert communities. A better understanding of the local institutional and social histories that have shaped the variety of nitrogen uses and managements around the world will be critical to inform future decisions to move forward more sustainable practices.

Scholarship on knowledge governance has proved effective in the analysis of many environmental issues globally (van Kerkhoff and Pilbeam 2017; Cash et al. 2003). However, researchers of the global nitrogen challenge have not paid enough attention to the processes that shape the circulation and production of nitrogen-related knowledge across institutions, regions, and farming practices (San Martín 2020). Organizations such as INI, INMS, and INCOM – although instrumental in the arena of global environmental science and policy – will require a better understanding of how to improve the mechanisms by which the production and circulation of nitrogen knowledge occur at local and regional scales.

In sum, the study of the global nitrogen challenge as part of a longer history of knowledge and technology transfer initiated during the Green Revolution suggests that close attention to institutional frameworks and knowledge governance systems will be critical in determining the impact of any solutions at both local and global scales. The **fourth challenge** is one of designing institutional frameworks and partnerships connecting expert communities, farmers, and both public and private organizations. Further attention to the governance of nitrogen knowledge across experts and stakeholders will be fundamental to improve nitrogen management locally and globally.

Nitrogen and Sustainable Development: Future Directions

Nitrogen has been vital to the concept of sustainable development and its guiding principles. Several international institutions, including the World Health Organization (WHO) and the Food and Agriculture Organization (FAO), published synthesis statements on the human and environmental effects of nitrogen from the late 1950s through the 1970s (WHO 1958; NAS 1969; FAO 1972). In 1970, as nitrogen grew as an environmental hazard, *Scientific American* included this element along with DDT as one of the major environmental issues of the time (Scientific American 1970; Delwiche 1970). Scientific interest on the global

effects of nitrogen in humans and other species expanded during that decade (Bolin and Arrhenius 1977). In many of these assessments, researchers raised questions about the dependency of developing countries on nitrogen and the lack of knowledge of its impacts, and how this leads to social and environmental inequality (Bolin and Arrhenius 1977). Many of these accounts arose before the official rise of the concept of sustainable development in the arena of international relations. However, all of these assessments highlighted the centrality of nitrogen in terms of (1) a key resource to tackle food insecurity and economic development, and (2) as a growing socioenvironmental hazard that increases inequalities across species. In 1987, the Brundtland Commission – which marked the origins of the concept of sustainable development in official policy circles – reported on the unequal global distribution of nitrogen use and pollution (Brundtland Commission 1987). The Brundtland report consolidated nitrogen as part of the environmental hazards increasing socioecological disparities globally. Different from recent approaches that emphasize the integration of nitrogen in SDGs debates as an inaugural turning point (Morsetto 2019; Dobermann 2016; Kanter et al. 2016), these accounts show that nitrogen has been imbedded – in many ways – at the center of debates on sustainability and development for most of the last century.

Despite this, nitrogen is not explicitly present in the UN 17 Sustainable Development Goals, and nitrogen research has only recently officially entered the debates on the mechanisms for their achievement (Morsetto 2019; Dobermann 2016; Kanter et al. 2016; Zhang et al. 2015; UNEP 2019a, b; Sutton et al. 2019). Many scholars and organizations have discussed the preeminent absence of nitrogen from the SDGs and, at the same, argue for its centrality to achieve several of them (Morsetto 2019; Dobermann 2016; Kanter et al. 2016; Zhang et al. 2015; UNEP 2019a, b; Sutton et al. 2019). There is a general agreement that although nitrogen is not explicitly present in the SDGs, nitrogen management is essential to achieve many of the targets (Morsetto 2019; Dobermann 2016; Kanter et al. 2016; Zhang et al.

2015; UNEP 2019a, b; Sutton et al. 2019). Researchers argue that the multiplicity of nitrogen forms and their impacts can be transformed into a set of assets that if managed appropriately would assist in providing co-benefits for many of the 17 goals (Sutton et al. 2019; INMS 2019; Kanter et al. 2016).

The recent resolution of the UN Environment Assembly on sustainable nitrogen management, signed in March 2019, recognized the multiple threats resulting from anthropogenic N_r and called for the exploration of options through which the SDGs could be achieved (UNEP 2019a). The eighth conference of the International Nitrogen Initiative (INI 2020) (rescheduled for 2021) will be devoted to discussing the role of nitrogen management across the UN SDGs. The conference theme emerges from the premise that most of the SDGs are closely interlinked with the nitrogen cycle and that nitrogen research and management are central pillars of the SDGs (<https://ini2020.com>). Table 1 shows the various benefits of nitrogen management that scholars have identified across all 17 SDGs.

Nevertheless, the future of nitrogen in sustainable development policy is daunting. The goals and benefits listed in Table 1 need to be translated into practical actions and measurable achievements (Doberman 2016). Many of the benefits listed above will only be achievable if several of the four challenges examined within this chapter are resolved. For instance, Challenge 2 (Linking nitrogen forms, expert communities, and policy frameworks) and Challenge 4 (Designing institutional frameworks and effective knowledge governance systems) will be fundamental to provide effective training in sustainable nitrogen management (SDG/Benefit 4), strengthen partnerships (SDG/Benefit 17), and contribute to environmental diplomacy (SDG/Benefit 16).

Similarly, the needs of low-nitrogen consuming countries have been generally associated with SDGs 1 and 2 (no poverty and zero hunger). Agricultural transitions in these regions need to incorporate technologies and practices that avoid the inefficient use of nitrogen and new areas of pollution. This means leading processes of agro-technological change that effectively provide the benefits of nitrogen use while

Global Nitrogen in Sustainable Development: Four Challenges at the Interface of Science and Policy, Table 1 Benefits from nitrogen management to achieve SDGs

SDGs	Benefits from nitrogen management to SDGs
1. No poverty	Supporting livelihoods by improving nitrogen fertilizer efficiency and reducing nitrogen loss
2. Zero hunger	Nitrogen fertilizer efficiency and biological nitrogen fixation to sustain food production
3. Global health and well-being	Improved health through better nitrogen air & water quality
4. Quality education	Education and training in sustainable nitrogen management
5. Gender equality	Valuing nutrients in manure and other organic nutrient sources helps to address gender inequality in vulnerable communities
6. Clean water and sanitation	Decreased nitrate (NO ₃) contamination of drinking water & rivers
7. Affordable and clean energy	Bioenergy and biogas with reduced nitrogen footprint
8. Decent work and economic growth	Nitro-finance to mobilize growth and expand the circular economy
9. Industrial innovation and infrastructure	Nitro-innovation for resource recovery in air and water
10. Reduced inequalities	Widening access to cost-effective nitrogen resources
11. Sustainable cities and communities	Decreased nitrogen oxides (NO _x) and PM _{2.5} improve urban air quality
12. Responsible consumption and production	Nitrogen full-chain approach, nitrogen footprint, and nitrogen neutrality
13. Climate action	Less nitrous oxide (N ₂ O) as a long-lived greenhouse gas
14. Life below water	Less nitrogen water pollution helps protect reefs and avoid coastal dead zones
15. Life on land	Decreased ammonia (NH ₃) and NO _x emissions help protect terrestrial biodiversity
16. Peace, justice, and strong institutions	Nitrogen cooperation as a contribution to environmental diplomacy

(continued)

Global Nitrogen in Sustainable Development: Four Challenges at the Interface of Science and Policy, Table 1 (continued)

SDGs	Benefits from nitrogen management to SDGs
17. Partnerships for the goals	Strengthened partnerships through the nitrogen coordination mechanism

Adapted from: Sutton et al. (2019). Based on: Dobermann (2016), Kanter et al. (2016), UNEP (2019b), Zhang et al. (2015)

limiting the multiscale effects of new anthropogenic N_r (Challenge 1).

Also, reducing social inequalities by widening access to cost-effective nitrogen resources (SDG/Benefit 10) will require adapting the assessments of costs and benefits to various farming practices and the value of different socioecological factors (Challenge 3). Finally, coordinating distinct metrics and indicators such as NUE (Kanter et al. 2016), nitrogen responsiveness (Swarbreck et al. 2019), or reducing nitrogen waste in half (Sutton et al. 2019) will be critical to effectively assess the impact of these actions in achieving the SDGs.

The advancements of nitrogen research and its integration in the international policy arena since the 1960s have been vast. However, many of the benefits of better nitrogen management listed above – conditions for the effective integration of nitrogen in the SDGs – are still unsettled by the scientific and policymaking communities. Furthermore, sustainable development policy goes beyond the 17 SDGs. The concept and practices of sustainable development have required compromises across sectors. NGOs were critical in the process that gave rise to sustainable development in the arena of international relations (Macekura 2015). Unlike other environmental issues, discussions of nitrogen pollution have not been picked up by the NGO community, profoundly limiting its sphere of action in public debates (Dittmar 2015). Scholars and policymakers will need to build broader networks with non-state actors and engage in conversations that are preeminent in the environmental movement today, such as economic inequality and intergenerational environmental justice. Both

dimensions have had limited attention in nitrogen research. As this process advances, the improvements in each of the four challenges described here, and the lessons from the local histories of nitrogen use and policymaking will be fundamental to effectively build a new nitrogen governance system across expert communities, farming practices, and policy circles.

Cross-References

- [Agricultural Practices and Sustainable Management in South Asia](#)
- [Biodiversity and Ecosystems Management](#)
- [Biological Diversity: Global Threats](#)
- [Climate Change Effects](#)
- [Ecosystem Services](#)
- [Freshwater Ecosystems](#)
- [Land Use Intensity and Change: Impacts on Biodiversity](#)
- [Soil Contamination and Remediation](#)
- [Soil Erosion, Salinization and Laterization: Causes and Prevention](#)
- [Soil Fertility](#)
- [Soil Pollution Management](#)

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