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Quantifying Nutrient Budgets for sustainable nutrient management

A World of Cobenefits: Solving the Global Nitrogen Challenge

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Key Points:
- Global nitrogen solutions generate cobenefits for (i) world hunger, (ii) pollution, (iii) climate change, and (iv) biodiversity
- We provide the most comprehensive, solutions-focused strategy for global nitrogen to date
- We call for an IPCC-type organization focused on global nitrogen issues and public-private partnerships to scale solutions

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Abstract Nitrogen is a critical component of the economy, food security, and planetary health. Many of the world's sustainability targets hinge on global nitrogen solutions, which, in turn, contribute lasting benefits for (i) world hunger; (ii) soil, air, and water quality; (iii) climate change mitigation; and (iv) biodiversity conservation. Balancing the projected rise in agricultural nitrogen demands while achieving these 21st century ideals will require policies to coordinate solutions among technologies, consumer choice, and socioeconomic transformation.

1. Introduction

Technological breakthroughs in the creation, distribution, and application of nitrogen fertilizers have underpinned major advances in food, fuel, and fiber production, yet substantial disparities in the world's nitrogen balance remain. While developed nations have benefited from advanced nitrogen fertilizer technologies since the early to middle1900s (Erisman et al., 2008), many subsistence farmers in parts of Africa, Asia, and Latin America continue to suffer from inadequate access to commercial fertilizers, often relying on depleted soil nitrogen capital to grow food and support agricultural exports (Austin et al., 2013; Vitousek et al., 2009). Lack of universal access to nitrogen threatens food security, which in turn hinders education, human health, economic growth, and societal resilience (Sánchez, 2010). Conversely, poor management practices and inefficient nitrogen fertilizer applications to agricultural lands are harming the economy: several hundred billion USD of annual financial losses are ascribed to excess nitrogen use in developed nations (Brink et al., 2011; Compton et al., 2011). Much of the social cost of nitrogen inefficiency is embedded in human health risks, such as cancer and upper respiratory disease (Townsend et al., 2003), in addition to accelerated nitrous oxide emissions leading to global climate change and high nitrogen loadings resulting in impaired drinking water and toxic algal blooms in downstream ecosystems (Davidson, 2009; Galloway et al., 2003). Similar to coordinated efforts toward a low-carbon economy amid social, political, and technological transformation (Rockström et al., 2017), disruptive pathways to a modern "nitrogen revolution" are needed for planetary health, climate mitigation, and food security. The opportunity to generate cobenefits through global nitrogen innovations hinges on public policy coordination and public-private partnerships in the new millennium.

2. Framing the Global Nitrogen Challenge

Put simply, the global nitrogen challenge can be framed as maximizing the net positive outcomes of commercial nitrogen fertilizers (including inorganic and organic varieties) for economic, human health, and environmental prosperity. Though manure and legumes can provide a portion of total nitrogen demands of crop production, these nitrogen sources alone are not presently capable of supporting the demands of current or future generations. Thus, commercial fertilizers are envisaged to continue to be a major and perhaps growing component of agricultural productivity in the 21st century, with opportunities to both eliminate nitrogen deficiencies and reduce nitrogen losses, generating cobenefits of increased agricultural nitrogen-use efficiency and crop yields, reduced greenhouse gas emissions, and reactive nitrogen water, air, and soil pollution

Much has already been written about the varied history of human nitrogen interventions (Erisman et al., 2008). Briefly, in the early 1900s, the world was confronted with limited plant-available nitrogen fertilizer supplies (in guano and desert salts; Battye et al., 2017). In response to Germany's diminished nitrogen feedstock to produce munitions in World War I, Fritz Haber and Carl Bosch developed the capacity to convert inert, dinitrogen gas, which comprises 80% of ambient atmosphere into readily available forms of nitrogen contained in industrial products and commercial fertilizers. Today, Haber-Bosch fertilizers have unlocked the key constraint to feeding greater than half of the world's human population (Erisman et al., 2008).

While the distribution and application of commercial nitrogen fertilizers have provided benefits to some of the world's human population, the collective use of commercial fertilizers, manure, and legume crops has imposed risks on public health, the economy, and the environment (Rockström et al., 2009; Townsend et al., 2003; Vitousek et al., 1997). These risks include reductions in biodiversity (Clark & Tilman, 2008); accelerated climate change through the production of nitrous oxide gas, accounting for ~6% of global radiative forcing (Davidson, 2009), is also one of the main causes of human-caused stratospheric ozone depletion (Ravishankara et al., 2009), widespread air, and water pollution leading to growing incidences of upper respiratory disease and cancer in humans (Townsend et al., 2003); eutrophication and hypoxic "dead zones" in the coastal ocean (Diaz & Rosenberg, 2008); and acidification of soils and forests of natural ecosystems (Driscoll et al., 2003). An especially growing public concern is the rise in toxic $PM_{2.5}$ (fine particles in the air <2.5 μm in aerodynamic diameter) levels attributable to nitrogen fertilizer use, which can result in economic damages and health risks in downwind communities (Paulot & Jacob, 2014).

Nitrogen fertilizer applications (manure and commercial fertilizer) and biological nitrogen fixation by legume crops over the period of 1900 to 2000 have increased 100-fold while global nitrogen-use efficiency (defined here as the nitrogen derived from applied fertilizer in crops/total nitrogen applied as fertilizer) has declined from an estimated >60% to ~46%, with regional trends showing either modest improvements, decreases, or no net changes over the past several decades (Wang et al., 2017; Zhang et al., 2015). Fossil fuel combustion has also increased the amount of nitrogen oxides circulating through the air and deposited in ecosystems (Duce et al., 2008; Galloway et al., 1995).

Paradoxically—and in sharp contrast to widespread access of Northern Hemisphere industrial nations to commercial fertilizers since at least the middle 1900s—large areas of Africa and smaller but significant regions of Asia and Latin America continue to experience delays in access to affordable nitrogen fertilizers to grow food (Austin et al., 2013; Vitousek et al., 2009; Figure 1). Such deficiency in combination with many other (geopolitical and cultural) factors contributes to famine, economic stagnation, food insecurity, and social unrest (Sanchez, 2002). Past studies have highlighted the need for socioeconomic and political transformation to solve the nitrogen deficiency issues facing underdeveloped economies (Austin et al., 2013).

Together, geopolitical disparities in nitrogen availability underscore the complexity on which the global nitrogen challenge rests, and so the important question is—what can we do about it?

3. A Five-Pronged Strategy

We have identified five targets and a corresponding Strengths, Weaknesses, Opportunities, Threats analysis (Table 1), which reflect our current understanding of scalable opportunities that have greatest potential to bring balance to the global nitrogen cycle for maximum societal impact. These targets cover a broad class of issues and technologies, recognizing that there are many technical sources of information available on

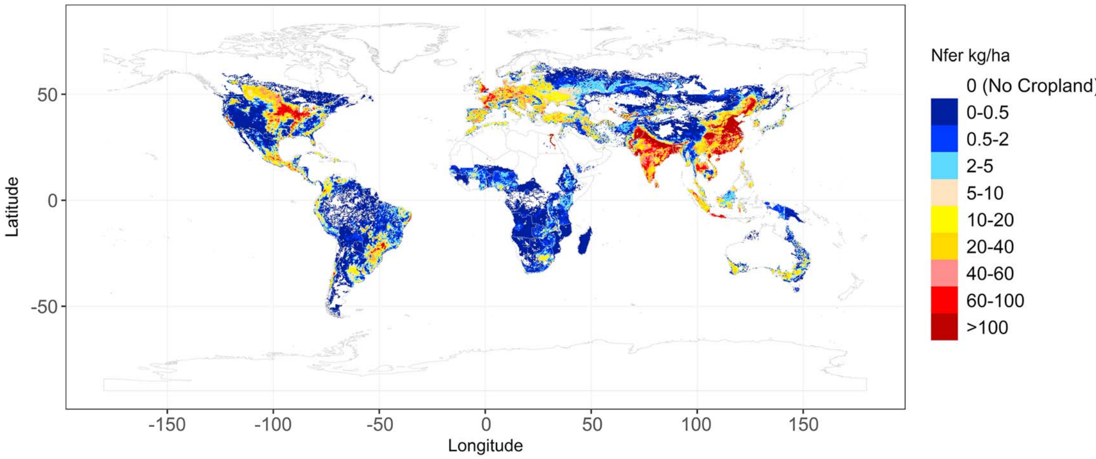

Figure 1. Synthetic nitrogen fertilizer rates (kg N/ha) in global croplands for year 2015 (map derived based on Zhang et al., 2015, and Monfreda et al., 2008; see section 5).

the solutions we highlight (see, e.g., Zhang et al., 2015). Hence, this is not a comprehensive list. Instead, each target is identified vis-à-vis its potential for investment, deployment, and ability to generate cobenefits for people, the economy, and planet (Table 1):

1. *Rapidly improving nitrogen-use efficiency for food, fiber, and fuel production*. Improving nitrogen-use efficiency can be accomplished by adopting a mix of agricultural practices and technologies. Generally, this target includes shifting fertilizer technologies and practices, using improved crop varieties, and boosting soil health to increase the fraction of nitrogen fertilizer that enters agricultural products, creating incentives for improved nitrogen management and following the 4Rs of nitrogen fertilizer application: *right rate*, *right type*, *right placement*, *and right timing* (Johnston & Bruulsema, 2014; Zhang et al., 2015). Continuing to share these approaches to improve nutrient management among developed and developing countries could offer lessons to avoid problems with nitrogen excess and legacies in those areas in the future. Improvements in nutrient efficiencies must also embody animal production systems, with efforts to reduce unwanted nitrogen release to the environment via animal nutrition and waste management programs (Oenema & Tamminga, 2005). Some of the more promising options include widespread adoption of slow-release fertilizers and fertigation (i.e., fertilizers supplied with irrigation water) technologies that more precisely deliver nutrients in proportion to crop demands, fertilizers and amendments that alter microbial transformations in favor of nitrogen retention (i.e., slow-release fertilizers, soil amendments, and nitrogen stabilizers), conservation-management practices (e.g., organic inputs, no-till agriculture) that recycle crop residues and diminish soil erosion, genetic modifications that improve how nitrogen is used by crops, breeding crops with greater root zones and beneficial microbial communities (i.e., mycorrhizae and rhizobium), and farm-level management of nitrogen-use efficiency and nitrogen surplus (Davidson et al., 2015). Recent advancements in sensor technologies that directly monitor fertilizer nitrates in the plant rooting zone could greatly improve nitrogen-use efficiency similar to the advances in water smart irrigation technologies. Meanwhile, reducing implementation costs and other socioeconomic barriers that inhibit the extension of 4R-related measures can help to achieve scalable impacts and encourage farmer adoption. Haber-Bosch accounts for ~1% to 2% of the world's energy usage (Erisman et al., 2008), so developing industrial-scale processes to synthesize carbon neutral fertilizers via hydrogen generation from renewables (solar, wind, and hydropower) can reduce the upstream greenhouse gas emissions and cut energy costs (Esteves et al., 2015; Michalsky et al., 2012).
2. *Getting nitrogen to where it is needed most*. While much of the developed world has affordable and easy access to nitrogen fertilizers to bolster food security, many developing nations still lack access to adequate nitrogen supplies (Figure 1). This disparity is most pronounced in parts of sub-Saharan Africa, where nitrogen is mined from diminishing soil pools to grow food (Wang et al., 2017). Improved nitrogen fertilizer availability, using the most efficient and technologically advanced approaches, is critical to reducing famine and promoting resilience. Solving this facet of the global nitrogen challenge will require intergovernmental cooperation and policies that incentivize the private sector, local NGOs, and citizens

Table 1
Five Strategic Imperatives for Policy Coordination in Global Nitrogen Solutions

	Strengths	Weaknesses	Opportunities	Threats
Rapidly improving nitrogen-use efficiency of food production	Economic benefit to farmers Reduces nitrogen-based global warming, air, and water pollution	Under utilized Technological advancement slow Challenging to monitor Adoption and cost incentives Spatial separation of animal and crop systems	Creation of jobs that promote innovation in precision agriculture and smart sensor technologies Incentivize increased nitrogen-use efficiency with outreach, engagement, and incentives for farmers and ranchers	Fertilizer is inexpensive versus the external costs of reactive nitrogen in developed nations and subsidized in some emerging market nations (e.g., India and China). Costs of excess nitrogen damages not internalized to the food economy Food security is still often conflated with excess fertilizer application
Getting nitrogen to where it is needed most	Improves health and livelihoods, including the agricultural workforce Enhances crop resilience to climate change Reverses mining of soil nutrients and can help build soil organic matter Protects against famine-based migration; improves international security	Increased nitrogen emissions to the environment Inadequate existing supply chains and distribution networks Inequities of access to fertilizer and other resources	Appropriately targeted fertilizer subsidies in least developed countries with phase out provisions as access is improved Private and public sector partnerships Increased economic development in least developed countries	Government noncooperation; corruption; lack of subsidies/incentives It is not only nitrogen but also many other factors (e.g., other nutrients, water, and seed sources) Climate change impacts also threatens crop production Resistance from stakeholders promoting only organic farming solution
Removing nitrogen pollution from the environment	Regain recreational value of lakes, rivers, and streams and safeguard biodiversity Visible improvement on short time scales Health benefits for people	Requires prioritization of sites Multidistrict issue Many locations to consider Lack of regulation or internalized market drivers Only relevant in some areas	Couple with reduced nitrogen loss Community interest Reducing visible and odiferous forms of air and water pollution Increased habitat for wildlife, such as waterfowl	Pollution swapping; inefficient nitrogen removal leading to N_2O, for example Cost incentives
Reducing food waste	Potential financial benefits to farmers and consumers Reduce greenhouse gases Greater food security	Requires on-farm and supply chain infrastructure investments and changes in consumer habits	Use food waste to feed people/animals or re-fertilize land Increase farmer profits by reducing crop spoilage	Political will/societal support Innovation and finance Food safety and regulation
Encouraging diets with low nitrogen footprints	Decrease health risks, reduced health-care premiums Decrease greenhouse gases Increased public engagement in and understanding of sustainability issues	"What's nitrogen?" Lack of understanding or interest by the public Strong cultural preferences for animal products, especially red meat	Public outreach and education; learning opportunities regarding consequences of personal choices Carbon/nitrogen footprint labeling	Cultural norms Perceptions of equity or fairness Lack of knowledge of supply chains, nitrogen emissions, and differences among practices in which food is grown

to make fertilizers accessible to all. Government subsidies, when properly administered with phase-out provisions, have potential to overcome cost barriers and have been shown to improve food production in some cases (Sánchez, 2010). However, nitrogen fertilizer access should not be viewed as a panacea: education, community, and culture must also be considered within the quest to improve agriculture, restore ecosystems, and achieve food security in developing nations. The objective of universal access to commercial nitrogen fertilizers in combination with improving agricultural practices has cobenefits for food security in famine-stricken nations and the manifold issues facing national security and unsustainable migration patterns.

3. *Removing nitrogen pollution from the environment*. Mitigation of nitrogen pollution encompasses both agroecological and engineering/technological solutions, producing cobenefits for the economy, environment, and public health. The catalytic converter is a clear success story, reducing nitrogen emissions from automobiles and improving air quality nationwide (Houlton et al., 2013). Removing nitrogen from polluted water can be achieved through wetland and riparian restoration projects, whereby vegetation, soils, and microbes absorb nitrogen fertilizer in runoff and convert it to biomass or harmless dinitrogen gas (Craig et al., 2008). While natural floodplains can provide such benefits, evidence suggests that restored floodplains may be even more effective at removing nitrogen pollution from agricultural runoff, particularly when they are designed to slow drainage waters and accelerate denitrification (Hanrahan et al., 2018). This approach has the added benefit of providing habitat that increases biodiversity; benefiting wildlife; and improving fish populations for recreational hunters, anglers, and ecotourists; and storing carbon in wetland soils, which can help to offset carbon emissions at local scales (Craig et al., 2008; Pimentel et al., 1997). Additional technological approaches involve the construction of microbial bioreactors either in streams or within drainage tile networks beneath crop production fields that absorb nitrogen pollution before it enters receiving waters (Schipper et al., 2010). Further, algal ponds can be strategically arrayed along fertilized fields to convert nitrogen waste products into biofuels, similar to how regenerative farm systems capture methane from animals to achieve local energy self-sufficiency. Given the generally high abatement costs of nitrogen pollution mitigation, it is critical that such solutions complement improved nitrogen-use efficiency and reductions in nitrogen emissions and discharge.
4. *Reducing food waste*. Food waste is estimated to cost $1 trillion (USD) globally, including costs of waste disposal and landfills, water pollution, and greenhouse gas emissions, such as methane and nitrous oxide. Reducing food waste holds multiple benefits for the economy, food security, climate, and the environment. Comprehensive analysis suggests that approximately one fourth of all global food produced is wasted along the supply chain (Kummu et al., 2012; Springmann et al., 2018). This means that a large fraction of the nitrogen fertilizers applied to grow food are also needlessly wasted in the food that is not consumed. The majority of food waste in developing economies occurs on the farm; hence, reducing waste will require improved coordination among storage and transport of food to avoid spoilage on farms and improved short-term storage technology to reduce losses to pests and pathogens. Food waste can also be repurposed as animal feed, reducing the pressure for feed production and nitrogen fertilizer applications therein. In developed nations, food waste occurs largely at the consumer level, revealing the importance of public awareness programs that reduce overbuying and composting programs that allow for recycling of spoiled food to decrease food waste emissions. To reduce nitrogen losses to the environment from food waste, these interventions should occur at governmental, industrial, social, and individual levels.
5. *Encouraging diets with low nitrogen footprints*. Dietary choices have both environmental and human health consequences. Understanding where food comes from, and how it was grown and processed, can help consumers make informed choices that are consistent with their individual values and culture. Healthy food options provide benefits for personal health and can reduce rising health care costs, associated heart disease, high cholesterol, and obesity (Anekwe & Rahkovsky, 2013). Several studies have shown that diets that moderate dairy and meat consumption can improve health and average life spans while reducing global warming impacts (Tilman & Clark, 2014). On average, beef for consumption retains ~10% or less of the initial nitrogen fertilizer that was applied to grow crops for animal feed; hence, a significant fraction of the nitrogen has escaped the production stream. However, not all crops, dairy, or meat are created equally, and research and knowledge on supply chains and life cycle assessments, particularly how different food growing practices influence nitrogen footprints (Leach et al., 2012; Leach et al., 2016), will help consumers make decisions that are consistent with health recommendations and environmental sustainability (Whitmee et al., 2015).

4. The 21st Century Imperatives

Since the early 1970s, excessive use of nitrogen fertilizers has been recognized as a threat to environmental and human health (Delwiche, 1970); and more recently, sustained and growing nitrogen deficiencies have been identified as a major risk factor to subsistence farmers and communities in food-insecure regions

(Sanchez, 2002). We have provided a set of organizing principles through which global nitrogen solutions can work through policy, technology, and innovation to create substantial cobenefits for the world (opportunities; Table 1). Several barriers (threats; Table 1) face the five core targets we have identified, which will need to be overcome that cobenefits of nitrogen solutions can be realized.

Importantly, our Strengths, Weaknesses, Opportunities, Threats analysis (Table 1) suggests a qualitative framework for stimulating cross-sectoral discussions. Complementing this framework with quantitative modeling should be seen as a high research priority. A particularly useful approach would be to examine the costs and benefits of technologies to improve nitrogen-use efficiency and how the deployment of a portfolio of different solutions would affect growers, society, climate, and the environment. Global to regional-scale efforts, such as the International Nitrogen Initiative (http://www.initrogen.org/), the European Nitrogen Assessment (Sutton et al., 2011), the U.S. Nitrogen Assessment (Suddick et al., 2013), and the California Nitrogen Assessment (Tomich, 2016), among others, point to auspicious test cases; however, explicit coordination among such efforts can be enhanced. A United Nation-based mandate to examine the global nitrogen challenge, analogous to the Intergovernmental Panel on Climate Change, would help to facilitate regional, continental, and global efforts and create a science-informed policy mandate.

Another fundamental obstacle lies in existing social-economic and cultural systems, which have substantially delayed progress on global nitrogen solutions for decades. Nitrogen-use efficiency has shown improvement in the U.S. maize systems (Cassman et al., 2002) and regionally in parts of Europe, where nitrogen-use efficiency has increased by 10% to 40% from the 1960s to mid-2000s in the Netherlands, Greece, and France (Lassaletta et al., 2014). Despite such progress, nitrogen losses from agriculture continue to cause widespread environmental degradation across the globe (Mueller et al., 2017; Wang et al., 2017; Zhang et al., 2015). An emphasis on “uncommon partnerships,” wherein farmers, scientists, economists, NGOs, citizens, and industries bring their knowledge to bear on the global nitrogen challenge, is thereby urgently needed. Such broad stakeholder engagement is critical for overcoming knowledge gaps, which can come into focus via large-scale (multiple hectare) demonstration projects that test and perfect new nitrogen innovations, driving commercialization opportunities, new business development, and job creation. In addition, similar to global carbon issues (Rockström et al., 2017), finance models are yet to be optimized for nitrogen solutions; despite substantial economic damages of excess nitrogen, public policies have not acted systemically, reducing the market's appetite for technological breakthroughs. Progressive policies and pricing mechanisms that internalize nitrogen's social costs (and benefits) have the potential to spur nitrogen innovations and workforce development via the free market.

Finally, in the case of the crippling effects of nitrogen impoverishment on human health and well-being, a coordinated emphasis on universal access to and appropriate management of commercial nitrogen fertilizers is paramount. These fertilizers can come in synthetic and organic forms and, when coupled to animal agriculture, offer pathways to reduce environmental and human-health risks of manure while creating more “closed loop” systems of nutrient regeneration. Improving access to nitrogen is consistent with United Nation Sustainable Development Goals, representing both a humanitarian and environmental imperative for the 21st century. Regions where lack of access to commercial nitrogen fertilizers is contributing to food insecurity generally correspond with those where climate change impacts are predicted to reduce yields in the coming decades (e.g., parts of Africa and Latin America; Jones & Thornton, 2003). Nitrogen access can substantially improve crop yields (Sánchez, 2010), which, along with proper infrastructure and food storage, offers resilience to climate-impacted communities as they navigate growing incidence of extreme weather. The opportunity of global nitrogen solutions lies in the rapid generation of cobenefits. In many respects, this characteristic places nitrogen in a unique space among the many global problems faced by our world today.

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5. Methods

The map of synthetic nitrogen fertilizer application rates (defined as kilogram nitrogen per hectare of earth surface area; Figure 1) was derived from the distribution of crop harvested area (Monfreda et al., 2008) and nitrogen fertilizer application rates by country and crop type (Zhang et al., 2015). Monfreda et al. (2008)

provides gridded harvested area data by crop type for the year 2000. We aggregated the data to 15 arcmin by 15 arcmin grid cells. To estimate the crop distribution in 2015, we assume each grid cell's harvested area by each crop type ($HA_{\mathrm{cr},i}$; cr denotes crop type and i denotes grid) changes proportionally with their corresponding national harvested area from 2000 to 2015. The nitrogen fertilizer application rate (defined as kilogram nitrogen per hectare of harvested area) for crop-type cr and country co ($NR_{\mathrm{cr,co}}$) was derived for year 2015 following methodologies described in Zhang et al. (2015) with data from the Food and Agriculture Organization and International Fertilizer Association. Consequently, we calculate the synthetic nitrogen fertilizer application rates for grid i (NM_i) by

$$NM_i = \frac{\sum_{\mathrm{cr}} NR_{\mathrm{cr,co}} \times HA_{\mathrm{cr},i}}{GA_i}$$

where GA_i is the surface area for grid i and co denotes the country grid i belongs to.

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