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EDITORIAL

Synthesis and review: Tackling the nitrogen management challenge: from global to local scales

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Abstract

One of the 'grand challenges' of this age is the anthropogenic impact exerted on the nitrogen cycle. Issues of concern range from an excess of fixed nitrogen resulting in environmental pressures for some regions, while for other regions insufficient fixed nitrogen affects food security and may lead to health risks. To address these issues, nitrogen needs to be managed in an integrated fashion, at a variety of scales (from global to local). Such management has to be based on a thorough understanding of the sources of reactive nitrogen released into the environment, its deposition and effects. This requires a comprehensive assessment of the key drivers of changes in the nitrogen cycle both spatially, at the field, regional and global scale and over time. In this *focus issue*, we address the challenges of managing reactive nitrogen in the context of food production and its impacts on human and ecosystem health. In addition, we discuss the scope for and design of management approaches in regions with too much and too little nitrogen. This focus issue includes several contributions from authors who participated at the N2013 conference in Kampala in November 2013, where delegates compiled and agreed upon the '*Kampala Statement-for-Action on Reactive Nitrogen in Africa and Globally*'. These contributions further underline scientifically the claims of the 'Kampala Statement', that simultaneously reducing pollution and increasing nitrogen available in the food system, by improved nitrogen management offers win-wins for environment, health and food security in both developing and developed economies. The specific messages conveyed in the Kampala Statement focus on improving nitrogen management (I), including the reduction of nitrogen losses from agriculture, industry, transport and energy sectors, as well as improving waste treatment and informing individuals and institutions (II). Highlighting the need for innovation and increased awareness among stakeholders (III) and the identification of policy and technology solutions to tackle global nitrogen management issues (IV), this will enable countries to fulfil their regional and global commitments.

1. Introduction

Nitrogen (N) is one of the five major chemical elements that are necessary for life, but while nitrogen is the most abundant of these, more than 99.9% of it occurs as molecular di-nitrogen (N_2) and is not directly accessible to most organisms. In order to break the triple bond connecting the two nitrogen atoms, and to 'fix' nitrogen into usable forms, a substantial amount of energy is required, either through high-temperature processes (e.g., during combustion or in the Haber–Bosch process) or by biological nitrogen fixation (BNF), through the action of certain specialized bacteria. By contrast, most living

Food

1. Nitrogen and Food Security
- Linkages between nitrogen and malnutrition
- Strategies for increasing protein in farming systems and diets

2. N_r intensification in low input systems – Integrated soil fertility management
- Optimising contribution of indigenous soil N_r to food productivity
- Use of Biological Nitrogen Fixation (BNF) for addressing crop N requirements
- Targeting fertilizer application for productivity, profitability and tradeoffs

3. Improving N management in fertilizers and agricultural manures
- Methods for improving nitrogen use efficiency (NUE)
- Reduction of N_r emissions to air from fertilizers and manures
- Reduction of N_r emissions to water

Impacts

4. Nitrogen and human health
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- Impacts of nitrogen water pollution on health risks
- Diets as drivers of change in the N cycle

5. Nitrogen and ecosystem health
- Quantifying nitrogen effects on ecosystem health *(too little and too much N)*
- Terrestrial ecosystems and biodiversity
- Aquatic, coastal and marine ecosystems

6. Nitrogen and climate change
- Impacts of N use and N losses on climate drivers
- Consequences of climate change for the N cycle
- Improving N management under climate change

Management

7. Managing Nitrogen in Waste
- Sources of nitrogen in solid waste including composting
- Progress in managing N in waste water
- Recycling N containing wastes: including biogas, separating waste streams and novel technologies.

8. Reducing N emissions from combustion and industry
- Low N_r emission technology
- New technologies to recycle N_r from NO_x

9. Implementing N_r management policies
- Successes and challenges from around the world
- National, regional and international case studies
- The challenge of managing excess societal N_r consumption in food and energy
- Overcoming obstacles to increasing N_r use in low-N-input systems

Assessment

10. Interaction of the N cycle with other nutrients and the water cycle
- Synthesis and upscaling
- Quantifying regional and transboundary nitrogen fluxes and flows
- Harmonizing indicators on effects, losses and NUE
- Multi-criteria & cost-benefit analysis and identification of regional priorities.

Figure 1. Illustration of four key topic areas detailing the interactions between reactive nitrogen and the environment, and options for the assessment and management, as framed in preparation for the N2013 conference.

organisms are restricted to using the result of such fixation processes: reactive nitrogen (N_r) compounds. These include inorganic forms of nitrogen such as ammonia (NH_3), ammonium (NH_4^+), nitric oxide and nitrogen dioxide (NO and NO_2, collectively NO_x), nitric acid (HNO_3), nitrous oxide (N_2O), and nitrate (NO_3^-), as well as organic compounds like urea ($CO(NH_2)_2$), amines, proteins, and nucleic acids.

Releases of N_r into the environment are closely related to agricultural activities and the combustion of fossil fuels, or, in other terms, food production and energy conversion. After they are emitted, N_r compounds are subject to chemical transformation and can remain in the atmosphere, hydrosphere and biosphere for extended periods of time, circulating between different environmental media in what has been identified as the 'nitrogen cascade' (Galloway *et al* 2003) until the energy contained in N_r is eventually dissipated and it is denitrified back to N_2.

While N_r contributes to a wide range of negative effects on human and ecosystem health, nitrogen use for food production is essential to feed the growing world population, its use thus requires a strategic, integrated management approach (Galloway *et al* 2008, Sutton and Howard 2011, Sutton and Reis 2011, Sutton *et al* 2012, 2013a, 2013b, Davidson *et al* 2012, Austin *et al* 2013).

The overall goal of global activities such as the International Nitrogen Initiative (INI) is to optimize nitrogen's beneficial role in sustainable food production, while aiming to minimize its negative effects on human and ecosystem health originating from food and energy production. In order to achieve this, a balance needs to be established between reducing excessive losses of N_r in regions of the world where too much nitrogen is used (thereby improving nitrogen use efficiency, NUE), and increasing the availability and sustainable use of nitrogen in regions where food production is currently insufficient to sustain populations with a healthy diet.

These issues were addressed in preparing for the N2013 conference (Kampala, 18–22 November 2013). Four key areas were identified as a focus to achieve these objectives: *the role of N in food production, N management, N impacts on human health, ecosystems and in relation to climate change*, and methods for the *integrated assessment of N management options*. Figure 1 illustrates the key questions we have considered in the following sections of this article in relation to the contributions to this focus issue.

2. Nitrogen in food production

2.1. Nitrogen and food security

Natural BNF and lightning supply the biosphere with N_r compounds. However, it was already recognized over a century ago that this is not enough to produce enough food for an increasingly expanding and increasingly urbanized population, demanding higher intake rates of food production and associated dietary protein (Crookes 1898). Chemical and biological anthropogenic processes have dominated the creation of extra N_r globally over the last century (Billen *et al* 2013, Fowler *et al* 2013, Sutton *et al* 2013a). Populations in parts of the world (usually industrialized) where N_r is readily available have used it to intensify and increase agricultural production, provide richer and more diversified diets, all of which improve nutrition compared with the situation in the poorest counties. For example, increased consumption of livestock products not only provides high-value protein, but is also an important source of a wide range of essential micronutrients such as iron and zinc, and vitamins such as vitamin A. In contrast, excessive consumption of these diets in some world regions has led to excessive intakes of energy, fat and protein, leading to opportunities to optimize by reducing intake of meat and dairy products in these countries (e.g. Westhoek *et al* 2014, 2015).

In this focus issue, van Grinsven *et al* (2015) add to the debate by examining the case to consider 'sustainable extensification' as an alternative strategy to the more commonly discussed paradigm of 'sustainable intensification' (e.g., Garnett and Godfrey 2012). Van Grinsven *et al* (2015) conclude that, in Europe, extensification of agriculture can have positive environmental and biodiversity benefits, but at a cost of reduced yields, if it were combined with adjusted diets with reduced meat and dairy intake and the externalization of environmental costs to food prices. Changes in consumption patterns, for instance due to reduced animal protein intakes as part of a demitarian diet, may amplify or weaken these effects. Building on the work of Westhoek *et al* (2014), these authors considered a demitarian scenario, where European meat and dairy intake were halved, linking this also with potential health benefits associated with avoidance of excessive intake.

In contrast, other parts of the world that have limited access to sufficient N_r to replenish crop uptake from soils are faced with continuing food scarcity and nutritional insecurity. Per capita food consumption in sub-Saharan Africa, for example, was 2238 kcal per day during 2005/2007, being 67% that of the industrialized countries (Alexandratos and Bruinsma 2012), while livestock products remain a desired food for taste, nutritional value and social value. This highlights the continued challenge to provide access to sufficient nitrogen in sub-Saharan African contexts to prevent mining of existing soil N stocks in agricultural soils (Vitousek *et al* 2009). For example, according to the estimates of Zhou *et al* (2014) in this focus issue (see section 5.3), nitrogen export from the Lake Victoria catchment is substantially larger than imports or estimated N fixation, implying substantial soil N mining.

In preparing for the N2013 Kampala Conference, it had been anticipated that a discussion on reducing meat and dairy consumption would be highly sensitive in a continent where many citizens do not have access to sufficient healthy diets. Nevertheless, it was agreed to implement the principles of the *Barsac Declaration* (Sutton *et al* 2009), where the catering for the conference would provide half the usual amount of meat intake per delegate for such an international conference in this region, accompanied by a larger fraction of vegetable products. The discussion was welcomed by both the conference chef and the delegates, stimulating significant discussion on what constitutes a suitable balanced diet considering both health and environment. The topic was incorporated into the 'Nitrogen Neutrality' analysis of Leip *et al* (2014) (see section 5.1) and provided an important comparison with the experience of implementing the Barsac Declaration at the 'Nitrogen and Global Change' 2011 conference in Edinburgh (Sutton and Howard 2011).

Specifically, the baseline meat serving for a main meal (lunch or dinner) in other recent Edinburgh conferences had been 180 g per person, which was reduced in the 'Nitrogen and Global Change' conference to 60 g per person. By comparison, in Kampala, the baseline serving for the venue was 270 g per person, which was reduced in the N2013 conference to 140 g per person (equivalent to 340 g per day, Leip *et al* 2014, Tumwesigye *et al* 2014). The fact that baseline meat intake for international conferences in Kampala was 50% higher than for similar conferences in Edinburgh highlights the need not just to consider national or regional averages, but also the demographic structure of meat and dairy intake between different sectors of society. It also recalls Article 6b of the Barsac Declaration: '*In many developing countries, increased nutrient availability is needed to improve diets, while in other developing countries, per capita consumption of animal products is fast increasing to levels that are both less healthy and environmentally unsustainable.*'

In this focus issue, Billen *et al* (2015) examine these challenges, considering the implications for feeding a growing world population. They estimate that improving the agronomical performance in the most deficient regions is a key requirement in order to achieve global food security without creating even greater adverse effects of nitrogen pollution as they currently occur. They conclude that if an equitable human diet (in terms of protein consumption) is to be established globally (the same in all regions of the world), then the fraction of animal protein should not exceed 40% of a total ingestion of 4 kg N capita^{-1} yr^{-1}, or 25% of a total consumption of 5 kg N capita^{-1} yr^{-1}.

These challenges for nitrogen and food security were brought together during the N2013 conference, as reflected in the agreed '*Kampala Statement-for-Action on nitrogen in Africa and globally*' which summarized the conference conclusions and key messages (INI 2013). In particular, the Kampala Statement emphasized that Africa is entering a new Green Revolution where strengthened policies to support improved low-cost, reliable fertilizer delivery to smallholder farmers will be necessary to increase agricultural productivity. The messages specific to sub-Saharan Africa were complemented by global messages including the need to reduce nitrogen losses from agriculture and other sectors including industry, transport, energy and waste.

2.2. N_r intensification in low input systems and integrated soil fertility management

The growing demand for high-protein products recognized by the Kampala conference can have an undesirable impact on natural resources. A critical effect is the ongoing reduction in the soil's N_r capital (soil 'nitrogen mining'), where the labile pools of soil organic N (SON) seem to be well correlated with N release rates, such as particulate organic N and N in the light fraction of soil organic matter (SOM). While such soil N_r mining will maximize 'service flows' (usable outputs) and the value of crop production for several years (Sanchez *et al* 1997), it is not sustainable in the long term. In low-input smallholder systems, soil nitrogen stocks have reduced due to escapes into the environment as a result of over-farming, erosion and leaching (Stoorvogel and Smaling 1990) if the systems are not managed for sustainability.

This is not to exclude the possibility of making maximum use of existing soil nitrogen stocks. However, optimizing the contribution of existing N stocks will depend on determining and maintaining the minimal size of the N_r that allows the marginal costs of nutrient replenishment to be met by the marginal benefits. In addition to providing necessary inputs of N from external sources, maintaining soil N stocks can also be aided by more efficient N_r cycling, i.e. transfer of nitrogen already in the field from one component to another (Palm *et al* 1997).

In this focus issue, Powell (2014) demonstrates how the efficiency of N_r cycling in crop-livestock systems very much depends on optimizing approaches to feed and manure management and targeting application, whether in low-N-input or high-N-input dairy cattle systems as they impact manure N excretion, manure N capture and recycling, crop production and environmental N loss. They found that initial soil N stock largely determined the degree of manure N use efficiency, with high rates of N input being associated with low manure NUE, while low rates of N input were associated with high manure NUE. Similarly, the study reported in this issue by Sanz-Cobena *et al* (2014), on yield-scaled mitigation of ammonia emission from N fertilization, demonstrates how different rates, forms and methods of fertilizer N application can have significant implications for crop yield, N surplus and NUE. They show how these terms can be used as performance indicators that can help farmers' acceptance of technology and environmental protection measures.

Recent developments also show that anthropogenic driven BNF can be successful for N_r intensification in low-N-input systems, provided that appropriate legumes are inoculated with elite inoculants and ensuring that P is utilized as a key input. Over a period of 4 years, *N2Africa*'s BNF technology dissemination project[9] realized up to 15% increases in farm yields of grain legume and 17% in BNF (Woomer *et al* 2014).

[9] http://n2africa.org/

2.3. Improving N management in fertilizers and agricultural manures

Increased attention internationally is now being given to defining metrics of NUE as a basis to assess improvements in performance as a result of better nitrogen management (Norton *et al* 2015, Oenema *et al* 2015). In this focus issue, Yan *et al* (2014) investigate this topic using data from cropping systems across China. In particular, they assess fertilizer recovery efficiency for nitrogen (RE_N), which is based on within year uptake of fertilizer nitrogen by crops, with a fuller view that accounts for all sources of crop N inputs and for crop recovery of nitrogen in subsequent years. Overall, they acknowledge that RE_N is low in China at less than 30%. By contrast, the long-term effective RE_N including uptake in subsequent years is about 40%–68%. While they recognize that there are still substantial losses, including to denitrification, NH_3 volatilization, surface runoff and leaching, the study shows the importance of accounting for the residual effect of N when optimizing fertilizer inputs.

It is also critical that fertilization regimes be tailored to the biophysical environments and socio-economic status of farmers in order to optimize NUE. The response of agricultural soils to fertilizers application is, among other parameters, shown to be a function of the state of soil fertility. This is especially illustrated by the contrasting situation of low fertilizer N inputs in sub-Saharan Africa. Here smallholder farms that are cropped without any external nutrient inputs gradually become exhausted of nutrients and carbon stocks. Such soils have been shown to respond poorly to fertilizer application, while more efficient use of nutrients can be kick-started with additions of a carbon source, such as livestock manure (Zingore *et al* 2007). In the same way that sufficient available phosphorus is needed to maximize NUE, it is evident that balanced availability of all required nutrients is necessary if increased nitrogen fertilizer application is not to be associated with reduced NUE and increased air and water pollution.

These examples illustrate the classic two-sided nitrogen problem of too little and too much, both requiring efficient fertilizer N management, as illustrated for example by the 4R nutrient stewardship concept of the *International Plant Nutrition Institute*[10]: Right fertilizer, Right amount, Right time and Right placement, and in the 'Five Element Strategy' to improve NUE described in 'Our Nutrient World': Nutrient stewardship, Crop stewardship, Appropriate practices for irrigation, Integrated weed and pest management, site-specific nutrient management, including for manures (Sutton *et al* 2013a).

[10] http://ipni.net/4R

3. Nitrogen impacts

3.1. Nitrogen effects on human health

Nitrogen can affect human health through several different pathways. Examples include exposure to NO_x, due to the emission of NO in combustion processes, and to fine particulate matter, formed from secondary inorganic aerosols by combination of nitrogen oxide and ammonia emissions, which contribute to respiratory and cardio-vascular diseases (e.g. Moldanova *et al* 2011). At the same time, release of excess N and P nutrients into freshwater and coastal ecosystems can cause toxic algae blooms causing health effects from the consumption of fish and other seafood, as well as increased levels of nitrate in drinking water. Excess nutrient intake similarly leads to obesity, resulting in adverse effects on the cardiovascular system and causing a range of diseases, while high levels of nitrate intake may have adverse effects through the digestive tract, including increasing risk of colon cancer, as discussed by Brender (2016*)* as part of an accompanying volume on the Kampala conference. Finally, the contribution of nitrogen to tropospheric ozone formation reduces crop yield and ecosystem health, as well as contributing to global warming with health effects due to temperature rise, extreme weather events or the increase of vector-borne diseases.

As a contribution to this focus issue, Schullehner and Hansen (2014) illustrate these concerns for the population of Denmark, showing that the trends in nitrate exposure differ for users of public water supply compared with those dependent on private wells. Overall, the fraction of the Danish population exposed to elevated nitrate concentrations has been decreasing since the 1970s, as a result of lower nitrate levels in the public water supply. By contrast, nitrate levels have been increasing over this period amongst private well users. This leads Schullehner and Hansen to the hypothesis that the decrease in nitrate concentrations in drinking water is mainly due to structural changes rather than improvement of the groundwater quality of Denmark.

The risks of atmospheric emissions for human health are highlighted by the contribution of Singh and Kulshrestha (2014), who compare urban and rural concentrations of N_r in the air above the Indo-Gangetic plains of India. Their findings highlight an abundance of reactive nitrogen (NH_3 and NO_2) with exceptionally high concentrations at both types of site, with both NH_3 (6–150 $\mu g\ m^{-3}$; site means 41 and 52 $\mu g\ m^{-3}$) and NO_2 concentrations (2.5–64 $\mu g\ m^{-3}$; site means 19 and 24 $\mu g\ m^{-3}$) showing substantial seasonal variability. These concentrations of the gaseous precursors demonstrate the risk of extremely high secondary particulate matter concentrations, with substantial risks to human health. The concentrations observed in both sides are substantially higher than in populated areas in developed countries and demonstrate the need to focus observations and research into air pollution control measures in densely populated regions and cities of emerging and developing countries.

3.2. Nitrogen effects on ecosystem health

Increased N deposition around the world affects key environmental drivers such as biodiversity, health of terrestrial ecosystems (Dise *et al* 2011, Goodale *et al* 2011) the aquatic and marine environment (Borja 2014), with major interactions with health and well-being through eutrophication, acidification, and nitrogen–carbon-climate interactions (Butterbach-Bahl *et al* 2011, Suddick *et al* 2012).

Europe, the United States of America, China, India and others are the major hotspots for N emissions. Where stringent emission control policies have been enacted and enforced, such as, for instance, the Clean Air Act in the USA since 1970, measures to control NO_x emissions have resulted in a 36% decrease overall and resulted in reduced NO_3 deposition through precipitation. However, in the same country, NH_3 emissions have been mainly unregulated and this has resulted in increased NH_3 emissions with rising NH_4 in wet deposition in the same period (Bleeker *et al* 2009). A new comprehensive analysis in this focus issue by Du *et al* (2014) has assessed trends of wet deposition of ammonium, nitrate and total dissolved inorganic N (DIN, the sum of NH_4^+ and NO_3^-) for the period 1985–2012 over the USA. They applied statistical tests to analyze data from the National Atmospheric Deposition Program (NADP; Helsel and Frans 2006). Du *et al* found that wet DIN did not change significantly, but the mean annual NH_4–N/NO_3–N ratio increased from 0.72 to 1.49 over the period, as the dominant N species in wet deposition to USA ecosystems shifted from NO_3^- to NH_4^+. The result clearly reflects the effectiveness of NO_x emission controls and the lack of NH_3 emissions controls. Different N species (oxidized and reduced forms) also exert different effects on the environment (e.g., Sheppard *et al* 2011 showed a proportionately larger effect of NH_3 than NH_4^+ and NO_3^- per unit N input) indicating the importance of taking into account all N_r species in the development of regulations for controlling N emissions.

Another observation reported in this focus issue is that demand for synthetically produced N fertilizers through the Haber Bosch process has increased much faster than for P fertilizer (Sutton *et al* 2013a), which has substantially increased the N:P ratio in environmental pools (Glibert *et al* 2014). In parallel with a growing demand for N fertilizers and the extreme 'leakiness' of nitrogen use in agriculture, there has already been some levelling-off of global P losses to the environment as industrialized nations reduced P use in detergents and upgraded sewage treatment processes in the mid-1980s and 1990s. Glibert *et al* (2014) relate this increase in N:P ratio to the occurrence and proliferation of harmful algal blooms (HABs) in water bodies including lakes, rivers and coastal waters bringing about large negative economic and ecological impacts.

For example, Glibert *et al* (2014) show how fertilizer use in China, which has risen from 0.5 Mt in the 1960s to 42 Mt in 2010 with urea increasing fivefold in the last two decades (IFA 2014), has led to nitrogen export during the same period increasing from 500 to 1200 kg N km^{-2} in the Yangtze River catchment, with an increase from 400 to >1200 kg N km^{-2} in the Zhujiang (Pearl) River catchment (Ti and Yan 2013). Recognizing these changes, Wang *et al* (2014) in this focus issue, apply a mass balance model based on Howarth *et al* (1996) to estimate that N input to the whole Yangtze River basin was 16.4 Tg N in 2010, representing a twofold increase over a period of 20 years. Other major sources of inorganic N in the region include atmospheric NH_4^+ resulting from NH_3 emission, with livestock excretion, fertilizer N, crop residue and burning, human waste contributing (Luo *et al* 2014). The result, as Luo *et al* show in this issue, is extremely high rates of atmospheric nitrogen deposition to coastal seas. Improving NUE, with associated reduction in the N_r inputs and the consequent N_r pollution losses, would result in far reaching benefits to ecosystems. In contrast, van Meter *et al* (2016) analyzed long-term soil data (1957–2010) from 2069 sites throughout the Mississippi River Basin (MRB) to reveal N accumulation in cropland of 25–70 kg ha^{-1} yr^{-1}, a total of 3.8 ± 1.8 Mt yr^{-1} at the watershed scale. Based on a simple modeling framework to capture N depletion and accumulation dynamics under intensive agriculture, they show that the observed accumulation of SON in the MRB over a 30 year period (142 Tg N) would lead to a biogeochemical lag time of 35 years for 99% of legacy SON, even with complete cessation of fertilizer application. These findings make a critical contribution towards closing watershed N budgets by demonstrating that agricultural soils can act as a net N sink.

3.3. Nitrogen and climate change

Nitrogen climate interactions are recognized to operate in two ways. First, human alteration of the nitrogen cycle can alter N flows in the environment with potential impacts on climate by altering global warming potential. Secondly, ongoing climate change may lead to feedbacks with other consequences for the nitrogen cycle and its impacts. Both issues are highly complex, as increased N use and losses have both warming effects (increased N_2O emission, suppression of C sequestration due to tropospheric ozone) and cooling effects (increased C sequestration due to the forest fertilizing effect of atmospheric deposition), light scattering due to higher loading of nitrogen containing aerosol (Butterbach-Bahl *et al* 2011). In terms of the feedbacks of climate change on the nitrogen cycle, this can include alteration of carbon cycling, potentially threatening the stability of stored carbon pools (Suddick *et al* 2012) as well as lead to increased rates of N volatilization (Sutton *et al* 2013b).

The contributions addressing the nitrogen climate interaction in this focus issue all concentrate on the first part of this challenge, and specifically on understanding how to quantify and reduce emissions of the greenhouse gas N_2O. While methods to upscale N_2O emissions use a wide range of inventory approaches, Fitton *et al* (2014) highlight the importance of applying process-based models that can incorporate the effects of improved management actions. They applied the *Daily DayCent* (DDC) model to UK contexts assessing its performance to simulate measured N_2O emissions as compared with use of the IPCC Tier 1 methodology. They found the DDC model to be particularly sensitive to soil pH and clay content and were able to provide a more accurate representation of annual emissions than the Tier 1 approach.

One of the most widely discussed methods to reduce N_2O emissions in fertilized agricultural systems is the use of nitrification inhibitors, which slow the conversion of NH_4^+ to NO_3^-, thereby limiting build-up of soil NO_3^-, which is a key substrate for N_2O emission. Misselbrook *et al* (2014) assess their effectiveness for a range of UK field conditions, giving particular emphasis to the performance of dicyandiamide (DCD) additions to fertilizer, cattle urine and cattle slurry application to land. They found it to reduce N_2O emissions for ammonium nitrate, urea and cattle urine by 39%, 69% and 70%, while similar reductions for cattle slurry (56%) were more scattered and therefore not statistically significant. Overall, they estimated that the approach could reduce national agricultural N_2O emissions by 20% (without increasing NH_3 emission or NO_3 leaching), though more cost-effective delivery mechanisms are needed to make the approach more attractive to farmers. It is worth noting that the mitigation efficiencies of Misselbrook *et al* are higher than most previous studies (e.g., a meta-analysis of Akiyama *et al* 2010 found an average N_2O mitigation efficiency of 30%). This is likely because DCD applied in this study was sprayed across the whole soil surface, while in most other studies, DCD was combined with fertilizers and thus may have affected only fertilizer-induced emission.

Davidson and Kanter (2014) extend the theme of N_2O to the global scale, reporting results of an assessment initiated by UNEP (Alcamo *et al* 2013) on the actions that would be needed to reduce global N_2O emissions. Davidson and Kanter first compare and update recent estimates of global N_2O emissions and then consider possible emission scenarios up to 2050. They then show how several business-as-usual scenarios are expected to double N_2O emissions by 2050. By contrast, they estimate that a 22% reduction in emissions (compared with 2005) would be needed to stabilize N_2O concentrations by 2050 (at around 350 ppb).

According to their comparisons, this will only be possible with aggressive mitigation in all sectors (agriculture, industry, biomass burning, aqua-culture) and substantially reduced per capita meat consumption in the developed world.

4. Other options for nitrogen management

4.1. Managing nitrogen in waste

The management of nitrogen in waste has not been a core focus of the papers within this focus issue, however its importance as part of the anthropogenic nitrogen cycle is clear. Nitrogen in waste (from both household and industrial sources) includes both 'solid waste' (i.e. discarded food, products and packaging) or 'wastewater and sewage' (including industrial wastewater). The items with the highest nitrogen fraction in this system are sewage and wastewater, along with food waste—due to the nitrogen levels within protein (around 16%).

Due to the high quantity of nitrogen found within wastewater and sewage, its management is crucial for minimizing the impact of nitrogen on the environment. This has been highlighted in the Kampala Statement, which stated one of its Global Messages as '*Improving Treatment of Waste: Sewage treatment and solid municipal waste (household wastes) are sources of nitrogen losses that could be reduced by treatment and/or recycling.*' The need for this also stems from the large variation in management of wastewater and sewage globally. Hutchings *et al* (2014, this issue) can show ongoing improvements in wastewater treatment and increases in N_2 emission in the Danish national N budget. However, in Africa, in this issue, Zhou *et al* (2014) discuss the difficulties of estimating fluxes of wastewater to rivers in the Lake Victoria Basin due to the lack of wastewater treatment plants and wastewater collection facilities. Bustamente *et al* (2015, this issue) highlight that wastewater represents the largest source of total dissolved nitrogen (TDN) to coastal ecosystems in South America and whilst in Brazil access to clean water has improved, access to improved sanitation is still not available to 125 million residents. Singh and Kulshrestha (2014, this issue) also provide important comparative insights into both ammonia and NO_x emission profiles from rural and urban areas in India—where human waste (and municipal waste) led to high levels of ammonia concentrations. Wastewater and sewage also contribute to 3% of the global budget of N_2O—either directly from wastewater effluent or from bioreactors removing N in biological nutrient removal plants (Davidson and Kanter 2014, this issue). Finally whilst improved wastewater treatment avoids runoff into rivers, ultimately it also represents the loss of N from the system, which could otherwise be recycled.

Food waste is also a key battleground for nitrogen, once produced and collected, it can be incinerated or added to landfill, however anaerobic digestion of waste food (and separated sewage) to generate methane and carbon dioxide biogas is gaining in importance and yields are comparable to several energy crops which can be grown for the same purpose (Weiland 2009). Hutchings *et al* (2014, this issue) indicate that the Danish government has established targets for substantially increasing the recycling of organic waste. However, unlike sewage and wastewater, a large proportion of food waste is avoidable and therefore the potential benefits of decreasing food waste streams has also been discussed in this issue. Bodirsky and Müller (2014, this issue) highlighted the importance that decreasing food waste could have in increasing NUE in two of their three scenarios, Also in this issue, Leip *et al* (2015) stated that reducing over-consumption of food and food waste was central to achieve 'Nitrogen Neutrality' and again Hutchings *et al* (2014) discussed food waste in the context of a Danish nitrogen budget, and the potential gains that could be made in reducing the food waste from retailers, from restaurants and in institutional food preparation.

It is clear from this focus issue, that considering waste is important for nitrogen and more work is needed in terms of both minimizing waste streams, improving sanitation and waste collection and where possible increasing recycling and re-use. However, such solutions will need to be underpinned by improvements in data availability on N flows in waste streams.

4.2. Reducing nitrogen emissions from combustion and industry

As Galloway *et al* (2014) show in this issue, substantial reductions of N_r emissions from fossil fuel combustion sources have been achieved in most developed countries since the 1990s. For Europe, Vestreng *et al* (2009) report consistent downward trends in particular for emissions from road transport and large combustion sources. Due to the implementation of increasingly stringent air pollution control policies in Europe and the US, most large power plants today utilize both primary and secondary control measures, reducing the formation and emission of nitrogen oxides with varying efficiency. Primary emission control measures typically applied comprise modifications of the combustion process such as:

- burner optimization (e.g. excess air control or burner fine tuning)
- air staging (over fire air or two-stage combustion)
- flue gas recirculation
- low-NO_x burners.

While primary measures address the formation of N_r in the combustion chamber, secondary measures convert the formed oxides of nitrogen by treating the flue gas, for instance by selective catalytic and non-catalytic reduction through the injection of sal ammoniac, ammonia or urea. State-of-the-art secondary control measures can achieve reduction efficiencies of 80%–90% for NO_x, however, a small amount of ammonia may be released into the environment, the so-called 'ammonia slip', which reduces the overall efficiency for N_r control. (see e.g. Javed *et al* 2007, Johnson *et al* 2009).

Road vehicles have been subject to several stages of regulation with nominal reductions of NO_x emissions ranging from approx. 90% for diesel and 94% for gasoline engines, when considering the type approval limit values for a EURO 6 compliant passenger car relative to a EURO 1 compliant vehicle. By analogy for heavy duty vehicles (HDV), a EURO V compliant HDV emits less than 13% of NO_x emissions compared to a pre-EURO standard vehicle (European Commission 2008, Carslaw *et al* 2016).

Emission reductions of NO_x for road vehicles have been mainly achieved through the application of catalytic converters (e.g. the three-way catalyst), as well as the use of engine management systems. The latter have recently been the topic of public debate, as software manipulations as well as the exploitation of legal loopholes by vehicle manufacturers have resulted in less effective emission control for NO_x in real-world driving conditions than test cycles suggested (Burki 2015, Oldenkamp *et al* 2016). The real emission reductions achieved for road transport sources over the past decades is thus difficult to quantify until more advanced and wide-spread emission measurements are undertaken. In addition, a trade-off between state-of-the-art particle traps has been observed, which results in increased emissions of primary NO_2 from diesel vehicles (Chen and Borken-Kleefeld 2014).

As a result of these emission control efforts, a peak of NO_x emissions from fossil fuel combustion sources has happened in the late 1990s or early 2000s, dependent on the region, for industrialized countries. In contrast, emerging economies (e.g. Brazil, Russia, India and China—BRIC countries) still show rapidly increasing emissions of N_r from combustion sources, as efforts to control emissions are outpaced by rapid economic growth, leading to fast increasing vehicle fleets and fossil fuel power plants to satisfy growing energy demand, as recently shown by Liu *et al* (2013).

4.3. Progress in implementing nitrogen management actions

Previous successful examples of improving N use efficiency and reducing N_r loss by agricultural management, have been documented, for instance in the case of maize production at national scale in the United States (Cassman *et al* 2002), or rice production at farm scale in Asia (Dobermann *et al* 2002). In this focus issue, Dalgaard *et al* (2014) describe a case study demonstrating how, on a country scale, substantial reductions of N input have been achieved, while maintaining and even increasing agricultural produce output at the same time. The average N-surplus in Danish agriculture has been reduced from approximately 170 kg N ha^{-1} yr^{-1} to below 100 kg N ha^{-1} yr^{-1} during the past 30 years, while the overall NUE for the agricultural sector (crop + livestock farming) has increased from around 20%–30% to 40%–45%. As a result, N-leaching from the field root zone has been halved and N losses to the aquatic and atmospheric environment have been significantly reduced. This was achieved through the implementation of a series of policy action plans to mitigate losses of N and other nutrients since mid-1980s. However, the reduction in total N loadings to the environment did not response linearly to the reduction in surplus N, showing the need to gain a better understanding of the relationships between the different N pools and flows, including the denitrification of N, and the buffers of N in biotic N pools.

For the Taihu Lake region of China, a well-known high N load region, Xue *et al* (2014) document in this focus issue how reduced fertilizer input to rice–wheat rotation systems from farmer's conventional rates of 510 kg N ha^{-1} yr^{-1} to 390 kg N ha^{-1} yr^{-1} by improved management practices such as the combined use of organic and inorganic fertilizer, use of controlled release fertilizer, respectively to 333 kg N ha^{-1} yr^{-1} by adopting site-specific management, resulted in reduced environmental impacts of fertilizer N.

For livestock systems, Bealey *et al* (2014) describe how landscape structure can be used to limit net ammonia emission. They show in this issue the effect of tree canopy structure on recapturing ammonia from livestock production, using a coupled turbulence and deposition turbulence model. They found that using agro-forestry systems of different tree structures near 'hot spots' of ammonia in the landscape could provide an effective abatement option for the livestock industry in livestock operations in the UK. This example may be contrasted with rather different livestock systems in low-N input Africa, where Rufino *et al* (2014) report how only few data are available to date to understand the livestock-related N flows. They therefore propose joint efforts for data collection and the development of a nested systems definition of livestock systems to link local, regional and continental level and to increase the usefulness of point measurements of N losses.

5. Integrated assessment of nitrogen management strategies

5.1. Harmonizing indicators on effects, losses and nitrogen use efficiency

With N_r freely moving between different environmental pools (Galloway *et al* 2003), management strategies aiming to reduce emissions to the environment require integrated perspectives in order to avoid 'pollution swapping', i.e. exchanging improvement towards one pool by deterioration for another pool, while at the same time maximizing the beneficial synergies. Such an integrated assessment cannot be based on observing individual effects, but needs to take advantage of indicators, such as already discussed in the increasing adoption of NUE indicators (Norton *et al* 2015, Oenema *et al* 2015).

The concept of 'nitrogen neutrality', introduced by Leip *et al* (2014) in this focus issue, goes the next step to relate human actions to indicate environmental performance. Offsetting the release of N_r by way of compensating at a distinctively different entity will not remove local or regional effects, unless the spatial resolution of compensation matches the respective environmental effect. The major merit of compensation, however, consists of awareness raising to demonstrate how much effort is needed to compensate for a specific adverse human action.

Nitrogen neutrality as a concept addresses the effects of a certain activity over a whole life cycle, including preceding process stages. Such 'nitrogen footprint' analyses have been developed on several levels, for which Galloway *et al* (2014) provide an overview. These indicators include an 'N-calculator' to be used by individuals in selected countries to assess their private impacts (potentially also guided by an N-label attached to products), an institution-oriented footprint that can be used by organizations or companies, and an N-loss indicator to quickly evaluate N impacts of world regions or countries. Developing and harmonizing indicators allows easy benchmarking between entities and thus provides guidance towards possible improvements.

5.2. Interaction of the nitrogen cycle with other nutrients and the water cycle

An overarching perspective not only integrates over environmental pools, but also considers interactions between relevant effective constituents. With N_r being a potent plant nutrient, its relationship to other nutrients requires attention. In this focus issue, Bouraoui *et al* (2014) investigate the different and combined effects of N_r and phosphorous (P) in European inland waters. They employ a modeling approach to investigate the most effective means to abate pollution. Regarding P, they conclude that the ban of P in laundry detergents, together with the full implementation of European water protection legislation, would maximize effects. In addition, optimization of practices for organic manure application provides the ideal strategy to mitigate N_r-related water pollution. Retention of nitrogen as a part of nutrient management strategies has similarly been discussed by Grizzetti *et al* (2015), who here compare different modeling approaches. They conclude that the integration of all processes in the river basin, the possible lag time between nitrogen sources and impacts, and the difficulty in separating temporary and permanent nitrogen removal, and the associated N_2O emissions to the atmosphere, remain critical aspects and a source of uncertainty in integrated nitrogen assessments. As already noted, the impacts of nitrogen leaching to the long-term trends of drinking water have also been studied for the Danish situation by Schullehner and Hansen (2014).

5.3. Regional and global nitrogen assessment

The application of indicators mentioned in section 5.1 with consideration of the interconnections between N_r flows provide useful hooks to guide studies a regional level. In this focus issue, especially the overviews developed on situations of sub-Saharan Africa, allow insight in topics for which information is limited. In this way, Zhou *et al* (2014) apply net-anthropogenic nitrogen input (NANI) as an indicator to assess human impacts on the Lake Victoria watershed. On average, NANI was assessed to be in the order of 20 kg N ha^{-1} yr^{-1}, which was associated with soil mining due to lack of mineral fertilizer or food/feed N imports. Riverine N_r flows into Lake Victoria were thus relatively low, with human and animal wastes considered to be the major contributors to lake pollution.

Atmospheric nitrogen fluxes were evaluated by Galy-Lacaux and Delon (2014) from measurements along an ecosystem transect across Western and Central Africa, considering dry and wet savannah and forest. They find emissions and deposition of N_r roughly in balance at around 10 kg N ha^{-1} and year, with a clear discrepancy in forests (higher deposition), while in both savannah types the difference between estimated emission and deposition is insignificant.

Extending from Africa, a regional footprint of N_r due to anthropogenic activities is reported in the focus issue by Shibata *et al* (2014). These authors demonstrate that food imports are beneficial for Japan's N footprint as the specific impacts of local production are much higher. Footprints can be differentiated by population group, with younger people in Japan consuming less fish and more meat and thus impacting more strongly on the N cycle. Total footprints in Japan are comparable to Europe, but lower than those of the US.

In their analysis for the Netherlands and the European Union, van Grinsven *et al* (2015) demonstrate that economic outputs and food security not always benefit from more intensive agricultural production, especially when considering the external costs of pollution. Using specific scenarios, they argue that by halving meat consumption, pollution related costs could be decreased more strongly than the production-related GDP, resulting in a net economic gain. In a region rich in nitrogen, adjusted human diets and externalization of environmental costs of excess N_r could drive a sustainable extensification of agricultural production. In their assessment for the USA, Sobota *et al* (2015) estimated the health and environmental damages of anthropogenic N in the early 2000s to amount to \$210 billion yr^{-1} USD (range: \$81–\$441 billion yr^{-1}). Despite recognizing gaps and uncertainties that remain in these estimates, the overall work by van Grinsven *et al* (2015) and Sobota *et al* (2015) presents a starting point to inform decisions and engage stakeholders on the economic costs of N pollution.

Using analyses of selected watersheds in South America, Bustamante *et al* (2015) show median concentrations of TDN at 325 $\mu g\,l^{-1}$ and 275 $\mu g\,l^{-1}$ in the Amazon and Orinoco basins, respectively, increasing to nearly 850 $\mu g\,l^{-1}$ in La Plata Basin rivers and 2000 $\mu g\,l^{-1}$ in small northern Venezuelan watersheds. The median TDN yield of Amazon Basin rivers (approximately 4 kg ha^{-1} yr^{-1}) was larger than TDN yields of undisturbed rivers of the La Plata and Orinoco basins; however, TDN yields of polluted rivers were much higher than those of the Amazon and Orinoco rivers. They conclude that organic matter loads from natural and anthropogenic sources in rivers of South America strongly influence the N dynamics of this region.

Lassaletta *et al* (2014) have applied the NUE approach to investigate the global trajectories of N_r flows on a global scale over the last 50 years. Using data by the *Food and Agriculture Organization of the United Nations* (FAO), their study allows a comparison of the development in total N_r inputs and agricultural yields in 124 countries. The dataset compiled shows which countries of the world were affected by soil mining, where N_r has been applied excessively, and when these countries have managed to improve their NUE, often by a significant margin. While available data would not allow for the compilation of full nitrogen budgets and an evaluation of individual country's N_r related damage, the study clearly exemplifies to which extent indicators can be used to establish the potential of such damage and to develop (sub-)national benchmarks. Results for Europe presented by Leip *et al* (2015) show that the livestock sector contributes significantly to agricultural environmental impacts, with contributions of 78% (terrestrial biodiversity loss), 80% (soil acidification and air pollution due to ammonia and nitrogen oxides emissions), 81% (global warming), and 73% (water pollution, both N and P) respectively. Agriculture as a whole is one of the major contributors to these environmental impacts, ranging between 12% (global warming) and 59% (N water quality) impacts. Leip *et al* (2015) conclude that in order to make significant progress in mitigating these environmental impacts in Europe, a combination of technological measures reducing livestock emissions, improved food choices and reduced food waste of European citizens is required.

Based on a detailed analysis of nutrient discharges from aquaculture operations in China, Zhang *et al* (2015a) conclude that improvement of feed efficiency in cage systems and retention of nutrients in closed systems is necessary. Furthermore, strategies to increase nutrient recycling (e.g. applying integrated multi-trophic aquaculture), as well as socio-economic measures (e.g. subsidies), should be increased in the future. Zhang *et al* (2015a) recommend the use of hybrid agricultural-aquacultural systems and the adoption of NUE as an indicator at farm or regional level for the sustainable development of aquaculture, among other measures, to improve the sustainability of Chinese aquaculture. Liang *et al* (2015) propose the use of a *regionally optimal N rate* (RONR) determined from the experiments (on average 167 kg ha^{-1} and varied from 114 to 224 kg N ha^{-1}) for different regions in China. If these RONR were widely adopted in China, they estimate that ~56% of farms would reduce N fertilizer use, while ~33% would increase their use of N fertilizer. As a result, grain yield would increase by 7.4% and the estimated GHG emissions would decline by 11.1%, suggesting that to achieve improved regional yields and sustainable environmental development, NUE should be optimized both among N-poor and N-rich farms and regions in China.

6. Nitrogen challenges projected into the future

Observations of past developments may serve to guide an understanding of a possible future—a future for which all the N-related interactions described in this issue remain to be considered. Specifically two papers cover such future global scenarios. Billen *et al* (2014) report on a wide range of available options to satisfy global food demand—options that impact the N cycle in very different ways. Remarkably, the authors point to solutions where international trade is kept at a low level as those that produce less N losses to the environment. As with the scenarios of Davidson and Kanter (2014) for N_2O, already described, these results demonstrate, like many of the other examples reflected on here, that substantially improved nitrogen management is indeed possible if there is the required willingness. It is therefore in the hands of human society to decide on the future implementation of such nitrogen options, which will determine the extent of the future nitrogen benefits and the adverse environmental impacts.

Future challenges have remained in the center of attention in the time since the Kampala conference, which initiated this special issue. The planetary boundaries of nitrogen express the amounts of anthropogenic nitrogen fixation this world can handle sustainably. Steffen *et al* (2015) have established this boundary at a level of 62 Tg N yr^{-1}, while the current level is about two and a half times this value. Work is ongoing to break down the boundary to regional and to sectoral targets that are compatible with other sustainability goals. A key parameter to be considered in this respect is the NUE—and its different fate in different countries over time. Zhang *et al* (2015b) discussed the global and country trends, which follow the Environmental Kuznets Curve (EKC; improved situation as societies become more effluent) at least for some of the historic examples presented, and possibly could be extrapolated to other regions via sustainable intensification. NUE thus also provides the key theme for the next conference held in the same series in Melbourne, December 2016.

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