Title: Nitrogen footprints: Regional realities and options to reduce nitrogen loss to the environment

Authors:

Hideaki Shibata[1], James N. Galloway[2], Allison M. Leach[3], Lia R. Cattaneo[2], Laura Cattell Noll[2], Jan Willem Erisman[4], Baojing Gu[5], Xia Liang[6], Kentaro Hayashi[7], Lin Ma[8], Tommy Dalgaard[9], Morten Graversgaard[9], Deli Chen[6], Keisuke Nansai[10], Junko Shindo[11], Kazuyo Matsubae[12], Azusa Oita[13], Ming-Chien Su[14], Shin-Ichiro Mishima[7], Albert Bleeker[15]

Affiliation:

[1]Field Science Center for Northern Biosphere, Hokkaido University, Japan

[2]Department of Environmental Sciences, University of Virginia, USA

[3]Department of Natural Resources & the Environment, University of New Hampshire, USA

[4]Louis Bolk Institute, VU University, Amsterdam, the Netherlands

[5]Policy Simulation Laboratory, Zhejiang University, China

[6]Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Australia

[7]Carbon and Nutrient Cycles Division, National Institute for Agro-Environmental Sciences, Japan

[8]Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetic and Developmental Biology, The Chinese Academy of Sciences, China

[9]Department of Agroecology. Aarhus University, Denmark

[10]National Institute of Environmental Studies, Japan

[11]University of Yamanashi, Japan

[12]Tohoku University, Japan

[13]Yokohama National University, Japan

[14]National Dong-Hwa University, Taiwan

[15]Energy research Centre of the Netherlands, the Netherlands

Contact information of the corresponding author[1]:

Field Science Center for Northern Biosphere, Hokkaido University
Kita-9, Nishi-9, Kita-ku, 060-0809, Sapporo, Japan
Tel: +81-11-706-2520

Email: shiba@fsc.hokudai.ac.jp

Word count (including references): 7,687 words

Manuscript type: Perspective paper

Acknowledgements:

We would like to thank all participants of the International Nitrogen Footprint Workshop held in Hokkaido University, Sapporo, Japan in March 16-18th, 2015 for helping to develop this manuscript. We also would like to thank the funding support for the workshop from The KAITEKI Institute Inc., Japan; Green Network of Excellence - Environmental information (funded by Ministry of Education, Culture, Sports, Science and Technology, Japan); National Institute for Agro-Environmental Sciences, Japan; National Institute for Environmental Studies, Japan; Ministry of Education, Taiwan; National Dong Hwa University, Taiwan; Advanced Research and Education Center for Steel (ARECS), Tohoku University, Japan. This research was also partly supported by Science and technology research promotion program for agriculture, forestry, fisheries and food industry; Environment Research and Technology Development Fund (S-15) of the Ministry of the Environment, Japan. This is a contribution to the N-PRINT project (www.n-print.org), the www.dNmark.org research alliance, and to the International Nitrogen Initiative (www.initrogen.org).

Abstract

Nitrogen (N) management presents a sustainability dilemma: N is strongly linked to energy and food production, but excess reactive N causes environmental pollution. The N footprint is an indicator that quantifies reactive N losses to the environment from consumption and production of food and the use of energy. The average per capita N footprint (calculated using the N-Calculator methodology) of ten countries varies from 15 to 47 kg N capita^{-1} year^{-1}. The major cause of the difference is the protein consumption rates and food production N losses. The food sector dominates all countries' N footprints. Global connections via trade significantly affect the N footprint in countries that rely on imported foods and feeds. The authors present N footprint reduction strategies (e.g., improve N use efficiency, increase N recycling, reduce food waste, shift dietary choices) and identify knowledge gaps (e.g., the N footprint from nonfood goods and soil N process).

Keywords: Nitrogen effects, Nitrogen cycle, Nitrogen use efficiency, Nitrogen footprint

1. General introduction

1.1 Overview of global N issues and the need for N footprint tools

For most of human history, there has been little interference with the nitrogen (N) cycle and very small contributions of human-induced reactive N (Nr; all species of nitrogen except N_2) to the environment. The first introduction of human-induced Nr was about 12,000 years ago at the advent of agriculture when humans started planting legumes. This interference was minor and positive for humans, as it provided a source of Nr to these early farms. At the end of the 19th century, most of the world's Nr was created naturally and until ~1970, the most important anthropogenic source of new Nr was still legume cultivation; the total anthropogenic Nr creation was less than natural terrestrial rates (Galloway et al. 2013).

Four decades later, the situation is very different. Humans increased burning of fossil fuels and reliance on the Haber-Bosch process, an artificial nitrogen fixation process, to create fertilizer and other products. The human creation of Nr is ~220 Tg Nr yr^{-1}, compared to the natural terrestrial creation rate of ~60 Tg Nr yr^{-1}, and the oceanic natural creation of ~120 Tg Nr yr^{-1} (Fowler et al. 2013). In the early 21st century, humans created most of the world's Nr—about fourfold more than natural biological N fixation on land (Steffen et al. 2015; Vitousek et al. 2013). We do not know how much of the Nr is converted back to N_2. We do know that a portion (some estimate 50%) remains active (as Nr) and thus accumulates in the environment (Galloway et al. 2004; Fowler et al. 2013). This is a central uncertainty that needs further investigation.

Given the fundamental role that N has on ecosystem productivity, atmospheric chemistry, and the earth's radiation balance, it is not surprising that this alteration of the N cycle has profound impacts on the health of both ecosystems and humans (e.g., Erisman et al. 2013; Steffen et al. 2015; Westhoek et al. 2014; 2015). Anthropogenic Nr contributes to smog; atmospheric haze; atmospheric acidification; eutrophication of soils, groundwater, freshwaters, and coastal waters; reductions in ecosystem biodiversity; nitrate pollution in drinking water; global warming; climate change; and stratospheric ozone depletion. All of these impacts are linked in the N cascade: once an Nr molecule is created (i.e., NO_x or NH_3), it can move through the environment and contribute to all of those impacts in sequence (Galloway et al. 2003). It is not until that specific Nr molecule is either stored in a long-term reservoir or converted back to N_2 that the N ceases to have a potential impact.

Unlike the human creation of CO_2, we need Nr to produce food and we will need more of it in the future. In addition, per-capita consumption of animal protein—which is more N-intensive than vegetable protein—is expected to increase (e.g. Erisman et al. 2008; Winiwarter et al. 2013).

Hence we face an N dilemma: we need Nr for food production, but excess Nr has negative consequences for the climate, human health, and ecosystems. We need to optimize the use of N (i.e., increase nitrogen use efficiency in food production), while minimizing the negative impacts associated with its use by decreasing the amount lost to the environment or mitigating the negative impacts. In that regard, there are active technologies to decrease the amount of Nr created by humans during food (e.g., increase nitrogen use efficiency) and energy (e.g., Nr emissions controls) production. However, most reduction programs focus on the production sector (e.g., farms, energy production) and not on the consumer sector—the entity that actually creates the demand for the food and energy produced. This paper reviews the use of N-footprints, a consumer-based indicator, able to educate consumers about managing their resource use to both limit Nr creation and decrease its loss to the environment.

1.2 Concept and analytical approaches of the N footprint

Nitrogen footprints connect entities, such as individuals or institutions, with the direct and indirect Nr lost to the environment as a result of their activities. N footprint tools have been developed for individuals, institutions, and even individual food products as a part of the N-Print project (http://www.N-Print.org; Leach et al. 2012, 2013; Leip et al. 2014). Quantitative information provided by the N footprint may help entities understand the connection between Nr loss to the environment and the entities' daily activities.

The N footprint tool for individuals (i.e., N-Calculator) is a country-specific tool. The "footprint" is an indicator to help describe human impacts on the environment. The N footprint approach is designed to link consumer activities with N losses, which makes it similar to an N indicator for consumers (Leach et al. 2012; Galloway et al. 2014; Shibata et al. 2014). This indicator shows the potential loss of Nr to the environment as a result of the production and consumption of food and fossil fuels.

The N-Calculator determines the N footprint from information about an individual's resource consumption in the food, housing, transportation, and goods and services sectors. Per capita N footprints have been calculated for the USA, Netherlands, Germany, UK, Austria, and Japan using the N-Calculator model (Leach et al. 2012; Stevens et al. 2014; Shibata et al. 2014; Galloway et al. 2014), and are in development for Australia, China, Denmark, Portugal, Taiwan, and Tanzania (Table 1a). N footprints have also been calculated for China (Gu et al. 2013a), the European Union (Leip et al. 2014b), and 188 countries (Oita et al. 2016a) using a top-down N balance approach.

The major N-releasing activities accounted for in the N-Calculator are food (both consumption and production) and energy consumption. The food N footprint is calculated based on food intake (i.e., FAO estimates of food supply minus food waste) and the amount of N lost during the production of that food. The food production N footprint is calculated with virtual N factors (VNFs), which describe the total N lost to the environment during production per unit of N in the final consumed food product (Leach et al. 2012). These food production N losses include fertilizer not incorporated into the plant, crop residues, feed not incorporated into the animal products, processing waste, and household food waste. Recycling within the food production process (e.g., crop residue and manure recycled as fertilizer) is also accounted for in the VNF calculation. The energy component of N footprint (i.e., the Nr released from fossil fuel combustion) in the N-Calculator is calculated using average rates of energy consumption and country-specific emission factors. Further details of the calculation method are available in Leach et al. (2012).

Other methods to calculate the N footprint use top-down approaches, which are different from the N-Calculator. These methods are based on national N input-output budgets and N flows related to food, energy, and other materials using national statistics and regional or global databases (such as OECD database and FAOSTAT). These methods are also useful and are used to estimate the average per capita N footprints of countries (Gu et al. 2013a; Bleeker et al. 2012; Oita et al. 2016a). The purpose of the N-Calculator is to provide consumer-level indicators of the N footprint, though it does not address environmental impact indicators or sectors provided by other approaches, such as the Life Cycle Assessment (LCA) or Gross Nutrient Balance (GNB).

1.3 Objectives of this paper

Based on recent key outcomes of N footprint research and discussion during a workshop (International N Footprint Workshop, Japan, March 2015, http://www.n-print.org/japanworkshop), we provide a current perspective of N footprint research toward global sustainability. The objectives of this paper are:

- To summarize the state of knowledge on N footprints for stakeholders and consumers locally, regionally, and globally with attention to global connections that occur via trade;

- To propose possible options for reducing anthropogenic N pollution to the environment based on N footprint results, and;
- To identify the research gaps, key questions, and future direction of N footprint research for multiple stakeholders and consumers at the local, regional, and global levels.

2. Regional realities and comparisons of nitrogen footprints

National N footprints have been developed in three regions: Asia-Pacific, North America, and Europe (Table 1a). The most common property of the per capita N footprint is the dominance of the food N footprint (Leach et al. 2012; Shibata et al. 2014; Galloway et al. 2014). In all countries VNFs for crop products are lower than for animal products (Table 1b; Leach et al. 2012; Shibata et al. 2014; Galloway et al. 2014; Stevens et al. 2014; Pierer et al. 2014).

To understand the global pattern of and regional similarities or differences in N footprints, more national case studies are needed. Significant regional gaps exist for Southeast and Central Asia, the Middle East, South America, Africa, and Eastern Europe.

2.1 Asia-Pacific region

The average N footprint in Japan is 28 kg N capita^{-1} year^{-1} (Table 1; Shibata et al. 2014). This value was calculated using the N-Calculator approach and then incorporating the effect of food and feed import to Japan. The total N footprint in Japan was comparable to European countries and smaller than the USA (Table 1a; Leach et al. 2012). VNFs for meat and animal products produced in Japan were relatively high compared to the USA and Europe (Table 1b; Leach et al. 2012; Stevens et al. 2014). Incorporating international food and feed trade reduced most VNFs and the overall food N footprint in Japan. The VNFs with trade were calculated based on the self-sufficiency of food and feeds (i.e., what portion of demand is produced in-country) and the VNFs of domestic production and of production in the USA, which is the main exporter to Japan. Then, the N footprint incorporating trade was determined using these trade-adjusted VNFs (Shibata et al. 2014). Since Japan relies heavily on imported food (ca. 61%), a large portion of the N lost during the food production process is lost to the environment in the exporting country, though that portion of the N footprint was assigned to consumers in Japan.

Food preferences influenced the food N footprint for different age groups. In Japan, younger age groups tend to prefer meat and had a ~20% higher food N footprint than older age groups, who tend to prefer fish and seafood (Shibata et al. 2014).

China has been experiencing tremendous changes to its Nr use and to its per capita N footprint, which increased by over 50% from 1980 to 2008 (Gu et al. 2013a). These results were determined using a top-down footprint calculation instead of the N-Calculator methodology. The changes mainly result from an increase in per capita food and energy consumption and a decrease in grain production nitrogen use efficiency (NUE, which is defined as Nr harvested divided by total Nr input to cropland) (Ma et al. 2013; Gu et al. 2015). Despite the rapid increase in the per capita N footprint, this initial assessment suggested that the Chinese N footprint was still smaller than or close to those found in many developed countries (Gu et al. 2013a; Galloway et al. 2014). The per capita food N consumption in China is 5.3 kg N year^{-1}, with a lower portion of animal protein consumption (40% of total protein consumption) compared to other countries (Gu et al. 2013; 2015). However, the NUEs of crop and livestock production in China were also lower: only around 40% and 15%, respectively, compared to over 50% and 20%, respectively in the USA and European countries (Gu et al. 2015). These two opposite forces resulted in a relatively small food N footprint in China.

Once Nr enters the waste stream as sewage, some of it may be removed in wastewater treatment plants, especially those with advanced treatment that aims to convert Nr to N_2 (i.e., denitrification). This reduction in Nr released to the environment impacts a country's food consumption footprint. In China, sewage is rarely treated with denitrification technologies. In some developed countries, over 70% of sewage is treated this way, achieving up to an ~80% reduction in the food consumption footprint (Leach et al. 2012).

The per capita fossil fuel consumption in China was much lower than in the USA (Leach et al. 2012; Gu et al. 2015); however, there are limited control measures in place to reduce NO_x emissions during fossil fuel combustion (Gu et al. 2012). Therefore, China has a higher energy N footprint than the UK, Japan, Germany, and the Netherlands (Gu et al. 2013a; Shibata et al. 2014; Galloway et al. 2014).

Taiwan's economy has been growing in recent years. We present preliminary results of the per capita Taiwanese N footprint, derived using the N-Calculator method (Table 1a; Ming-Chien Su, unpublished data). Rice dominates Taiwanese cereals consumption (ca. 80% of domestic cereals production). Meat production is dominated by pig meat and poultry (ca. 52% and 40% of the total meat production, respectively). Since local energy sources are limited in Taiwan, 98% of energy sources are imported. The ten-year average per capita Taiwanese N footprint is 37 kg N capita^{-1} year^{-1}. The footprint is dominated by food production (average 32 kg N capita^{-1} year^{-1}) followed by transportation (2 kg N capita^{-1} year^{-1}) (Table 1a; Ming-Chien Su, unpublished data).

In both the food and energy sectors, Australia by far has the largest N footprint (47 kg N capita^{-1} yr^{-1}) of all countries that have calculated and estimated their N footprint using the N-Calculator model (Table 1a; Liang, unpublished data). Overall, the total food N footprint is 32 kg N capita^{-1} yr^{-1}, including N losses during food production (30 kg N capita^{-1} year^{-1}) and food consumption (2.0 kg N capita^{-1} year^{-1}). Animal products account for 82% of the food footprint, half of which is from beef production and consumption, followed by dairy (16%), poultry (13%), and lamb (6%). Among crop products, cereals represent the largest proportion (35% of the crop N footprint), followed by vegetables, potatoes, fruits, and legumes. A high-protein diet, extensive food production and relatively low food prices in Australia are considered to be drivers of the high food N footprint. One way to decrease the Australian food N footprint could be to reduce the portion of meat in the average Australian diet.

Australia also has the largest energy N footprint (15 kg N capita^{-1} year^{-1}), mainly due to the large N emissions associated with electricity generation. Australia relies heavily on coal for electricity; 73% of electricity was generated by coal from 2012-2013 (51% black coal, 22% brown coal) (Origin, 2015). Australia is more dependent on coal for electricity than any other developed country (e.g., 25% in Japan and 49% in the USA) due to the very large coal resources that support low-cost domestic electricity production (World Nuclear Association, 2015). While coal will continue to be the dominant in energy source, renewable energy sources are expected to become increasingly significant in Australia along with the advances in mitigation technologies (Geoscience Australia and BREE 2014) that will help to reduce the Australian energy N footprint.

2.2 North American region

The per capita N footprint in the USA is 39 kg N capita^{-1} year^{-1} (Leach et al. 2012). The food N footprint is the largest contributor, followed by transportation, which is relatively larger than in other countries (Table 1a; Galloway et al. 2014).

The N footprint concept has been applied to institutions in the USA (Leach et al. 2013). Institutions and universities have far-reaching impacts through activities like education and research; however, their operations can also negatively impact the environment. A N footprint tool (N-Institution) allows these institutions to assess and reduce their N impact. Many institutions already calculate their carbon footprint, and due to the similar data inputs, the carbon and N footprints could be combined. Institutions are particularly well-situated to reduce N pollution because they can both educate a community and make management decisions to reduce their contribution to N pollution.

The N footprint concept has also been applied to individual food products (e.g., N-Label; Leach et al. 2016) and to events (e.g., N-Neutrality; Leip et al. 2014a).

2.3 European region

Several N footprints have been developed for European countries: the UK (Stevens et al. 2014), Austria (Pierer et al. 2014), the Netherlands (Leach et al. 2012), Portugal (Galloway et al. 2014) and Germany (Stevens et al. 2014) (Table 1a), ranging from 24 to 29 kg N capita^{-1} year^{-1} (when using US/European hybrid VNFs for the UK, the Netherlands, and Germany; Table 1b; Leach et al. 2012). Nitrogen footprint studies are also in their initial phase for Denmark. In these European countries, advanced sewage treatment with denitrification technology is widespread and contributes to smaller food N footprints in these countries compared to others due to the decrease in the food consumption footprint (Leach et al. 2012).

In the UK, the per capita N footprint was estimated to be 27 kg N capita^{-1} year^{-1}, with food production being the largest proportion of the footprint. Stevens et al. (2014) examined how the N footprint in the UK has changed and increased slightly over time. Through scenario analysis, they demonstrated how shifting diets to food protein consumption levels recommended by the FAO and WHO can reduce the N footprint.

The N footprint in the Netherlands was 23 kg N capita^{-1} year^{-1} (Leach et al. 2012), with the majority of the footprint related to food production (21 kg N capita^{-1} year^{-1}). Average food N consumption in the Netherlands is 5 kg N capita^{-1} year^{-1}, close to that of the USA. However, because advanced sewage treatment with nutrient removal technology is utilized throughout most of the Netherlands, the food consumption N footprint is reduced to just 1.1 kg N capita^{-1} year^{-1}.

In Austria, the average N footprint was 20 kg N capita^{-1} year^{-1}, which is the smallest national N footprint of developed countries for which footprints have been calculated by N-Calculator (Table 1a; Pierer et al. 2014). Austria-specific VNFs were estimated for eight major food categories and these indicated that animal products are less N efficient than plant products (Table 1b).

Preliminary results for Denmark suggest that the portion of energy consumption from renewable energy is relatively high compared to other energy sources (Graversgaard et al. unpublished data). Ninety percent of the population is connected to advanced sewage treatment plants, which makes comparison to countries like the Netherlands obvious.

These European case studies and their comparisons to other countries and regions indicate that improved and N-focused sewage treatment can positively impact the per capita N footprint.

2.4 Alternative N footprint approaches

By using a top-down approach, Bleeker et al. (2012) calculated national average per capita N footprints (evaluated as N-Loss indicator) in all OECD countries and six BRIICS countries (Brazil, Russia, India, Indonesia, China, South Africa). The results ranged from 16 kg N capita^{-1} yr^{-1} (Indonesia) to 186 kg N capita^{-1} year^{-1} (Australia), reflecting their regional production and export activities. The world average was 29 kg N capita^{-1} yr^{-1}, which was similar to the results determined using the bottom-up N-Calculator (Table 1) although the specific values in some countries were much higher compared to those calculated by the N-Calculator (e.g., Australia). The top-down approach assumes that food and energy consumption and associated N losses occurred in the country where that food and energy is produced. In contrast, Oita et al. (2016a) calculated per capita N footprints that reflect consumption regardless of the production country, considering full supply chains of all sectors, including non-food agricultural products, as well as the sectors included in the N-Calculator for 188 countries. The N footprints ranged from less than 7 kg N capita^{-1} year^{-1} for developing nations such as Papua New Guinea, Côte d'Ivoire, and Liberia, to more than 100 kg N capita^{-1} year^{-1} for wealthy nations such as Hong Kong and Luxembourg. The world average of the N footprint of 27 kg N capita^{-1} year^{-1} by Oita et al. (2016a) was almost similar to the N-loss indicators by Bleeker et al. (2012) as described above. The higher N footprints in some countries (e.g., Australia) calculated with the top-down approaches may be caused by the inclusion of all potential Nr loss, some of which is not included by the N-Calculator.

2.5 Impact of global trade

The impact of global trade of food and feed on per capita N footprints using the N-Calculator was shown in a case study for Japan (Shibata et al. 2014) and is expected to also influence food production N footprint results for other countries that rely on imported resources. Oita et al. (2016a) calculated that 26% of total world industrial N emissions were embodied in international trade in 2010, similar to Lassaletta et al. (2014), who estimated that one third of the total N in world crop production is traded. Lassaletta et al. (2014) that the global N cycles has been increasing due to increasing N fertilizer use, largely as a result of the disconnection between crop production and livestock breeding. Oita et al. (2016a) pointed out that substantial local nitrogen pollution as a result of N footprint is driven by demand from consumers in other countries. Textiles and leathers are key non-food agricultural products that should be accounted for in the international trade N footprint (Oita et al. 2016a).

3. Possible options to reduce N losses to the environment

There are various mitigation strategies for different spatial scales that can address N losses to the environment that result from food, energy, transport, and goods and services sectors (Sutton et al. 2011, 2013). In this section, the authors propose possible mitigation strategies for direct and indirect Nr losses with special attention to farm NUE, food waste, personal dietary choices, and communication tools.

3.1 Improved nitrogen use efficiency in food production

The VNFs, which drive the food N footprint, are influenced by NUE during the food production and supply chain (Leach et al. 2012). NUE in agricultural process (harvest N / input N) of OECD member countries ranged from ca. 30% to 80%. Those of Korea and Japan, which were 30% and 40%, respectively, were the lowest in 2002–2004 (OECD 2008; Shindo 2012). These NUE values refer to crop harvest only, but NUE including both crop and livestock should be taken into account. The improvement of NUE in crop and livestock production could be achieved by implementing best management practices, including the way fertilizer is applied (right time, amount, place, and product; e.g., International Plant Nutrition Institute (http://www.ipni.net/)) and increased recycling within the system (e.g., Freney 2011; Giller et al. 2004). For example, applying alternative amino acids (such as lysine) for animal feed could reduce the amount of N waste from pig and poultry N by 20–30% compared with conventional feed application (Takemasa 1998).

To realize the above mentioned possible mitigation options (i.e., increase of NUE and recycling), policies can be designed to set certain limits on the N loads to the environment and to set standards for agricultural practices, thereby indirectly reducing the N footprints.

For example, in Europe the EU Nitrate Directive (1991) has had a strong influence on intensive livestock production systems (Oenema 2004) and the N pollution to the aquatic environment (van Grinsven et al. 2012). The Nitrate Directive regulates the use of N through its mandatory measures to designate areas vulnerable to nitrate leaching and to establish action programs and codes of good agricultural practice for these areas.

In Denmark a series of N policy action plans have been implemented since the mid-1980s with significant effects on the N surplus, the NUE, and the environmental loadings of N (Dalgaard et al. 2014). Dalgaard et al. (2014) describe how significant impacts have been achieved through a combination of N policies and N measures (ranging from command and control legislation, over market-based regulation and governmental expenditure to information and voluntary actions), with specific measures addressing the whole N cascade. However, to comply with the ecological conditions required in the EU Water Framework Directive further N reductions are required. The lesson for other countries is that general N regulation can be usefully applied to control widespread excessive applications of N. But, if further reductions in the negative impacts of N are necessary, a switch to more geographically targeted policies and measures may be required. In current Danish N research, different policy scenarios are informed by the N footprint results. In this context, policy scenarios are modelled and evaluated on their potential to support a more sustainable agri-food system, and the N footprint results can hereby show potentials on where and how to effectively reduce the N footprint by using policies and regulation (Graversgaard et al. 2016; www.dNmark.org).

There are several other options to improve the NUE in food production. In the agriculture sector, improving field management practices such as increasing the linkage between livestock and cropland (e.g., reusing livestock waste) is one option. Genetic advances to increase crop yields per Nr input can minimize the risk of pollution swapping or tradeoffs. In the animal food production process, improving feed conversion efficiency and decreasing maintenance costs can reduce Nr losses per unit of product and the extent of pollution swapping or tradeoffs. Increasing fertilizer equivalence values in manure during storage and land application with optimizing the rate and time of application to crop requirements would also reduce atmospheric NH_3 emissions.

3.2 Reducing food waste

Consumer-level food waste is significant in most developed countries (Gustavsson et al. 2011) and contributes to N loss to the environment. Here, consumer-level food waste is defined as edible food that is wasted at the consumer level (e.g., restaurants and households) and it excludes food wasted at the production level (i.e., crop and livestock farming, transportation). Food wasted by consumers in Europe and North America is 95–115 kg capita^{-1} year^{-1}, while in sub-Saharan Africa and South/Southeast Asia this is only 6–11 kg capita^{-1} year^{-1} (Gustavsson et al. 2011). Vanham et al. (2015) reported that N in avoidable food waste averages 0.68 kg capita^{-1} year^{-1} in EU countries and the food production N footprint is equivalent to the use of mineral N fertilizer by the UK and Germany combined. Food waste at the consumer level in industrialized countries (222 million Mg) is almost as high as the total net food production in sub-Saharan Africa (230 million Mg) (Gustavsson et al. 2011). Bellarby et al. (2013) indicate that food waste significantly contributes to global greenhouse gas emissions.

Consumers can avoid food waste by shopping according to their daily needs, using all food purchased, and limiting portion sizes. Policies to inform the general public about the food waste problem and to reduce food waste at the consumer level are needed. A reduction in food waste results in a reduction in N loss to the environment.

3.3 Shifting personal diets

Global diets are shifting from crop-based food to more meat and animal products, especially in developed countries (Galloway et al. 2014). VNFs of meat and animal products are generally higher than those of plant products (Table 1b), indicating that dietary choice is a significant driver of the per capita N footprint (Shibata et al. 2014). Different animal production practices (grain-fed vs grass-fed) have different Nr losses and can also impact an individual's N footprint (Cattell Noll et al. submitted, Liang et al. unpublished data). For countries where people consume more seafood, such as Japan (Shibata et al. 2014), developing countries in the Asia-Pacific region, and African coastal areas (Makino 2011), the type of seafood also matters; the VNF for aquaculture shrimp is 8.2 and wild-caught fish is 0.2 (Oita et al. 2016b). Therefore, the N footprint of different geographical diets (e.g., New Nordic Diet, the Mediterranean diet, and Asian diet) should be determined. Since diets based on less animal protein have been shown to be healthier (Tilman and Clark 2015) and have smaller N footprints (Stevens et al. 2014), effective communication to the public of the impacts of dietary choices using N footprints may lead to a reduction in N pollution. The reducing Nr loss to the environment through shifting diets would provide co-benefits for greenhouse gas emissions (Westhoek et al. 2014; 2015; Bodirsky et al, 2014).

3.4 Communication tools

Effective communication is essential for consumers and other entities to change their consumption patterns and to reduce their N footprints. Incorporating economic information into the N footprint (e.g., the cost savings from reduced N use on a farm) could help inform decision-makers about the co-benefits of reducing N use. There is an ongoing effort to develop the "N-label," which is a label for food products that displays the N footprint to inform consumer purchases. Leach et al. (2016) proposed an integrated label combining the carbon, nitrogen, and water footprint of a food product. Although many narrowly focused food sustainability labels are in use but not widely applied, the proposed integrated label could help consumers select products with lower footprints and ultimately minimize the environmental impacts from food production (Galloway et al. 2014; Leach et al. 2016).

The N footprint tools discussed so far focus on informing the user about their contribution to Nr losses to the environment. The N-Neutrality concept proposed by Leip et al. (2014a) is one option to measure, reduce, and compensate the N footprint for a specific event or activity. The N-Neutrality approach consists of two steps. First, the user needs to limit the loss of Nr to the environment by reducing over-consumption of food, reducing food waste, minimizing energy consumption, and choosing sustainable sources of energy and food. Then, to offset the remaining N footprint, the user contributes with a measured compensation in support of a project that would help mitigate or reduce Nr losses. An example is providing funding towards a sustainable agriculture project (e.g., locally implemented projects) (Leip et al. 2014a; Galloway et al. 2014).

3.5 The potential for integrated approaches to manage Nr losses to the environment

Given the range of adverse environmental effects from the N cascade, the most attractive mitigation options are those that offer simultaneous reductions of all N pollutants from all emitting sectors and in all environmental compartments (Figure 1, Table 2) (Galloway et al. 2008; Sutton et al. 2013).

An integrated approach to Nr management holds the promise of decreasing the risks of inconsistency, inefficiency, and pollution swapping (e.g. Erisman et al. 2001; 2005). Integration efforts should recognize the varying levels of success of Nr policies and aim to ensure balance across sectors to avoid pollution swapping or tradeoffs. Integration puts higher demands on interdisciplinary consensus-building between science, policy, and stakeholders.

Integrated policies are also important within sectors, such as agriculture, because of the large number of actors and the connections between sources, sub-sectors, and effects. Table 2 summarizes possible key actions as a basis for further developing integrated or interdisciplinary approaches to N management. For example, the fourth key action (low-emission combustion and energy-efficient systems) involves technical measures being combined with public incentives for energy saving and more efficient transport, linking Nr, air pollution, and climate policies. Similarly, each of the key actions in the food chain (key actions 1-3, 7 in Table 2) offers co-benefits with climate mitigation and the management of other nutrients, including phosphorus. Given the limited success so far in reducing agricultural Nr emissions, more effort is needed to link the proposed key actions, both to learn from successes and to ensure equitability between sectors.

4. Towards a global nitrogen footprint analysis: Knowledge gaps and questions

Table 3 indicates several questions about current knowledge gaps related to integrated global analysis of N footprints.

The N-Calculator approach to predict per capita N footprints for specific countries is, in principle, globally applicable (see Leach et al. 2012). However, the main limitation for such a global application is data availability. While a global dataset for some sectors is available (e.g., food consumption through the FAO database), other data are not readily available (e.g., N losses during food production). As described above, the global trade of food and feed has a significant impact on the local, regional, and global N footprint (Shibata et al. 2014; Galloway et al. 2014; Oita et al. 2016a). The VNFs are available for a few major exporting countries, however, there are few countries that have developed their own VNFs. The development of VNFs for major exporting countries is particularly important for accurately assessing the N footprint of countries that import food.

Secondly, the spatial dimension is an important aspect of N issues, which can be very global or very local (e.g., groundwater pollution, lake water eutrophication). Spatially intensive Nr loads are a fundamental cause of local problems. The N-Calculator, however, does not link to the local environment or any spatial component. Similarly, top-down approaches by definition do not capture local variation. The per capita N footprint in combination with spatial information such as the source area of Nr load (e.g., national land area, agricultural area) would provide information about spatial intensity (e.g., N footprint flux expressed as kg N ha^{-1} yr^{-1}) as references for local N pollution issues. More discussion is needed to further understanding of the impact of Nr on the local environment through a combination of parameters and approaches.

Several other components should be added to future N footprint models, such as the behavior of various Nr species, the nonfood agricultural N footprint, natural food resources (e.g., wild deer), soil N stocks, or indicator integration (see details in Table 3). Fertilizer application for food production is an important part of the N footprint, and fertilizer management can reduce the impacts of N on natural resources. Furthermore, well-managed fertilizer application can increase the nitrogen uptake efficiency of food production and store the nitrogen source as soil organic matter for future crop cycles. Interference with the N cycle is one of the greatest human-induced threats to the planetary system (Rockström et al. 2009). The impacts considered in the N footprint model can be represented by both environmental health and ecosystem vitality categories in the Environmental Performance Index (EPI) concept. Integrating EPI with the N footprint has the potential to emphasize the N cycle effects on both categories of EPI and is a valuable approach for global N management.

Conclusions

The nitrogen footprint is a useful indicator to predict Nr losses to the environment induced by consumption of food, housing, transport, goods, and services. Recent findings of several national case studies on the per capita N footprint clearly indicate that food production is the largest contributor to the total per capita N footprint. Our comparison of national studies of the N footprint indicates that differences in VNFs determined by food production/processing, per capita food intake, and sewage treatment greatly contribute to the differences in Nr loss to the environment among countries. Global trade and personal dietary choices greatly impact the food N footprint. Options for reducing Nr losses to the environment include improving NUE, increasing recycling, reducing food waste, and changing personal dietary choices. Energy consumption reduction and dietary shifting would be the most feasible changes at the consumer level. Key research questions and future challenges include data limitations and the need for applied usage and analysis of the N footprint in combination with other integrated environmental performance indicators such as EPI.

References

Bellarby, J., Tirado, R., Leip, A., Weiss, F., Lesschen, J.P., and Smith, P. 2013. Livestock greenhouse gas emissions and mitigation potential in Europe. *Global Change Biology*, 19: 3–18.

Bleeker, A., Sutton, M., Winiwater, W. and A. Leip. 2012. Economy-wide nitrogen balances and indicators: Concept and methodology. ENV/EPOC/WPEI 4: 3–22.

Bodirsky, B.L., Popp, A., Lotze-Campen, H., Dietrich, J.P., Rolinski, S., Weindl, I., Schmitz, C., Müller, C., Bonsch, M. et al. 2014. Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. Nat. Commun. 5, 3858. doi:http://dx.doi.org/10.1038/ncomms4858.

CME 2012. Electricity Prices in Australia: An International Comparison, A report funded by the Energy Users Association of Australia. from http://cmeaustralia.com.au/public-reports/

Dalgaard, T., Hansen, B., Hasler, B., Hertel, O., Hutchings, N.J., Jacobsen, B.H., Jensen, L.S., Kronvang, B. et al. 2014. Policies for agricultural nitrogen management – trends, challenges and prospects for improved efficiency in Denmark. Environmental Research Letters 9: 115002.

Emerson, J.W., A. Hsu, M.A. Levy, A. de Sherbinin, V. Mara, D.C. Esty, and M. Jaiteh. 2012. 2012 Environmental Performance Index and Pilot Trend Environmental Performance Index. New Haven: Yale Center for Environmental Law and Policy.

Erisman, J.W., De Vries, W., Kros, H., Oenema, O., Van Der Eerden, L., Van Zeijts, H., Smeulders, S. 2001. An outlook for a national integrated nitrogen policy. *Environmental Science and Policy* 4: 87–95.

Erisman, J.W., Domburg, N., de Vries, W., Kros, H., de Haan, B., Sanders, K. 2005. The Dutch N-cascade in the European perspective. *Science in China. Series C, Life sciences* 48: 827–842.

Erisman, J.W., Galloway, J.N., Seitzinger, S., Bleeker, A., Dise, N.B., Petrescu, R., Leach, A.M. and W. de Vries. 2013. Consequences of human modification of the global nitrogen cycle *Philosophical Transactions of the Royal Society B* 368: 20130116, DOI: 10.1098/rstb.2013.0116

Erisman, J.W., Galloway, J.A., Sutton, M.S., Klimont, Z., and W. Winiwater. 2008. How a century of ammonia synthesis changed the world. *Nature Geoscience* 1: 636–639.

Fowler, D., Coyle, M., Skiba, U., Sutton, M.A., Cape, J.N., Reis, S., Sheppard, L.J., Jenkins, A. et al. 2013. The global nitrogen cycle in the 21st century *Philosophical Transactions of the Royal Society B* 368 20130164, DOI: 10.1098/rstb.2013.0164

Freney, J.R. 2011. Management practices to increase efficiency of fertilizer and animal nitrogen and minimize nitrogen loss to the atmosphere and groundwater. Proc. of Int.

Seminar on Increased Agricultural Nitrogen Circulation in Asia: Technological Challenge to Mitigate Agricultural N Emissions. Taipei, Taiwan

Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C. et al. 2004. Nitrogen cycles: past, present and future. *Biogeochemistry* 70: 153–226.

Galloway J. N., Leach, A. M., Bleeker, A., Erisman, J. W. 2013. A chronology of human understanding of the nitrogen cycle. *Philosophical Transactions B,* 368: 20130120.http://dx.doi.org/10.1098/rstb.2013.0120

Galloway, N.J., Winiwarter, W., Leip, A., Leach, A.M., Bleeker, A. and J.W. Erisman. 2014. Nitrogen footprints: past, present and future. *Environmental Research Letters.* 9: 115003.

Geoscience Australia and BREE 2014. Australian Energy Resource Assessment. 2nd Ed. Geoscience Australia, Canberra.

Giller, K.E., Chalk, P., Dobermann, A., Hammond, L., Heffer, P., Ladha, J.K., Nyamudeza, P., Maene, L. et al. 2004. Emerging technologies to increase the efficiency of use of fertilizer nitrogen. In *Agriculture and the nitrogen cycle: assessing the impacts of fertilizer use on food production and the environment*, ed. A.R. Mosier, J.K. Syers, and J.R. Freney, 35–51, Washington, DC, Island Press.

Graversgaard, M., Dalgaard, T., Leach, A.M., Cattaneo, L.R. and Galloway, J.N. 2016. The Danish nitrogen footprint - Applying nitrogen footprints to build awareness about protein consumption and using policy scenarios to change behavior. Proceedings of the 7th International Nitrogen Initiative Conference, Submitted.

Gu, B., Ge, Y., Ren, Y., Xu, B., Luo, W., Jiang, H., Gu, B. and J. Chang. 2012. Atmospheric reactive nitrogen in China: Sources, recent trends, and damage costs. *Environmental Science & Technology* 46: 9420–9427.

Gu, B., Leach, A.M., Ma, L., Galloway, J.N., Chang, S.X., Ge, Y. and J. Chang. 2013a. Nitrogen footprint in China: food, energy, and nonfood goods *Environmental Science & Technology* 47: 9217–9224.

Gu, B., Chang, J., Min, Y., Ge, Y., Zhu, Q., Galloway, J.N. and Peng, C. 2013b. The role of industrial nitrogen in the global nitrogen biogeochemical cycle. *Scientific Reports*, 3: 2579.

Gu, B., Ju, X., Chang, J., Ge, Y., Vitousek, P.M. 2015. Integrated reactive nitrogen budgets and future trends in China. *Proceedings of the National Academy of Sciences of the United States of America* 112: 8792–8797.

Gustavsson, J., Cederberg, C. and U. Sonesson. 2011. Global food losses and food waste: Extent, causes and prevention. Study conducted for the International Congress

SAVE FOOD! At Interpack2011, Düsseldorf/Germany. FAO, Rome. (www.fao.org/docrep/014/mb060e/mb060e00.pdf)

Kitzes, J. 2013. An introduction to environmentally-extended Input-Output analysis. *Resources* 2: 489–503.

Lassaletta, L., Billen, G., Grizzetti, B., Garnier, J., Leach, A.M. and J.N. Galloway. 2014. Food and feed trade as a driver in the global nitrogen cycle: 50-year trends *Biogeochemistry* 118: 225–241.

Leach, A.M, Galloway, J.N., Bleeker, A., Erisman, J.W., Khon, R. and J. Kitzes. 2012. A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment. *Environmental Development* 1: 40–66.

Leach, A.M., Majidi, A.N., Galloway, J.N. and A.J. Greene. 2013. Towards institutional sustainability: a nitrogen footprint model for a university. *Sustainability: The Journal of Record* 6: 211–219.

Leach, A.M., Emery, K.A., Gephart, J., Davis, K.F., Erisman, J.W., Leip, A., Pace, M.L., D'Odorico, P., Carr, J., Cattell Noll, L., Castner, E., Galloway, J.N., 2016. Environmental impact food labels combining carbon, nitrogen, and water footprints. *Food Policy* 61: 213–223.

Leip, A., Leach, A., Musinguzi, P., Tumwesigye, T., Olupot, G., Tenywa, J.S., Mudiope, J., Hutton, O. et al. 2014a Nitrogen-neutrality: a step towards sustainability. *Environmental Research. Letters.* 9: 115001.

Leip, A., Weiss, F., Lesschen, J.P. and Westhoek, H. 2014b. The nitrogen footprint of food products in the European Union. *The Journal of Agricultural Science* 152: 20–33.

Ma, L., F. Wang, W. Zhang, W. Ma, G. Velthof, W. Qin, O. Oenema and F. Zhang 2013. Environmental Assessment of Management Options for Nutrient Flows in the Food Chain in China. *Environmental Science & Technology* 47: 7260–7268.

MAFF (Ministry of Agriculture, Forestry and Fisheries, the Government of Japan) (2014) Toward a reduction in food loss: Promotion of no-food loss project in Japan. http://www.maff.go.jp/j/shokusan/recycle/syoku_loss/pdf/losgen.pdf (March 2015) (in Japanese).

Makino, M. 2011. *Fisheries management in Japan: its institutional features and case studies*. Vol. 34. Springer Netherlands. doi:10.1007/978-94-007-1777-0.

OECD 2008. Environmental Performance of Agriculture in OECD Countries since 1990. ISBN 978-92-64-04092-2

Oenema, O. 2004. Governmental policies and measures regulating nitrogen and phosphorus from animal manure in European agriculture. *Journal of Animal Science* 82: 196–206.

Oita, A., Malik, A., Kanemoto, K., Geschke, A., Nishijima, S. and M. Lenzen 2016a. Substantial nitrogen pollution embedded in international trade. *Nature Geoscience* 9: 111-115

Oita, A., Nagano, I. and I. Matsuda 2016b. An improved methodology for calculating the nitrogen footprint of seafood. *Ecological Indicators* 60: 1091 –1103.

Origin. 2015. Coal in Australia. Origin Energy, Australia, Retrieved 22 July 2016, from https://www.originenergy.com.au/blog/about-energy/coal-in-australia.html

Pierer, M., Winiwarter, W., Leach, A.M. and J.N. Galloway. 2014. The nitrogen footprint of food products and general consumption patterns in Austria. *Food Policy* 49: 128–136.

Rockström J., Steffen, W., Noone, K., Persson, Å., Chapin, III, F.S., Lambin, E,F, Lenton, T.M., Scheffer, M. et al. 2009. A safe operating space for humanity. *Nature* 461: 472-475.

Shibata, H., Cattaneo, L.R., Leach, A.M. and J.N. Galloway 2014. First approach to the Japanese nitrogen footprint model to predict the loss of nitrogen to the environment. *Environmental Research Letters* 9: 115013 doi:10.1088/1748-9326/9/11/115013

Shindo, J. 2012. Changes in the nitrogen balance in agricultural land in Japan and 12 other Asian Countries based on a nitrogen-flow model. *Nutrient Cycling in Agroecosystems* 94: 47-61.

Singh, S. and B.R. Bakshi. 2015. Footprints of carbon and nitrogen: Revisiting the paradigm and exploring their nexus for decision making. *Ecological Indicators* 53: 49–60.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R. et al. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347: 1259855.

Stevens, C.J., Leach, A.M., Dale, S. and J.N. Galloway. 2014. Personal nitrogen footprint tool for the United Kingdom. *Environ. Sci. Process. Impacts.* 16: 1563–1569

Sutton, M.A., Oenema, O., Erisman, J.E., Leip, A., Van Grinsven, H., and Wilfried Winiwarter, W. 2011. Too much of a good thing. *Nature* 472: 159–161.

Sutton, M.A. Bleeker A., Howard C.M., Erisman J.W., Abrol Y.P., Bekunda M., Datta A., Davidson E., et al. 2013. Our Nutrient World: The challenge to produce more food and energy with less pollution. Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative.

Takemasa, M. 1998. Nutritional strategies to reduce nutrient waste in livestock and poultry production. *Chemistry and Biology* 36: 720–726. (in Japanese)

Tilman, D. and Clark, M. 2015. Food, Agriculture & the Environment: Can We Feed the World & Save the Earth? *Dædalus* 144: 8–23.

UBA Federal Environment Agency 2014. Reactive nitrogen in Germany. http://www.umweltbundesamt.de/publikationen/reactive-nitrogen-in-germany

Vanham, D., Bouraoui, F., Leip, A, Grizzetti, B. and Bidoglio, G. 2015. Lost water and nitrogen resources due to EU consumer food waste. *Environ. Res. Lett* 10: 84008–84022.

Vitousek, P.M., Menge, D.N.L., Reed, S.C. and C.C. Cleveland. 2013. Biological nitrogen fixation: rates, patterns, and ecological controls in terrestrial ecosystems *Philosophical Transactions of the Royal Society B* 368: 20130119 DOI: 10.1098/rstb.2013.0119

Westhoek, H., Lesschen, J.P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip A., Van Grinsven H. et al. 2014. Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Glob. Environ. Chang. Elsevier Ltd.* 26, 196-205.

Westhoek, H. Lesschen J.P., Leip A., Rood T., Wagner S., De Marco A., Murphy-Bokern D., Pallière C. et al 2015. Nitrogen on the table: The influence of food choices on nitrogen emissions and the European environment. (European Nitrogen Assessment Special Report on Nitrogen and Food.). Centre for Ecology and Hydrology, Edinburgh, UK.

Winiwarter, W., Erisman, J.W., Gallowaym J.N., Klimont, Z. and M. Sutton. 2013. Estimating environmental loads of reactive nitrogen in the 21st century. *Climate Change* 120: 889–901.

World Food Programme 2015. Food Aid Information System. http://www.wfp.org/fais/ (March 2015)

World Nuclear Association 2015. Australia's Electricity. Retrieved 22 July, 2016, from http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/appendices/australia-s-electricity.aspx

Figure caption

Figure 1. Conceptual diagram of possible key actions to reduce Nr losses to the environment in the N cycle. The background figures are modified from Galloway et al. (2008). The red boxes represent subsystems (HB: Haber-Bosch process, C-BNF: Cultivation-induced biological N fixation) where Nr is created. The light-green background represents the environment. Red arrows leaving the red boxes either

result in Nr lost to environment (fossil fuel and biofuel combustion) or inputs to the food production system (light gray box). The gray boxes within the light gray box represent subsystems within the food production system where Nr is used. Nr can either enter these subsystems (solid red lines), or be lost to the environment (dashed red lines). The numbers in green circles represent the points of where key actions to reduce Nr losses to the environment, listed in Table 2 in detail.

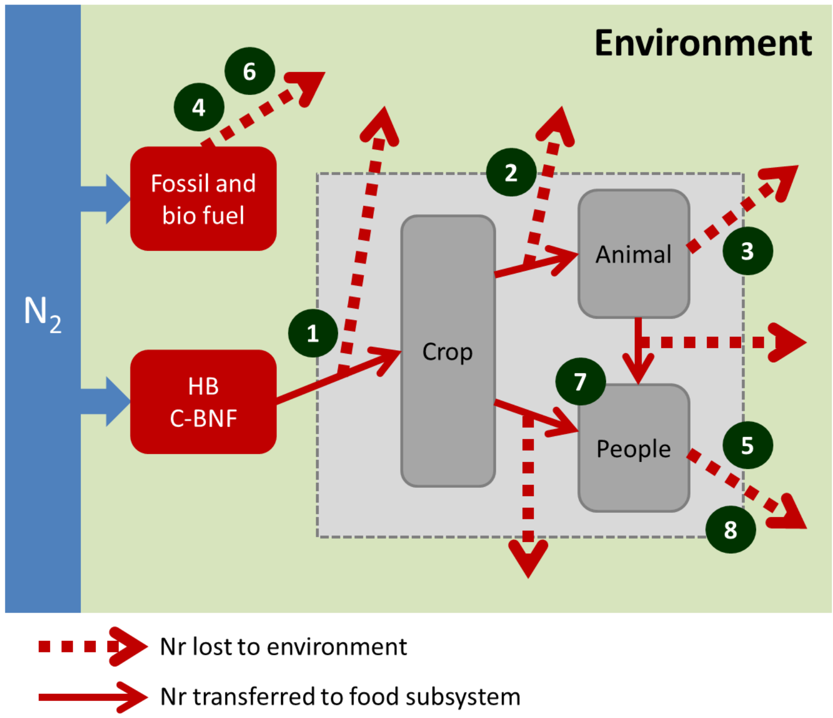

Figure 1. Conceptual diagram of possible key actions to reduce Nr losses to the environment in the N cycle. The background figures are modified from Galloway et al. (2008). The red boxes represent subsystems (HB: Haber-Bosch process, C-BNF: Cultivation-induced biological N fixation) where Nr is created. The light-green background represents the environment. Red arrows leaving the red boxes either result in Nr lost to environment (fossil fuel and biofuel combustion) or inputs to the food production system (light gray box). The gray boxes within the light gray box represent subsystems within the food production system where Nr is used. Nr can either enter these subsystems (solid red lines), or be lost to the environment (dashed red lines). The numbers in green circles represent the points of where key actions to reduce Nr losses to the environment, listed in Table 2 in detail.

Table 1a. Per capita N footprints using the N-Calculator in various countries (kg N capita^{-1} yr^{-1})

Category	USA[1)]	Portugal[5)]	UK[3)]	The Netherlands[1)]	Germany[1)]	Austria[2)]	Tanzania[5,8)]	Japan[4)]	Taiwan[6)]	Australia[7)]
Food	28	24	23	21	19	17	14	26	32	32
Housing	3	0.7	2	0.8	1.6	0.8	0.2	0.8	1.7	9
Transportation	6	3.5	1.1	1.1	1.8	1.6	0.8	0.7	2	2
Goods and Services	2.5	0.5	1.1	0.5	0.7	0.6	0.2	1.0	1.7	4
Total	39	29	27	23	24	20	15	28	37	47

[1)] Leach et al. 2012, updated; [2)] Pierer et al 2013; [3)] Stevens et al 2014; [4)] Shibata et al. 2014; [5)] Galloway et al. 2014; [6)] Su et al. unpublished; [7)] Liang et al. unpublished; [8)] Hutton et al. Unpublished

Table 1b. Virtual Nitrogen Factors (VNFs) in various countries and region

Food category	USA[1)]	Europe[1,3,5)]	Austria[2)]	Tanzania[5,8)*]	Japan[4)**]	Taiwan[6)*]	Australia[7)*]
Meat (Pork)	4.4	4.4	3.6	3.3	6.7	8.6	5.5
Meat (Chicken)	3.2	3.2	2.5	0.8	6.0	9.3	4.0
Meat (Beef)	7.9	7.9	5.4	7.0	12.4	23.9	13.4
Animal products (Milk)	4.3	3.9	3.7	8.3	2.7	6.4	5.0
Meat (Mutton)	5.2	5.2	3.8	3.3	5.6	11.9	9.3
Fish	4.1	2.9	N/A	0.2	2.9	1.8	1.9
Vegetables	9.6	8.2	4.3	4.1	5.5	4.7	8.0
Starchy roots	1.5	1.1	2	1.8	4.9	8.5	4.9
Legumes	0.5	0.5	0.4	0.3	1.3	7.4	1.2
Fruits	9.6	8.2	4.3	4.1	5.5	12.4	9.4
Cereals	1.4	1.3	1.2	6.2	1.5	1.4	1.8

*Results are preliminary

**Weighted for trade

Table 2. Possible key actions to reduce Nr losses to the environment.

Sectors	Key actions	Description
Agriculture	1. Improving N use efficiency in crop production	This includes improving field management practices (including increasing the linkage between livestock and cropland, which can reuse more livestock waste) and genetic options to increase yields per Nr input, thereby minimizing the risk of pollution swapping or tradeoffs.
	2. Improving N use efficiency in animal production	As with crops, this includes management practices and genetic potential, with an emphasis on improving feed conversion efficiency and decreasing maintenance costs to reduce Nr losses per unit of product and the extent of pollution swapping or tradeoffs.
	3. Increasing the fertilizer N equivalence value of animal manure	Increasing fertilizer equivalence values requires conserving the Nr in manure during storage and land application (especially reducing NH_3 emissions), while optimizing the rate and time of application to crop requirements.
Transport and Industry	4. Low-emission combustion and energy-efficient systems	These include improved technologies for both stationary combustion sources and vehicles, increasing energy-efficiency and the use of alternative energy sources with less Nr emission.
Sewage treatment	5. Recycling N from wastewater systems	Current efforts at sewage treatment for Nr (especially in Europe) focus on denitrification back to N_2. While policies have been relatively successful, this approach consumes the energy used to produce Nr. An ambitious long-term goal should be to recycle Nr from wastewater, utilizing new sewage management technologies.
Personal consumption patterns	6. Energy conservation and alternative transport	Encouraging the use of fuel-efficient cars, limiting long-distance holidays, using alternative transit options, shifting to renewable energy sources, and conserving household energy can together greatly contribute to decreasing NO_x emissions.
	7. Lowering the human consumption of animal protein where it is over-consumed	Lowering the fraction of animal products in diets to the recommended level (and shifting consumption to more N-efficient animal products) will decrease Nr emissions with human health co-benefits, where current consumption is over the optimum.
	8. Consumer-level food waste	Consumer-level food waste can be reduced by only purchasing what is needed and consuming all purchased food. Any remaining food waste can be composted to return its nutrients to agricultural production.

Refers to section 3.5 about the interaction among each key actions.

Table 3. Further advances, questions and possible approaches towards a global N footprint analysis.

Questions	Description and possible approaches
What datasets are needed to further advance N footprint calculations?	The global trade of food and feed has a significant impact on the local, regional and global N f for major exporting countries, however, are quite limited at this point. The development of a major exporting countries is necessary to complete a global analysis. The development of use estimate the various VNFs using international and/or local databases of agricultural practic
How can the N footprint be put in a spatial context?	The per capita N footprint in combination with spatial information such as source area of Nr agricultural area) would provide information of spatial intensity (e.g., N footprint flux ex references for local N pollution issues.
How does the N footprint change over time?	Calculating N footprints over time would reveal trends in changing consumption patterns or inform N mitigation strategies.
What are the parameters/indicators to be added, and applied perspectives in the N footprint analysis?	<u>Specific forms of nitrogen</u>: Different Nr species cause different environmental conse characteristic is not incorporated in the current concept of the N footprint based on the N-C The different Nr species lost during food and energy consumption are not evaluated accor such as ammonium, nitrate, organic N, nitrous dioxide etc.
	<u>N footprint of nonfood agricultural goods</u>: Besides food and energy, the consumption of nonfo nylon etc.) also contributes a significant amount of N to the footprint (Gu et al. 2013a). The n nonfood goods will not be lost to the environment immediately since nonfood goods have an 2013b). How nonfood goods influence the overall N footprint still needs to be further investiga are included (as a whole) in the N footprint caused by use of the good & services in the N-Ca
	<u>Natural resources</u>: Utilization of natural resources for food (e.g., wild deer), animal fe reproducible quantity is effective to improve sustainability and lower the N footprints. It incorporate the aspect of damage on natural resources beyond their sustainability into the N
	<u>Soil N pool</u>: Soil organic matter (SOM) can retain some of the Nr that is accounted for in th The Nr stored as SOM would have a long residence time and would be a N source to futu changes in cropland soil N stock over time would provide useful information to evaluate th losses to the environment.
	<u>Integrated environmental indicators</u>: A series of indicator systems have been introduce changes from human activities. The Environmental Performance Index (EPI) (Emerson et a combining the categories of environmental health and ecosystem vitality with 25 indicators. footprint could be a valuable approach for global N management.

Author/s:
Shibata, H;Galloway, JN;Leach, AM;Cattaneo, LR;Noll, LC;Erisman, JW;Gu, B;Liang, X;Hayashi, K;Ma, L;Dalgaard, T;Graversgaard, M;Chen, D;Nansai, K;Shindo, J;Matsubae, K;Oita, A;Su, M-C;Mishima, S-I;Bleeker, A