The human creation and use of reactive nitrogen: a global and regional perspective

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The Human Creation and Use of Reactive Nitrogen: A Global and Regional Perspective

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Abstract

More food and energy allow for more people who then require more food and energy, and so it has gone for centuries. At the same time, economic progress leads to a different lifestyle with an increasing demand for energy and food, also accelerating food waste. Fueling this food-energy-population dynamic is an ever-increasing conversion of unreactive dinitrogen (N_2) to reactive N (Nr), which then results in a cascade of positive (food and energy for people) and negative (damage to people, climate, biodiversity, and environment) impacts as Nr is distributed throughout Earth systems. The most important step in reducing the environmental impacts of Nr is limiting its human-based creation. In this article, therefore, we focus on this most important first step: the conversion of N_2 to Nr by human activities. Specifically, we examine Nr creation and use (they are different!) on a global and regional basis and Nr use on a global and regional per capita basis. In addition, we introduce the metric Nr Use Index (NUI), which can be used to track and project Nr use relative to a fixed point in time. We then assess the progress in Nr management over the past 20 years. Our article presents a case study of the Netherlands to show what one country, beset by Nr-related problems that have led to an N crisis, did to address those problems and what worked and what didn't work. The article concludes with an assessment of what the future might hold with respect to Nr creation and use, including a review of other projections. We expect that NUI will increase especially in Asia, Latin America, and Africa. The other parts of the world are consolidating or even decreasing NUI. In Latin America and Asia, there is limited agricultural land, and by increasing NUI for food the risk of Nr pollution is very high. The Netherlands has shown not only what effects can be expected with increasing NUI but also what successful policies can be introduced to limit environmental losses. Our assessment shows that Nr creation needs to be limited to prevent local to global environmental impacts.

Contents

Reactive nitrogen (Nr): any nitrogen compound that is biologically, chemically, or radiatively reactive

1. INTRODUCTION

All biological species require a form of reactive nitrogen (Nr) for survival. The atmosphere around us is full of nitrogen. So, what's the problem?

The atmosphere is composed of 78% of dinitrogen (N_2). All organisms on Earth need Nr to sustain biological processes and therefore life. Nr—any form of nitrogen except for N_2—is naturally created through lightning and biological N fixation (BNF). Humans invented all kinds of ways to collect or produce Nr to be used in agriculture to boost agricultural production; the most well-known and broadly used Haber-Bosch (HB) process is the best example. Together with the creation and emission of Nr due to burning of fossil fuels, humans have disrupted the N cycle for more than a century (1–3).

A half century ago, Delwiche (4) noted that in 1968 the world's annual output of industrially fixed Nr created by the HB process was ~30 Tg N/year. He then estimated that by the year 2000 the industrial fixation of Nr might exceed 100 Tg N/year and that because the rate of denitrification was not keeping up with the rate of Nr creation, Nr would be accumulating in the Earth's reservoirs. With the benefit of hindsight, we have learned that he was correct on both counts. In the year 2000, Nr creation by the HB process exceeded 100 Tg N/year (108 Tg N/year), and some of that Nr was accumulating in the environment (5). Moreover, when the Nr creation rate by fossil fuel combustion (FF) and cultivation-induced biological N fixation (CBNF) are included, the total rate was 157 Tg N/year. A half century has passed since Delwiche's work—what has happened in the meantime and what is likely to happen in the future spanning the same amount of time (30 years) that Delwiche used for his predictions?

Given the breadth of these questions, we focus on the most important step in the entire process—the conversion of N_2 to Nr. Once this reaction occurs, the newly formed Nr can be distributed throughout the Earth's environmental reservoirs, contributing to a myriad of negative impacts on the health of ecosystems, people, climate, and the environment itself. Additionally, because the rate of conversion of Nr back to N_2 is less than its formation, Nr is accumulating in environmental systems, which not only contributes to current problems but also leaves an unfortunate legacy for future generations.

We approach this issue in the following manner:

1. We examine Nr creation rates on a global and regional basis.
2. We discuss the differences between regional Nr creation (where it is produced) and regional Nr use (where it is consumed).
3. We introduce the concept of the Nr Use Index and examine it on a global, regional, and per capita basis.
4. We assess what Nr management programs have been the most successful.
5. We present a case study of the Netherlands, one of the world leaders in active management of Nr-related issues.
6. We review future scenarios of Nr creation and use.

The data used for calculating the Nr creation rates on a global and regional basis and the Nr Use Index are taken from different sources. There are three contributors to Nr creation: FF, Haber-Bosch process for producing ammonia for fertilizer (HBF), and CBNF. The HBF data related to the use of fertilizer Nr are taken from the Food and Agriculture Organization of the United Nations (FAO) database (6). The data reflect the official data provided by the different countries and are gap-filled when country contributions were missing. The calculation procedure from Lassaletta et al. (7) was used for CBNF, taking FAO data for the period 1961–2018 on nitrogen fixing crops in the different regions of the world. According to Lassaletta et al. (7), the actual method for estimating the CBNF can produce differences in the final result, with a calculation based on production (as used here) providing much better estimates. The FF data are based on the BP Statistical Review of World Energy (8), from which information on energy use for oil, gas, coal, and biofuels is taken for the period 1965–2018. Estimates for 2019 and 2020 were extrapolated from the previous ten years. Although these data represent reported energy consumption information by individual countries, Hoesly & Smith (9) found that approximately 70% of the nonzero data points for 17 editions of the BP Statistical Review (2001–2017) were adjusted after

Haber-Bosch (HB): process produces ammonia from H_2 and N_2; the ammonia is used for both fertilizer and as an industrial feedstock

Nr creation: the conversion of unreactive N_2 to a chemically, biologically, or radiatively active form of N

Fossil fuel combustion (FF): burning of fossil fuel, with the production of nitrogen oxides and nitrous oxide as a negative side effect

Cultivation-induced biological N fixation (CBNF): agricultural creation of reactive nitrogen due to biological nitrogen fixation (e.g., legume cultivation)

Nr use: where the created Nr is actually used (e.g., N fertilizer is created on one continent but may be used on another continent)

Nr use efficiency (NUE): the fraction of applied nitrogen that is absorbed and used by the plant

the first publication. These adjustments resulted in a change of 1.3% of a country's total fossil fuel use on average. Emission factors for converting Mtoe (mega tonnes of oil equivalents) for these products into Nr losses through nitrogen oxides (NO_x) emissions were taken from the IPCC's 2001 factors, in combination with conversion factors provided by the BP Statistical Review. Data for FF, HBF, and CBNF were linearly extrapolated up to 2020 using available data on these items for the period 2008–2018.

2. Nr CREATION ON A GLOBAL AND REGIONAL BASIS

2.1. Global Analysis

Over the period 1961–2020, all three contributors to Nr creation [FF, HBF and Haber-Bosch industrial (HBI), and CBNF] increased (**Figure 1**).

We estimate that in 2020, the total global Nr creation rate was 226 Tg N/year (HBF, 106; HBI, 43; FF, 34; CBNF, 43). HBF is dominant by a factor of 2 or more but has been approximately constant since 2014, as has FF. In contrast, both HBI and CBNF have steadily increased at a more rapid rate over the past decade. For comparison, the natural fixation of Nr is estimated at 58–128 Tg N/year (10–14).

FF-N is a by-product without any usage in contrast to Nr created by CBNF and HBF, which contributes to food production and therefore human health and wellbeing. Nr creation by FF decreased over the past few decades due to efficient NO_x controls in many developed countries. The agricultural Nr use decreased in developed countries due to not only increased Nr use efficiency (NUE) of agricultural production as a result of environmental considerations but also to the increased cost of fertilizers, e.g., in OECD (Organisation for Economic Co-operation and Development) countries. The economic turnover in Eastern Europe also meant a strong decrease in fertilizer production and use and associated wastage in that part of the world. However,

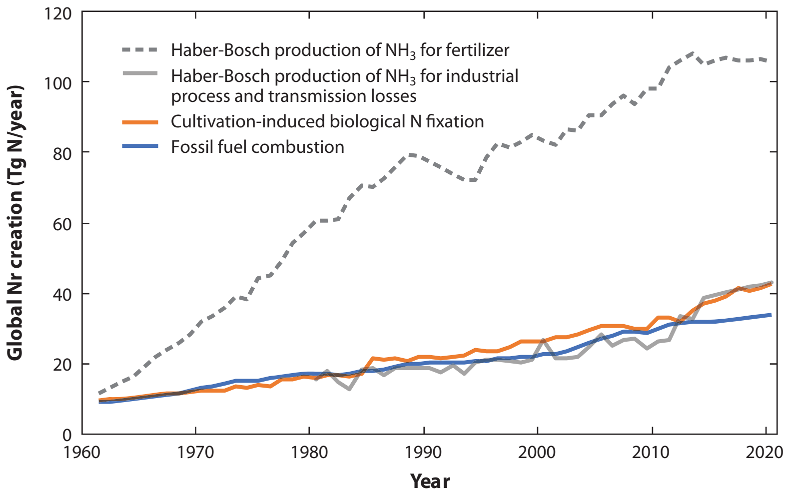

Figure 1

Global Nr creation by fossil fuel combustion, cultivation-induced biological N fixation, Haber-Bosch production of NH_3 for fertilizer and Haber-Bosch production of NH_3 for industrial process and transmission losses (HBI). Data are for the period 1961 to 2018, except for HBI, which is for 1980 to 2018. Estimates for 2019 and 2020 were extrapolated from the previous ten years. Data from author calculations based on FAO (6), Lassaletta et al. (7), and BP Statistical Review of World Energy (8).

production of corn for biofuel, the strong increase in meat production, and especially change in diets in large parts of the developing world caused significant increases in fertilizer use.

Over the period 1980–2020, 18% to 28% of HB creation of NH_3 has been used for nonfertilizer purposes (HBI), mainly in the chemical industry. The percentage has generally risen with time (1980, 18%; 2020, 28%). Given that data on HBI are not available prior to 1980, the remainder of the article considers only HBF.

2.2. Regional Analysis

A necessary distinction prior to embarking on the Nr regional analysis is to differentiate between Nr creation and Nr use. On the global scale, creation and use are identical, as there are no internal transfers. Global Nr creation is therefore a good indicator of global human reactive N production. At the regional scale, however, this is not the case for CBNF and HBF, because a portion of the Nr can be used in a different region from which it is created. For example, HBF-N can be created in one region and then exported to another region to be used (i.e., N fertilizer produced in Europe and applied to the ground in Africa). Similarly, CBNF-N can be created in one region and then exported to another region to be used (i.e., soybeans produced in Latin America and used for feed in another region).

Given this distinction, we first discuss regional Nr creation and then in Section 3, we discuss regional Nr use. Nr creation by FF on a regional basis is assumed to be equal to Nr use, because the Nr is emitted directly into the atmosphere at its point of creation.

There is substantial regional variation in the amount of Nr created with time (**Figure 2**). Asia now accounts for ~50% of the Nr created; North America, Europe, and Latin America have intermediate rates; and Oceania and Africa have the lowest rates.

This information can be subdivided by region and process—the regional Nr creation by FF, CBNF, and HBF (**Figure 3**). Within each region, the relative importance of the three primary sources of new Nr is quite different (**Figure 4**).

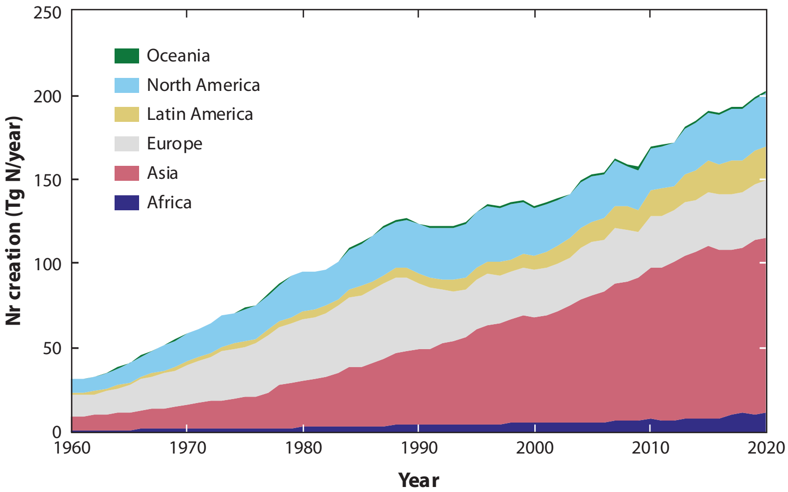

Figure 2

Total regional Nr creation for the period 1961–2020 by fossil fuel combustion, cultivation-induced biological N fixation, and Haber-Bosch production of NH_3 for fertilizer. Data from author calculations based on FAO (6), Lassaletta et al. (7), and BP Statistical Review of World Energy (8).

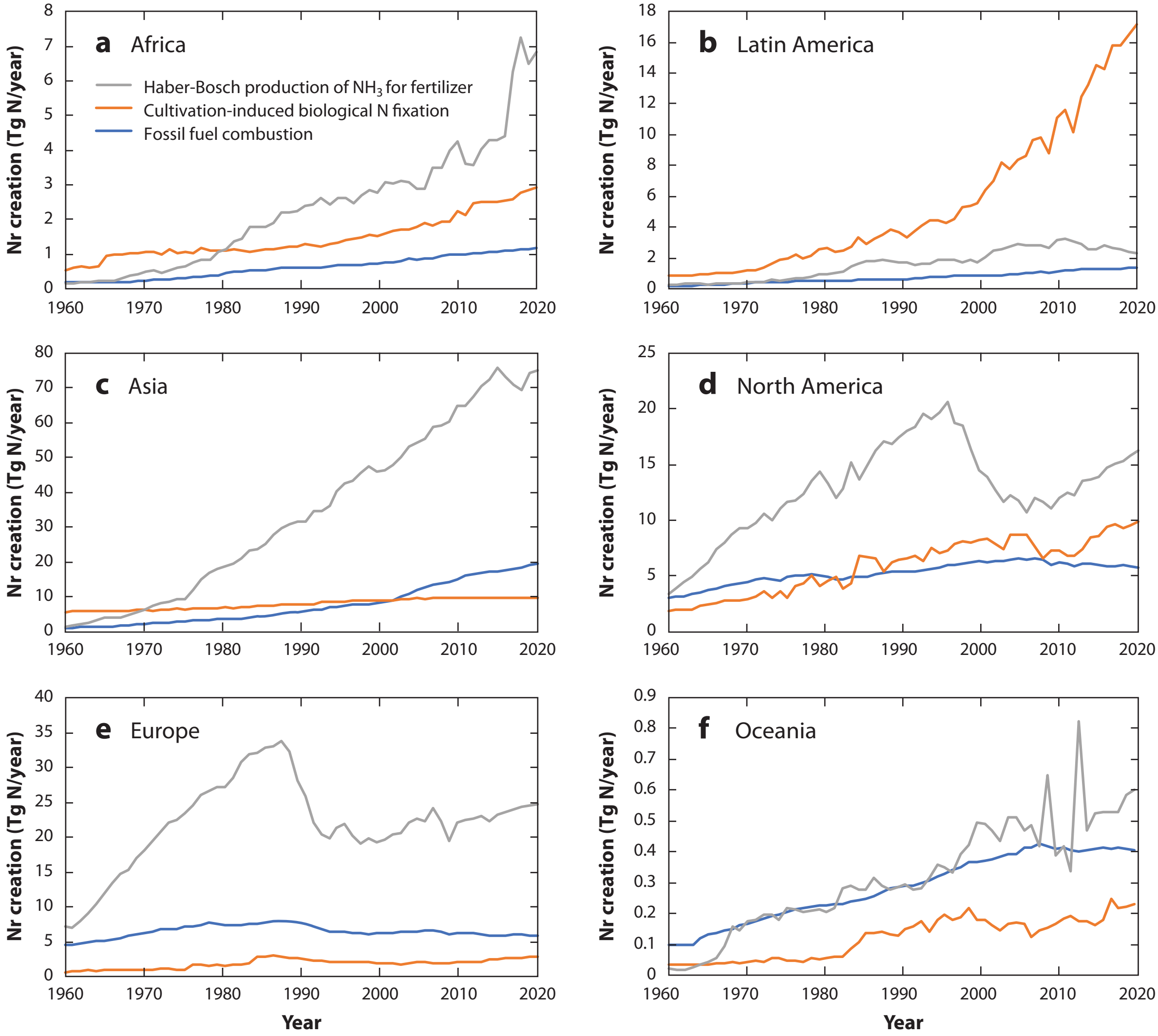

Figure 3

Nr creation by Haber-Bosch production of NH_3 for fertilizer, cultivation-induced biological N fixation, and fossil fuel combustion for (*a*) Africa, (*b*) Latin America, (*c*) Asia, (*d*) North America, (*e*) Europe, and (*f*) Oceania. Data from author calculations based on FAO (6), Lassaletta et al. (7), and BP Statistical Review of World Energy (8).

In all regions, except Latin America, HBF is the most important source of new Nr. It is mainly used in agriculture. In Latin America due to the large-scale soy production, CBNF is the most important source, more than twice that of HBF. CBNF differs significantly among the different regions. In North America, where there is also an appreciable amount of soy production, the contribution to the total Nr is high. In all other regions, it is much smaller than HBF, except for Africa where both CBNF and HBF are low.

For Africa, HBF is larger than CBNF and FF. All three show a steady increase, mainly focused on food production. For Latin America, CBNF is the largest and has always been dominant, mainly

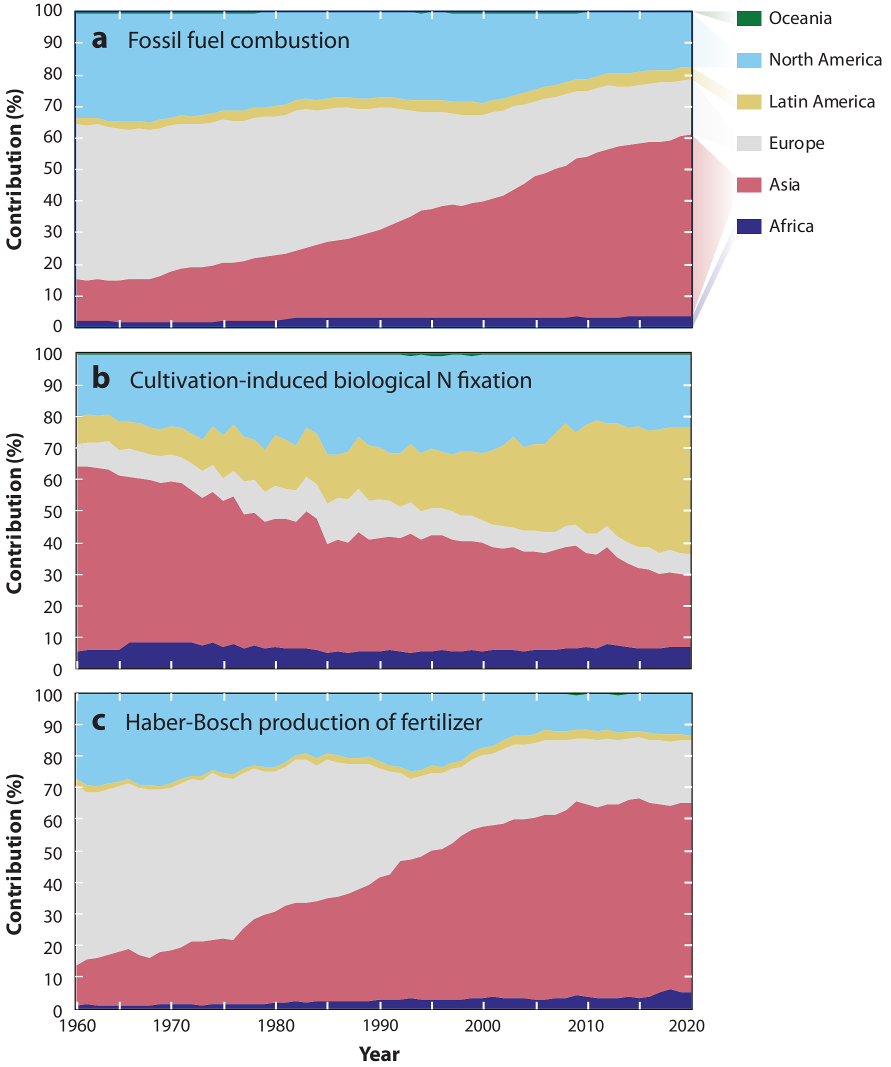

Figure 4

The relative importance (%) of Nr creation by (*a*) fossil fuel combustion, (*b*) cultivation-induced biological N fixation, and (*c*) Haber-Bosch production of fertilizer by region, over the period 1961–2020. Data from author calculations based on FAO (6), Lassaletta et al. (7), and BP Statistical Review of World Energy (8).

because of large-scale soy production (∼40% of global Nr production in 2020). HBF has been constant over the past two decades, whereas FF is slowly increasing over the entire 1961–2020 period. HBF dominates Nr creation in Asia and is also large on a global scale (∼60% of the global total). Whereas BNF is relatively small, FF is steadily increasing over the whole period. For North America, HBF is larger than both BNF and FF. After an increase in HBF and BNF Nr creation, they both dropped by the end of the past century but are increasing again since 2010. FF-N creation has been approximately constant since the 1990s. For Europe, HBF is larger than Nr creation by both FF and CBNF. The HBF-N creation dropped in the late 1980s, due to the economic breakdown in Eastern Europe after the collapse of the USSR. Overall, Oceania is at the low end of the Nr creation rates for the different items, but all three (HBF, FF, and CBNF) increased over the 1960–2020 period.

The previous section examined the temporal patterns of Nr creation by FF, CBNF, and HBF within each of the six regions. This section examines how the six regions varied with respect to Nr creation by FF, CBNF, and HBF.

Over a ~60-year period, the regions where the majority of Nr was created have changed dramatically. In 1961, Asia (CBNF) and Europe (FF and HBF) were dominant in Nr creation. In 2020, it was Asia (FF and HBF) and Latin America (CBNF).

More specifically, FF in Europe and North America were dominant in Nr creation prior to the mid-1990s. In the meantime, Asia was trending up. This resulted in Asian FF becoming dominant in Nr creation since the mid-1990s. Although the Asian absolute emission rate is approximately constant, its relative importance continues to increase because of decreasing emissions in North America and Europe. Both North America and Europe currently contribute approximately 20% of the global FF-N creation. Oceania is not playing an important role in the global FF-N creation, and Africa and Latin America show a FF-N creation of less than 10%. Overall, the pattern for the Haber-Bosch production follows that for FF, with Asia showing the highest contribution since the early 1990s. The Nr creation due to CBNF shows a different pattern. Although Asia dominated the CBNF-N creation in 1960 (~60%), its share decreased due to a growing CBNF-N creation in Latin America. Around 2010, Latin America overtook Asia as the largest CBNF-N producer, with a total share of approximately 40% in 2020. Although at different levels, the other regions show an approximately constant trend in terms of their share in the global CBNF-N creation.

With respect to Nr creation on a global and regional basis, we provide the following summary:

1. Globally, we estimate that in 2020, the total human global Nr creation rate was 226 Tg N/year. HBF is dominant by a factor of 2 with the others about the same. Since 2014, HBF has been approximately constant, as has FF. In contrast, both HBI and CBNF have steadily increased at a more rapid rate over the past decade.
2. Regionally, Asia now accounts for ~50% of the Nr created, with North America, Europe, and Latin America having intermediate rates, and Oceania and Africa, the lowest rates.
3. HBF is the most important source of new Nr in all regions except for Latin America where, due to large-scale soy production, CBNF is the most important source, more than twice that of HBF.
4. The regions where the majority of Nr was created have changed dramatically for this ~60-year period. In 1961, Asia (CBNF) and Europe (FF and HBF) were dominant in Nr creation. In 2020, it was Asia (FF and HBF) and Latin America (CBNF).

3. Nr USE ON A GLOBAL AND REGIONAL BASIS

The human impact on the N cycle is driven by increased creation of Nr by food and energy production (11, 15–18). Once created, the Nr is active within the environment until it is either sequestered or converted back to N_2 by denitrification (5, 19). In the previous section, we did a regional comparison of how Nr creation has varied over time. Although this is informative given the significant resource use among regions, it does not provide information on where the Nr is actually used and thus injected into the environment where it pollutes soil, water, and air and contributes to a range of impacts, such as climate change, biodiversity loss, and fish kills (20–23).

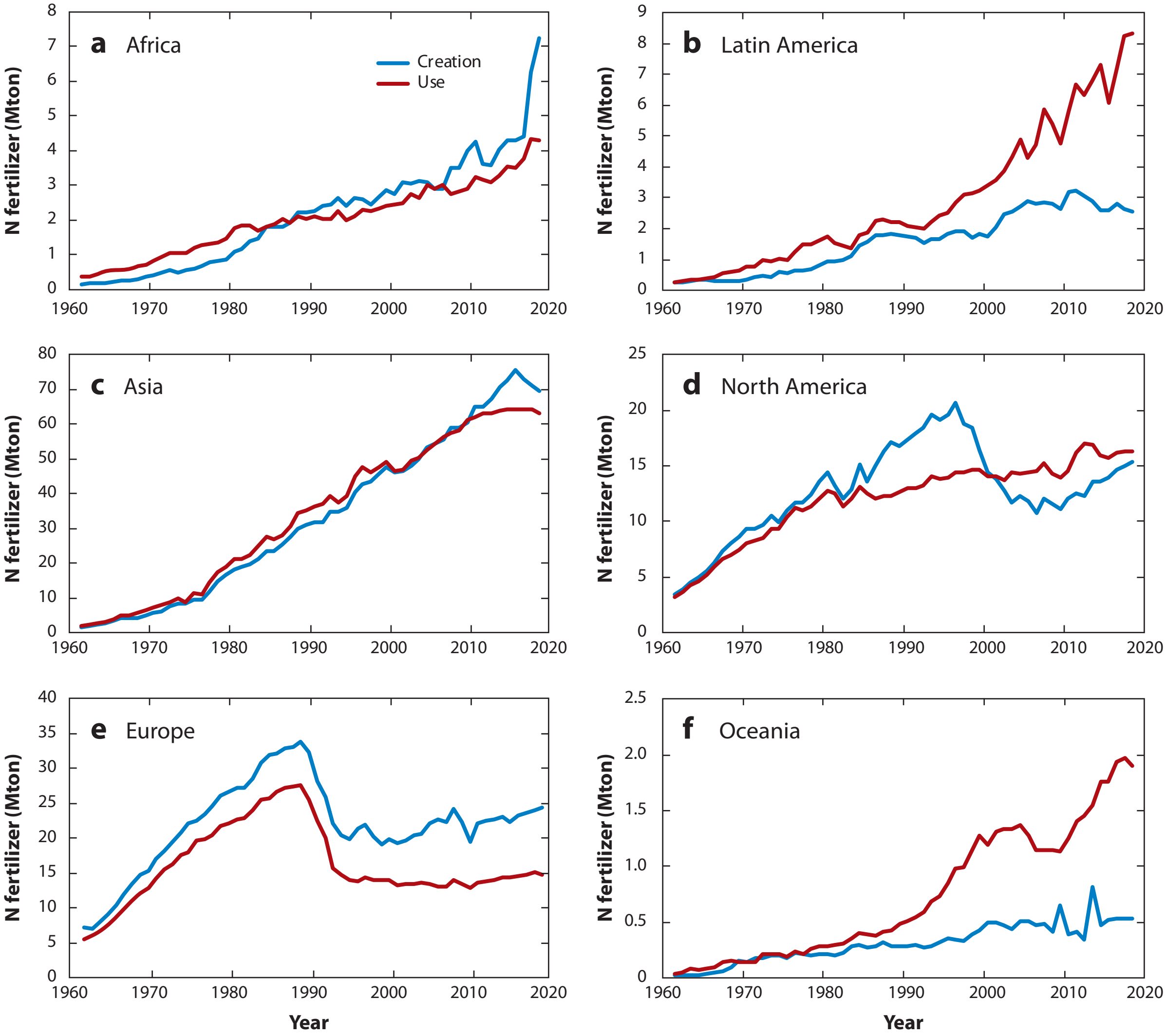

Figure 5

Global Nr creation (production) and use (consumption) Haber-Bosch production of NH_3 for fertilizer on a regional basis for (*a*) Africa, (*b*) Latin America, (*c*) Asia, (*d*) North America, (*e*) Europe, and (*f*) Oceania. Data from author calculations based on FAO (6).

Therefore, we introduce the metric Nr use. On a global basis, Nr creation and Nr use are the same. However, this is not the case for all regions. Nr use takes into account the substantial exchange of Nr created in one region but used in another region.

Nr is created by FF, HBF, and CBNF. For the first process, creation and use are the same—the NO_x is emitted to the atmosphere quickly after it is formed. However, this is not the case for HBF (**Figure 5**) and CBNF (**Figure 6**).

With respect to HBF, **Figure 5** shows HBF-N creation and use for the world's regions as a function of time. For Asia and Africa, creation and use of HBF-N are similar with time. Although there may be imports and exports from one region to others, they are balanced.

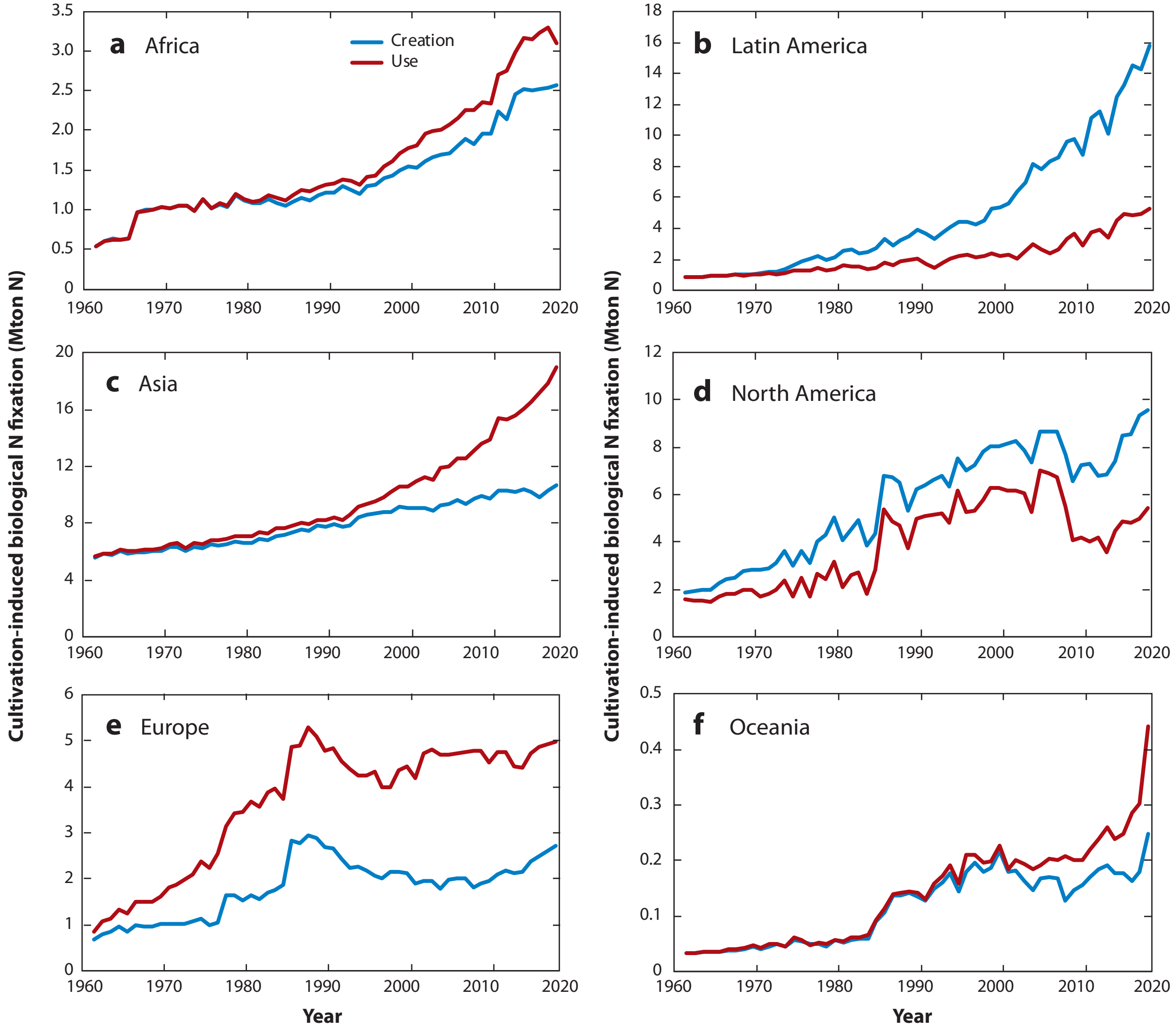

Figure 6

Nr creation by cultivation-induced biological N fixation (production) and use of cultivation-induced biological N fixation (consumption) on a regional basis for (*a*) Africa, (*b*) Latin America, (*c*) Asia, (*d*) North America, (*e*) Europe, and (*f*) Oceania. Data from author calculations based on FAO (6) and Lassaletta et al. (7).

The largest changes relatively and in absolute magnitude for Nr creation versus Nr use were for Europe and Latin America. In the former, Nr creation and use dropped precipitously in the late 1980s associated with the fall of the former Soviet Union and the resulting economic crisis. For a few years in the mid-1990s, both creation and use were constant, but by the late 1990s, creation increased, whereas Nr use stayed constant to the end of the record. In essence, Europe has become a supplier of Nr to the rest of the world, whereas its own use of Nr has stayed constant. For Latin America, until approximately 2000, HBF-N creation and use rose together and creation kept increasing, but Nr use almost tripled over a ∼20-year period.

In Oceania, creation and use show a similar pattern as for Latin America. They increased together until approximately 1990, at which point Nr use increased significantly while Nr creation slowly increased. The region thus became more dependent on HBF-N from other regions.

CBNF is the other type of Nr creation in which there are discontinuities between where Nr is created and where it is used (**Figure 6**). Over the period of record, Europe has always used more Nr created by CBNF than it created itself (i.e., import of soy material for animal feed). Since approximately 2000, Asia has shown the same pattern. For Africa and Oceania, the creation and use of Nr from CBNF has been increasing about the same amount with time.

With respect to Nr use on a global and regional basis, we provide the following summary:

1. For HBF, creation and use of HBF-N were approximately balanced in the early 1960s for all regions, and for some regions (notably Asia) that is still the case (i.e., self-sufficient in HBF use). In Europe, Nr creation has steadily been increasing relative to Nr use (i.e., a supplier of HBF to other regions). For Latin America and Oceania, HBF use has steadily increased relative to HBF creation (i.e., net importers of HBF).
2. For CBNF, Latin America and North America are suppliers of substantial Nr in the form of soy products to all other regions of the world. It is these other regions that are seeing enhanced consequences of Nr pollution.

4. GLOBAL AND REGIONAL Nr USE ON A PER CAPITA BASIS

4.1. Global

Galloway et al. (24) showed that there are three phases in per capita Nr production globally: Over the period 1850–1950, Nr creation increased roughly proportional to the population, followed by a period of rapid increase in per capita Nr creation (until approximately 1980) and finally a period until now where the global per capita Nr creation reached a new equilibrium between population growth and Nr creation.

Since 1970, we have learned much about the drivers controlling Nr creation (food, energy, industry) and fine-tuned our knowledge of the inefficiencies of the food supply chain. We have also developed a better understanding of how much of the Nr created during FF and used for food production is lost to the environment—all of it, and most of it, respectively. Furthermore, we have increased knowledge on the types of negative impacts on the environment (in soils, air, water) and their growing spatial extent. Throughout this time of getting smarter about Nr, there have been large increases in the Nr creation rate and the global population. The per capita Nr creation rate has two distinct periods, both approximately 30 years. Over the first period (1961–1990), the rate increased rapidly from ~10 kg N/capita/year to 24 kg N/capita/year. Over the next 30-year period (1991–2020), the rate initially dropped to ~20 kg N/capita/year and then slowly increased to ~24 kg N/capita/year and has been constant for the past decade (**Figure 7**).

4.2. Regional

This section examines per capita Nr use on a regional basis (**Figure 8**). It provides perspective for policymakers and other stakeholders to increase NUE, thereby reducing the negative effects.

For Africa, the per capita Nr use is consistently low compared with the other regions. This implies that the overall standard of living with respect to Nr does not seem to increase. High population numbers are balancing the overall Nr use, showing the low per capita Nr use. Although Asia started at the same level of per capita Nr use around 1960, it has been on a trajectory of slow, steady growth until 2000, after which the per capita Nr use is constant. Also, Latin America was at the lower end around 1960 but has shown a steady rise in per capita Nr use over the entire 60-year

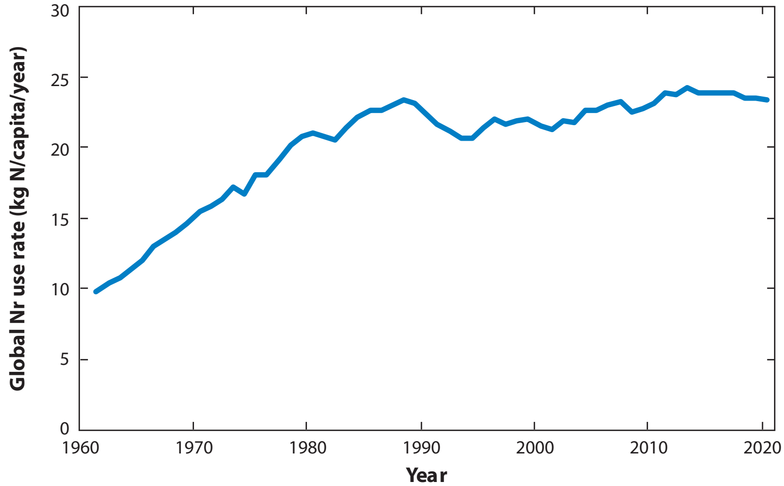

Figure 7

The per capita Nr use rate on a global basis, kg N/capita/year, from Haber-Bosch creation of NH_3 for fertilizer, fossil fuel combustion, and cultivation-induced biological N fixation. Note that this is the same as the Nr creation rate, when expressed on a global basis. Data from author calculations based on FAO (6), Lassaletta et al. (7), and BP Statistical Review of World Energy (8).

period. This increase has been mainly driven by CBNF. Oceania has shown a steady increase of the per capita Nr use until 2000, after which it became constant. Although Europe showed a steady rise from 1960 until approximately 1990, the per capita Nr use suddenly dropped by 40% due to the fall of the USSR. After that, it stayed constant at a level of approximately 30 kg N/capita/year. The Netherlands and Denmark are the two countries in the world that significantly reduced Nr

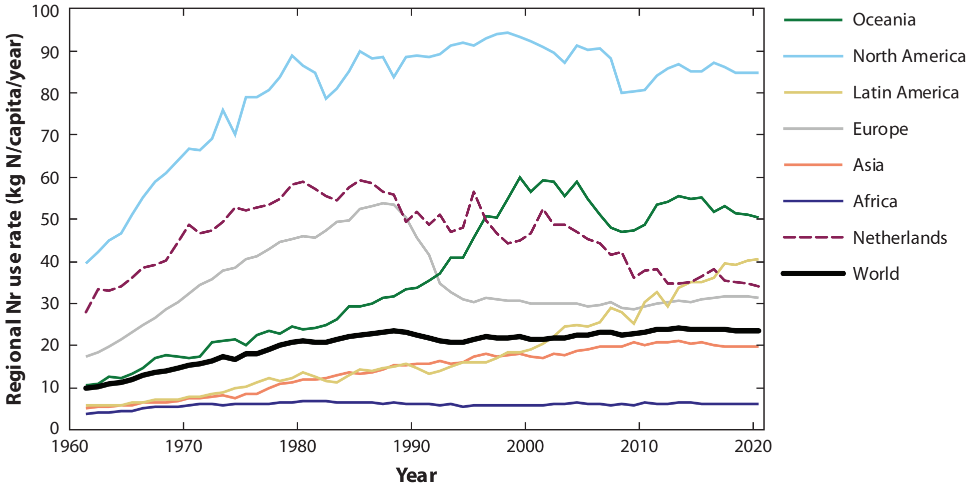

Figure 8

The per capita Nr use rate on a regional basis, kg N/capita/year. Data from author calculations based on FAO (6), Lassaletta et al. (7), and BP Statistical Review of World Energy (8). Data for the Netherlands are included in support of a case study in Section 7; they are also included in the data for Europe.

losses to the environment, while at the same time increasing production (7). In this article, the Netherlands serves as a case study and is therefore shown in **Figure 8**.

Nr Use Index (NUI): used to track and project Nr use relative to a fixed point in time

North America started off from a level of 40 kg N/capita/year and showed an increase until 1980. The per capita Nr use then stayed constant until approximately 2000, after which there seems to be a slight decrease. If we look at the per capita Nr use rates in 2020, Africa shows the lowest per capita Nr use with less than 5 kg N/capita/year, followed by Asia (~20 kg N/capita/year), Europe (~30 kg N/capita/year), Latin America (~40 kg N/capita/year), Oceania (~50 kg N/capita/year), and finally North America with approximately 85 kg N/capita/year. HBF-N is highest in North America and lowest in Africa.

What we might conclude from this comparison is that the highest per capita Nr use is 85 kg N/capita/year in North America. We take this as the absolute maximum for future predictions. Furthermore, we see that there are regions that are still increasing, others are consolidating, and one area—the Netherlands—is decreasing. For policy development, the Netherlands example is especially interesting, and therefore we devote a section to a Nr case study for the Netherlands.

Whereas HBF and CBNF are an indication for total food production, FF-N is an indication for the energy intensity of the region, given that the major source of NO_x is fossil fuel burning used for energy production and use (i.e., transport, industry). The information on HB, CBNF, and FF Nr creation per capita can be subdivided by region. **Figure 9** shows this subdivision for the six regions in the world.

Compared to the other regions, Nr use is lowest for Africa; furthermore, it is static with time. This approximately constant rate for CBNF and FF also holds for the other regions, with the exception of Latin America, where the rate for Nr use by CBNF is dominant and drastically increasing over time (an overall sevenfold increase since 1961). The HBF-N use shows more variation for the different regions. Overall, HBF is dominant for all regions except Latin America, with clear increasing HBF-N use. Although at different rates, both the HBF-N use for Africa and North America leveled off since the early 1980s. For Asia and Oceania, Nr use kept on increasing, only leveling off since 2000. For Europe, the pattern is different, with HBF-N use increasing by 250% in the period 1961–1989 and then dropping by approximately 45% after the collapse of the Soviet Union. Since 1995, HBF-N use has been approximately constant for Europe at approximately 20 kg N/capita/year.

With respect to global and regional Nr use on a per capita basis, we provide the following summary:

1. On a per capita basis, Nr use rate has two distinct periods, both approximately 30 years. Over the first period (1961–1990), the use rate increased faster than the population from ~10 kg N/capita/year in 1961 to ~24 kg N/capita/year in 1990. Over the next 30-year period (1991–2020), the rate varied between ~20 kg N/capita/year and ~24 kg N/capita/year. It has been constant for the past decade.
2. On a regional basis, with the exception of Latin America (driven by HBF and CBNF), over the past ~20 years the per capita use rate has remained constant.
3. The regional per capita Nr use is highest in North America at about 85 kg N/capita/year. We regard this as the maximum level that can be reached on this scale.

5. INTRODUCTION OF THE Nr USE INDEX

The Nr Use Index (NUI) is a measure of the rate of change in Nr use rate. Functionally it normalizes Nr use to 1961, the base year. On a global basis, it permits the easy assessment of the rate of change in Nr use—for example, globally Nr use has increased sixfold over the ~60-year period (1961–2020). When expressed as its component parts, Haber-Bosch use of fertilizer has

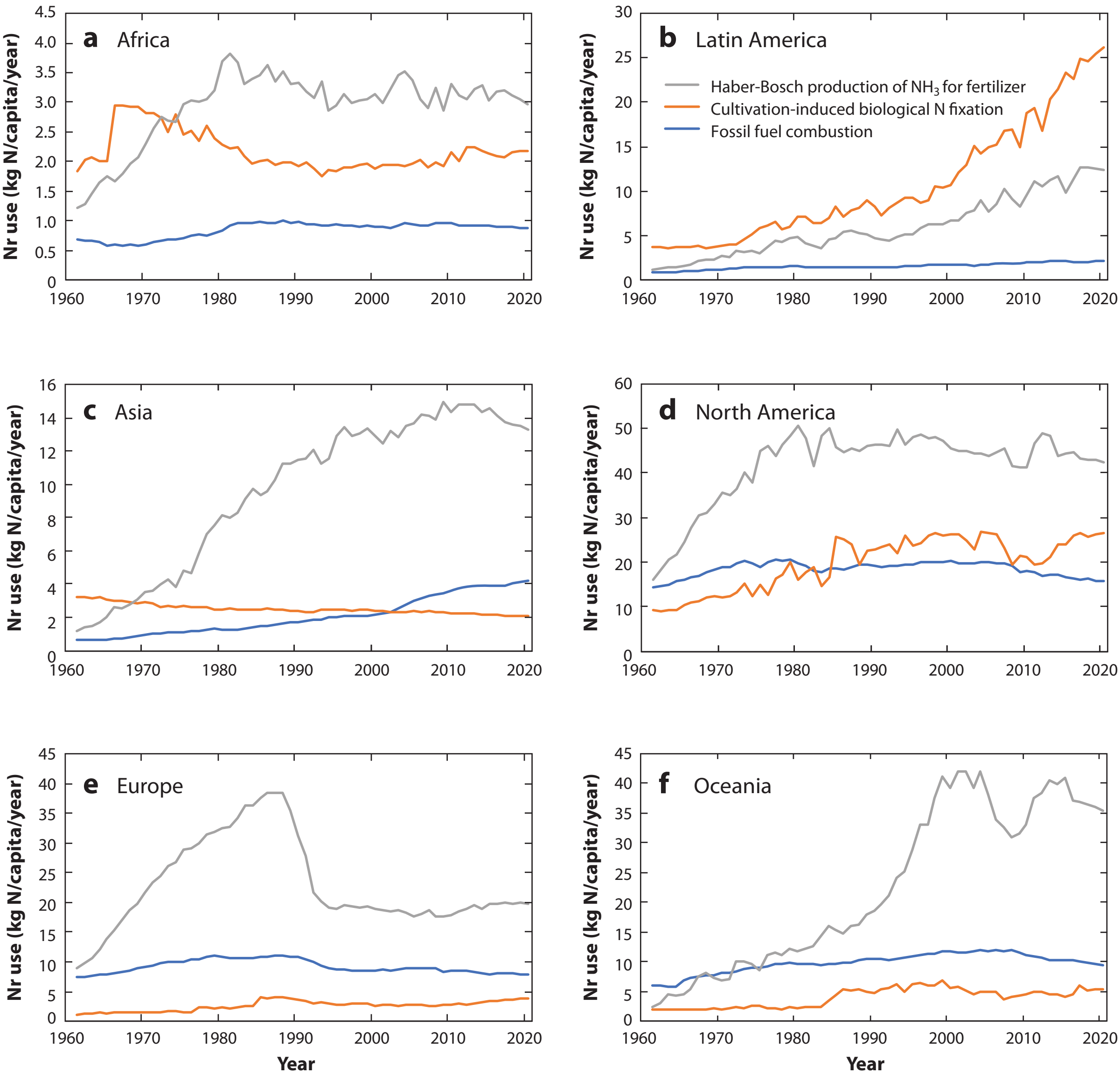

Figure 9

The per capita Nr use rate on a regional basis, kg N/capita/year, from Haber-Bosch creation of NH_3 for fertilizer, cultivation-induced biological N fixation, and fossil fuel combustion for (*a*) Africa, (*b*) Latin America, (*c*) Asia, (*d*) North America, (*e*) Europe, and (*f*) Oceania. Data from author calculations based on FAO (6), Lassaletta et al. (7), and BP Statistical Review of World Energy (8).

increased ninefold, and CBNF and FF contributions to Nr use have increased approximately fourfold (**Figure 10**).

5.1. Nr Use Index on a Regional Basis, Total and Per Capita: 1961–2020

The NUI provides a relative assessment of the evolution of the contribution of Nr creation processes and an indication of the potential trajectory of change. As noted above, on a global basis

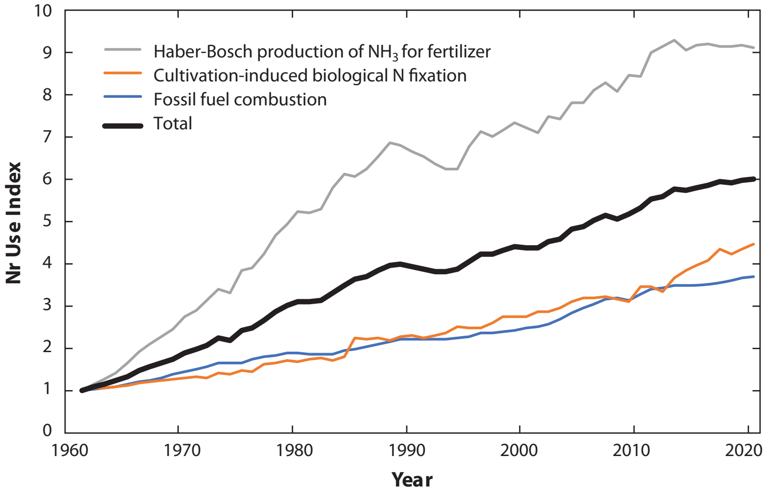

Figure 10

Global Nr Use Index by fossil fuel combustion, use of Nr created by cultivation-induced biological N fixation, and use of NH_3-created fertilizer. The data are for the period 1961–2020. Data from author calculations based on FAO (6), Lassaletta et al. (7), and BP Statistical Review of World Energy (8).

this provides general information. On a regional basis it identifies which processes are the most important contributors to the regional-level environmental issues and how they change with time. The NUI can be expressed as a total (**Figure 11*a***), on a per capita basis (**Figure 11*b***), and on a per-area basis (**Figure 11*c***).

Europe and North America have relatively invariant Nr use since approximately 1990. The same is true on a per capita basis. This is indicative of a mature economy with stable populations. Africa has a growing NUI but a stable per capita NUI. This indicates that NUI is just keeping pace with population growth. For all three of these regions, the average contribution of a person to Nr use in their region has been constant over the past several decades.

For Oceania, prior to 2000, the NUI had a steady increase, with slighter increases afterwards. The post-2000 increases were due to population increases. Taking into account population growth, the NUI for a person has been slowly decreasing. For Asia, prior to 2010, both total and per capita NUI steadily increased. After 2010, both leveled off with the per capita NUI actually decreasing.

In the case of Latin America, the NUI has steadily increased. This was driven by CBNF and was not related to changes in population. In fact, it is unlikely that the average person ever "sees" the Nr created, as it is mostly exported for animal feed. So, in a sense, Latin America is subsidizing Nr pollution around the world!

5.2. Nr Use Index on a Land Area Basis: 1961–2020

Another indicator for Nr is the NUI per agricultural land area. This gives some impression of the environmental burden. **Figure 11*c*** shows the NUI/hectare (ha) data for the different regions of the world. The land area used for this indicator is the agricultural land area, taken from FAO (FAOSTAT Land Use domain). Interestingly, the NUI per capita has stabilized in certain regions, whereas the NUI per ha increases everywhere, except for the Netherlands. NUI/ha for the regions used here rises to more than 50 kg/ha. Within these regions, the intensity can be much higher. This is illustrated by the Netherlands, a small region in Europe that had NUI/ha values

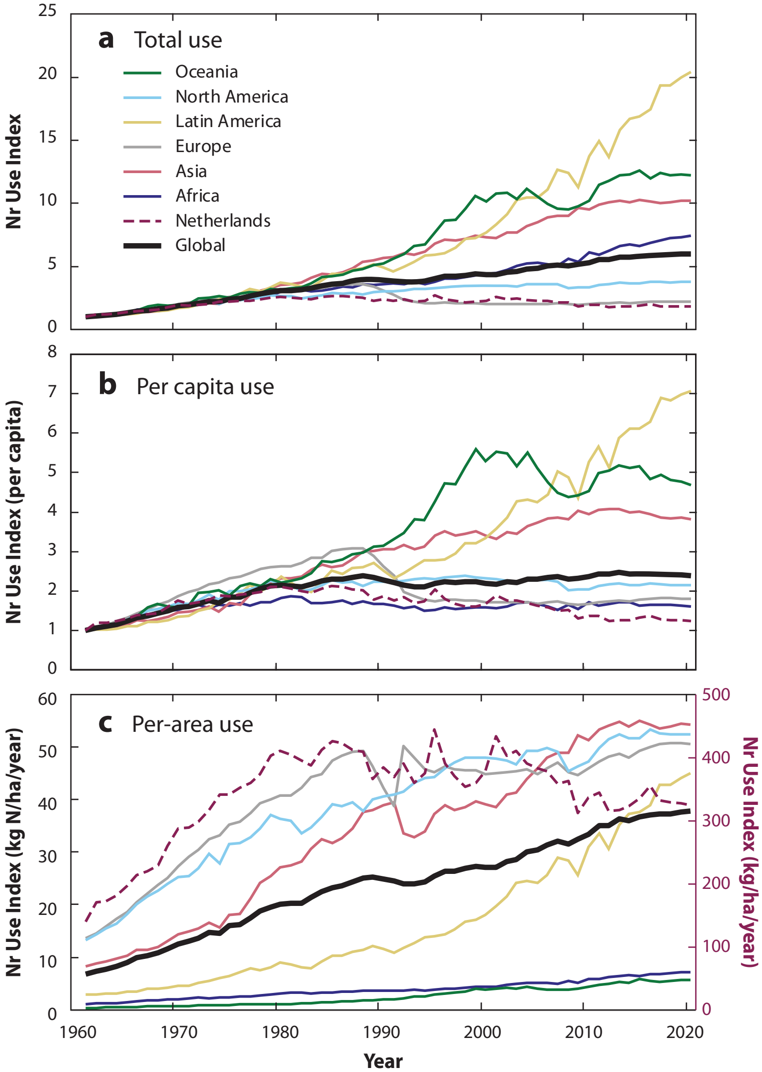

Figure 11

Regional Nr Use Index (NUI) data for (*a*) total use, (*b*) per capita use, and (*c*) per-area use. The NUI is a measure of the rate of change in Nr use rate. Functionally it normalizes Nr use to 1961, the base year. The data are for the period 1961–2020. Data for the Netherlands are also shown (right *y*-axis), to tie into the case study discussed in Section 7. Data from author calculations based on FAO (6), Lassaletta et al. (7), and BP Statistical Review of World Energy (8). Nr Use Index is the absolute amount of Nr used in a given year, divided by the amount used in a base year (e.g., 1961).

up to 400 kg/ha. The Netherlands has a very high (factor of 10 more) NUI per ha and is very intensive, with major environmental losses (see Section 7). This is not so much expressed in the NUI nor NUI per capita where the Netherlands has reached the lowest score because of high population density. Policy to reduce manure and fertilizer since the beginning of the 1990s first stabilized and later decreased the NUI.

In summary, the NUI is a measure of the rate of change in Nr use rate. Functionally it normalizes Nr use to 1961, the base year. Where the NUI per capita is a good indicator of the total footprint of Nr use and an indicator for the many effects of Nr, the environmental impacts on soil, water, and air are more strongly related to the Nr use per land area in agriculture. Therefore, agricultural land area should be considered when interpreting NUI.

6. NITROGEN MANAGEMENT: PROGRESS OVER THE PAST 20 YEARS

This article has thus far focused on how Nr creation has changed with respect to time (1961–2020), type (HBF, CBNF, FF), and region (Asia, etc.) and has introduced the concept of the Nr Use Index. This section examines how the management of Nr has evolved in the first two decades of the twenty-first century.

In the past 20 years, there has been an enormous increase in knowledge and understanding of the Nr challenge. This has been initiated by the International Nitrogen conferences that started in 1998 in the Netherlands (25) and was followed by conferences in the United States (2002), where the International Nitrogen Initiative was initiated, China (2004), Brazil (2007), India (2010), Uganda (2013), Australia (2016), and Berlin [2020 and 2021 (online)]. All these conferences have led to growing attention worldwide to the Nr issues and have created an international community that closely works together to address the complex Nr issues under, e.g., the International Nitrogen Management System (INMS) (26).

Here, we summarize scientific and policy development progress that is essential to understand Nr management options.

6.1. Scientific Progress

There have been major scientific developments during these past decades. This can best be illustrated by the number of publications on Nr that increased with a factor of two per decade since 1998. Not only the number of papers but also the impact factor changed, with many papers from high impact factor journals such as *Science*, *Nature*, *Biogeochemistry*, *One Earth*, and *Ambio* (see 3, 18, 19, 26–35 for some example overviews). The literature covers a broad range of topics related to Nr issues, such as Nr use, the sources, and pathways into the environment and transport and exchange processes, impacts, up to policy options to reduce the impacts. A breakthrough in communicating the Nr issue was achieved by Rockström et al. (36), who introduced the planetary boundaries concept showing that the boundary for Nr is exceeded with a factor of 4. In 2011, the European Nitrogen Assessment was published, a major effort putting all the Nr-related knowledge together with policy options in one book for one region of the world (31). In 2013, *Our Nutrient World* (37), with a more global focus, was published. Here the innovative aspect was the integral view on the Nr issues and the cost-benefit analysis of Nr pollution. Other major innovations up to 2016 include the N-C interactions in terrestrial systems (30); the quantification of the role of Nr in climate in Europe (38) and globally (39); advances in different mechanisms of CBNF pathways and the role of different organisms such as bacteria and microbes (11); the Anammox process (anaerobic ammonium oxidation), a microbial process in natural environments and also used for ammonium removal technology (40); the N cascade (19); human health impacts including diets (5); isotope research (41); N_2O as the major stratospheric ozone depleting compound (42); and technology development (manure handling, processing, and application techniques; e.g., 39).

Global nitrogen balances have been reported by several authors (1, 12, 13, 43–45), and recently detailed regional assessments have been made for different areas, such as Europe (31), California (46), China (47), and India (48). From these assessments and a range of studies on Nr there is an urgent call for Nr management (5, 25, 36, 49–54).

6.2. Policy Preparation

The influence of policy can be demonstrated by an increasing number of meetings and initiatives devoted to the policy aspects. One of the major achievements was the initiation of the Taskforce on Reactive Nitrogen (TFRN) under the UNECE Convention of Long-Range Transport of Air Pollution. The TFRN represents the policy framework for dealing with the nitrogen cascade in the Northern hemisphere. It was the first official body to engage with other policy areas related to Nr, developing technical and scientific information and mitigation options. In the United States, the Integrated Nitrogen Committee was organized by the Science Advisory Board of the Environmental Protection Agency (EPA). A report was produced and endorsed by the EPA with recommendations for Nr research and policies in the United States (55). The United Nations Environment Programme (UNEP) and several other stakeholders established the Global Partnership on Nutrient Management (**http://www.nutrientchallenge.org/**) aiming at triggering strategic discussion, advocacy, and action among countries on more effective nutrient management. INMS was initiated by the United Nations Global Environmental Fund in 2016. INMS is a global program that aims to contribute to reducing Nr pollution through a global Nr assessment and providing inputs to Nr management policies (26, 56). In 2019, UNEP published the Frontiers report with emerging issues including Nr and launched the UN Global Campaign on Sustainable Nitrogen Management, calling for more attention to Nr management (56). In addition, in the coming years it is expected that further global assessment will become available.

6.3. Success in Nitrogen Management

Kanter et al. (34) provide an overview of the Nr-related policies around the world. They see that policies to combat water pollution by Nr have been most effective. Policies to reduce impacts from agriculture are almost absent and actually stimulate intensification and thus Nr losses. Erisman et al. (57, 58), Galloway et al. (29), Sutton et al. (37), and Zhang et al. (33) provide an overview of options to reduce Nr effectively. For NO_x, this is mainly through technology: It is a waste product and can be solved by technological options, such as the three-way catalyst in exhaust pipes of cars to reduce emissions or to prevent the use of fossil fuel burning through sustainable energy. The most important measure in agriculture, as we explain in Section 7 on the Netherlands, is implementing a Mineral Accounting System (MINAS) with area-specific targets for losses to the environment. This is cheap and gives the farmer insight into the losses and associated costs. That stimulated not only increasing NUE at the farm level for reducing losses to the environment but also use in areas where there is shortage and/or mining of Nr at the farm. In addition to MINAS, technology can provide reduction in environmental losses, such as manure treatment and biogas production, creating buffer strips for limiting leaching losses and low-emission housing systems, covering of manure storage facilities, and incorporating manure in soil for limiting ammonia losses.

7. THE NITROGEN CASE STUDY FOR THE NETHERLANDS

The Netherlands and Denmark are the two countries that have been implementing Nr policies since the 1980s (59–61). The policies were designed to mitigate poor air quality due to nitrogen oxide emissions, to offset nitrate pollution of ground and surface waters due to overloads of nutrients, and finally to limit the contribution of NO_x and NH_3 emissions to the eutrophication and acidification of seminatural areas and the reduction of biodiversity in these systems (57, 58, 61). The Netherlands has always been in the forefront of international research in this arena, including the development and evaluation of ammonia reduction technologies with manure applications (62), deposition measurements and modeling (63–65), low-emission housing systems (66), low-emission application (67), and manure processing (68).

The Netherlands is an interesting case study because, as shown in **Figure 8**, the per capita NUI and the per hectare NUI have decreased since the country implemented its policies. Furthermore, despite successful Nr policies, the country is experiencing a Nr crisis: Permitting of a new Nr emitting activity, such as expanding agricultural production, building roads or houses, new industries, etc., has been blocked by the ruling of the State Council in 2019 (36, 69). Further reductions in Nr deposition are necessary before new permits can be allowed. Here we discuss the trend in Nr indicators and the most successful policies. Furthermore, we discuss the primary drivers that determine Nr pollution and policies.

7.1. The Effect of Nitrogen Policies in the Netherlands

The most important policies to reduce Nr pollution in the Netherlands were initiated in the 1980s, and monitoring networks were initiated in 1990 (70, 71). **Figure 12** shows the relative change in several indicators either measured (e.g., concentration of Nr in coastal zones and rivers), calculated based on input–output balances (Nr surplus) or by using emission factors and activity data such as emissions of N_2O, NH_3, and NO_x, and by dispersion modeling: Nr deposition (58). Overall, the indicators show a reduction between 40 and 60%, except for the Nr concentration in Dutch coastal areas. The latter is largely determined by the inflow of Dutch rivers but, because of strong currents, also by other countries and the open sea. The loads of the river Rhine almost halved in this period. **Figure 12** also shows the change in crop (N) and animal (N) production. Crop N production decreased by 20% due to lower Nr application rates, but this did not adversely affect crop production in terms of yield. Animal production increased by almost 20% while considerably decreasing the losses to the environment.

The Netherlands has been very successful in reducing its Nr emissions to the atmosphere. Both agricultural ammonia and transport and industry NO_x were reduced by almost 65% since 1990. Whereas transport NO_x is still being reduced, NH_3 emissions have remained constant since 2005 (**Figure 12**).

A wide selection of measures determined the overall success of the Dutch Nr policy so far. Not all measures focused only on emissions. Some aimed at reducing Nr loads to ground and surface water, with the side effect of reducing emissions to the air too (60). The emission reduction for

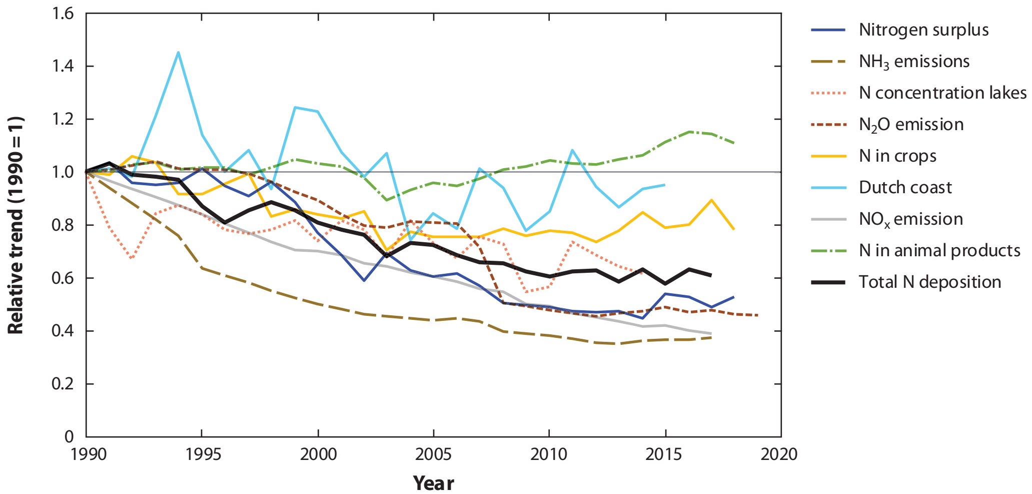

Figure 12

Trend in Nr pollution indicators in the Netherlands relative to 1990. Data from the Environmental Data Compendium (71).

ammonia is largely due to the reduction of fertilizer inputs combined with the implementation of low-emission fertilization techniques (58, 72). Despite the strong reduction in Nr emission, the critical Nr deposition loads on nature areas are still exceeded. The consequence is that the Netherlands cannot guarantee the conservation target for these areas agreed upon in the Habitat and Birds Directives (35, 69, 73).

The deposition to nature areas still exceeds the critical load for these areas in more than 70% of the cases (74). Therefore, the State Council of the Netherlands, based on a ruling by the European Court, decided in May 2019 that the Dutch policy to reduce Nr deposition by the Programmatic Approach on Nitrogen (PAS) was insufficient to meet the targets of the European Bird and Habitat Directives. Under these directives, European "Natura 2000" areas have to be preserved. The Natura 2000 areas represent regional natural habitats with specific species relevant to European mainland and waters. The consequence is that the Netherlands is experiencing a so-called Nr crisis because permitting is not allowed for any planned activity that brings new Nr into the atmosphere: construction of houses or roads, traffic, agriculture, energy production, industry, etc. Therefore, during the coming years the government has to take action to reduce Nr deposition significantly to show that the quality of the Natura 2000 areas will be maintained or even improved before new permits can be granted (35, 69, 73).

7.2. What Is the Current Situation?

The current (2021) Nr issue in the Netherlands is related to high Nr deposition loads to nature areas (35). Although this had been an ongoing issue for many years, it became more apparent after the European Bird and Habitat Directives called for sustainable conservation of the different habitats in nature areas protected under the Directive, the so-called Natura 2000 areas. The excessive Nr load to these areas turned out to be a problem for future plans and projects potentially releasing additional Nr and thus contributing to the Nr deposition.

The PAS was introduced to address this issue (61). The whole system was built on the assumption that future Nr emissions would decrease following current policies. On the basis of that assumption, permits for the plans and projects were released even though this future emission decrease was not secured. It was that lack of securing that brought the European Court to the final decision about the Dutch system. Before permits are allowed again, a Nr emission reduction needs to be secured by means of fully implemented policies. Furthermore, the government has to implement more measures in order to bring down the overall level of Nr deposition in the Netherlands (75).

It is now more than two years since the ruling of the Dutch State Council in May 2019. Although the problems related to the building permits were imminent, a sense of urgency at the responsible ministries seemed to be lacking. After a long period of seemingly inaction, a short list of short-term measures was brought into the political arena. These measures aim at reducing the Nr emissions and deposition only minimally and just enough to balance the additional Nr due to the new building activities. However, they are not enough to lower the overall level of Nr deposition to the degree needed for habitats to reach their sustainable conservation status (76, 77).

7.3. What Are the Most Effective Policies to Reduce Nitrogen?

After World War II, which ended with a severe hunger winter in the Netherlands, the Dutch and European agricultural policy was focused on increasing production such that there would never be another hunger winter. Furthermore, policies were focused on mechanization and specialization to decrease human labor while increasing food production. Traditionally, the farmers are strongly represented in regional and national politics, and the farmers' lobby has been strong (78, 79). This is true not only in the Netherlands but also for many other countries in the world (79). This has always limited strong policies that increased farmers' costs. The two most important policies that led to reduction in Nr were the introduction of the Nitrate Directive in 1992 and the introduction of the MINAS (60, 80). The MINAS made the farmers realize that they are overusing nutrients, and this is also an economic loss for them. However, that people feared a new hunger winter also contributed to preventing strong policies that affect food production. The farmers regularly emphasize this emotion in their protests by bringing up slogans like "no farmers, no food." Also, there is an economic limitation to transitions in agriculture. The profit margins are small for farmers and, due to overproduction and world food markets, prices are low and costs are increasing (76, 81, 82). This leads to intensification and more pollution. Other countries in Europe and beyond do not need to make the investments required by new regulations, and therefore their costs are lower, and the playing field is not level. The reform of the agricultural sector and therefore Nr pollution needs immense financial support for farmers in the coming years in order to end the Nr crisis (76, 77).

There are technological solutions that have successfully led to a reduction in emissions, e.g., NO_x. The three-way catalyst in cars and the selective catalytic reduction in energy production and industry has led to a 60% emission reduction since 1990, while traffic intensity and energy production have increased (83). In agriculture, technical solutions such as emission-poor housing systems, coverage of manure storage, and manure injection when applied in the field have contributed to the reduction of ammonia emissions. However, costs are high and there are negative side effects, such as decreasing soil quality, more greenhouse gases, and nitrate pollution (57, 58, 60, 74, 80).

In summary, what worked is setting targets and putting them in the legal system so they can be enforced. The reductions in Nr losses to the environment were mostly achieved by the Nitrate Directive and the ammonia policies. Technical measures to reduce losses also contributed, but mainly the MINAS provided farmers insight into their performance, and (economic) fertilizer losses led to reduced Nr inputs and losses.

8. Nr USE IN THE FUTURE

8.1. Introduction

There have been numerous projections as to what the Nr balances would look like in the future. An early projection related to Nr was made in the eighteenth century by Thomas Robert Malthus (84), who hypothesized that population growth would outstrip gains in per capita resources until food supplies finally acted as a barrier to further growth. Since then, several authors have made scenario predictions that relate to Nr management, food, or other issues:

- Nr deposition (85–88; 89 for Europe)
- Air pollution (87, 90, 91)
- Food (2, 4, 45, 92–97)
- N cycles (5, 22, 37, 52, 98, 99)
- Climate (46, 48, 52, 100, 101)
- Nr management (2, 21, 25, 52)
- Bioenergy (102, 103)

Most of these projections use primary drivers from the demand perspective, such as food or bioenergy, from the effects' perspective, such as climate change, deposition, or air pollution, and from the N-cycle perspective. Erisman et al. (2) and Winiwarter et al. (98) used six primary drivers for the major changes in fertilizer production:

- Population growth

- Diet optimization
- Biofuels
- Food equity
- NUE
- Fossil fuel use, sustainable energy production, energy savings

These drivers were chosen because of their link with climate policies. The following are other drivers:

- Agricultural production systems (specialization with technology or integrated agroecological approaches)
- Global trade and local food chains
- Technology development, such as precision farming, industrial meat production, and LED-supported light plant production in greenhouses
- Circularity, which involves policies to reduce resource use by limiting new inputs and reuse of resources and products
- Lifestyle changes including less meat consumption, public transport, decreasing flights, circularity in reusing products

Most recently, Kanter et al. (34) provided a broad framework for Nr futures in the shared socioeconomic pathways.

In this analysis of future projections, we take two approaches: The first is based on a review of Nr creation projections distilled from the literature; the second is based on our assessment of per capita Nr use as a predictor for future Nr use together with the projected lifestyle changes in the regions.

8.2. Nitrogen Use Projections from the Literature

Nr use is composed of HBF, HBI, CBNF, and FF. In order to derive scenarios for 2050 we searched for predictions in the literature on the following:

- HBF and HBI ammonia predictions
- FF, based on NO_x emissions predictions from air and climate policies
- CBNF

Since there are very few projections for HBI, we did not include any projections.

8.2.1. Haber-Bosch fertilizer. **Table 1** provides an overview of the projections of fertilizer use in 2030 and 2050. Most projections are based on cropland requirements to provide enough food, decrease Nr surplus, and improve NUE or based on scenarios taking major management options into account. Most important for future predictions is how NUE in agriculture will improve in the future (7, 33, 92–94). In the future, further extensification and further intensification of croplands are both likely, given a projected increase in food demand and per capita consumption rates (45, 104). Forecasts based on past trends suggest that one billion ha of natural ecosystems could be converted to agriculture by 2050, accompanied by more than doubling of fertilizer and pesticide use (91). The land use expansion for agriculture is important for fertilizer use. Most studies do not take these into account. There are several regions and countries in the world that have managed to increase yields while reducing fertilizer inputs (e.g., Europe, the United States) while other countries in Asia and Pacific regions have not seen similar improvements in NUE (7, 31, 33, 37, 97).

Table 1 shows a huge range of approximately 80 to 260 Tg N/year in the predictions of N fertilizer use in 2030 or 2050. The lowest are 25–125 Tg N/year when different mitigation scenarios are used. Trends ranging from 82 to 190 Tg N/year projected by Sutton et al. (37) were

Table 1 Fertilizer production based on global predictions of fertilizer use and food requirements

Global N fertilizer consumption (Tg N/year)	Explanatory note	Reference
For 2030		
124–138 (slow-fast growth)	2030 based on Integer and LMC project (106)	Heffer & Prud Homme (107)
137	Fertilizer demand in relation to soil nutrient status in nine regions	Tenkorang & Lowenberg-DeBoer (108)
For 2050		
232 (reference) 25–125 (mitigation scenarios)	Model of Agricultural Production and its Impact on the Environment (MAgPIE)	Bodirsky et al. (93)
82–109	Integrated Model to Assess the Global Environment (IMAGE)	Bouwman et al. (99)
82–190	Trends in global consumption of mineral fertilizer nitrogen projected possible futures, illustrating ranges from published scenarios.	Sutton et al. (37)
85–260	Cropland fertilizer following Nr use efficiency (NUE) [Zhang et al. (33)] using IMAGE	Mogollon et al. (109)
90–160 (literature cited) 70–240 (range identified in the paper)	Climate Representative Concentration Pathway (RCP) scenarios: biofuels, NUE, diet, population, food equity as drivers	Erisman et al. (2)
95–130	Climate RCP scenarios: biofuels, NUE, diet, population, food equity based on Erisman et al. (2)	Winiwarter et al. (98)
160	Regionally based on reduction in N surplus	Zhang et al. (33)
170–320	Based on annual N use from producing and consuming food	Galloway et al. (104)
263	Based on relation between yields and fertilizer	Alexandratos & Bruinsma (105)

Data from References 2, 33, 37, 93, 98, 99, 104, 105–109.

based on previously published scenarios: Nr low from Bouwman et al. (99), Nr mid from Davidson & Kanter (101) and Nr high from Bodirsky et al. (49) interpolated between their 2040 and 2100 estimates. Erisman et al. (2) published ranges from the literature prior to 2008 using climate Representative Concentration Pathway (RCP) scenarios based on biofuels, NUE, diet, population, and food equity as drivers. Winiwarter et al. (98) continued analyzing Climate RCPs in 2013 and published a similar range, 95–130 Tg N/year. Most studies give a global estimate or range, but no regional numbers. For some studies the fertilizer use is the result of their scenarios on food demand, but numbers are not given (45, 92). Two studies provide regional estimates for 2005: Zhang et al. (33) and Alexandratos & Bruinsma (105). We used Zhang et al.'s (33) estimates for the projections presented in **Table 2**.

8.2.2. Biological N fixation. There is also a wide range of BNF estimates in the literature, with a large uncertainty for current CBNF in agriculture and for BNF in natural terrestrial systems. **Table 3** provides current estimates, and **Table 4** provides estimates for 2050. Generally, the literature suggests that the current agricultural BNF range is between 30 and 60 Tg N/year, and projections to 2050 are about the same.

8.2.3. Fossil fuel nitrogen projections following NO_x emissions. These NO_x projections for 2050 are based on air quality and climate scenarios as reported in the literature:

- Van Vuuren et al. (91): 30–70 Tg N/year

Table 2 Regional fertilizer use in 2010 and projections for 2050 adopted from Zhang et al. (33)

Region	Current input N (Tg N/year) for 2010	Required input N (Tg N/year) for 2050
China	51	27
India	25	19
United States and Canada	21	25
Europe	14	13
Former Soviet Union	6	8
Brazil	11	15
Latin America (except Brazil)	12	15
Middle East and North Africa	5	5
Sub-Saharan Africa	5	13
Other OECD countries	2	2
Other Asian countries	19	17
Total	**174**	**160**

Table 3 Current estimates for cultivation-induced biological N fixation (CBNF) in agriculture and for biological N fixation (BNF) in natural terrestrial systems

CBNF (Tg N/year)	Natural BNF (Tg N/year)	Reference
50–70	Not available	Herridge et al. (14)
60 +/− 30%	58 +/− 50%	Fowler et al. (10)
30–51	40–127	Battye et al. (12)
60 (50–70)	58–128	Scheer et al. (13)
Not available	58 (40–100)	Vitousek et al. (11)

Data from References 10–14.

Table 4 2050 estimates for BNF in agricultural terrestrial systems

CBNF (Tg N/year)	Reference
32–42	Mogollon et al. (109)
53–56	Bouwman et al. (99)
30–50	Winiwarter et al. (98)

Data from References 98, 99, and 109.
Abbreviations: BNF, biological N fixation; CBNF, cultivation-induced biological N fixation.

- Winiwarter et al. (98): 14–40 Tg N/year
- Lamarque et al. (87): 39–48 Tg N/year
- Kanakidou et al. (88): 3–40 Tg N/year
- Amann et al. (90): 190 Tg N/year (no control), 92 Tg N/year (2018 legislation), 17 Tg N/year (clean air)

Table 5 The contribution (in %) of the different world regions to global Nr use for 1961, 2020, and 2050

	Africa	Asia	Europe	Latin America	North America	Oceania
1961	4%	29%	35%	4%	27%	1%
2020	4%	50%	13%	15%	17%	1%
2050	6%	50%	9%	21%	12%	1%

Data from author calculations based on FAO (6), Lassaletta et al. (7), BP Statistical Review of World Energy (8), and UN World Population Prospects 2019 (54).

In summary, total Nr use from the literature ranges from

- 80–260 Tg N/year for fertilizer, with a best guess of 160 Tg N/year
- 30–56 Tg N/year for BNF
- 17–92 Tg N/year for NO_x
- 127–408 Tg N/year with a best estimate of 260 Tg N/year

From these estimates of Nr use in the future, we make estimates for the Nr use.

8.3. Future Nitrogen Use with Per Capita Nitrogen Use as the Predictor

Between 2020 and 2050, 99% of the global population increase will occur in Asia and Africa. Moreover, by 2100, 40% of the world's population will live in Africa (54, 110). These population increases coupled with increases in per capita N use will result in large increases in Nr losses to the Asian and African environments due to increasing Nr use in those regions. In addition, there will also be impacts in other regions that are producing food/feed that are exported to Asia and Africa. The rest of this section provides more detail on this issue.

By 2050, the world population is estimated to be relatively stable at 10 billion people (54). **Figure 13** presents two possible situations with respect to the Nr use in the future: one according

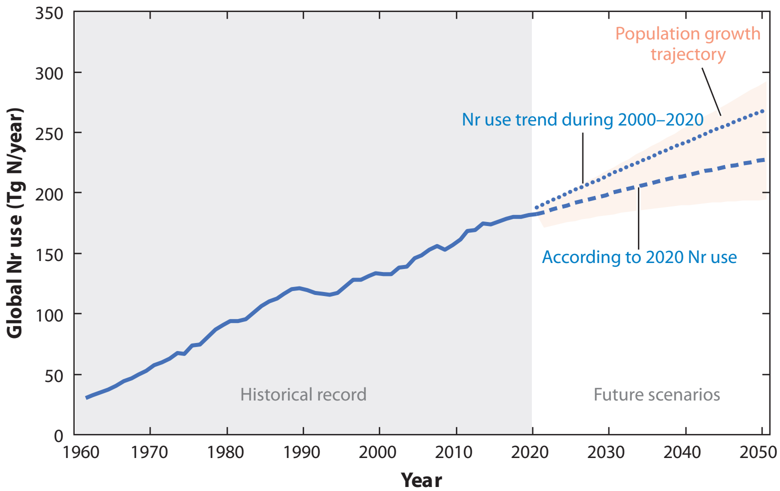

Figure 13

Nr use into the future following two scenarios: future Nr use according to 2020 Nr use (*dashed line*) and future Nr use according to Nr use trend in the period 2000–2020 (*dotted line*). The pink shaded area represents the range of population growth trajectories, combined with the two Nr use scenarios. Data from author calculations based on FAO (6), Lassaletta et al. (7), BP Statistical Review of World Energy (8), and UN World Population Prospects 2019 (54).

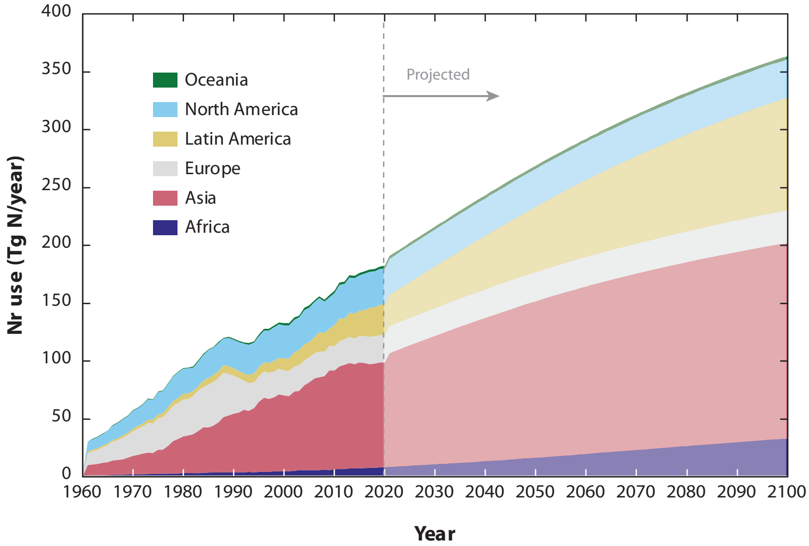

Figure 14

Nr use into the future for the different world regions based on the growth scenario, with future Nr use according to Nr use trend for the period 2000–2020 (*dotted line* in **Figure 13**). Data from author calculations based on FAO (6), Lassaletta et al. (7), BP Statistical Review of World Energy (8), and UN World Population Prospects 2019 (54).

to current Nr use per capita, extended into the future. The trend for this scenario thus only represents the future population change. The second scenario builds on a population change in combination with a trend in Nr use per capita as calculated for the period 2000–2020. With the population projections to 2050 taken from the UN World Population Prospects 2019 (54), the Nr use rate for the medium population growth projection will be ∼230 Tg N/year compared to ∼190 Tg N/year in 2020 (with Nr use per capita as calculated for 2020). However, when the world stays on its current course with respect to Nr use, the Nr use rate will be approximately 270 Tg N/year in 2050 compared to ∼190 Tg N/year in 2020 (does not include HB-N created for industrial uses).

Using the medium population growth with future Nr use according to the Nr use trend scenario from **Figure 13**, we provide in **Figure 14** and **Table 3** the future regional Nr use. Although the overall Nr use in the world in 1961 was more or less equally divided over Asia, Europe, and North America, the contributions changed over the years. In 2020, half of the world's Nr use took place in Asia. Latin America had a contribution comparable to that of Europe and North America. Following the trajectory presented in **Figure 14**, approximately half of the Nr use is still taking place in Asia, but a further increase is expected for Latin America to approximately 20% in 2050.

The range of Nr use from the literature is very large and is broader than our projections based on per capita Nr use and population growth. The best guesses from the two projections are remarkably close: 260 versus 270 Tg N/year for 2050.

8.4. Will the Risk of Nitrogen Losses Increase?

Even though the per capita NUI is a good indicator to predict future Nr use, it cannot grow endlessly because of the limitation by land and the increasing losses of Nr to the environment. For Nr, the law of diminishing returns is applicable: The yields are increasing but the environmental losses are increasing even more (111). As shown in the case study of the Netherlands, when too

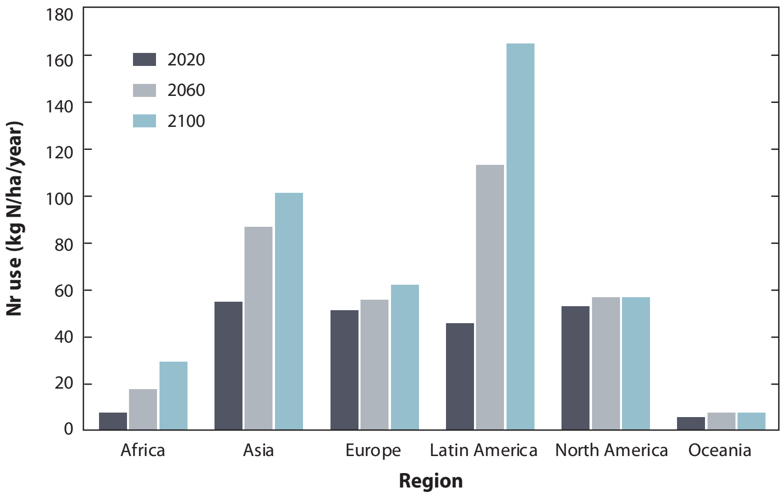

Figure 15

Nr use in kg/ha—using the agricultural area for 2020 according to FAO (how much would the intensity need to change, assuming no change in area) and the Nr Use Index scenarios from **Figure 14**. Data from author calculations based on FAO (6), Lassaletta et al. (7), BP Statistical Review of World Energy (8), and UN World Population Prospects 2019 (54).

much Nr is used in agricultural lands the pollution also rises. There is an optimum of Nr inputs that depends on soil type, climate, and landscape. Furthermore, the number of hectares to be used for agriculture is also limited. We want to preserve nature areas; we need land to live and for other economic purposes (resource mining, industry, etc.). Therefore, assuming that agricultural areas are stable, we can plot the NUI per hectare for the different scenarios in the regions (**Figure 15**).

As expected, the per-hectare use of Nr increases since the per capita demands increase. What needs to be taken into account is that these are averages over large areas and as demonstrated by the case study of the Netherlands in the context of Europe as a whole the local variation in Nr application can be large. Van Grinsven et al. (112) demonstrated that better distribution of agricultural production within Europe is a win-win because the too intensive regions such as the Netherlands can reduce Nr inputs and limit environmental pollution while other regions such as Ukraine can increase their production and simultaneously respect the environmental boundaries. Relating to the title of this section, **Figure 15** shows, however, that there is an increasing risk of Nr losses to the environment, especially in Asia and Latin America.

8.5. What Are Potential Policies?

In this section we discuss potential policies relying on the Dutch N case and the overview of the 20-year policies, together with two recent papers (34, 53). Kanter et al. (34) discussed a framework for Nr futures as a function of socioeconomic pathways. The landmark study introduces a framework for new Nr-focused narratives based on the widely used Shared Socioeconomic Pathways that include all the major Nr-polluting sectors (agriculture, industry, transport, and wastewater). Houlton et al. (53) proposed that approaches to balance the projected rise in agricultural Nr demands—while achieving the twenty-first-century ideals on climate, environment, and biodiversity—will require policies to coordinate solutions among technologies, consumer choice, and socioeconomic transformation. On the global scale, there are always two facets of Nr: situations where more development is needed requiring more N for agricultural inputs and more losses due to increasing energy usage and the developed areas where Nr is in excess. In the past, the first priority has always been economic development and ending hunger and then addressing environmental issues. These two studies are excellent examples of the types of policy approaches that are needed to address the globally connected Nr issues.

Ending hunger requires local policies that often go beyond the agricultural production system itself. It is affected by politics, other priorities, and conflicts. For agricultural production, long-term investment is often needed to create resilient systems through agroecological approaches, sometimes with the aid of inputs (7, 16, 37, 51).

An important question for policymakers and stakeholders in developed countries is how Nr pollution can be abated as (cost-)effectively as possible. The best mitigation options are those that tackle Nr emissions at the source. These options increase Nr efficiency of energy and food production and decrease multiple emissions species to the environment. This contrasts with mitigation measures that target one effect in the nitrogen cascade only. The most drastic and cost-competitive reductions in Nr fluxes can be achieved via usage of low-protein animal diets, less (synthetic) use of fertilizers, and a balanced nutrient input for crops. Insights such as Nr balances help the farmer and other Nr users realize how much Nr they lose. The MINAS that was introduced in the Netherlands is a good example of such a tool (see the section on the Dutch nitrogen case). It can also help farmers in developing countries to focus on how Nr management can help increase yields while limiting losses (35, 92).

Far-reaching improvement of Nr efficiency is most effective using the 4R approach [the right fertilizer source, at the right rate, at the right time, and in the right place (113)] and, e.g., urease inhibitors, controlled release fertilizers, coverage of manure storage, enhancement of aeration of soils, and winter crop management. The agronomical knowledge and insight in NUE are also useful for developing countries that want to use their scarcely available Nr as efficiently as possible. The most promising options that tackle one Nr category only are the creation of wetlands and fitting selective (non-)catalytic reduction on combustion technologies. Yet again, these categories may not be effective as they tackle just one effect, one kind, or one source of Nr pollution.

SUMMARY POINTS

1. We estimate that in 2020, the total human global Nr creation rate was 226 Tg N/year [Haber-Bosch fertilizer (HBF), 106; Haber-Bosch industrial (HBI), 43; fossil fuel combustion (FF), 34; cultivation-induced biological N fixation (CBNF), 43]. This is three- to fourfold greater than the natural terrestrial biological N fixation rate (~58 Tg N/year).
2. Globally HBF was the dominant source of new Nr but was approximately constant since 2014, as was FF. In contrast, both HBI and CBNF steadily increased at a more rapid rate over the past decade.
3. Although Nr creation (production) is important, where Nr is used (consumption) is the most appropriate metric to relate to the resulting impacts on the regions.
4. On a per capita basis, Nr use rate has two distinct periods, both approximately 30 years. Over the first period (1961–1990), the rate increased rapidly from ~10 kg N/capita/year to ~24 kg N/capita/year. Over the next 30-year period (1991–2020), the rate initially dropped to ~20 kg N/capita/year and then slowly increased to ~24 kg N/capita/year and has been constant for the past decade.
5. The Nr Use Index (NUI) is a measure of the rate of change in Nr use rate. Functionally it normalizes Nr use to 1961, the base year. In addition, because the environmental

impacts on soil, water, and air are more strongly related to the Nr use in per land area in agriculture, agricultural land area should be considered when interpreting NUI.

6. The Netherlands has been relatively successful in managing N-related issues. Its success stems from setting targets and putting them in the legal system so they can be enforced. In the agricultural community, the introduction of the Mineral Accounting System providing insight on the nitrogen use efficiency, combined with technologies to reduce ammonia, successfully decreased Nr losses during food production.

FUTURE ISSUES

1. Over a ~60-year period, the majority of Nr creation shifted from Asia (CBNF) and Europe (FF and HBF) to Asia (FF and HBF) and Latin America (CBNF).
2. For CBNF, Latin America and North America are suppliers of substantial Nr in the form of soy products, which are used in all other regions of the world, primarily to support animal production. It is these other regions that are seeing the consequences of Nr pollution.
3. Global Nr use due to FF, CBNF, and HBF production in 2050 is projected to be ~270 Tg N/year, compared to the 2020 value of ~180 Tg N/year. This ~50% increase is driven primarily by food production. The strongest increase is projected for Asia. Prudent investment in enhanced efforts on how to increase agricultural Nr use efficiency (NUE) would be appropriate.
4. The best mitigation options are those that tackle the Nr emissions at the source. For FF this means developing and introducing technologies that catalytically convert NO_x into N_2, or better, introduce sustainable energy production systems. For agriculture, the focus should be on knowledge about agroecological systems, tools that provide more insight into NUE for the farmer and technologies that focus on improving NUE.

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