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Global and regional estimation of net anthropogenic nitrogen inputs (NANI)

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ABSTRACT

Since the Industrial Revolution, human activity has greatly altered the Earth's reactive nitrogen (N) cycle, leading to widespread N pollution that can have adverse effects on human health, ecological functions, and biodiversity. Quantifying the net anthropogenic nitrogen input (NANI) has proven to be a powerful method of evaluating the extent of human alteration of the N cycle on watershed and regional scales. In this study, NANI was estimated in 98% of the land area, covering 99% of the population of countries and regions around the world during the years of 1961, 1980, 1990, 2000 and 2009. The NANI estimation methodology considered atmospheric N deposition, N fertilizer consumption, the net import or export of N in agricultural commodities (human food, livestock feed, etc), and N fixation in agriculture and planted forests as its main sources. The global NANI level has increased from 1961 to 2009 (from 378 to 1226 kg N/km^2/yr). Asia, the Caribbean region, Europe and North America yield higher-than-average NANI values. The increase in the net N inputs of Asia is the main reason for this increase in global NANI. In 1961, the main sources of NANI are net oxidized N deposition (42%) and N fixation (34%). Since 1961, the largest component of global NANI has been N fertilizer consumption (59%–64%), followed by net atmospheric N deposition (16%–23%) and N fixation (18%–20%). Globally, replacing fossil fuels with clean energy, limiting population growth, reducing the excess consumption of proteins per capita, reducing the proportion of animal product protein in the human diet, and balancing the application of N fertilizers between regions are all potential ways to reduce NANI. However, each of these practices have drawbacks. For any country or region, in addition to the above practices, NANI can also be decreased by reducing synthetic fertilizer consumption, decreasing food import, and sustainably leasing or co-cultivating agricultural land in other countries or regions. In addition, the application of highly efficient organic fertilizers and high-yielding crop species, as well as the promotion of precision agriculture, can to some extent also reduce NANI.

1. Introduction

Nitrogen (N) is essential for all life and is one of the most common elements on earth However, the vast majority of N is present as molecular N_2. Prior to the widespread intervention of humans in the N cycle, N was mainly biologically available through the bacterial process of N fixation (Gruber and Galloway, 2008; Schindler et al., 2008; Poikane et al., 2019), and some abiotic production from lightning induced NOx in the atmosphere (Galloway et al., 2004). The biological availability of N and its relative scarcity in many ecosystems control the rates of photosynthesis and affect biodiversity across most of the planet (Rotundo and Cipriotti, 2017). Since the Industrial Revolution, with increased economic development and the continuous expansion of the population, the global N cycle has become increasingly dominated by human activities, and the human creation of reactive, biologically available N has exceeded the natural rate of N fixation on land since the 1970s (Galloway et al., 2004; Gruber and Galloway, 2008; Vitousek, Menge, Reed, and Cleveland, 2013). This process has accelerated greatly since the 1960s, with the increased use of synthetic N fertilizer that fuelled the Green Revolution. Additionally, increases in N fixation by agricultural crops and increased atmospheric N pollution due to fossil fuel combustion have also contributed to the biological

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availability of N. Atmospheric N deposition includes all N elements from NH_x and NO_x in both dry deposition and wet deposition, while in this study organic N deposition was largely ignored. From a global perspective, compared with the end of the 19th century, the 10-fold increase of reactive N generated from food and energy production greatly changed the N cycle, leading to many serious environmental problems, such as greenhouse warming, ozone depletion in the stratosphere, the creation of ozone near ground-level in the troposphere, acid rain, ground and surface water nitrate pollution, and eutrophication and the creation of coastal dead zones. This excess N threatens environmental sustainability, human health, and sustainable economic development (Townsend and Howarth, 2010; Sutton et al., 2013).

While global warming and stratospheric ozone depletion related to N_2O are truly global issues, most other reactive N cycles through the atmosphere, rivers, and ocean currents on scales of tens to thousands of kilometres. Therefore, because many of the consequences of N pollution are manifested on local to regional scales, and management policies are often developed at the country level, it is appropriate to assess the sources of N on these scales (McKee and Eyre, 2000; Bouwman et al., 2011; Hong, Swaney, and Howarth, 2011). Changes in the sources and sinks of N have previously been estimated on global and continental scales and, for some countries, on national scales. However, a comprehensive country-by-country analysis of global net N inputs from all human activities has, to our knowledge, not been performed to date. In this study, we conducted such an analysis for the recent past, including four distinct years: 1961, 1980, 1990, 2000 and 2009. Our goal was to address the following two questions: 1) how have net anthropogenic nitrogen inputs (NANI) changed spatially and temporally in different countries and regions? and 2) how did different human activities contribute to N inputs in these different regions?

We applied the NANI methodology to each of the major countries in the world. Our goal was to provide scientific support for developing regulations, policies and measures for reducing N pollution from human activities by quantitatively analysing NANI on global, regional, and national scales.

2. Materials and methods

Our analysis includes all 208 countries and regions in the world. NANI is estimated by summing the following four terms: atmospheric N deposition, N fertilizer consumption, net import or export of N in agricultural products, and agricultural N fixation (see Fig. 1).

Double-counting may occur in these four terms due to nitrogen (N) cycling. Notably, nitrogen may be lost to the atmosphere via volatilization from the soil surface, waste treatment lagoons, manure stockpiles and other sources, and redeposited locally or downwind via atmospheric deposition. Most of these losses occur in the form of ammonia, which can be redeposited locally. For this reason, many studies of NANI include only oxidized nitrogen assuming a local balance of emissions and deposition of reduced forms of nitrogen, including ammonia. Here, we have chosen to use total oxidized nitrogen deposition:

$$NANI = N_{dep} + N_{fer} + N_{fix} + N_{tra} \tag{1}$$

where NANI is net anthropogenic N inputs, kg N/km^2/yr;
N_{dep} is atmospheric oxidized N deposition, kg N/km^2/yr;
N_{fer} is total N fertilizers, kg N/km^2/yr;
N_{fix} is N fixation, kg N/km^2/yr;
N_{tra} is N in the food trade, kg N/km^2/yr.

We calculated the net N input values of 160, 161, 161, 181 and 181 countries and regions during the years of 1961, 1980, 1990, 2000 and 2009, respectively, which account for 97.0%, 97.8%, 97.8%, 97.6% and 97.7% of the annual global land area and 99.2%, 99.2%, 99.2%, 98.9% and 98.7% of the global population, respectively. Other countries were not taken into consideration due to the lack of data. NANI per unit area of each country is obtained by dividing its N input by its area.

2.1. Atmospheric N deposition

Atmospheric N deposition (N_{dep}) represents the total net oxidized N deposition, including both dry deposition and wet deposition (i.e., it includes total NO_y deposition). The atmospheric N deposition in 1961, 1980, 1990, and 2000 was calculated using deposition results obtained within the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) (Lamarque et al., 2013). The 2009 values of developed countries (including Europe, the Russian Federation or the former USSR, North America, Australia and New Zealand, Israel, and Japan) and developing countries (i.e., all remaining countries) were interpolated between 2000 and 2030 using the RCP2.6 and RCP8.5 scenarios, respectively. We assumed that for 2009, RCP 2.6 is more suitable to be used as the trajectory for developed countries and RCP 8.5 is more suitable for its application to developing countries.

Country averages represent averages that are weighted by the size of the grid cells. All grid cells whose centres fell within a country were used in the calculation of the average. Please refer to Lamarque et al. (2013) for details of the specific method used to calculate atmospheric N deposition.

For some small islands, N deposition could not be directly estimated, so we used the average value of global ocean N deposition. The small countries and regions used in this study are Antigua and Barbuda, Bahrain, Barbados, Dominica, Falkland Islands (Malvinas), Faroe Islands, French Polynesia, Grenada, Saint Kitts and Nevis, Saint Lucia, Sao Tome and Principe, and Seychelles. These countries and regions account for 0.02% of the global area and 0.03% of the global population.

2.2. N fertilizer consumption

N fertilizer consumption (N_{fer}) data for different countries and regions are from the Food and Agriculture Organization of the United Nations (FAO), which were downloaded in 2015.

(http://www.fao.org/faostat/en/#data/RF, http://www.fao.org/faostat/en/#data/RA).

2.3. Biological N fixation

N fixation is generally derived from agricultural lands, forest lands, and grasslands. Globally, grasslands are formed naturally, with little human interference. As of 2009, only 5.8% of grasslands had been artificially cultivated (http://www.fao.org/faostat/en/#data/RL). Therefore, in our study, biological N fixation (N_{fix}) comprised N fixation ($N_{c\text{-}fixed}$) in crops and N fixation in planted forests ($N_{f\text{-}fixed}$).

$$N_{fix} = N_{c-fixed} + N_{f-fixed} \tag{2}$$

N fixation in cropland ($N_{c\text{-}fixed}$) was estimated using the method of Lassaletta et al. (2014a,b). To estimate the crop biological nitrogen fixation by fixing crops included in the FAOstat database we used a yield-based approach, assuming that crop yield is the factor that best aggregates variables associated with crop, soil and climatic conditions including available N, soil moisture, vigor of stand, and other management factors influencing N_2 fixation:

$$N_{c-fixed} = \%Ndfa \times \frac{Y}{NHI} \times BGN \tag{3}$$

where *%Ndfa* is the percentage of the N uptake derived from N fixation;
Y is the harvested yield, kgN/ha/yr;
NHI is the N harvest index;
BGN is a multiplicative factor.

The values of %Ndfa, NHI, and the BGN factor were used to estimate the total biological N-fixation by legumes (Table S1). For sugar cane, rice, crop lands other than used for legumes and rice, we applied a constant rate of biological fixation per hectare, as suggested by

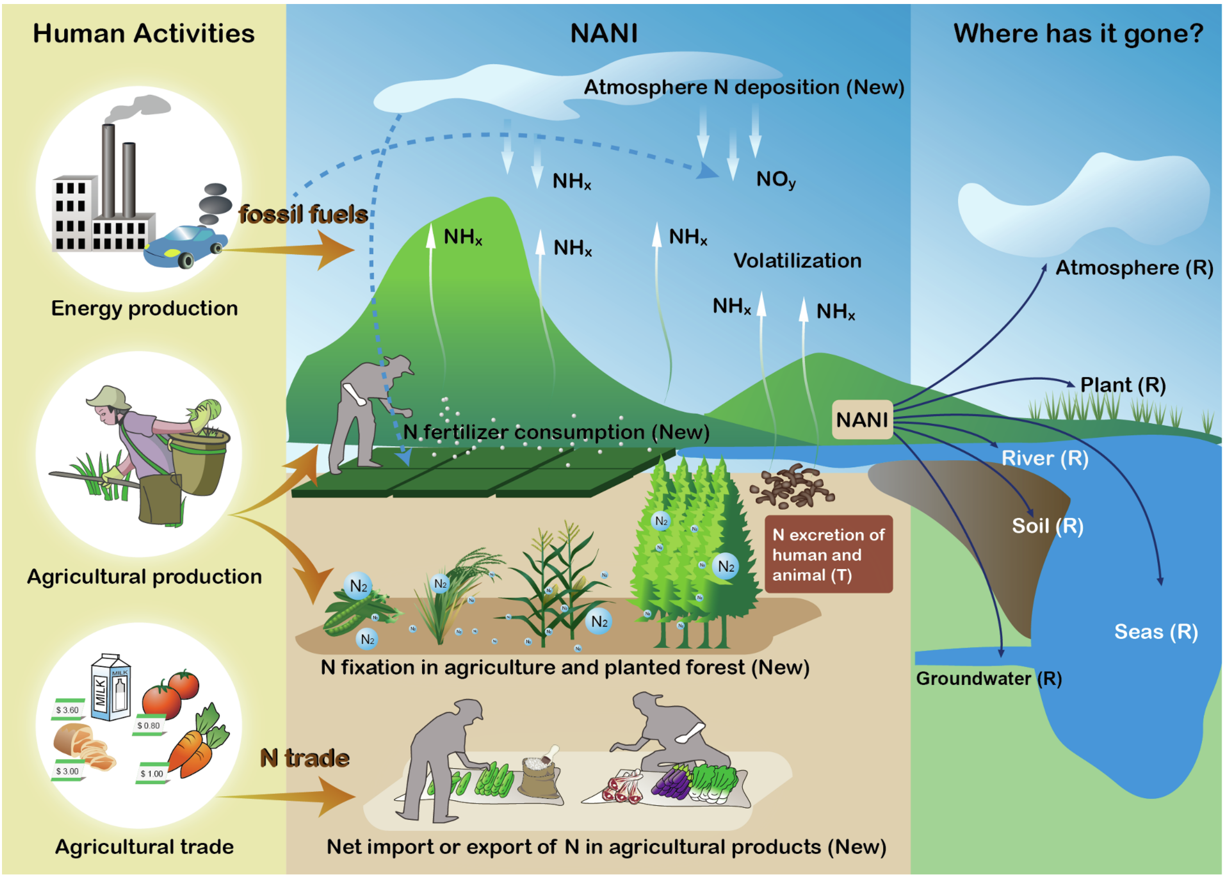

Fig. 1. Cycle of NANI. "New" represents an immediate source of NANI, "T" represents the transformation of the N input, "L" represents the loss of an N input, and "R" indicates the recirculation of NANI.

Herridge et al. (2008) (Table S2).

N fixation in planted forests is given by:

$$N_{f-fixed} = N_{AF} \times A \quad (4)$$

where N_{AF} is the forest N fixation per unit area, 500 kg N/km^2/yr (McKee and Eyre, 2000).

A is the planted forest area.

The planted forest areas for the years of 1990, 2000 and 2009 were obtained from the FAO (http://www.fao.org/faostat/en/#data/GF). Data for 1961 and 1980 were not available from the FAO. A linear formula is established for each country based on the data of the country in 1990, 2000, and 2009 to estimate the planted forest area of the corresponding country in 1961 and 1980.

In this study, the N fixation of the global planted forest accounted for 3.8–4.7% of the total biological N fixation and 0.001% of the total NANI. Therefore, the estimation of this factor has little effect on the final calculated NANI value, and we believe that any error associated with this approach is negligible.

2.4. N trade

The N trade was estimated using imported and exported crops and livestock products, as well as their N contents.

$$N_{tra} = \sum (T_{imp} \times N\%) - \sum (T_{\exp} \times N\%) \quad (6)$$

where T_{imp} is the quantity of imported products, kg;

T_{exp} is the quantity of exported products, kg;

$N\%$ is the percent of N of the corresponding product (%, Table S3).

Data of the imported and exported crops and livestock products of all countries and regions were obtained from the FAO (http://www.fao.org/faostat/en/#data/TP). The N contents of traded commodities were obtained from Lassaletta et al. (2014a,b).

2.5. Data analysis

Spatial and temporal changes in NANI are analysed using ArcInfo 9.3 (ESRI Inc.).

We also investigate differences in NANI and its components between different years using SPSS19.0.

3. Results and discussion

3.1. Spatial and temporal variations in NANI

Between 1961 and 2009, NANI increased globally by 224% (from 378 to 1227 kg N/km^2/yr) (Fig. 2 and Table 1). From 1961 to 2009, the NANI of Europe and Caribbean increased initially and then decreased, however, the NANI of the other regions increased all the time. The fastest change in the absolute value of NANI occurred in Asia (increasing from 463 to 2841 kg N/km^2/yr), followed by Caribbean (from 725 to 1525 kg N/km^2/yr). The increase rate of the NANI in Asia was the largest (513%), followed by Latin America (308%) and Oceania (286%). Geographically, on a per-area basis, Asia had the highest NANI, followed by the Caribbean and Europe in 2009.

From 1961 to 2009, the net N inputs in Asia increased by 78 Tg, 70% of the global net increase in N inputs (112 Tg) (Table S4). It is evident that the increase of net N inputs in Asia is the main driver of the increase in global NANI.

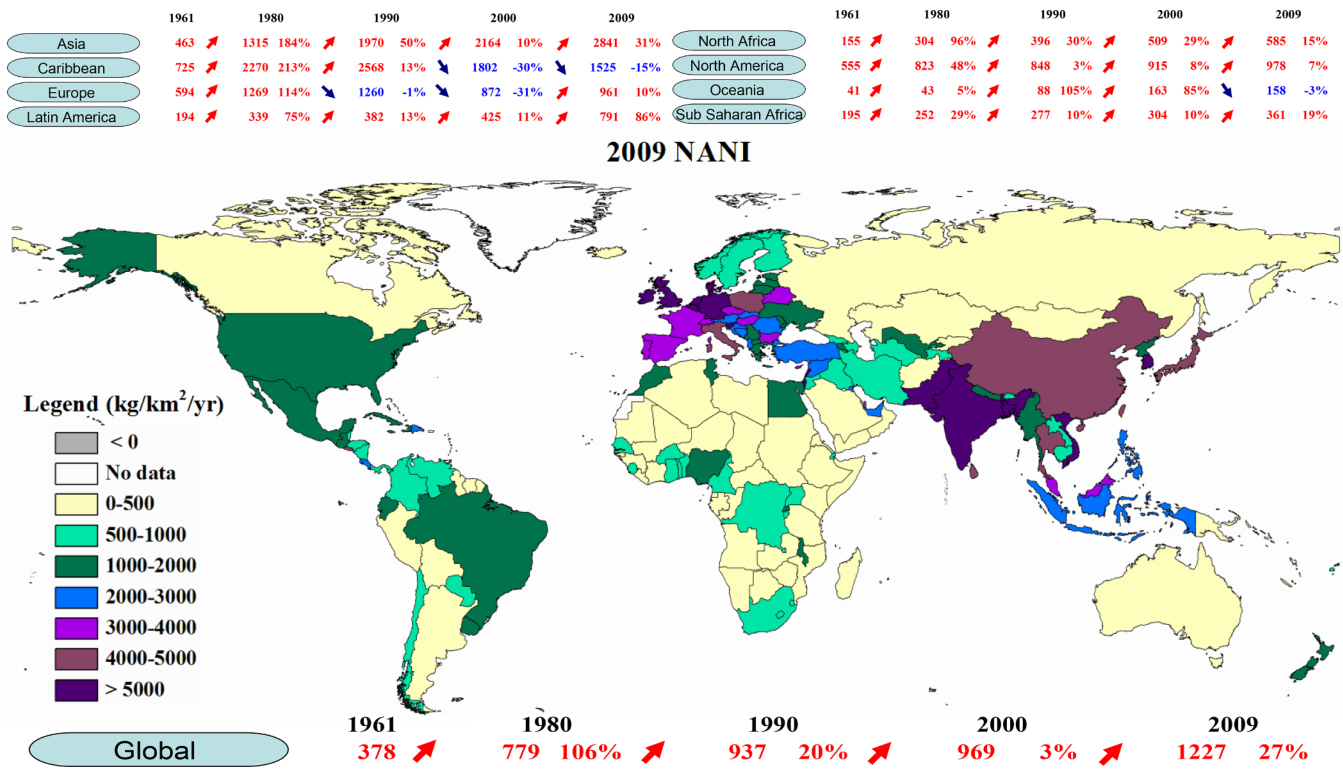

Fig. 2. NANI values in each unit for 1961, 1980, 1990, 2000 and 2009.

3.2. Change in components of NANI

In 1961, the largest component of global NANI was atmospheric N deposition (159 kg N/km^2/yr, 42% of the total), followed by total N fixation (130 N/km^2/yr, 34%) and N fertilizer consumption (89 kg N/km^2/yr, 23%) (Table 1 and Table S5). From 1980 to 2009, the largest component of global NANI was N fertilizer consumption (462–743 kg N/km^2/yr, 59%-64% of the total), followed by total atmospheric N deposition (178–200 kg N/km^2/yr, 16%–23%) and N fixation (142–245 kg N/km^2/yr, 18%-20%) (Table 1 and Table S5). The net import or export of N in traded agricultural products must sum to zero on a global scale, so does not contribute there, despite being a significant component in many regions. It is useful to consider which regions have the highest intensities of NANI. Two regions, Asia and the Caribbean, stand out, exceeding the global average, as well as all other region, yet the two regions have many differences. First, the Caribbean represents a small fraction of global area compared to Asia, so the NANI values expressed on a total mass basis instead of per area, would show a very different ranking. Second, NANI has increased in Asia over the period studied, but decreased in the Caribbean over the same period.

In Asia, N fertilizer consumption was the most important component of the change, jumping from 76 kg N/km^2/yr in 1961 to 1926 kg N/km^2/yr in 2009 (Table 1). During the same period, the N in imported food and feed also increased reflecting Asia's prominence as a major food importing region. The Caribbean saw a sharp increase in fertilizer consumption from 1961 to 1990 (from 279 to 1536 kg N/km^2/yr) to improve the yield of crops and then a major decline from 1990 to 2009 (from 1536 to 378 kg N/km^2/yr) due to the reduction in crop production. The shift in the relative importance of fertilizer and food/feed imports in the region suggests a transformation from regional self-sufficiency in food production to dependence on food imports since the 1980s.

This may not be entirely negative, considering an example from Asia. The use of fertilizer has caused many environmental problems in Asia (Mori, 2013). For example, the eight largest watersheds in China have experienced very serious N pollution due to fertilizer usage (Han et al., 2014). Although the Chinese government has attempted to mitigate pollution and improve water quality, it has achieved only limited success (Han et al., 2014). Therefore, reducing fertilizer consumption could be an effective method of improving the environment and decreasing NANI in China if it could be achieved without dramatic decreases in crop production and avoiding negative impacts elsewhere.

From 1980 to 2009, Europe was the only region other than the Caribbean to see a decline in NANI over the period, also mainly due to a decline in N fertilizer consumption. Although the population increased between 1980 and 2009 in Europe and the Caribbean (by 6% in Europe and 39% in the Caribbean), fertilizer consumption decreased from 826 to 546 kg N/km^2/yr in Europe (from 514 to 234 kg N/km^2/yr in Eastern Europe and from 2632 to 1863 kg N/km^2/yr in Western Europe) and from 1380 to 378 kg N/km^2/yr in the Caribbean. Like the Caribbean, Europe is also a major food/feed importer, but net food/feed N is a relatively minor component of NANIduring the period studied (Table 1 and Table S4).

3.3. Protein consumption

From 1961 to 2009, the worldwide protein consumption per capita increased (Table 2), largely due to the increased consumption of meat, which requires a higher level of agricultural production and the associated use of fertilizer (Bringezu et al., 2014). Oceania, North America and Europe exhibited the highest annual protein consumption per capita, and all of these regions recorded higher consumptions of protein from animal products (mainly meat) (Westhoek et al., 2014; Billen et al., 2015). The production of meat is a process by which plant-based protein is converted to animal protein, during which significant N is lost in animal waste. For a given level of total N demand by humans, diets rich in animal protein require more N than vegetarian diets. The overall N utilization efficiency is therefore reduced by meat production. Human dietary patterns favouring meat over plant protein are thus key factors in determining regional N balance (Kastner et al., 2012); advocating diets with lower amounts of animal product protein can reduce NANI inputs and volatile losses of animal N excretion in many

Table 1
The regional area-weighted averages of each component of NANI between 1961 and 2009.

Region	Area ($10^3 km^2$)					Atmospheric oxidized N deposition (kgN/km^2)					N fertilizers (kgN/km^2)				
	1961	1980	1990	2000	2009	1961	1980	1990	2000	2009	1961	1980	1990	2000	2009
Asia	27,767	27,812	27,814	31,991	31,990	86	183	234	269	314	76	775	1330	1460	1926
Caribbean	229	228	228	228	228	101	131	147	163	150	279	1380	1536	699	378
Europe	27,352	27,352	27,352	22,955	22,956	267	230	211	216	188	200	826	822	577	546
Latin America	19,266	20,318	20,318	20,290	20,290	102	117	125	133	126	18	125	165	246	336
North Africa	5753	5753	5753	5753	5753	86	100	108	115	122	37	132	181	247	272
North America	19,614	19,614	19,614	19,617	19,816	241	250	254	259	218	161	599	581	613	633
Oceania	8524	8524	8524	8524	8524	59	68	73	77	70	5	31	58	139	144
Sub Saharan Africa	21,934	21,951	21,951	21,951	21,951	156	162	165	169	172	6	45	48	47	60
Global	130,440	131,552	131,551	131,310	131,509	159	178	188	201	200	89	462	586	615	743

N fixation (kgN/km^2)					N trade (kgN/km^2)					NANI (kgN/km^2)					NANI increase rate (%)
1961	1980	1990	2000	2009	1961	1980	1990	2000	2009	1961	1980	1990	2000	2009	
287	300	338	333	363	14	57	69	101	238	463	1315	1970	2164	2841	513
242	351	358	308	279	103	408	527	632	718	725	2270	2568	1802	1525	110
82	77	90	72	76	44	137	137	7	151	594	1269	1260	872	961	62
84	130	175	263	419	−10	−33	−82	−217	−90	194	339	382	425	791	308
23	25	30	28	34	8	47	77	119	158	155	304	396	509	585	278
206	216	234	328	388	−52	−242	−221	−285	−260	555	823	848	915	978	76
11	15	20	29	28	−34	−70	−63	−82	−83	41	43	88	163	158	286
40	45	59	79	102	−7	−1	5	9	27	195	252	277	304	361	86
130	142	165	200	245	0	−3	−2	−48	38	378	779	937	968	1226	224

NANI increase rate was calculated by dividing its change from 1961 to 2009 by the value in 1961.
Negative value in N trade indicates an output of N instead of an input, and negative value in NANI increase rate indicates a negative growth.

Table 2
Per capita protein consumption for years 1961, 1980, 1990, 2000 and 2009 in different regions.

	Animal products protein (kg/cap/yr)					Vegetable products protein (kg/cap/yr)					Grand total protein (kg/cap/yr)					Average body weight (kg) (WHO, 2007)	Safe minimum level of protein intake (kg/cap/yr)
	1961	1980	1990	2000	2009	1961	1980	1990	2000	2009	1961	1980	1990	2000	2009		
Asia	3	4	5	7	9	15	16	17	18	18	18	20	22	25	27	57.7	17
Caribbean	6	8	8	7	9	11	12	11	12	13	17	20	19	19	22	67.9	21
Europe	15	20	21	19	21	18	17	17	16	16	33	37	38	35	37	70.8	21
Latin America	8	11	11	14	15	15	14	14	14	15	23	25	25	28	30	67.9	21
North Africa	4	4	6	7	8	16	21	24	24	26	20	25	30	31	34	60.7	18
North America	23	24	25	26	25	12	12	14	15	15	35	36	39	41	40	80.7	24
Oceania	23	21	21	19	19	13	11	11	10	10	36	32	32	29	29	74.1	22
Sub Saharan Africa	4	5	4	4	5	14	14	14	14	15	18	19	18	18	20	60.7	18
Global	7	8	9	10	11	15	16	16	17	17	22	24	25	27	28	62.0	19

Minimum required level of protein intake 0.83 g kg^{-1} body weight day^{-1} of protein (Kastner et al., 2012).
Data on population and protein supply quantity are from FAO (http://faostat3.fao.org/download/FB/CC/E).

countries, particularly those (e.g., North America, Europe, Oceania, and Latin America) where the dietary proportions of animal protein are much greater than the global average animal protein consumption.

According to the results of a study performed by the World Health Organization (WHO & UNU, 2007), a safe level of protein intake per capita consistent with nutritional requirements is 0.83 g/kg per day (WHO & UNU, 2007). We calculated the actual values of protein intake in these regions using average body weight (Walpole et al., 2012) (Table 2) and found that in 2009, all regions recorded levels protein consumption higher than this minimum level, indicating that human demand for food protein exceeds nutritional requirements. This excess demand leads to wasted resources and exerts excessive pressure on the environment, as has been well documented in previous studies (Smil, 2002; Vitousek, et al., 2009; Billen et al., 2011). If, hypothetically, the world went on a low protein diet, adopting the WHO level of protein intake as a standard, the world could reduce its protein demand by 32%. Of course, significant numbers of people around the world are in health crisis, and currently consume less than the safe level of protein. What is reasonably called for is consideration of the environmental health costs of excessive protein consumption as well as the usual human health concerns.

3.4. Per capita NANI

In previous studies (Hong et al., 2011; Han et al., 2014), as well as this study, NANI generally has been expressed per land area; however, assessing the NANI per capita within individual countries can also yield valuable insights, as demonstrated by the IPAT equation for environmental impacts (I), expressed as the product of population (P), “affluence” per capita (A), and technological factors (T) (Chertow, 2000; OECD-FAO, 2016). Although many current studies have demonstrated that there is a close correlation between the NANI per unit area and regional environmental quality, very few studies have characterized the human activity levels with respect to N input. NANI per capita, is calculated simply by normalizing the total NANI by the population in a given country or region instead of area. The larger the resulting value, the more natural resources are used per capita, or the greater the impact on the environment, required to meet the population’s needs (Ehrlich and Holdren, 1971). The results of these calculations (Table 3) show that the global population increased by 123% from 1961 to 2009. The per capita NANI of all the regions increased except that the per capita NANI of Sub Saharan Africa decreased by 49%. Table 1 shows that the global NANI per unit area has increased by 224%. Therefore, although NANI per capita has increased slightly, one of important reasons for the increase of global NANI is the increase in human population.

In this study, the values of global per capita NANI range from 16 to 24 kg N/cap/yr (Table 3). The differences between individual regions are greater. The per capita NANI values of North America, Europe and Oceania are far higher than those of other countries and regions, indicating that each person in these regions uses more consumable N elements, most likely by using plant-based protein to produce animal protein for food (Rahman, 2017). This is also the reason for their higher consumptions of animal product protein (Table 2). These results indicate that in these regions, the per capita consumption of resources is higher, and the per capita N input is greater. Although the per capita NANI in Asia is less than the global average value, the intensity of human activities per area in these regions is higher because of their increasingly large populations (which increased by 143% from 1961 to 2009), which is the main reason for the deterioration of the environment in densely populated regions (Rahman, 2017). Policies targeted at alleviating population pressure can, in principle, ease the regional ecological environmental impacts, thereby improving the environment. However, national population control policies (Cao et al., 2015), including those of China and India, have had at best modest success over the long term, and in some case, notable failures. It is hoped that

Table 3
Per capita NANI and Population.

	NANI (kg N/cap/yr)					Population ($\times 10^9$)					NANI increase rate (%)	Population increase rate (%)
	1961	1980	1990	2000	2009	1961	1980	1990	2000	2009		
Asia	8	14	17	19	22	1.70	2.63	3.2	3.71	4.12	190	143
Caribbean	8	18	18	11	9	0.02	0.03	0.03	0.04	0.04	10	97
Europe	25	46	44	28	30	0.65	0.69	0.72	0.73	0.73	19	13
Latin America	18	21	19	18	29	0.20	0.34	0.41	0.49	0.55	57	172
North Africa	15	19	19	20	20	0.06	0.11	0.14	0.17	0.2	29	247
North America	52	64	59	57	57	0.21	0.25	0.28	0.31	0.34	9	63
Oceania	23	17	30	48	40	0.02	0.02	0.03	0.03	0.04	75	162
Sub Saharan Africa	20	15	13	11	10	0.22	0.37	0.49	0.64	0.82	−49	276
Globe	16	23	23	21	24	3.07	4.44	5.30	6.12	6.84	49	123

NANI increase rate and population increase rate were calculated by dividing the change from 1961 to 2009 by the value in 1961.

educational programs and increasing welfare will lead to decreasing fertility rates (Becker, 1960; Bloom and Canning, 2004; Samir and Lutz, 2017) with concomitant benefits to the environment.

3.5. Approaches for reducing NANI

Since NANI is directly related to watershed N export per area, reducing NANI is of great significance for preventing or mitigating regional pollution. Globally, in addition to food consumption, NANI can be associated with two types of human activities: energy production and agricultural production.

3.5.1. Energy production

NANI produced in the process of energy production mainly originates as products of the combustion of fossil fuels. The relevant N-containing pollutants from combustion are mainly nitrogen oxides (NO_x). Clean energy (i.e., solar and wind power) is gradually being used to replace fossil fuels, thereby reducing atmospheric NOx pollution (Lassaletta et al., 2014a,b). Especially in China, people are encouraged to replace fuel vehicles with electric vehicles, which can have a positive effect on regional nitrogen loads and other pollutants.

3.5.2. Agricultural production

Globally, NANI produced to meet human demand for food mainly originates from the application of fertilizer and biological N fixation (Herridge et al., 2008; Bicer et al., 2017). It is worth noting that industrial fertilizer production itself consumes significant energy, and thus adds to atmospheric N pollution (Bicer et al., 2017). The widespread use of synthetic N fertilizers is a dominant feature of modern global food production. The strategy of reducing N fertilizer use in an effort to improve environmental quality in the absence of improved nitrogen use efficiency could lead to a reduction in global food production and increase the risk of regional food insecurity. Synthetic fertilizer consumption can be reduced by replacing it with more effective recycling of manure to crops at local scales. This represents a potentially important pathway to increased nutrient use efficiency (Chadwick et al., 2015; Le Noë et al., 2017; McCrackin et al., 2018), but, to date, the associated manure management costs, including transport and storage, have been a barrier to widespread effective adoption of manure as fertilizer. There are significant regional imbalances in existing fertilizer applications as well (Table 1) (Mosier et al., 2005; Sutton et al., 2013; Zhang et al., 2015) for which regional-scale policies may provide solutions.

Developing a balanced inter-regional agricultural production and consumption system is problematic for political, social and economic reasons. The import and export of large quantities of food can lead to dependence of food importers on food exporters. If a diplomatic crisis arises and food-exporting countries stop exporting food, food-importing countries may suffer from food shortages or even social unrest.

3.6. Regional fertilizer balance

Balancing the application of global N fertilizer between regions can help improve the utilization efficiency of fertilizers and reduce the global NANI. Currently, the global utilization efficiency of N fertilizers is approximately 47% (Herridge et al., 2008) in the United States, this value can reach up to 70%-80% (Herridge et al., 2008). Other regions could improve efficiencies as well. Fertilizer is consumed at high rates in Asia, and at much lower rates in Africa, Oceania and Latin America. Maintaining current global fertilizer consumption, if Asia reduced its fertilizer consumption reallocating its unused fertilizer to these regions, the global N utilization efficiency would be improved, assuming the same efficiencies, thereby increasing global food production capacity. In Asia, food demand could be met by importing food (Bodirsky et al., 2014) as has been done in the past in times of shortages, and increasingly today. In principle, based on the current level of global fertilizer consumption, if the global utilization efficiency of N fertilizers increased by 10%, global food production could increase by 21%, or fertilizer consumption could decrease by 18%, and still maintain the current quantity of food production. It is evident that this requires policies involving interregional trade in agricultural commodities and redistribution of fertilizer. Depending upon the relative use efficiencies in different regions, global NANI may be best managed to improve global N utilization efficiency through interregional trade. Note that this ignores political and economic impacts of such policies.

3.7. Organic fertilizers

In addition, the current global fertilizer utilization efficiency is related to fertilizer type. To the extent that organic fertilizers have high utilization efficiencies and low nutrient loss rates (Nyamadzawo et al., 2017), it is feasible to use new organic fertilizer to replace traditional agricultural fertilizer to reduce the consumption of synthetic N fertilizer and reduce NANI. Moreover, new organic fertilizers can reduce NO_y emissions from agricultural soils (Yan et al., 2005). According to previous studies, agricultural soils will release 2.41 TgN/yr NO_y into the atmosphere (Bodirsky et al., 2014), equivalent to 2% of NANI globally. Slow-release fertilizer can reduce N loss, thereby reducing the atmospheric impacts of the increased NANI. Other agricultural practices, such as the adoption of high-yielding crop species and the promotion of precision agriculture (e.g. timing fertilizer applications to periods of highest crop demand), can also improve agricultural production capacity without increasing fertilizer consumption.

3.8. Co-cultivation

N in imported and exported food is important to the dynamics of N within a single region. As mentioned earlier, large increases in food import or export require policy changes and may be subject to complex political and economic concerns. Food may be transferred in other ways. For example, China can cooperate with countries or regions where agricultural production is underdeveloped due to the lack of fertilizers (e.g., some countries in Africa) by leasing or co-cultivating land in these countries or regions to directly obtain food to meet its domestic food needs. Historically, such practices been associated with the abuses of colonialism, and risk degrading the environment of the "partner" country (e.g. by increasing NANI and associated environmental consequences or producing foods at prices not affordable or desirable to the local population). However, with proper safeguards and management, such approaches could possibly improve the living standards of local people and also solve the problem of food shortages caused by agricultural production shortfalls in regions of large populations. In 2009, for example, the fertilizer consumption per unit area in Asia is significantly higher than the world average. Therefore, reducing the fertilizer consumption in Asia and developing co-cultivating land with other regions are effective ways to reduce NANI in Asia. If a country wishes to increase its agricultural production (and exports) by increasing fertilizer consumption, an essential precondition should be that the increase in fertilizer consumption does not increase agricultural N pollution in that country (Bodirsky et al., 2014). In other words, maintaining or increasing food production in the interest of food security should not be achieved at the expense of environmental security for all countries concerned.

During the period analysed in our study, global agricultural land area changed by less than 5%, but the value of N fixation increased by 72%, mainly due to the increased cultivation of N-fixing crops (such as soybeans). Because the fixation of N by crops has fewer obvious negative impacts on the environment than other anthropogenic sources of N, we do not recommend reducing NANI by reducing biological N fixation.

The analysis of NANI, which was applied in this study for the first time to all countries of the world on a national scale, represents a method of assessing the sources of N pollution and assigning regional priorities. Our results revealed extreme differences in the values of NANI between regions, whether expressed per area or per capita.

3.9. Uncertainty

The data on N fertilizer consumption, food import or export, and N contents in food were all obtained from the FAO and Lassaletta et al. (2014a,b); thus, the uncertainty of these data was not analysed. The uncertainty associated with NANI in this study mainly originates from the error in the estimation of some components (i.e., atmospheric N deposition, and N fixation in crops). Global atmospheric N deposition was estimated using the ACCMIP multi-model average depositions. The error between the results of the estimation and the results of the multi-model is estimated at less than 10% (Lamarque et al., 2013), corresponding to an error in global NANI of about 1.6–2.3%. The N fixation in this study is 142–245 kg N/km^2/yr, and its error is less than 9%, compared with the results of other estimates (Lassaletta et al., 2014a,b). The corresponding potential error in the global NANI is less than 1.6–1.9%. According to data from FAO in 2009, the area of artificially cultivated grassland is 19.16×10^5 km^2, grassland N fixation per unit area is 500 kg N/km^2/yr, so the corresponding potential error in the global NANI is less than 1.0%; Therefore, we estimate the total error associated with the global value of NANI in this study to be less than 4.2–5.2%.

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Appendix A. Supplementary data

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