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Anthropogenic nitrogen autotrophy and heterotrophy of the world's watersheds: Past, present, and future trends

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[1] Anthropogenic nitrogen autotrophy of a territory is defined as the nitrogen flux associated with local production of harvested crops and grass consumed by livestock grazing (in kg N/km^2/yr). Nitrogen heterotrophy is the nitrogen flux associated with local food and feed consumption by humans and domestic animals. These two summarizing characteristics (anthropogenic nitrogen autotrophy and heterotrophy (ANAH)) indicate the degree of anthropogenic perturbation of the nitrogen cycle by agriculture and human consumption: their balance value provides information on either the potential for commercial export or the need to import agricultural goods; in a watershed, their vector sum is related to the nitrogen flux delivered to the sea. These indicators were calculated for all the watersheds in the Global Nutrient Export from Watersheds (NEWS) database for 1970 and 2000, as well as for 2030 and 2050, according to Millennium Ecosystem Assessment scenarios. During this 30 year period, many watersheds shifted from relatively balanced situations toward either more autotrophic or more heterotrophic conditions. This trend is predicted to become more pronounced over the next 50 years.

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1. Introduction

[2] The advent of agriculture has been a major factor disturbing nutrient cycles in many areas of the world. However, in most traditional farming systems, the yield and potential for export of agrosystems were still constrained by the nitrogen fixation capacity of associated seminatural terrestrial ecosystems (Figure 1a), which strongly limited the possibility of exporting large amounts of food and feed outside the rural territory [*Mazoyer and Roudart*, 1998; *Smil*, 2002; *Billen et al.*, 2007b, 2009a]. The large-scale use of synthetic nitrogen fertilizers produced through the Haber-Bosch process, as well as the development of inexpensive means of transportation, dramatically changed this situation [*Erisman et al.*, 2008], rendering possible an unprecedented opening of the nitrogen cycle on the regional and global scales (Figures 1b and 1c). The increased nitrate contamination of groundwater and surface water resulting from the leaching of nitrogen fertilizers and the increase in commercial food and feed exchanges over long distances are two facets of the same major perturbation of the nitrogen cycle characterizing today's industrial world. The fluxes associated with riverine nitrogen export from land to sea and with the international trade of agricultural products are now comparable in magnitude and account for a large share of the total regional nitrogen metabolism [*Grote et al.*, 2005; *Burke et al.*, 2009; *Galloway et al.*, 2007].

[3] Urbanization (of now more than half the world's population) has been made possible by, and has also contributed to, the increase in long-distance export of agricultural goods from rural regions. The specialization of some rural areas in livestock farming, using imported feed produced in remote regions, is another cause of increased long-distance commercial exchanges of agricultural products. In both cases, the wastes produced by human or animal consumption far from the site of crop production can no longer be easily recycled in the agricultural sector [*Howarth et al.*, 2002; *Galloway et al.*, 2007; *Smaling et al.*, 2008].

[4] The functioning of any ecosystem is classically described by the equilibrium between its two main functions, autotrophy (A) and heterotrophy (H) [*Odum*, 1971]: if the primary production of an ecosystem exceeds its consumption (A/H > 1), it is regarded as autotrophic; conversely, if respiration exceeds production (A/H < 1), the system is heterotrophic. Most ecosystems unperturbed by human activity are in approximate balance (P = R), although open systems such as the different sectors of a river continuum can display spatial patterns of autotrophic and heterotrophic distribution [*Vannote et al.*, 1980; *Garnier and Billen*, 2007]. In an attempt to characterize the spatial organization of food production within regional watersheds, *Billen et al.* [2007a, 2009a]

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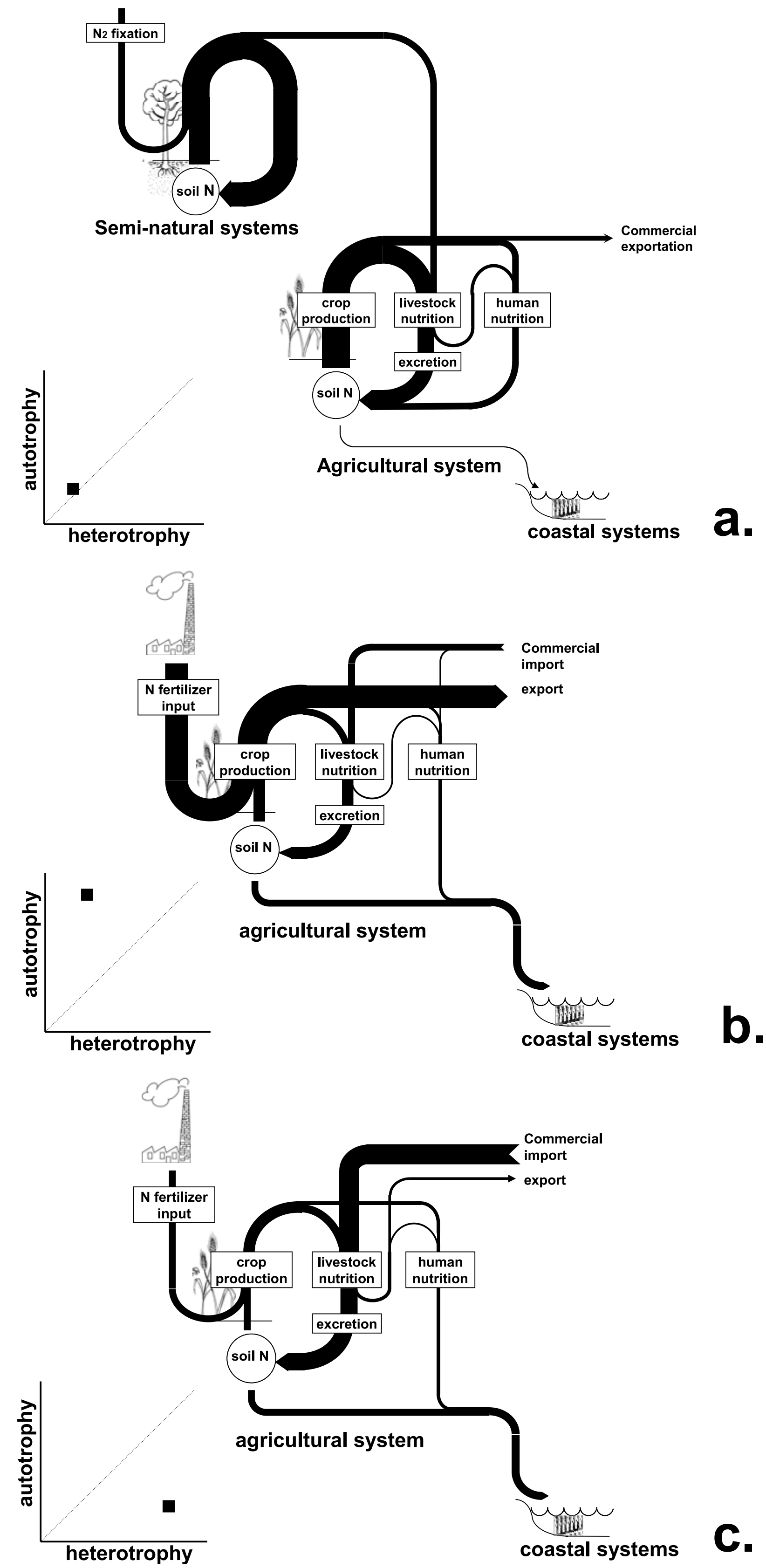
N2 fixation
soil N
Semi-natural systems
Commercial exportation
crop production
livestock nutrition
human nutrition
excretion
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Agricultural system
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coastal systems
a.
Commercial import
export
N fertilizer input
crop production
livestock nutrition
human nutrition
excretion
soil N
agricultural system
autotrophy
heterotrophy
coastal systems
b.
Commercial import
export
N fertilizer input
crop production
livestock nutrition
human nutrition
excretion
soil N
agricultural system
autotrophy
heterotrophy
coastal systems
c.

Figure 1

have proposed recasting the calculations of autotrophy/heterotrophy in terms of nitrogen (N) flows and evaluating the principal flows of nitrogen associated with food and feed production and consumption associated with the distribution of humans and livestock over the landscape. They defined anthropogenic nitrogen autotrophy of a given territory as its production of food and feed (harvested and grazed products), expressed as N content, and nitrogen heterotrophy as the N content of food and feed required to sustain the local population and livestock (Figure 1). Urban areas, where food is consumed but not produced, are purely heterotrophic. Rural regions specialized in crop production are autotrophic and export nitrogen as food and/or feed, while those characterized by intensive animal farming sustained by imported feed are heterotrophic. The autotrophic or heterotrophic character of a given territory thus reflects the geographic distribution of agriculture and human populations as well as the technical organization of trade activities. The net commercial export (or import) of agricultural products (i.e., the surplus (or shortage) of agricultural production over the requirements of the local population and livestock) can be calculated as the balance between autotrophy and heterotrophy.

[5] In this paper, we apply this simple anthropogenic nitrogen autotrophy and heterotrophy (ANAH) concept to the global data of land use, crop and livestock production and N surface balance established by *Bouwman et al.* [2006, 2009] using the IMAGE 2.4 model, over the 1970–2000 period and for the four Millennium Ecosystem Assessment (MEA) scenarios, within the UNESCO–Intergovernmental Oceanographic Commission (IOC) Global Nutrient Export from Watersheds (Global NEWS) work group. This exercise highlights a number of trends in the world food resource allocation during the 1970–2000 period and in the different future scenarios envisaged by the MEA. Although the databases are available with a 0.5 × 0.5 degree resolution, our analysis will here be applied on the scale of major fluvial watersheds considered as territorial units. Our results reveal the increasing separation of agricultural production and consumption on the regional scale in the context of urbanization and growing international trade, the resulting regional allocation of food resources and their impact on nitrogen fluxes to coastal systems. The comparison of the prospective MEA scenarios provides an indication of the room to maneuver in future societal choices.

2. Methods

[6] As explained above, anthropogenic nitrogen autotrophy (A) of a territory (in kg N/km^2/yr) is defined as the nitrogen flux associated with the plant production of all harvested crops and grazed forage and grass in this territory over 1 year. Heterotrophy (H) (in kg N/km^2/yr) is defined as the nitrogen flux associated with total annual food and feed consumption by humans and domestic animals in the territory (Figure 1). In this sense, autotrophy and heterotrophy refer here only to the human-cultivated, agricultural portion of the territory; these terms do not include the primary production and consumption of the uncultivated natural or seminatural ecosystems unless they are grazed by livestock. Nor are managed forests taken into account. Although there may be exceptions, for example, in peat bog areas or intensively harvested forests, we implicitly assume that these systems are nearly equilibrated (A = H) so that their contribution to the autotrophy of the entire territory is balanced by their heterotrophy and can be ignored.

[7] In the Global NEWS/IMAGE databases [*Bouwman et al.*, 2009], crop production figures are directly available; the values for 34 different crop groups have been converted into N uptake considering the mean N content of harvested products [*Bouwman et al.*, 2005a]. The production of grass and fodder crops in mixed and pastoral farming systems (where both crop and livestock production occur) is included in these crop N uptake figures. We refer to *Bouwman et al.* [2005c] for a detailed description of the calculation of this term. In contrast to the surface balance approach reported by *Bouwman et al.* [2009, 2005a, 2005c], we added an amount equivalent to the animal manure used for other purposes than agricultural fertilization (such as fuel or building material) to the calculation of autotrophy, since this amount of manure originates from grass and other feedstuffs.

[8] For human food consumption, the figures of N emissions by human populations calculated by *Van Drecht et al.* [2009], on the basis of a per capita N diet value dependent on economic indicators, were used. Food consumption by cities, defined as "grouping of populations not producing their food subsistence themselves" [*Ascher*, 2001, p. 9], was calculated as the total food consumption by the urban population, using the same per capita N diet figures as for the rural population of the same country. Animal net consumption was estimated as the excrement production, computed from animal stock figures and per capita N excretion rates [*Bouwman et al.*, 2009]. As the local meat and milk consumption by humans is included in human consumption, this accounts for possible export of animal products (Figure 1c).

[9] Note that our analysis does not include fish and seafood, which is, however, implicitly included in the human N diet figures; this totals about 3 Tg N/yr (based on landing 130 Mton fresh material [*Food and Agriculture Organization of the U. N.* (*FAO*), 2008a] and a 2.5% N content). Fish meal is used as feed in both terrestrial livestock and aquacultural production. The maximum available quantities are approximately 6–7 Tg fresh weight per year [*Tacon and Metian*, 2008]. The production of aquatic plants, also used for animal feed, was about 2 million tons in 2000 [*FAO*, 2008b],

Figure 1. Schematic representation of nitrogen fluxes in agricultural systems. N autotrophy is defined as the nitrogen uptake by crop, and N heterotrophy is defined as the nitrogen content of local human food and livestock feed consumption. The balance between A and H represents the net export (import) of food and feed. (a) Traditional agrosystems were dependent on the N-fixing capacity of associated seminatural ecosystems; autotrophy and heterotrophy are generally close to balance. (b) Modern, synthetic fertilizer-based agrosystems can export a large part of the crop production and represent autotrophic systems. (c) Modern animal farming systems, importing a large share of feed, are typically heterotrophic systems.

Table 1. Nitrogen Autotrophy and Heterotrophy and Net Export (A − H) of Agricultural Products by Continent, as Calculated From the Global NEWS Databases for 2000[a]

Continent	Area (10^6 km^2)	Total Population (M inhabitants)	Percent Urban	Autotrophy (Tg N/yr)	Heterotrophy (Tg N/yr)	A − H (Tg N/yr)	A/H	Human Consumption (Tg N/yr)	Urban Consumption (Tg N/yr)
Europe	9.4	651.3	72.2	17.6	15.4	2.3	1.15	2.5	1.8
North America	20.8	454.7	74.7	17.8	13.9	4.0	1.29	1.9	1.4
South America	17.5	325.6	79.0	16.6	16.9	−0.3	0.98	1.1	0.9
North Asia	15.9	130.7	53.1	3.8	2.9	0.9	1.32	0.4	0.2
South Asia	25.2	3182.8	35.6	42.1	44.5	−2.4	0.95	9.8	3.6
Africa	29.3	756.3	36.2	17.2	19.1	−1.9	0.90	2.2	0.8
Australia/Oceania	10.3	270.2	47.7	6.7	5.4	1.2	1.23	0.9	0.4
Total	128.4	5771.6	46.3	121.9	118.1	3.8	1.03	18.7	9.2

[a]The share of total human and urban consumption in total heterotrophy is also shown. NEWS, Nutrient Export from Watersheds. A, autotrophy; H, heterotrophy.

with an N content of 5% [*Lourenço et al.*, 2006], for a total of 0.1 Tg N/yr. Compared to the total N in terrestrial agricultural production of 93 Tg N/yr in the year 2000, the contribution of fish products and aquatic plants is negligible. The use of mineral N supplements, such as urea, in animal feed is not known on the global scale, but it may be important in industrialized countries as an additive to protein-poor animal feed such as molasses. We assumed that the contribution of these feedstuffs and feed additives is negligible on the global scale.

[10] Our figures for autotrophy also ignore backyard farming, as food production of this kind does not enter the market and is not included in the *FAO* [2008a] statistics or in the IMAGE database. Some authors have estimated that it can account for as much as 15% of domestic food intake in some countries of South and Southeast Asia, South America and Africa [*Hoogerbrugge and Fresco*, 1993; *Mitchell and Hanstad*, 2004], but it is probably much lower in most other countries.

[11] The net commercial export (or import, respectively) from a territory was estimated as the surplus (or deficit) of agricultural production (autotrophy (A)) over food and feed requirements of the local population and livestock (heterotrophy (H)), both expressed as N (A − H). Alternatively, the balance of export (E) and import (I) of agricultural products (E − I) can also be directly calculated by country from the FAO statistics on international trade, converted into N by using the same N content coefficients as for N crop production and those cited by *Van der Hoek* [1998] for animal products. Given the production statistics and the trade statistics are independent of each other, this comparison allowed us to validate our approach. Note that only the net commercial exchanges can be approached in this way, as the absolute magnitude of the international trade fluxes in the globally interconnected world can rise to much higher levels than required by the imbalance between local production and consumption.

3. Analysis of the Situation in 2000

3.1. Autotrophic and Heterotrophic Areas of the World

[12] The comparison of autotrophy and heterotrophy calculated either by country or by watershed indicates which areas in the world are producing food and feed surpluses with respect to their local requirements, and which ones depend on importation to cover their needs. Table 1 summarizes the results of this analysis at the continental scale for the situation described by our database for the year 2000. Globally, autotrophy totals 122 Tg N/yr and matches heterotrophy (118 Tg N/yr) within 3%. In view of the uncertainties in our estimates, we consider this a remarkably coherent result, since, although interannual differences can obviously occur with some variations in food and feed stocks, we do not expect a large departure from equilibrium between autotrophy and heterotrophy globally. At the continental scale, disequilibrium might be greater: North America, Europe, North Asia and Australia have significant excess food and feed production over consumption, while Africa and South Asia show significant deficits. Given that these excesses or deficits of food and feed production with respect to consumption should be reflected in the continents' trade balance, we compared them with the figures of international commercial exchanges, compiled from FAO trade statistics for the year 2000 (Table 2). The general trends and order of magnitude of the results of both approaches are similar, although they differ for Europe, which shows a surplus of 2.3 Tg N/yr in the A − H approach and a slight deficit (−0.15 Tg N/yr) in the trade balance. The magnitude of the South Asian and African deficits calculated as A − H (−2.4 and −1.9 Tg N/yr, respectively) are close to that estimated from trade statistics (−2.8 and −0.8 Tg N/yr), and the match is also good for the North American excess (4.0 Tg N/yr from A − H and 3.2 Tg N/yr from trade balance).

[13] Overall, a reasonably good correlation is found between the A − H and trade balance figures by country:

$$A - H\left(\mathrm{kg\,N/km^2/yr}\right) = 1.14\left(\mathrm{net\,export\,kg\,N/km^2/yr}\right) - 55(r = 0.71, n = 180).$$

Significant discrepancies exist, however, between the two estimates for several major countries. According to trade statistics, India is slightly food exporting (+25 kg N/km^2/yr), while our estimation of the balance of autotrophy and heterotrophy indicates a slight heterotrophic character (−463 kg N/km^2/yr). According to the available figures, which are subject to large uncertainties, India has about 16% of the global cattle, and even 57% of the global population of buf-

Table 2. Nitrogen Fluxes Associated With International Trade of Crop and Livestock Products, Established From FAO Trade Statistics for 2000[a]

Continents	Import (Tg N/yr)	Export (Tg N/yr)	Export − Import (Tg N/yr)
Europe	2.43	2.28	−0.15
North America	0.31	3.51	3.20
South America	1.21	1.27	0.06
North Asia	0.18	0.22	−0.01
South Asia	3.72	0.88	−2.83
Africa	0.93	0.09	−0.84
Australia/Oceania	0.04	0.67	0.64
Total	6.38	6.64	0.21

[a]Nitrogen content of imported and exported cereals, pulses, oilseeds, cassava, groundnuts, bananas, meat and milk. FAO, Food and Agriculture Organization of the U. N.

faloes. This large population, although with low productivity, causes a total N excretion of 16 Tg per year. More than 40% of feed resources for livestock production in India are unaccounted for, possible candidates being grazing in forests, roadside grazing and domestic waste [*Van der Hoek*, 2001; *Bouwman et al.*, 2005b]. Hence, a large part of the feed for cattle comes from outside the agricultural system and is very difficult to accurately estimate.

[14] China, for which the A − H estimate (−53 kg N/km^2/yr) better agrees with the trade deficit (−48 kg N/km^2/yr), is different. This country has gradually been changing into a major importer of animal feed and cereals. For example, China's nitrogen imports from Brazil as soybean and soybean cake for feeding pigs and poultry increased from 0.7 to 2 Tg N/yr between 1999 and 2004 [*Smaling et al.*, 2008]. The difference between our A − H estimates and the net trade deficit by FAO statistics might result in part from the fact that FAO statistics include Hong Kong in China but not Taiwan, while the reverse is true for the IMAGE data.

[15] Brazil is another interesting case. According to our calculations, the Amazon Basin is a slightly heterotrophic system (−6 kg N/km^2/yr), reflecting the importance of livestock production in the region with imports of feedstuffs from other parts of Brazil. Other parts of Brazil such as the Cerrado savanna regions are autotrophic, as is the whole country (+25 kg N/km^2/yr), reflecting the production and export of food, feed and energy crops, and meat. Also, the densely populated coastal regions are heterotrophic.

[16] Figure 2, based on the A − H data at the watershed scale, provides a much higher-resolution image of the distribution of autotrophic and heterotrophic areas. Hot spots of autotrophy can be seen in western Europe, central North America, northern Asia, Australia and central Africa. Strongly heterotrophic areas are observed on the Indian subcontinent, sub-Saharan Africa and eastern Africa, but also in Japan, the eastern coasts of North and South America and Australia, and in some northwestern European regions. Except for the discrepancies discussed above, the general trends illustrated in Figure 2 are in agreement with the trade balance trends provided by FAO trade statistics [*FAO*, 2008a] (Figure 3).

[17] Another important point revealed by the data displayed in Table 1 is that the share of human consumption in total heterotrophy, although significant, is only about 16% at the global scale and reaches a maximum of 22% in South Asia; the weight of urban consumption in heterotrophy is still lower (8%) at the global scale (Table 1). This indicates that livestock nutrition, rather than human protein consumption, is by far the largest component (84%) of heterotrophy, because of a rather low efficiency of protein conversion in livestock farming [*Van der Hoek*, 1998].

3.2. Autotrophy-Heterotrophy of Watersheds and River N Export

[18] The Global NEWS dissolved inorganic, dissolved organic and particulate nitrogen models calculate the nitrogen fluxes, by form, delivered to the ocean by all the world's watersheds [*Dumont et al.*, 2005; *Beusen et al.*, 2005; *Harrison et al.*, 2005; *Seitzinger et al.*, 2010]. The distribution of nitrogen autotrophy versus heterotrophy for the 5600 largest watersheds in the database (those with an area greater than 5000 km^2) is illustrated in Figure 4: both autotrophy and

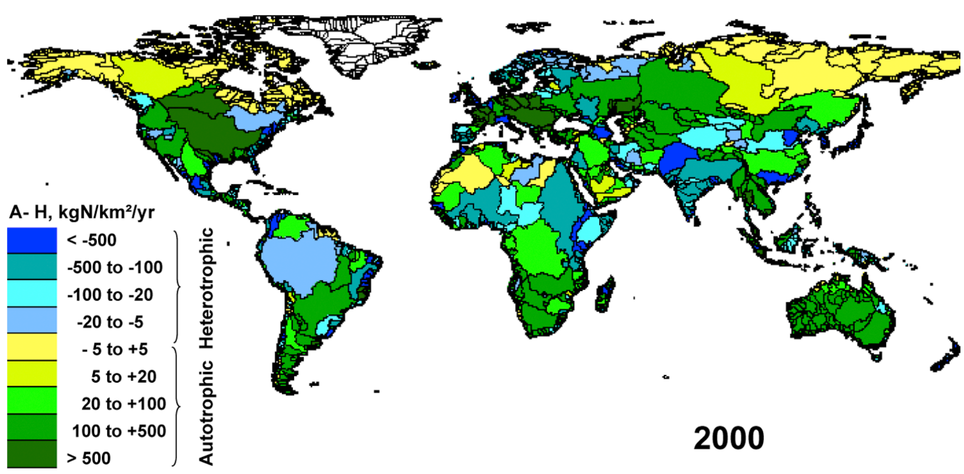

Figure 2. Difference between autotrophy and heterotrophy, expressed in kg N/km^2/yr, calculated at the watershed scale from the Global Nutrient Export from Watersheds (NEWS) database for 2000.

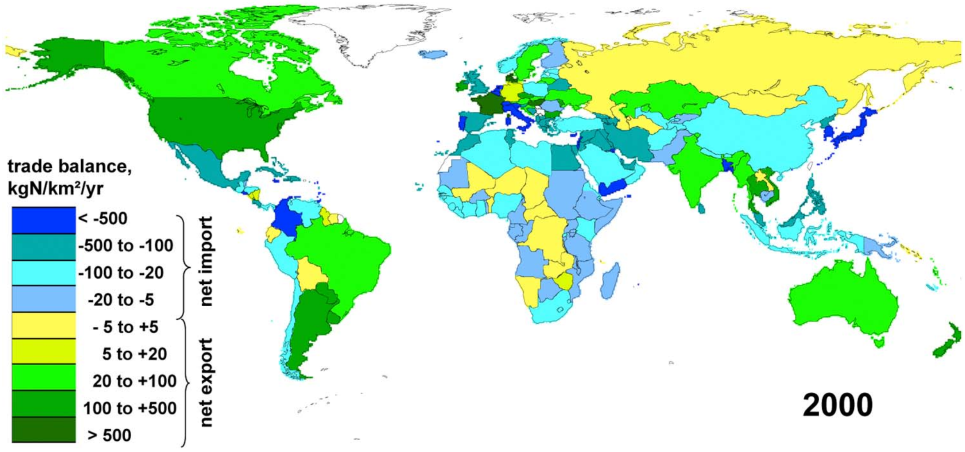

Figure 3. Balance of import and export of N as crops and livestock products by country in 2000, calculated from Food and Agriculture Organization of the U. N. (FAO) trade statistics.

heterotrophy vary from 0 to 10,000 kg N/km^2/yr. The median A/H ratio is 0.8. The position of a few typical basins is indicated in Figure 4. The Seine (France) and the Mississippi (United States) rivers are examples of strongly autotrophic basins, exporting a large part of their agricultural production outside the limits of their watershed [*Billen et al.*, 2009b]. The Po (Italy), the Hudson (U.S. east coast) and the Ganges (India) rivers are three examples of watersheds with rather intensive agricultural activity, but large livestock and population densities, making these areas clearly heterotrophic. The Thames River (United Kingdom) is slightly heterotrophic with very high autotrophy and heterotrophy, while the Kiso River (Japan) shows an extremely pronounced heterotrophic character due to urbanization of its watershed. The Hong (Red River, Vietnam) is nearly balanced (as already discussed by *Quynh et al.* [2005]). The four African watersheds taken as examples (Zaire, Nile, Niger and Limpopo) have much lower agricultural production and are nearly balanced.

[19] The concept of anthropogenic N autotrophy and heterotrophy has been developed for characterizing the perturbation of the nitrogen cycle leading to increased riverine nitrogen export from specific watersheds [*Quynh et al.*, 2005; *Billen et al.*, 2007]. Autotrophy is a summarizing indicator of the intensity of agriculture; heterotrophy is related to human and livestock nutrition, hence to production of excrement. It will be shown here that A and H (or more specifically a combination of the value of both terms, as measured by their vector sum in an A versus H diagram, as shown in Figure 4: $A\&H = (A^2 + H^2)^{1/2}$) are direct drivers of the hydrologic N flux from watersheds. However, this relation is not direct and cannot be demonstrated by a simple statistical approach for two reasons: (1) many other sources of nitrogen than those directly linked to agricultural production and consumption contribute to riverine nitrogen export; (2) hydrological conditions, as characterized namely by specific runoff, play a significant role in determining the fraction of nitrogen input to the watershed that is exported at the outlet of the river network.

[20] Let us first show that A&H is a good indicator of the overall anthropogenic perturbation of the nitrogen cycle. At the watershed scale, this perturbation can best be assessed by the net anthropogenic nitrogen inputs (NANI) as defined by *Howarth et al.* [1996], i.e., the sum of fertilizer application, crop nitrogen fixation and atmospheric deposition, all three values defined in the Global NEWS database, and net input of food and feed, the difference between heterotrophy and autotrophy. As shown in Table 3, a good correlation exists between NANI and A&H in the world's watersheds. This relationship is not trivial at all, as only the difference between H and A (and not their sum) is involved in the calculation of NANI; it indicates that agricultural production and human/

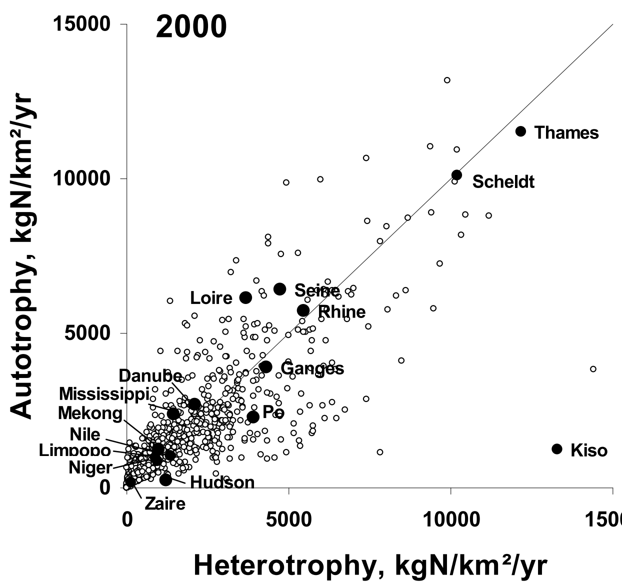

Figure 4. Autotrophy and heterotrophy of watersheds >5000 km^2 in 2000. The names of a number of selected watersheds taken as examples are indicated.

Table 3. Relationship Between Net Anthropogenic Nitrogen Input to Watersheds (kg N/km^2/yr) (y) as Calculated From the Global NEWS Database and the Vector Sum of Autotrophy and Heterotrophy ($\sqrt{A^2 + H^2}$)(y) for All Basins Larger Than 5000 km^2 on the Different Continents

Area	Relationship	n	R
Europe	$y = 1.4\,x + 309$	750	0.77
North America	$y = 1.2\,x + 52$	1754	0.88
South America	$y = 1.1\,x + 567$	448	0.81
North Asia	$y = 0.88\,x - 54$	664	0.79
South Asia	$y = 0.78\,x + 65$	737	0.85
Africa	$y = 0.78\,x + 428$	510	0.91
Australia and Oceania	$y = 1.1\,x + 196$	814	0.83
All continents	$y = 1.0\,x + 338$	5677	0.79

livestock consumption plays a central role in the various human activities leading to nitrogen enrichment of terrestrial systems, even though atmospheric deposition also contributes significantly.

[21] To demonstrate the relationship between NANI and nitrogen riverine export, the effects of non anthropogenic nitrogen inputs as well as the hydrological control by runoff must be taken into account. *Howarth et al.* [1996] and *Boyer et al.* [2002, 2006] suggested a general relationship between nitrogen delivery and either NANI or net total nitrogen input (NTNI) (net total anthropogenic nitrogen input = NANI + nonagricultural nitrogen fixation). They stressed, however, the role of hydrology as a factor controlling the fraction of NTNI transferred to the outlet with respect to the fraction retained or eliminated in the landscape. By comparing the Global NEWS model total N fluxes calculated with NTNI on the same watersheds (restricted to watersheds greater than 5000 km^2), we found that the fraction of exported NTNI shows a sigmoid relationship of runoff (Figure 5) so that total N export can be expressed as a simple relationship of NTNI and runoff, with very good agreement with the Global NEWS results (Table 4). Besides showing the coherency between the Global NEWS and the NANI/NTNI modeling approaches, this result points out that A&H is a useful metric in the context of hydrological nitrogen export.

4. Past and Future Trends (1970→2000→2030→2050)

[22] The database established by the NEWS group comprises a detailed global N surface balance not only for the year 2000, but also for 1970 on the basis of historical data, as well as for the four Millennium Ecosystem Assessment (MEA) scenarios projected to 2030 and 2050 [*Alcamo et al.*, 2006]. The latter correspond to four different views of the world's future, based on various combinations of international cooperation and environmental consciousness: Global Orchestration (GO), Order from Strength (OS), Technogarden (TG) and Adapting Mosaic (AM). The storylines of the four scenarios, the corresponding hypothesis regarding the development over time of the main drivers of change in agriculture, demography and economy, as well as the simulation of livestock production systems, land cover and land use based on the IMAGE 2.4 model [*Bouwman et al.*, 2006] are described in detail by *Bouwman et al.* [2009] and *Van Drecht et al.* [2009]. Only GO and AM, the most contrasted scenarios will be discussed here. In brief, the two scenarios differ in terms of demography (the 2050 global population projections reach 7.8 and 9.1 billion in the GO and AM scenarios, respectively), economic growth (the assumption is an annual GDP growth rate of 4.3%–4.7% in GO versus 3.0%–3.6% in AM for developing countries, and 2.3% in GO versus 1.7%–1.3% in AM for the industrialized world), human diet (per capita meat consumption is directly related to per capita GDP in both scenarios), and synthetic fertilizer use (human excreta are used as a substitute for synthetic fertilizers in AM). The resulting population, nitrogen autotrophy and heterotrophy figures, as well as the agricultural surpluses and deficits by continent are shown in Table 5. From 1970 to 2000, according to these figures, the world population grew from 3.5 to 5.8 billion inhabitants; agricultural production increased by 47%, slightly more than food and feed demand.

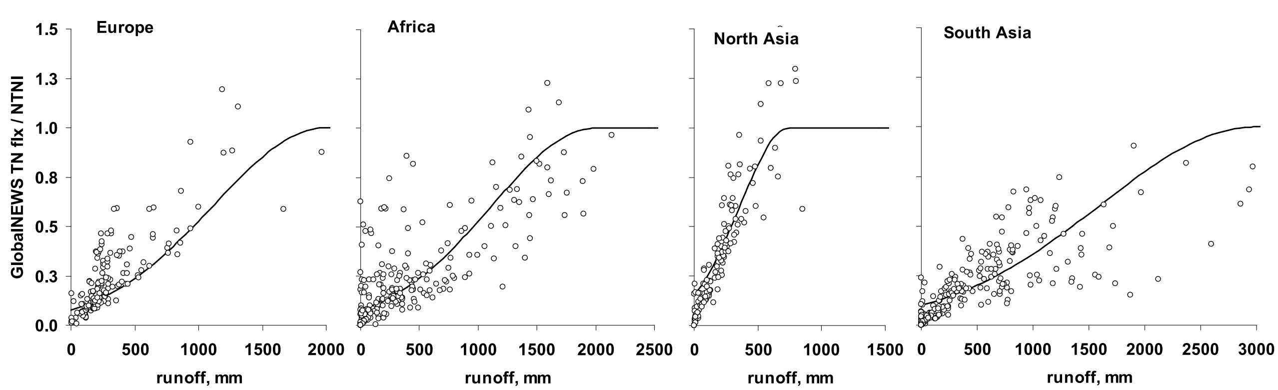

Figure 5. Relationship between the fraction of net total nitrogen input to the watershed (NTNI) exported at the outlet and runoff for different continents. The solid line is the best fit of a sigmoid relationship of the form $\exp(-(Q - Qm)^2)/Qs^2)$ where Q is the runoff (mm/yr) and Qm and Qs are two adjusted parameters (see Table 3).

Table 4. Correlation Between the Estimates of Total Nitrogen Flux Exported at the Outlet of All Basins Larger Than 5000 km^2 on the Different Continents From the F_{NTNI} and F_{GN} Approaches[a]

Area	Correlation (F_{NTNI} Versus F_{GN})	*Qm* (mm yr^{-1})	*Qs* (mm yr^{-1})	*n*	*r*
Europe	$F_{NTNI} = 1.04\ F_{GN} - 66$	2000	1250	750	0.91
North America	$F_{NTNI} = 1.08\ F_{GN} - 23$	1900	1275	1754	0.87
South America	$F_{NTNI} = 0.66\ F_{GN} + 131$	3000	2000	448	0.85
North Asia	$F_{NTNI} = 0.98\ F_{GN} + 31$	750	550	664	0.86
South Asia	$F_{NTNI} = 0.80\ F_{GN} + 254$	3000	1975	737	0.79
Africa	$F_{NTNI} = 0.99\ F_{GN} - 55$	2025	1125	510	0.91
Australia and Oceania	$F_{NTNI} = 0.75\ F_{GN} + 1$	3800	3000	814	0.72
All continents	$F_{NTNI} = 0.97\ F_{GN} + 120$	2025	1300	5677	0.78

[a]F_{NTNI} is calculated according to the simple relationship F_{NTNI} = net total nitrogen input (NTNI) × $\exp(-(Q - Qm)^2/Qs^2)$, where Q is the mean specific runoff (mm/yr) of each watershed and Qm and Qs are two continent-specific parameters characterizing the fraction of NTNI retained or denitrified in the watershed. F_{GN} is the sum of nitrogen exported as dissolved inorganic N, dissolved organic N, and particulate N calculated by the Global NEWS models.

Europe, North America and Australia increased their production, while their consumption has leveled off: this creates surpluses that compensate for the growing deficits of South Asia. Africa, which was producing surpluses in 1970, had a slight deficit in 2000 due to more rapidly increasing food and feed demand than production. In South America, autotrophy and heterotrophy increased at the same rate. Globally, the share of livestock accounted for 88% of total heterotrophy in 1970, a surprising figure in that it is higher than the rate for 2000 (84%), although human meat consumption increased during the period from 1970 to 2000. This is explained by an increase in the efficiency of protein conversion by livestock farming.

[23] The figures for 2030 and 2050 (Table 5) show the results for the two MEA scenarios. GO depicts a world with a high level of international cooperation that is successful in limiting demographic growth but promotes specialization of territories resulting in a high rate of international food and feed exchanges: although South Asia comes close to balance, Africa shows much more severe deficits, while Europe and North America further increase their surplus production. Globally, the figures obtained with the IMAGE model show a significant deficit of 7 Tg N/yr in 2050. Although this deficit remains below 5% of the predicted total production, it indicates strong pressure on food resources.

[24] In contrast, the AM scenario depicts a world in which locally based ecosystem management strategies are developed with a strongly proactive approach based on simple technologies privileging local economic circuits. World population increases more than in the previous scenario, but much less international trade is necessary to compensate for food deficits. Globally, autotrophy shows a positive balance over heterotrophy on the same order of magnitude as the deficit shown in the GO scenario. The share of livestock in total heterotrophy is predicted to be 80% by 2050 in the AM scenario, while it would be 85% in the GO scenario, owing to a lower proportion of animal protein in the human diet in the former than in the latter. The situation in the AM scenario differs particularly from GO for Africa, which develops much less heterotrophy in the former than in the latter scenario and, as a consequence, a much lower food and feed production deficit, in spite of a larger population. The same is true for South America. The same general trends are shown at the watershed resolution by the global maps of nitrogen autotrophy–heterotrophy for 1970 and 2050 for the two MEA scenarios (Figure 6; for comparison, see the 2000 situation shown in Figure 2).

[25] The individual trajectories of selected basins are displayed in Figure 7. In general, the dispersion of the watersheds from the origin and the diagonal of the ANAH diagram considerably increased from 1970 to 2000; it will continue to do so in the future according to the GO scenario, and to a lesser extent in the AM scenario. After a large increase in autotrophy between 1970 and 2000, Europe (Figure 7a) shows a trend toward stabilization in the GO or even decrease in the AM scenario, as shown for the Rhine and the Loire watersheds. In North America (Figure 7b), the Mississippi strongly increased its autotrophy from 1970 to 2000 and this trend continues in all cases, although to a lesser extent in the AM than in the GO scenario. In contrast, the Hudson basin, which was already severely heterotrophic in the 1970s, increases its heterotrophy in both scenarios; autotrophy completely vanishes by 2030 in GO but not in the AM scenario. Many Asian basins, such as the Ganges and the Mekong (Figure 7c), increase both their autotrophy and heterotrophy, yet remain close to equilibrium; the Kiso, due to increasing urban pressure in Japan, decreases its autotrophy and increases its heterotrophy, again to a lesser extent in the AM than in the GO scenario. In Africa (Figure 7d), the trend for the Nile, the Limpopo, and the Zaire basins shows a substantial increase in both autotrophy and heterotrophy, with an increase in the heterotrophic character in the GO scenario, while more balanced conditions are maintained in the AM scenario.

5. Discussion and Conclusion

[26] The concept of anthropogenic nitrogen autotrophy and heterotrophy (ANAH) of watersheds provides summarizing information about the organization of agricultural activities in a territory and the resulting perturbation they induce on the nitrogen cycle. The difference between autotrophy (agricultural production of food and feed) and heterotrophy (human and livestock consumption) is a measure of the net export (or import) of food and feed nitrogen. As a validation of our approach, we successfully compared our balance estimates by country with the balance of commercial exchanges of the most important crop and livestock products (Tables 1 and 2 and Figures 2 and 3). As previously shown by *Grote et al.* [2005] and *Burke et al.* [2009], the international trade of

Table 5. Population, Nitrogen Autotrophy and Heterotrophy, and Agricultural Surpluses or Deficits[a]

	Total Population (M inhabitants)	Percent Urban	Autotrophy (Tg N/yr)	Heterotrophy (Tg N/yr)	A − H (Tg N/yr)	Human Consumption (Tg N/yr)	Urban Consumption (Tg N/yr)
Europe (9 10^6 km^2)							
1970	585.0	62.4	16.4	17.1	−0.7	2.00	1.3
2000	651.3	72.2	17.6	15.4	2.2	2.5	1.8
GO 2030	654.8	78.8	18.8	14.6	4.2	3.0	2.4
GO 2050	651.3	82.2	19.2	14.6	4.6	3.4	2.8
AM 2030	593.1	78.6	18.0	13.3	4.7	2.6	2.0
AM 2050	536.3	81.9	17.9	12.5	5.4	2.5	2.1
North America (21 10^6 km^2)							
1970	301.2	67.6	10.1	13.2	−3.1	1.14	0.8
2000	454.7	74.7	17.8	13.9	4.0	1.9	1.4
GO 2030	585.6	81.7	23.5	18.1	5.4	2.9	2.4
GO 2050	644.2	84.7	26.2	20.3	5.9	3.7	3.1
AM 2030	610.2	81.3	22.1	16.8	5.4	2.8	2.3
AM 2050	689.3	84.2	24.0	18.0	6.0	3.5	3.0
South America (18 10^6 km^2)							
1970	180.7	59.4	10.2	10.7	−0.5	0.57	0.3
2000	325.6	79.0	16.6	16.9	−0.3	1.1	0.9
GO 2030	423.6	87.6	24.9	27.0	−2.0	1.7	1.5
GO 2050	457.0	90.9	28.3	31.1	−2.8	2.2	2.0
AM 2030	490.1	87.6	23.3	24.3	−1.0	1.8	1.6
AM 2050	574.6	90.9	25.8	26.3	−0.4	2.4	2.2
North Asia (16 10^6 km^2)							
1970	86.4	48.7	4.7	3.7	1.1	0.26	0.1
2000	130.7	53.1	3.8	2.9	0.9	0.4	0.2
GO 2030	169.1	58.7	5.0	3.8	1.1	0.6	0.3
GO 2050	184.8	63.3	5.4	4.5	0.8	0.7	0.5
AM 2030	177.3	58.1	4.5	3.4	1.1	0.6	0.3
AM 2050	198.2	62.7	4.9	3.8	1.1	0.7	0.5
South Asia (25 10^6 km^2)							
1970	1869.5	21.9	24.6	25.7	−1.0	5.15	1.2
2000	3182.8	35.6	42.1	44.5	−2.4	9.8	3.6
GO 2030	3959.8	51.2	73.0	72.4	0.6	14.4	7.6
GO 2050	4059.3	59.4	83.3	82.9	0.4	17.6	10.7
AM 2030	4413.1	50.6	65.0	65.6	−0.6	15.0	7.7
AM 2050	4845.6	58.6	71.8	72.3	−0.6	18.4	10.9
Africa (29 10^6 km^2)							
1970	339.0	22.6	11.3	10.2	1.1	0.96	0.2
2000	756.3	36.2	17.2	19.1	−1.9	2.2	0.8
GO 2030	1183.3	51.2	31.7	42.7	−11.0	3.5	1.8
GO 2050	1382.0	59.8	39.5	57.6	−18.0	4.6	2.7
AM 2030	1405.1	51.3	25.6	29.9	−4.3	4.1	2.1
AM 2050	1845.8	59.9	30.3	35.8	−5.5	5.7	3.4
Oceania/Australia (10 10^6 km^2)							
1970	149.7	26.0	5.5	4.9	0.6	0.43	0.1
2000	270.2	47.7	6.7	5.4	1.2	0.9	0.4
GO 2030	353.9	66.9	9.7	8.2	1.5	1.4	0.9
GO 2050	377.4	74.1	10.8	9.5	1.3	1.8	1.3
AM 2030	394.9	66.5	8.9	7.2	1.7	1.4	1.0
AM 2050	452.4	73.6	9.6	7.9	1.7	1.9	1.4
World total (128 10^6 km^2)							
1970	3511.4	35.4	82.9	85.5	−2.6	10.5	4.0
2000	5771.6	46.3	121.9	118.1	3.8	18.7	9.2
GO 2030	7330.1	59.1	186.7	186.8	−0.2	27.5	16.9
GO 2050	7756.1	66.2	212.7	220.6	−7.8	34.0	23.1
AM 2030	8083.8	58.3	167.5	160.5	7.0	28.3	17.1
AM 2050	9142.1	65.0	184.3	176.5	7.7	35.1	23.5

[a](A − H) by continent in 1970–2000 and in 2030 and 2050 for Global Orchestration (GO) and Adapting Mosaic (AM) Millennium Ecosystem Assessment (MEA) scenarios.

agricultural products currently comprises quite significant transfers of nitrogen between continents. A large share of these transfers is related to livestock nutrition, which accounts for more that 80% of global heterotrophy.

[27] We showed that both area-specific autotrophy and heterotrophy (more specifically, their vector sum in an ANAH diagram) is strongly correlated with the net anthropogenic nitrogen inputs to watersheds, which is itself related to riverine export of nitrogen (Table 3 and Figure 5). This implies that not only the intensity of autotrophy and heterotrophy of a watershed, but also the degree of imbalance between them, are factors of nitrogen loss to hydrosystems.

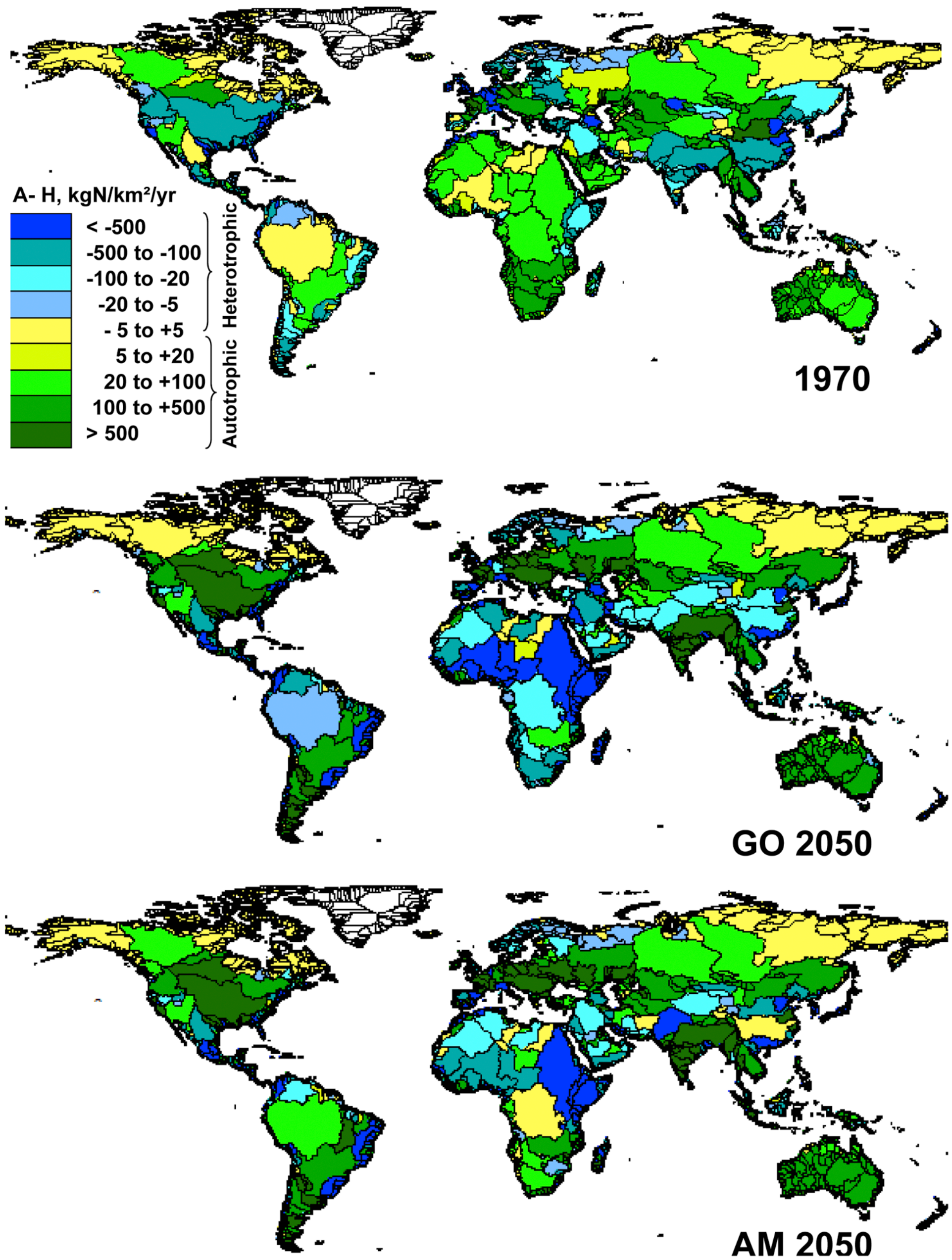

Figure 6. Difference between autotrophy and heterotrophy, expressed in kg N/km^2/yr, calculated at the watershed scale from the Global NEWS database for 1970 and 2050 according to the Millennium Ecosystem Assessment (MEA) Global Orchestration and Adapting Mosaic scenarios (see Figure 2 for the situation in 2000).

Characterizing a watershed by its autotrophy and heterotrophy thus directly reveals the exchanges of nitrogen across its boundaries through both hydrological and commercial fluxes, two major, closely interrelated aspects, besides atmospheric transport, of the current opening of the N cycle on the regional and global scale.

[28] Our hindcast analysis for 1970–2000 showed that most watersheds in the world shifted during this period toward either more autotrophic or more heterotrophic conditions. During the same period, the total flux of nitrogen associated with the international trade of food and feed increased from 3.5 Tg N/yr in 1970 to 8.9 Tg N/yr in 2000 [*FAO*, 2008a]. According to the MEA scenarios, this trend will be reinforced during the next 50 years, although to a lesser extent in the Adapting Mosaic scenario (22 Tg N/yr) than in the Global Orchestration scenario (30 Tg N/yr). The former scenario, which involves implementation of proactive actions based on simple technologies at the local scale, although it would result in a higher global population at the 2050 horizon, would paradoxically lead to lower inputs of nitrogen to the coastal

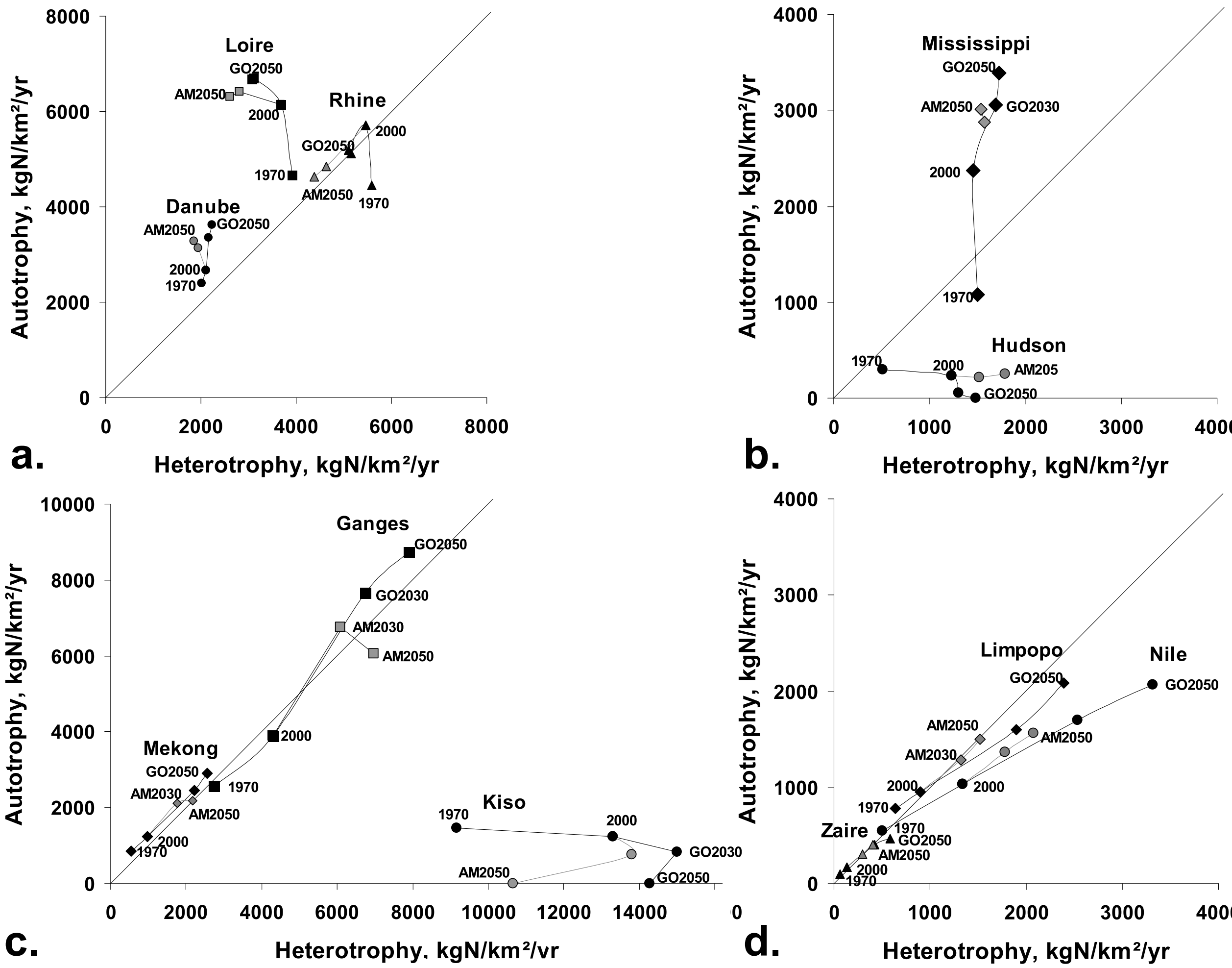

Figure 7. Trajectories of selected basins in the anthropogenic nitrogen autotrophy and heterotrophy (ANAH) diagram over the 1970–2000 period and 2030–2050 for Global Orchestration (GO) (black symbols) and Adapting Mosaic (AM) scenarios (gray symbols): (a) European basins: Loire (squares), Rhine (triangles), and Danube (circles); (b) North American basins: Mississippi (diamonds) and Hudson (circles); (c) South Asian watersheds: Ganges (squares), Mekong (diamonds), and Kiso (circles); (d) African watersheds: Nile (circles), Zaire (triangles), and Limpopo (diamonds).

ocean (44 Tg N/yr) than the GO scenario (50 Tg N/yr) [*Seitzinger et al.*, 2010].

[29] The estimations presented here did not consider the contribution of energy crops to total crop N uptake. This was negligible in 1970 and in our 2000 reference. The MEA considered an important role of biofuel production in land use changes only in one of its four scenarios (Technogarden), where it accounts for up to approximately 4% of the global total agricultural area in 2030 and 12% in 2050 [*Bouwman et al.*, 2009]. In the other three scenarios, the area cropped to biofuels is considered less than 2% of the total agricultural area in 2050. We therefore did not include this aspect in the present paper, which only analyzes the GO and AM scenarios. However, the fraction of crop production for biofuels has become substantial in some countries by 2009, e.g., the United States and Brazil [*Howarth and Bringezu*, 2009], and is likely to increase in the coming years at a rate that has probably been underestimated by the MEA scenarios. As it could potentially affect the equilibrium between autotrophy and heterotrophy, this aspect deserves further consideration.

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