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Food and feed trade as a driver in the global nitrogen cycle: 50-year trends

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Abstract The alteration of the global nitrogen (N) cycle is creating severe environmental impacts. This paper analyses the increasing importance of the international trade of food and feed in the alteration of the N cycle at the global scale in two ways. First, using the information on food and feed trade across world countries, and assuming that N constitutes 16 % of proteins, we quantified the N annually traded in the period 1961–2010. We observed that in that period, the amount of N traded between countries has increased eightfold (from 3 to 24 TgN) and now concerns one-third of the total N in world crop production, with the largest part corresponding to animal feed. Secondly, we divided the world into 12 regions and studied the N transfer among them in two reference years: 1986 and 2009. The N flow among these regions has dramatically intensified during this period not only due to an increase in the population but also in the proportion of animal protein in the diet of some countries. Nowadays, in terms of proteins and N, a small number of countries (e.g., USA, Argentina and Brazil) are feeding the rest of the world. At the global scale the system is becoming less efficient because of the disconnection between crop and livestock production across specialised regions, increasing the environmental impacts. As human diet is an additional clear driver of the observed changes, the solutions must rely not only on the producers, but also on the consumers. The results of our study provide new insights into the food dependency relationships between the different regions of the world as well as the growing importance of international food and feed trade in the global N cycle.

Keywords International trade · Global nitrogen cycle · Crop production · Livestock production · Human diet

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Introduction

The global agricultural sector has been deeply transformed during the past few decades. The number of people employed in agriculture has declined (25 % in 1961–2004 period) while production has increased (150 % for cereals in 1961–1998 period) (Anderson 2010; Tilman et al. 2002). The intensification of agriculture together with the expansion of agricultural land have led to a significant rise in total agricultural production (Godfray et al. 2010), but have been accompanied by numerous adverse environmental consequences on freshwater and terrestrial resources, climate and air quality (Foley et al. 2005).

Agriculture is one of the major contributors to the alteration of the global nitrogen (N) cycle. The extensive use of synthetic nitrogen fertiliser, produced by the Haber–Bosch process, has sustained the increase in agricultural production and has provided food for a growing population (Erisman et al. 2008). However, this increase in production has also introduced substantial new reactive nitrogen (Nr, i.e. any nitrogen compound other than N_2) to the environment. This reactive nitrogen can then contribute to negative impacts on air and water quality, which are magnified by the nitrogen cascade (Galloway et al. 2003, 2008; Romero et al. 2013; Sutton et al. 2013).

One remarkable aspect of the changes in the global agricultural system is the significant increase of the international flows of food and feed. International trade of agricultural products has increased by a factor greater than 10 during the past six decades, and it is expected to continue to grow in the future, further increasing land-use changes, greenhouse gas (GHG) emissions, and reactive nitrogen losses (Schmitz et al. 2012). The demand for more protein rich food in regions with increasing population has been a major driver for this change, together with the reduction of costs, and the generalization of several international liberalization measures. For example, the Blair House Agreement (1992) finalized the Uruguay Round of the General Agreement on Tariffs and Trade (GATT), which established a ceiling to European oilseed production and favoured imports of soybeans from Americas to Europe (Anderson 2010; Josling et al. 2010).

The increased opportunities of food and feed trading, as well as the availability of synthetic N fertilizers providing an alternative to manure, have allowed the territorial specialization of large regions into either crop or livestock farming, often creating a disconnection of crop production from livestock breeding (Naylor et al. 2005; Billen et al. 2010). Indeed, crop production of large territories can be sustained by the application of synthetic fertilizers without the need for animal manure, while other areas specialize in meat and milk production sustained by feed imports from distant areas (Billen et al. 2010).

The trading of food and feed has also altered the input of new reactive nitrogen brought to a region, in a way similar to the nitrogen input associated with synthetic fertilization. In fact, as food and feed contain proteins, and proteins are composed by $\sim$16 % of nitrogen, the trade of food and feed also results in a movement of nitrogen from one region to another (Grote et al. 2005; Galloway et al. 2007; Burke et al. 2009; Swaney et al. 2012).

The influence of trading on N global fluxes is however more complex than merely the N flows associated with import or export of food and feed. During the crop and animal production process, part of the reactive N added by fertilisers and feed, respectively, is lost to the environment, impairing air and water quality. This input of N required for the production of a commodity that is not embedded in the final consumed good has been defined as "virtual nitrogen" (Galloway et al. 2007; Burke et al. 2009; Leach et al. 2012). Virtual nitrogen includes all nitrogen that is released to the environment throughout the entire food production process but that is not contained in the final consumed food product. Most of the N losses to the environment, and therefore their negative impacts, are located where the goods are produced. So the magnitude of the commercial exchanges of agricultural products complicates the localization of the environmental losses of reactive nitrogen linked to agriculture and food production. Trading may distance the environmental impacts far away from the place where the goods are consumed. Some world regions can receive large amounts of reactive N in the form of food and feed (Billen et al. 2010; Lassaletta et al. 2012, 2013) while the negative consequences of the production of these imported commodities remain in the producer countries.

The human alteration of the N cycle on a global scale is significant and is driven by increased creation of reactive nitrogen due to food and energy production. In 2010, human activities created $\sim$210 Tg of reactive nitrogen compared to $\sim$58 Tg of reactive N by natural processes (i.e., BNF) on continents (Fowler et al. 2013; Vitousek et al. 2013). Once created, anthropogenic reactive nitrogen can be distributed via the atmosphere, rivers, and international trade. While the first two distribution mechanisms are important, they are mostly regional in scope due to the short residence times of Nr in the atmosphere and to the inherently regional character of hydrosystems. However, distribution via international trade is by definition global in scale and accounts for the majority of the

N that is transported on the intercontinental scale. For these reasons, international trade exchanges of agricultural products have to be considered as major biogeochemical processes, shaping the nitrogen cycle at the global scale.

This paper analyses for the first time the trends in terms of nitrogen content of all the agricultural products (food, feed and fibers) traded between all world countries during the last 50 years. First we study the evolution of the total N embedded in agricultural products that is exchanged between countries at the global scale from 1961 to 2010. Secondly, we analyse the evolution of the dependence of each world country on food and feed imports, which allows us to define groups of contiguous countries having similar trajectories from that respect. Finally, we provide a geographically explicit description of the N fluxes between these regions in 1986 and 2009. The results provide new insights into the food dependency relationships between the different regions of the world as well as the growing importance of international food and feed trade in the global N cycle.

Materials and methods

This work is mainly based on the data provided by the Trade Module of the FAOSTAT database (http://faostat.fao.org/) for world countries. The Module contains the information on commodities traded across countries, including food, feed and fiber. Two levels of information are available per country: (1) the total annual import and export (total trade), and (2) the annual import and export from/to all the other countries (trade per country), thus including the geographical information about the origins of imports and the destination of exports. Data on total trade are available for 210 countries for the period 1961–2010, while data on trade per country are available for 143 countries and cover the period 1986–2009. For the latter, 92 % of the world's population and 91 % of the world's crop production reside in the reported 143 countries (2009 data).

Trends in total N traded

To study the long term variations of the total N embedded in agricultural products that is exchanged between countries at the global scale, we used the yearly information on imported quantities for 535 commodities over the 1961–2010 period (data on total trade). We assigned the N content to every product (407 vegetable, 128 animal products) with data from different sources (McDougall et al. 1993; FAO 2011; Asmala et al. 2011; USDA 2012; Lassaletta et al. 2012) (list available as Supplementary Material S1), and we finally calculated the total amount of N globally exchanged every year by summing up the import of all countries. At the global scale the sum of imports of agricultural products should correspond to the sum of exports; however, data are self-reported by countries, and some slight discrepancies exist. We used the data on imports as they were more accurate when comparing the total trade and the trade per country data in the FAOSTAT database. The same calculation carried out based on exported quantities provides a figure differing only by 2.6 %. In our analysis we considered all commodities belonging to food, feed and fibers, but as the latter represent only 0.15 % (in terms of protein content) of the total crop production, in the rest of the analysis we refer to only food and feed, although fibers are included in the computations.

Net importer and net exporter countries

Using the data on total trade, we calculated the difference between the total N imported and exported for each of the 210 countries for the years 1961, 1986 and 2010. We chose these years to analyse the temporal changes, as they represent the oldest data, the newest data, and a midpoint. We call a country a *net importer* (with respect to N or protein) when total imports of N are higher than total exports; a country is a *net exporter* when the N export exceeds the import. We refer to the difference (N import–N export) as Net Import. We define as *highly net exporting* a country where the Net Import is lower than −50 GgN and a *highly net importing* a country where the Net Import is higher than 50 GgN. In 2010, these two classes concern about one-third of the world countries.

N traded among world regions

To provide a geographically explicit description of the net exchanges between different parts of the world, we used the detailed FAOSTAT data on trade per country (http://faostat.fao.org/). This database provides the amount of each product that is imported to a country, broken down into the amount from each country exporting that product to the importing country. The first year with available information at this level of detail is 1986 and the last year is 2009. Thus 1986 and 2009 were considered for the temporal analysis. We calculated the difference between imports and exports for each pair of countries. Then the world's countries were grouped into 12 regional units (Supplementary Fig. S2) based on their geographical proximity and on their behaviour as a net importer or net exporter in 2009. Here again, the data on exports could have been used instead, but the import data were preferred as they are more accurate in the FAO database (the difference between total N traded of the detailed vs. the global approach estimated using the imports is only 3 % while for exports is 15 %). We prepared a squared matrix where the net N import between any pair of countries was represented. This matrix and the grouping by region were translated into maps, showing the net N import (or export) of a region from (or to) each other country and region for the two reference years 1986 and 2009. Unfortunately, the detailed information on trade per country is not available for all 210 countries included in the total trade data. In particular, information for sub-Saharan African countries is often not reported in the FAOSTAT database (and for this reason not presented in the resulting maps). However, the total volume of traded N considered in this detailed approach represents, for 1986 and 2009, respectively, 77 and 95 % of the total global fluxes estimated using total trade data (according to the methodology presented in "Trends in total N traded" section).

To prepare the maps, the internal fluxes among countries of the same region were calculated and subtracted. Finally, we estimated the percentage of the net N import over total crop production in each region, with the aim to compare the new production of N (and proteins) with the net input from outside the region. To do so, we estimated the total yearly agricultural N production of the 178 primary crops cultivated in all countries (1986 and 2009). The N content was assigned to each product and this was multiplied by their total production as given in the Production Module of the FAOSTAT database. The crop production of each country belonging to each region was added to obtain the region's total primary agricultural production. We used the proportion of net N imported as food and feed with respect to local production as an indicator of the region's self-sufficiency or dependence on protein imports from other regions. Total animal protein production by region was also estimated using the 18 categories of meat, 5 categories of milk and 1 of eggs provided in the Livestock Primary Module of the FAOSTAT database and multiplying each one for its respective N content. Diet characteristics, namely N available per capita and year, and percentage of N of animal origin, were calculated from the Food Supply Module of the FAOSTAT database.

Re-exportation of imported commodities can cause a bias in country by country trade balance analysis (Burke et al. 2009; Schipanski and Bennett 2012). To evaluate the effect of re-exports in our calculations, we have estimated the proportion of re-exportation for the most traded products, namely soybeans, wheat, maize and rice (including their co-products), which together represent 65 % of the total international fluxes. We estimated the re-export for each product country by country for 2009 by using both the conservative approach of Schipanski and Bennett (2012) and the one used by Burke et al. (2009) each representing a maximum estimate. The re-exportation of these 4 commodities represents between 5 and 9 % of the total exportation according to these two methods. Moreover, the re-exported commodities are traded mostly within the same region and have therefore no effect on our regional approach. We therefore neglected the effect of re-exports on our analysis.

Results

Trends of total N traded

The total amount of N traded, embedded in the 535 commodities, between world countries has increased almost eightfold during the past 50 years from 3.0 TgN in 1961 to 23.6 TgN in 2010, whereas total crop and animal protein production has increased only threefold (from 25.2 TgN in 1961 to 79.4 TgN in 2010 for crops and from 3.8 to 11.4 TgN for animal products). The share of the different commodities in this total has also changed: in the 1960s, 48 % of N traded consisted of cereals, 17 % animal products and only 11 % of soy products, while the latter now represents the largest share (44 %) and cereals and animal products only 26 and 9 % of the total,

Fig. 1 Long term variation of the amount of N internationally traded throughout the world. Traded products have been grouped in categories. Soybeans category includes soybean cake. The category "others" includes all fruits, tubers and vegetables for human consumption

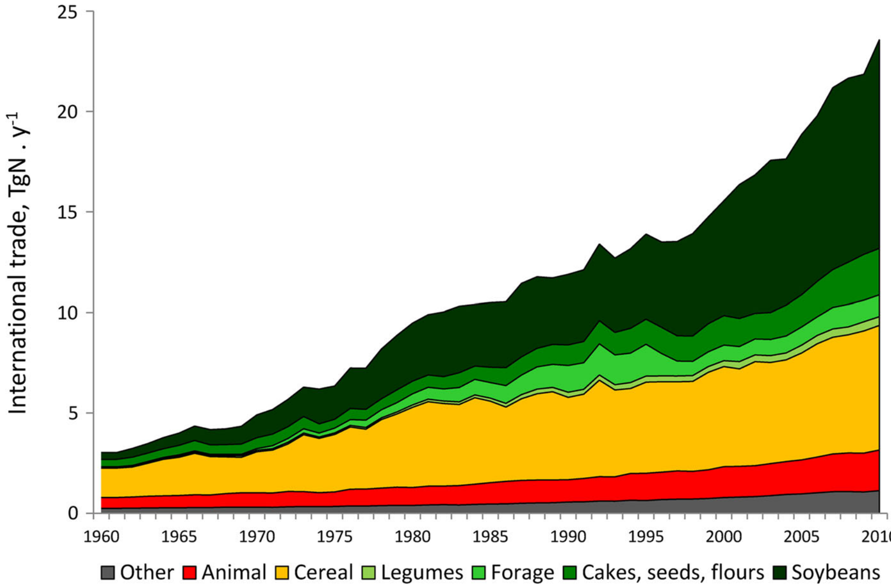


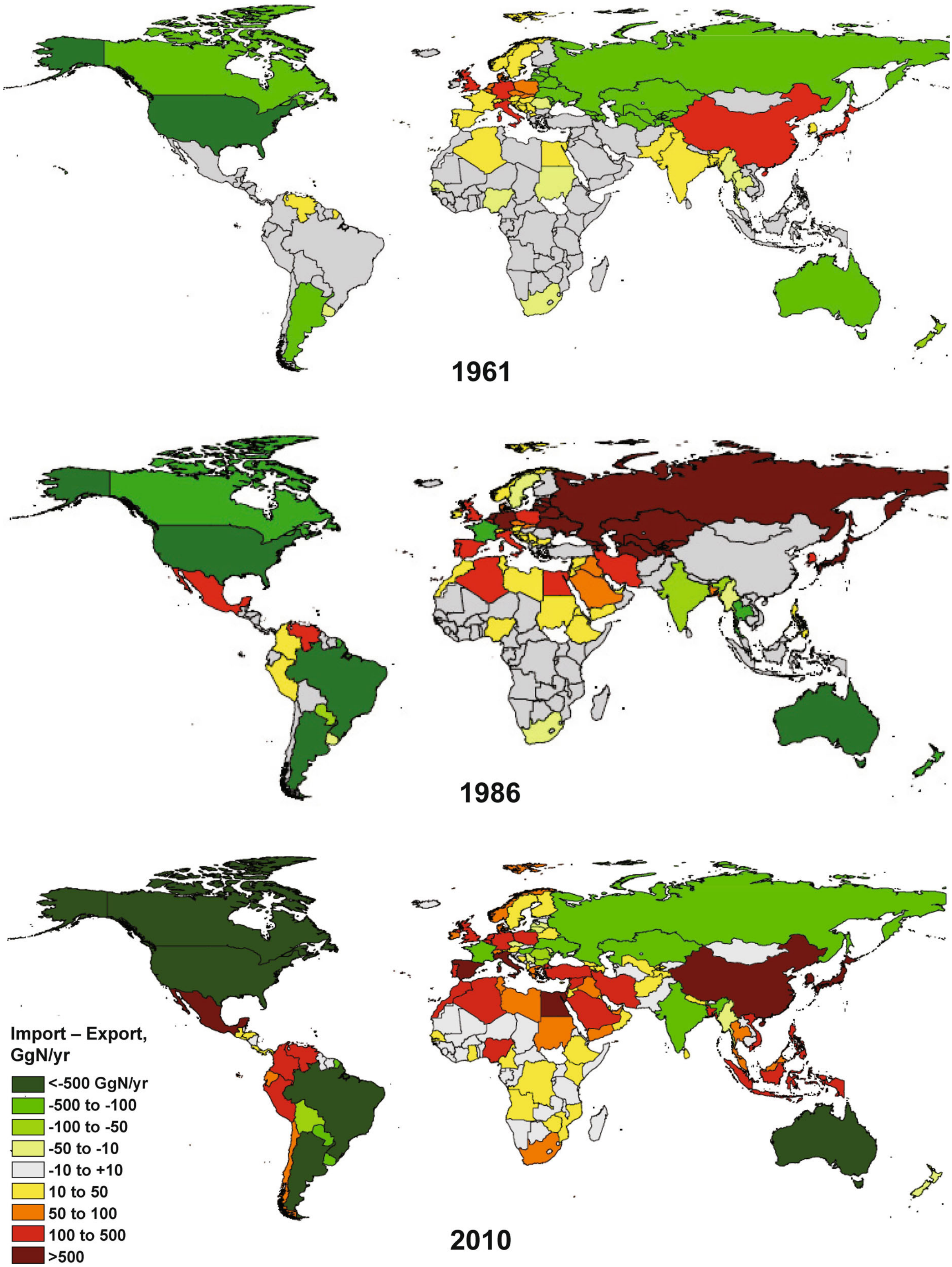
Table 1 Contribution of the most traded commodities to the global net N exchanges

1961			1986			2010		
Commodities	GgN	%	Commodities	GgN	%	Commodities	GgN	%
Wheat	782	26	Wheat	1,719	16	Soybeans	5,816	25
Soybeans	249	8	Soybeans	1,647	16	Soybean cake	4,589	19
Maize	217	7	Soybeans cake	1,616	15	Wheat	2,817	12
Wool, greasy	187	6	Maize	895	9	Maize	1,630	7
Barley	128	4	Gluten feed & meal	753	7	Gluten feed & meal	586	2
Rice	105	3	Barley	346	3	Rapeseed cakes	564	2
Other	1,364	46	Other	3,547	34	Other	8,169	33
Total N trade	3,032			10,523			23,585	

respectively (Fig. 1). Taking into account that almost all soy products, cakes, seeds, flours, fodder crops and a substantial part of cereals are used as feed, this clearly indicates that the largest part of the current international trade is devoted to feeding animals. Table 1 shows the most imported individual commodities in terms of N fluxes. A small number of products among the list of 535 contribute to a large part of the total imports. In 2010 81 % of the exported soy commodities were produced in USA, Brazil and Argentina. Assuming that the percentage of plant N derived from N_2 biological fixation in soybean crops is 60 % for USA and 80 % for Brazil and Argentina (Herridge et al. 2008), almost one-third of the N embedded in international trade was biologically fixed, whereas in 1961 N fixed in soybean only represented a little more than 5 % of the N in traded proteins.

Net importer and net exporter countries

A countries status as net N importer or exporter over time is shown in Fig. 2 and Supplementary Table S3a. With only a few exceptions (like South Africa), the behaviour of individual countries has not changed but previous trends have strongly intensified: many countries have evolved from near equilibrium between nitrogen imports and exports in food and feed to a much more unbalanced situation (Supplementary Table S3b).


1961
1986
2010
Import – Export, GgN/yr
<-500 GgN/yr
-500 to -100
-100 to -50
-50 to -10
-10 to +10
10 to 50
50 to 100
100 to 500
>500

◀ **Fig. 2** Net import or export of N embedded in traded commodities for each country for the years 1961, 1986 and 2010. *Green* countries = exportation is higher than the importation, i.e. net exporting N; *yellow–red* countries = countries that are net importing N; *grey* countries = imports and exports are balanced. (Color figure online)

The number of highly net exporting countries has not increased very much (from 6 in 1961 to 16 countries in 2010, out of the 210 countries analysed), but the the amount of N exported increased from 1,645 to 15,322 GgN/year (Supplementary Table S3b). For example, Argentina's net exports totaled 197 GgN in 1961 and 3261 GgN in 2010, and Brazil net exports totaled only 4 GgN in 1961 but has become the third most exporting country of the world with 2,778 GgN exported in 2010.

In contrast, the number of highly net importing countries has significantly increased. Only 10 countries were net importers of more than 50 GgN in 1961, whereas in 2010 the number of such countries has increased to 47. Several Mediterranean, American and Asian countries are now very far from a balanced situation, net importing a large amount of food and feed. This analysis reveals a world with increasing specialization and interdependence, where quite a small number of highly productive countries (e.g., USA, Argentina and Brazil) are supplying protein to an increasingly large number of dependent countries (e.g., China, Japan, Mexico, Spain and Egypt).

N traded between world regions

Based on their geographical proximity as well as their behaviour as net importers or exporters of nitrogen by food and feed trade, world countries were grouped into 12 regions throughout the world, namely: sub-Saharan Africa (Africa), Maghreb and Middle East (Maghreb–M. East: all North African countries from Morocco to Egypt and all West Asian countries including Pakistan), China, Central and South-Western America (C. & SW. America), Europe, the Former Soviet Union (F.S.U.), India, Japan–South Korea (Japan–S. Korea), North America (N. America), South-East Asia (S.-E. Asia), the South American Soy Countries (including Brazil, Argentina, Uruguay, Paraguay and Bolivia) and Oceania (Supplementary Fig. S2). With a few exceptions, most countries considered in this analysis had complete data for both 1986 and 2009. Table 2 shows the net importer or net exporter status of the 12 regions for both periods. Only China and the Former Soviet Union have switched from net exports to net imports. China has changed from a small net exporting country to a highly unbalanced country that imports large amounts of feed. The other regions have significantly intensified their imbalances. In addition to China, the most remarkable increases correspond to S.-E. Asia, C. & SW. America and Maghreb–M. East since they have increased their net import nine-, four- and threefold, respectively. On the other hand, S. American Soy Countries have increased their nitrogen exportation fivefold. Only Europe and Oceania have remained at a constant level of net exporting and net importing, respectively. Regarding the fluxes between regions (Fig. 3), changes between 1986 and 2009 can be observed not only in the magnitude, but also in the origin and destination of the N trade.

Table 2 Net N import in the regions studied in 1986 and 2009 (positive values are net imports and negative values net exports)

Region	Net import (GgN)	
	1986	2009
Africa	116	338
Maghreb and Middle East	535	1,656
China	−308	2,895
Central and South-Western America	332	1,330
Europe	2,170	2,337
Former Soviet Union	555	−622
India	−47	−188
Japan and S. Korea	1,486	2,296
N. America	−3,433	−4,850
Oceania	−461	−458
S.-E. Asia	57	528
S. American Soy Countries	−1,002	−5,263

Regions net importing N

In 1986, the Maghreb–M. East (Supplementary Fig. S4) was importing nitrogen from N. America, Europe and Oceania. By 2009 the net import quadruplicated and the region was also importing N from the S. American Soy Countries and the F.S.U. (Supplementary Fig. S4). Similarly, today the S.-E. Asia (Supplementary Fig. S4) is net importing N from the S. American Soy Countries, N. America, India and Oceania, although it is also net exporting N to Japan–

S. Korea, Europe and China. The number of regions from which Japan–S. Korea (Supplementary Fig. S4) is net importing N has increased significantly and even the African countries considered in this study (not represented) are exporting N to this region. The highly net importing behaviour of China (Fig. 4a, b) in the present period is mainly generated by the intense import of feed products from N. America and the S. American Soy Countries.

Europe has remained a net importer, but the magnitude and source of its imports has changed over time (Fig. 4c, d). N. America used to be an important supplier of N to Europe, more recently that role has been filled by S. American Soy countries, while N. America is now providing only the same amount of N as the F.S.U. Europe also used to import N from China, whereas the net flux of N is now into China from Europe.

Fig. 4 N fluxes from some of the studied regions to the other regions and countries for the years 1986 and 2009. The region analysed in each map is marked in *black*. *Green* countries are those which are net exporting N to the analysed region. *Yellow–red* countries are those which are net importing N from the analysed region (negative values). (Color figure online)

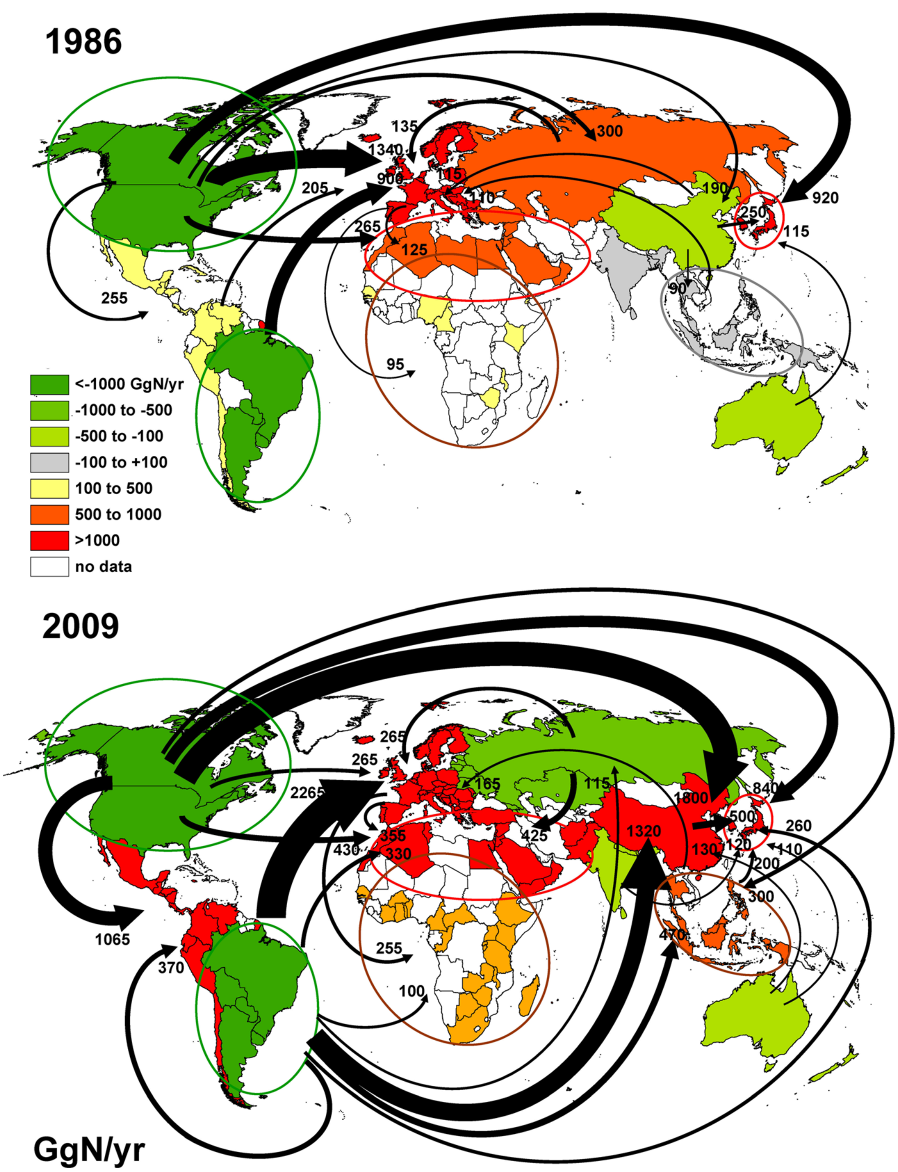


Fig. 3 N fluxes from each region to the others for the years 1986 and 2009. *Arrows* show the fluxes between the regions (only fluxes higher than 90 GgN are represented)

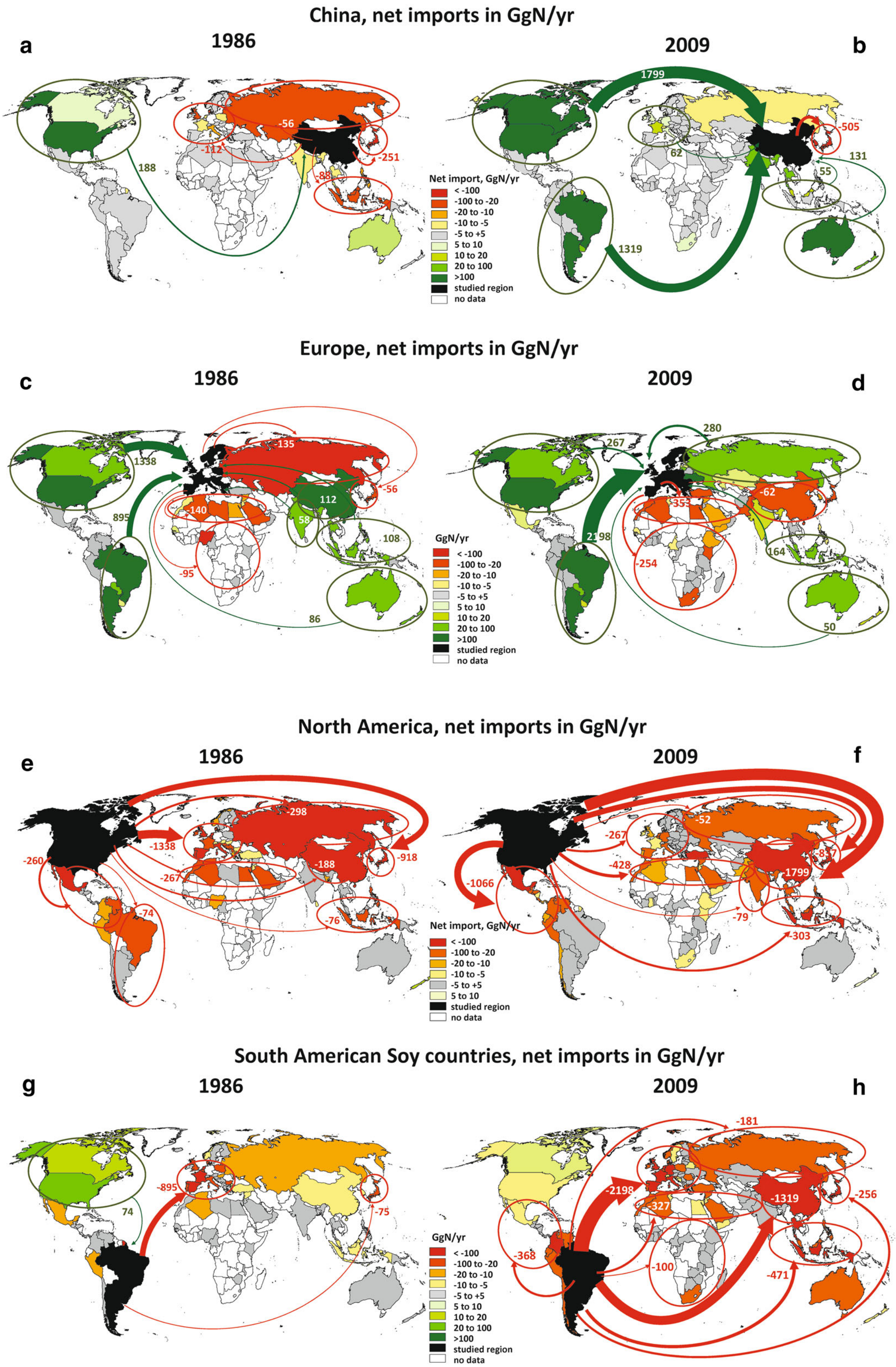

China, net imports in GgN/yr
a
1986
2009
b
188
-56
-112
-251
-88
1799
62
-505
131
55
1319
Net import, GgN/yr
< -100
-100 to -20
-20 to -10
-10 to -5
-5 to +5
5 to 10
10 to 20
20 to 100
>100
studied region
no data
Europe, net imports in GgN/yr
c
1986
2009
d
1338
-135
-56
112
58
895
-140
108
-95
86
280
267
-62
-353
2198
-254
164
50
GgN/yr
< -100
-100 to -20
-20 to -10
-10 to -5
-5 to +5
5 to 10
10 to 20
20 to 100
>100
studied region
no data
North America, net imports in GgN/yr
e
1986
2009
f
-298
-1338
-918
-260
-188
-267
-74
-76
-52
-267
-857
-428
-1799
-1066
-79
-303
Net import, GgN/yr
< -100
-100 to -20
-20 to -10
-10 to -5
-5 to +5
5 to 10
studied region
no data
South American Soy countries, net imports in GgN/yr
g
1986
2009
h
-895
74
-75
-181
-2198
-1319
-256
-327
-368
-100
-471
GgN/yr
< -100
-100 to -20
-20 to -10
-10 to -5
-5 to +5
5 to 10
10 to 20
20 to 100
>100
studied region
no data

Table 3 Regional dependence on imports expressed by the ratio of net import to regional production

Region	Ratio of net import to regional production (%)	
	1986	2009
Africa	18	17
Maghreb and Middle East	30	47
China	−4	22
Central and South-Western America	31	85
Europe	33	26
Former Soviet Union	10	−13
India	−1	−3
Japan and S. Korea	238	453
N. America	−27	−32
Oceania	−70	−49
S.-E. Asia	3	18
S. American Soy Countries	−26	−60

Regions net exporting N

Between 1986 and 2009 N. America (Fig. 4e, f) has reduced its net exports to Europe but has dramatically increased its exports to China, C. & SW. America and Japan–S. Korea. With the sole exception of Canada, the S. American Soy Countries are now net exporting to all regions (Fig. 4g, h), but especially to Europe and China. In 1986, the F.S.U. net imported food and feed from N. America, Europe, China and Oceania, while today the F.S.U. countries have become N net exporters to Maghreb–M. East and Europe. Few changes are observed in Oceania (i.e. Australia and New Zealand; Supplementary Fig. S4). China and S.-E. Asia are now net importers of products from Oceania, while the exchange with the F.S.U. countries is now quite balanced. Finally, India (Supplementary Fig. S4) has reduced its net exportation of N to Europe and has become a small net exporter to S.-E. Asia and Japan–S. Korea.

Regional dependence on imports

Some considerations on the changes in the regions' dependency on the import of proteins (and N) can be made by looking at the relationship between the net imports of food and feed, the local crop production, and the change in local crop production between 1986 and 2009. Self-sufficiency has decreased in some of the regions studied, as shown in Table 3. The most remarkable cases are those of C. & SW. America and Japan–S. Korea regions. In the former, the net importation shifted from 33 % of the local crop production in 1986 to 85 % in 2009. Similarly, Japan–S. Korea's net importation of N was twice as high as local production in 1986 and 4.5 times higher in 2009. The external dependence has remained relatively high and constant in Europe (33 and 26 % for 1986 and 2009, respectively). China has evolved from a quite balanced situation, net exporting 4 % of its local production in 1986, to a moderate external dependence (22 %) in 2009. Maghreb–M. East have always been highly dependent on external production, moving from 30 to 47 % during the period studied. N. America has net exported a nearly constant proportion of its local production (27 and 32 % for 1986 and 2009, respectively), whereas S. American Soy Countries have considerably increased their net exports from 26 % of their production in 1986 to 60 % in 2009.

At the global scale, taking into account that more than 90 % of exported commodities are vegetal, our figures indicate that, in 2009, one-third of the primary agricultural production (expressed in N content) is internationally exported.

Discussion

Regional patterns in global N trade

This analysis reveals the rapid development of global trade exchanges of N embedded in food and feed during the past 50 years. The picture that emerges for the current situation is that of a world clearly divided into a small number of net exporting regions (such as N. America and the S. American Soy Countries and to a lesser extent the F.S.U. and Oceania) that are feeding a large number of countries, and animal production in those countries, belonging to highly net importing regions (namely C. & SW. America, Europe, Maghreb–M. East, S.-E. Asia, China and Japan–S. Korea). Of the 12 regions identified in this analysis, only India remains in a relatively balanced situation. This stresses the significance of international trade as a driver in the global nitrogen cycle representing the major flow of nitrogen between continents.

The observed trade change has been made possible by cheap energy, technical innovations (e.g., reduction of the cost of transport and storage), agricultural changes (e.g., the decoupling of crops from livestock production with the generalization of the use of synthetic fertilizers and the expansion of fixing crops namely soybeans) and political agreements (e.g., the global trade liberalization).

Erb et al. (2009) noted how the main trade fluxes respond to an exchange from countries with low population density to countries with high population density in order to overcome supply deficits. However, these deficits in less developed countries are often exacerbated by the massive imports of cheap products from countries with highly subsidized agriculture such as the USA and EU countries, consequently preventing the receiving countries from developing their local agriculture in the long run (Mazoyer 2001; Grote et al. 2005). During the last 5 years several developed countries and corporations have started to acquire a large surface of land in developing countries as part of an energy and food security strategy (Rulli et al. 2013). This new phenomenon, known as "land grabbing," will also exert an important effect in the amount and type of commodities traded and also in the loss of forest or agricultural area of the "grabbed" countries.

The role of human diet in global N trade

Human diet plays a crucial role in the global nitrogen fluxes. The transformation of vegetal into animal protein is highly inefficient (only 7–21 %, 12 % for world average, of the feed is transformed into animal protein, Bouwman et al. 2011). Therefore, in addition to the effects of population growth, an increase in the share of animal protein in the human diet will have an important effect on the agro-food system. Indeed, the largest share of traded N actually concerns feed. Galloway et al. (2007) and Burke et al. (2009) have addressed the non-negligible effect of industrial production of chickens and pigs (accounting for 70 % of total meat production) on global international N trade.

At the global scale during the last 25 years, the population grew by 38 % and animal protein production grew 60 %, whereas per capita protein ingestion increased 13 % and the proportion of animal protein in the diet rose by 12 % (Table 4). This means more people, each consuming on average more food and demanding more animal protein. The amount of meat and milk ingestion per capita is expected to continue rising during the next 40 years for both developing and developed countries (Thornton 2010). In different regions, either population growth or changing dietary patterns can drive an increased demand for primary agricultural goods (Kastner et al. 2012). For example in Maghreb–M. East, the population has increased 66 % in the 1985–2009 period, while local crop production increased only by 45 % (Table 4). At the same time, meat and milk consumption remained very low, so that the rise of the external dependency on international trade in the Maghreb–M. East region is mainly due to population growth. Conversely, the population of China has only grown 24 % in the last 25 years, whereas the transformation of the diet has been remarkable in terms of total protein (48 % increase), the share of animal protein in the diet (from 19 % animal protein to 39 %) and as a consequence the production of animal products increased by 300 %. These data are in line with those presented by Liu et al. (2008) regarding the water supply, showing that dietary change rather than population growth is the main factor responsible for the high demand on water resources in China. Overall the situation in Europe has remained relatively constant during period of analysis. This is not the case, however, for all European countries. For instance in Spain, the human diet has gradually shifted from a Mediterranean diet (33 % animal protein) in 1961 to a typical Western diet (64 % animal protein) in 2007 (Lassaletta et al. 2013). To maintain this diet, the amount of N net imported to Spain, mostly as feed, currently equals the total production of national crops, whereas in 1985 net N importation only represented 35 % (Lassaletta et al. op. cit.).

Consequences of global N trade

The growth of international food and feed trade, now representing globally one-third of total N crop production, has largely contributed to the specialization and simplification of agricultural systems in exporting as well as in importing regions, with, in both cases, severe environmental consequences.

Exporting countries, like N. America and S. American Soy Countries, have developed large scale areas of intensive crop farming completely disconnected from livestock breeding. In such systems, as

Table 4 Characteristics of the regions studied in 1986 and 2009 in terms of agricultural production, population and human diet

Region	Crop production TgN			Animal production TgN			Population 10E6			Nitrogen ingestion (kgN/cap/year)			% Animal protein in human diet		
	1986	2009	% Increase	1986	2009	% Increase	1986	2009	% Increase	1986	2009	% Increase	1986	2009	% Increase
Africa	1.5	2.8	87	0.2	0.3	90	337	604	79	3.1	3.6	15.7	22	20	−7
Maghreb and Middle East	2.5	3.6	45	0.3	0.7	128	319	530	66	4.2	4.5	7.4	26	31	19
China	8.4	12.9	54	0.5	2.2	305	1,099	1,366	24	3.7	5.5	48.2	18	39	123
Central and South-Western America	1.1	1.6	43	0.3	0.6	100	209	304	46	3.9	4.6	18.2	39	46	17
Europe	8.9	9.3	5	2.0	1.9	−4	482	543	13	5.9	6.0	1.7	58	58	0
Former Soviet Union	5.8	5.1	−11.8	1.0	0.7	−30	280	282	1	6.2	5.5	−11.6	51	49	−5
India	4.4	7.5	70	0.4	0.8	127	836	1,258	50	3.1	3.3	6.6	16	20	24
Japan and S. Korea	0.6	0.5	−18.7	0.2	0.2	20	162	175	8	5.3	5.2	−0.6	49	53	8
N. America	12.7	15.3	21	1.1	1.6	41	270	341	27	6.1	6.5	7.6	66	63	−4
Oceania	0.7	0.9	42	0.2	0.3	57	25	35	42	5.1	4.6	−8.3	65	63	−3
S.-E. Asia	2.2	3.8	70	0.1	0.3	138	394	578	47	2.7	3.5	28.2	24	30	26
S. American Soy Countries	3.9	8.8	129	0.4	1.0	140	183	253	38	4.1	5.1	23.7	49	55	12
Total world	54	79	46	7.0	11.1	60	4,941	6,818	38	4.1	4.6	13.3	35	39	12

highlighted by Lemaire et al. (2013), uncoupling between C and N lead to increased N losses through leaching and denitrification. A typical example is the corn belt area in the Mississippi basin, with maize-soybean rotation accounting for most of US N exports, but also largely contributing to the eutrophication of the Gulf of Mexico (Alexander et al. 2008). In Brazil, the loss of N resulting from the conversion of forest and savannah to soybean cultivation and from the N export by exported harvest has been compensated by the significant input of N fixed by soybeans (Smaling et al. 2008; Filoso et al. 2006; Martinelli et al. 2012). The consequences of these major changes are not fully evaluated yet (Bustamante et al. 2006; Martinelli et al. 2012), however, higher N flows seem to be associated to soybean watersheds when compared to Amazonian natural ones (Neill et al. 2013). In the case of Argentina, soil N mining (Austin et al. 2006) and increased N_2O emissions (Dalgaard et al. 2008) are problems related to the massive cultivation of export crops. In addition to the problems related to the perturbation of N cycle, the exporting countries suffer other environmental burdens of intensive and specialized agricultural production, such as air and water pollution, loss of soil fertility and erosion, GHG emission, water and land grabbing, loss of biodiversity and deforestation (Klink and Machado 2005; Galloway et al. 2007; Burke et al. 2009; McAlpine et al. 2009; DeFries et al. 2010; Schipanski and Bennett 2012; Weiss and Leip 2012; Sutton et al. 2011; Bellarby et al. 2013; Houlton et al. 2013).

On the other hand, in importing countries, like China and Europe, large areas have specialized in livestock farming based on massive imports of feed, thus disconnected (sometimes completely, like in feedlot systems) from local crop or forage production. This is the case in China where the intensification of the livestock production systems based on imported soybeans leads to considering manure as a waste directly discharged in waterways (Gerber and Menzi 2006; Sun et al. 2012; Hou et al. 2013) instead of being applied to cropland. Even when application of manure to agricultural land is the rule, as in Europe, the import of feed creates a structural imbalance of N, and excess fertilization generates several environmental problems related to N pollution (Oenema 2004; Lassaletta et al. 2012; Grizzetti et al. 2012; van Grinsven et al. 2012; Passy et al. 2013). The examples of Catalonia (Spain) and Brittany (France) are well documented (Campling et al. 2005; Penuelas et al. 2009)

The disconnection of crop and livestock farming made possible at the scale of world regions by the expansion of international trade thus result in the opening of nutrient cycles in agro-ecosystems. The nutrients extracted as harvest from one region of the world and exported far away do not return to the croplands as manure and have to be replaced by new N inputs (either as fertilizers or biological fixation). On the other hand, crop residues such as straw cannot be used by livestock and they are usually burnt. When the exported feed is not finally returned to the soil in the importing region, or is returned in excess, as occur in Europe and China, the overall result at the global scale is clearly a loss of nitrogen use efficiency.

The environmental problems generated by these losses are generally externalities not included in the price of the product, which explains in part the low cost of the traded food and feed. The "virtual N" lost to the environment is not considered in this analysis, but could be included in future works to capture the total global N impact of the trade of agricultural products. Regarding to climate change policy, international trade can contribute to the 'leakage' of GHG emissions, i.e. the outsourcing of emissions from a country of the Annex B of the Kyoto Protocol by trading products produced in a non-Annex B country (Peters et al. 2011). Lassaletta et al. (submitted) have recently studied how a significant amount of N_2O emissions are being 'leaked' from Spain to Brazil and Argentina due to the soybean/feedlot livestock systems.

Even if several mitigation measures taken at the farm scale can reduce the impact of production systems on the N cycle, structural changes, involving re-sourcing of agricultural production close to consumption areas, are needed to obviate the negative effects of the opening of the nutrient cycles in agro-food systems. Several authors have discussed the benefits of integrated crop-livestock systems for improving nutrient use efficiency by enhancing manure recirculation and use of crop residues (Wilkins 2008; Herrero et al. 2010; Khumairoh et al. 2012). Billen et al. (2013) have recently modelled the effect of a re-localization of agricultural production at the global scale, showing a significant reduction (35 %) of total N surpluses from 143 to 93 TgN/year in a scenario where livestock is re-allocated to every large world watershed according to the requirement of the current human population. Some countries have opted to export animal products entirely produced inside the nation. This is the case of New Zealand specialized in the export of dried milk. This entails indeed an advantage regarding to nutrient efficiency, but, in this case all the externalities of the production remain completely outside from the importing country.

The consumption patterns of the importing countries are a major cause of the environmental burdens. This includes both their diet and their food waste rate, which has been shown to have an important role in global N fluxes (Grizzetti et al. 2013). Thus, the solutions must rely not only on the production level, but also on the consumption level. Since a large part of the production system is devoted to the vegetal to animal protein conversion, the human diet is a clear driver of the demand for primary agricultural products (Liu et al. 2009; Steinfeld and Gerber 2010). A shift from cattle meat to poultry consumption could reduce nitrogen flows due to a higher efficiency of feed conversion of the poultry (Bouwman et al. 2011). However, despite of their lower efficiency of feed conversion, ruminants can make good use of crop residues and pastures while non-ruminants such as poultry and pigs generally depend entirely on grain feed. A reduction of the share of animal protein in the diet of people eating presently much more meat and milk than recommended by WHO would produce enormous environmental benefits (Nine 2009; Stehfest et al. 2009; Popp et al. 2010; Billen et al. 2012, 2013; Sutton et al. 2011, 2013).

Conclusions

In this paper we have analysed the international trade of food and feed products as a biogeochemical process playing a role in the transfers of N at the global scale. In fact, as N is found in all food and feed, the trade of food and feed results in a movement of nitrogen from one region to another. We observed that during the last 50 years, the amount of N traded between countries has dramatically increased (from 3 to 24 TgN, 1961–2009) and now concerns one-third of the total N in world crop production. At the present time, the international trade of food and feed constitutes a significant component of the global N cycle being a major way of intercontinental N transfer. The largest proportion of these traded N and proteins corresponds to feed. Nowadays, the world is clearly divided into a small number of net exporting countries, which are feeding a large number of net importing countries. The international flows among these regions have been intensified and the external dependency of several regions on the import of proteins has increased. These changes are explained not only by an increase in the population, but also by the rise in the share of animal protein in the diet of some countries. Many environmental problems (such as loss of soil fertility, delocalization of the aquatic and atmospheric pollution problems, increase of the inefficiency of the N use and deforestation) have arisen from this decoupling of the production process, and from the fact that market driven agriculture in many regions is not balanced by a strategy of natural resource efficiency. Mitigation measures at the production level must be combined with changes in consumption patterns to reduce the alteration of the global N cycle and the consequent environmental pollution.

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