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LETTER

Nitrogen use in the global food system: past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand

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Abstract

Nitrogen (N) limits crop and grass production, and it is an essential component of dietary proteins. However, N is mobile in the soil-plant system and can be lost to the environment. Estimates of N flows provide a critical tool for understanding and improving the sustainability and equity of the global food system. This letter describes an integrated analysis of changes in N in human diets, N use efficiency (NUE) of cropping and livestock systems, N pollution and N in traded food and feed products for 12 world regions for the period 1960–2050. The largest absolute change in consumption of animal proteins during the period 1960–2009 is seen in China, while the largest share of animal protein per capita is currently observed in North America, Europe and Oceania. Due to the substantial growth of the livestock sector, about three quarters of contemporary global crop production (expressed in protein and including fodder crops and bioenergy byproducts) is allocated to livestock. Trends and levels of NUE and N surpluses in crop production are also diverse, as some regions show soil N depletion (developing regions, e.g. Africa), improving efficiency (industrialized regions, e.g. USA and Europe) and excessive N use (e.g. China, India). Global trade between the 12 regions has increased by a factor of 7.5 for vegetable proteins and by a factor of 10 for animal proteins. The scenarios for 2050 demonstrate that it would be possible to feed the global population in 2050 with moderate animal protein consumption but with much less N pollution, and less international trade than today. In such a scenario, optimal allocation of N inputs among regions to maximize NUE would further decrease pollution, but would require increased levels of N trade comparable to those in a BAU scenario.

1. Introduction

The rapid increase of global food demand during the past 5 decades has been driven largely by population increase and a dietary shift towards a larger share of meat and dairy products. The world agro-food system has been changing to meet this growing demand. One of the most prominent changes is intensification, with increasing crop production per unit of area owing to increasing inputs of nutrients among other factors. Indeed, the use of synthetic nitrogen (N) fertilizers has increased eight-fold and now represents more than half the total direct input of N to cropland (Fowler *et al* 2013, Lassaletta *et al* 2014a).

The degree of agricultural intensification shows large disparities between countries (Bodirsky *et al* 2012, Mueller *et al* 2012, Swaney *et al* 2012, Bouwman *et al* 2013a, Niedertscheider *et al* 2016). In some countries such as China, Egypt or several European countries, excessive use of fertilizers generates high N surpluses leading to dramatic environmental problems, while in others (e.g. several African countries) low manure and fertilizer application rates deplete soil N reserves (Vitousek *et al* 2009, Sutton *et al* 2013, Lassaletta *et al* 2014a, Mueller *et al* 2014). At the same time, international trade of food and feed products, which represents huge flows of N in the form of vegetable or animal protein between continents, has increased considerably (Lassaletta *et al* 2014b). However, currently the largest part of traded agricultural commodities consists of animal feedstuffs, often transported to countries with livestock-oriented agricultural systems, where the proportion of animal products in the human diet is high or where a dietary transition towards more animal protein consumption is occurring (Kastner *et al* 2012, Lassaletta *et al* 2014b, Davis and D'Odorico 2015). This disconnection of crop and livestock production between countries and usually continents is one of the causes of N surpluses and inefficient use of N due to the inability to close nutrient cycles (Bai et al 2014, Lassaletta *et al* 2014a, Billen *et al* 2015, Leip *et al* 2015, Strokal *et al* 2016). These large N surpluses are lost to the environment via surface runoff, leaching to ground and surface water, and gaseous emission (Sutton *et al* 2013). Water and air pollution by reactive N have high economic costs for society (Van Grinsven *et al* 2013, Sobota *et al* 2015).

In this letter we provide an analysis of the trends in agricultural performance in 12 world regions focusing on the N cycle in the agricultural production system. This analysis is used as a basis for addressing how N use can be improved by optimizing the role of human diet, international trade and local production. We first describe observed 50 year trajectories of human protein demand and supply, self-sufficiency with regard to proteins, performance of cropping and livestock systems, and environmental N loss for each region. Subsequently, we use four scenarios differing in human diets, livestock distribution and fertilizer use to analyze changes in international trade, N losses and N use efficiency (NUE).

2. Data and methods

2.1. The representation of agro-food systems

We use the generic representation of agro-food systems (GRAFS) (Billen *et al* 2013, 2014) which is based on functional relationships between crop farming, livestock breeding, and human nutrition expressed in terms of protein-N transfers. The system's driving variables are (1) the size of the human population; (2) the human apparent diet, including wastes generated at consumption; (3) the livestock population and grass consumption by grazing livestock; and (4) the intensity of fertilization of cropland by synthetic fertilizers, animal manure, symbiotic fixation and atmospheric deposition.

The approach starts with the calculation of a yearly N budget over the period 1961–2009, based on production data from FAOSTAT (FAO 2012), for 12 world regions. These regions were defined by Lassaletta *et al* (2014a), on the basis of their current level of self-sufficiency with regard to their local protein needs for feeding humans and livestock (supplementary material S1).

NUE of the agro-food system is calculated as the ratio between N in harvested crop products to N inputs. N inputs (fertilization) include synthetic fertilizers, animal manure, symbiotic fixation and atmospheric N deposition. We assume a one parameter hyperbolic relationship between crop yield (Y expressed as $kg\,N\,ha^{-1}\,yr^{-1}$) and total N inputs (F) as shown in equation (1)

$$Y(F) = Y_{max} \frac{F}{F + Y_{max}}. \qquad (1)$$

The asymptote of this curve, Y_{max}, can be expressed as $Y_{max} = YF/(F - Y)$. Changes in management, crop mix, improved crop varieties or irrigation can cause a shift towards a higher Y_{max}.

Crops include all annual and perennial food and feed crops, biofuels, fruits, vegetables, stimulants, fibers and rubber. N contents used to calculate N harvest are from Lassaletta *et al* (2014a). Ornamental crops are not included in this study. Total N inputs to arable land include synthetic fertilizer application (corrected for estimation of fertilizer application to grassland, see Lassaletta *et al* 2014b), symbiotic N fixation (estimated according to the approach developed by Lassaletta *et al* 2014b and Anglade *et al* 2015), manure application (calculated from animal excretion according to Lassaletta *et al* 2014b) and atmospheric deposition obtained from Dentener *et al* (2006).

Grass production is defined as grass consumed by ruminants (in terms of N), and it is calculated from the food and feed balance of each region. Grass production is calculated as the sum of human and animal consumption of plant proteins minus the sum of local crop production and net import of crop products (see supplementary material S2 for a discussion about the uncertainties of this estimation). The results obtained with this budget approach are not strictly grass production but include any other sources of feed not included in official statistics, such as backyard production, scavenging and swill use. Our estimates of grass production are in good agreement with estimates from the integrated model to assess the global environment (IMAGE) (Bouwman *et al* 2005, Stehfest *et al* 2014).

Animal excretion is calculated from animal stocks of ruminants (cattle, sheep, goats and other ruminants) and monogastrics (pigs, poultry and other

domesticated birds) using time- and region-specific excretion coefficients. A fraction of the excreted N is applied to crops as estimated by Lassaletta *et al* (2014a) and it has now been corrected for The Netherlands, Ireland and United Kingdom. Animal production is the N content of carcasses, milk and eggs produced, skins, offals and fats. However, in the estimation of human consumption a non-edible fraction of offals, fats, and skins is subtracted.

Animal ingestion is calculated as the sum of excretion plus production. The livestock N conversion efficiency is defined as the ratio of edible production to ingestion. Ammonia volatilization is calculated as 30% of the excreted N that is stored and managed before spreading of manure (Bouwman *et al* 1997, Bouwman *et al* 2002). The calculations were made separately for ruminants and monogastrics. Similarly, cereal consumption (as well as total crop consumption excluding fiber) by animals is also estimated from the food and feed balance of each region. Cereal consumption by animals is total cereal production plus net import minus human consumption and use. The food waste of cereals at post-harvesting, processing, and distribution stages (ranging from 1%–8% according to FAO balance sheets) is not considered in this analysis.

Seafood, including freshwater fish, represents 15% of human animal protein consumption and is not included in this analysis. This does not influence human meat consumption, because fish ingestion was calculated separately (see supplementary information S6). Ignoring fish production implies that all compound feeds as obtained from FAOSTAT (FAO 2012) are allocated to livestock production, and are thus not corrected for the share devoted to aquaculture. The potential errors caused by this are small, because currently the volume of compound feeds used in aquaculture (Tacon and Metian 2008) is minor compared to feed crop use in livestock (FAO 2012) and because a large part of the world's seafood consumption comes from direct capture (Bouwman *et al* 2013b). However, the volume of feed crop allocated to fish is expected to dramatically increase during the coming years (Fry *et al* 2016).

Actual human diets are compared to what is considered to be an equitable diet, which is also healthy in terms of animal protein N, i.e., a total protein ingestion of 4 kg N per capita per year with a fraction of 40% animal proteins (1.6 kg N per capita per year). This diet corresponds to the richest diet which could be shared by all regions in the world at current levels of agronomic performance (Billen *et al* 2015). This diet is about 20% above the WHO (2007) recommendations for a healthy diet in terms of protein consumption, and in turn accounts for unavoidable losses at the consumption level (Gustavson *et al* 2011).

N trade is trade of N embedded in products, not virtual N as has been sometimes considered (Galloway *et al* 2007, Oita *et al* 2016). The trade N fluxes are estimated from the N content (protein-N) of traded agricultural products (not including fertilizers). In our approach, international trade flows between countries of the same region are excluded. This results in smaller trade flows than a previous study (Lassaletta *et al* 2014b), which included trade flows between countries.

In the GRAFS approach, the basis for establishing a comprehensive budget of N transfers through the agro-food system further allows for recalculating budgets for future scenarios including population growth, diet shifts, or changes in production systems, the latter being characterized by the region-specific parameters of the yield-fertilization relationship and the conversion efficiencies of ruminant and monogastric livestock.

2.2. Scenario construction

We constructed four scenarios to illustrate the trade-offs between protein in human diet, environmental impact of N losses in agriculture, and the role of inter-regional food and feed trade. To this end, we considered two contrasting development paths, i.e., (i) the business as usual (BAU) approach and (ii) and an alternative approach here called self-sufficiency/equitable diet (SSED). In the BAU approach, it is assumed that production trends, in particular regional specialization, continue, and that world regions with production exceeding domestic demand export proteins to regions where domestic production is insufficient to meet local demand, assuming that no barriers to international trade exist. In the SSED approach, it is assumed that regions attempt as a matter of priority to meet domestic demand of both animal and vegetal proteins by local, diverse production and aim at limiting their dependence on imports, while converging to a healthy human diet (e.g. Bodirsky and Popp 2015). In this approach, therefore, inter-regional trade occurs only when local needs cannot be met by local production given the other constraints considered.

Using these two paths, we designed four contrasting scenarios of the agro-food system in 2050; BAU standard, SSED local, and one variant of each assuming optimized allocation of production (table 1). In all scenarios, population in each region is that projected by United Nations (2011), the area of cropland and grassland is constant at the 2009 level (FAO 2012). The agronomic performances of crop and livestock production systems, characterized by Y_{max} of crop systems and the protein-N conversion efficiency for livestock, are extrapolated from the trend observed during the last decades. These trends are depicted for each region in supplementary material S6, and the extrapolated values of the parameters for 2050 are listed in table 2.

Regarding the future human diet, the two BAU scenarios use the implementation of the Global Orchestration/A1 scenario considered by the MAgPIE

4

Table 1. Description of the four scenarios considered for the global agro-food system in 2050[a]; business as usual (BAU) and self-sufficiency/equitable diet (SSED), with standard and optimum allocation of fertilization.

Scenario	BAU standard	BAU optim alloc	EqD local	EqD optim alloc
Population	As predicted by demographic projections of FAO (2014)			
Human diet	Unequal diet as projected by the MAgPIE economic model		Equitable diet	
Land use	Same as in 2009			
Cropping and livestock system performances	Extrapolated from the trends observed during the last 30 yrs			
Livestock	Livestock distributed across the regions in the same proportions as predicted by economical models		Ruminant ingestion adjusted to grassland production +20% feed; monogastric production adjusted to animal protein requirements of humans not filled by ruminant production, with a minimum monogastric ingestion set to 5% of ruminant ingestion.	
Cropland production and fertilization	Distribution of crop production between all regions in the same proportion of total world production as in GO/A1 2050 scenario	Fertilization (hence production) adjusted in such a way that NUE is the same in each region taking into account their different Y_{max}	Fertilization adjusted in each region to provide local crop production meeting human and livestock requirements	Fertilization (hence production) adjusted in such a way that NUE is the same in each region taking into account their different Y_{max}

[a] A detailed description of the scenarios in each of the 12 world regions is available under the form of an xlsx file in supplementary information S7.

Table 2. Performance of cropping (Y_{max}) and livestock systems (N conversion efficiency) from 1961 to 2009. Extrapolation of these values to 2050 are provided based on trends over the last 30 years (1980–2009).

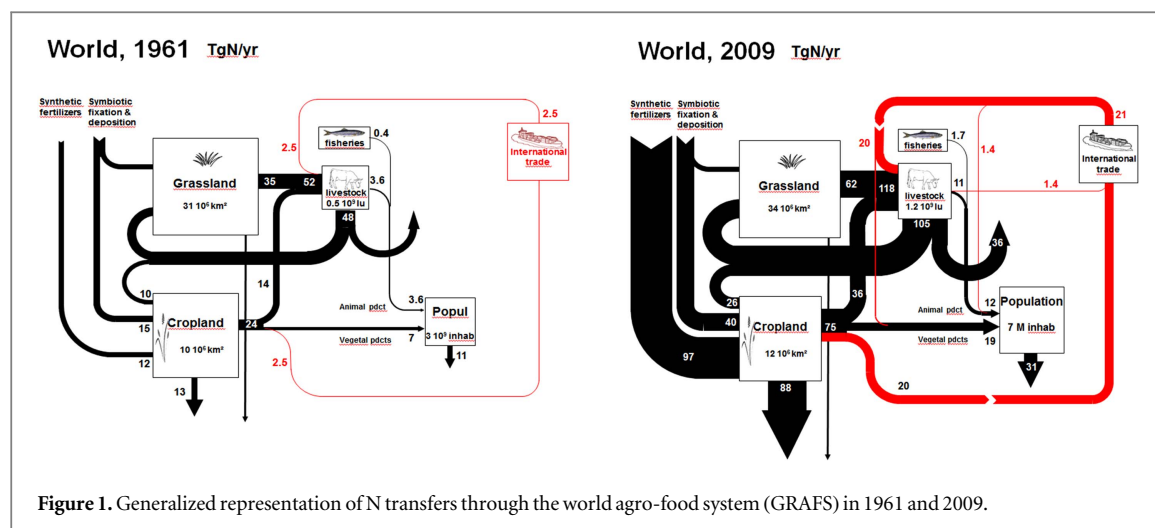|	Y_{max} (kg N ha^{-1} yr^{-1})			veg to anim conv (ruminants)			veg to anim conv (monogastric)		
	1961	**2009**	2050	**1961**	**2009**	2050	**1961**	**2009**	2050
Africa	253 (sm)	105	185	0.02	0.03	0.03	0.10	0.14	0.15
China	100	127	173	0.01	0.05	0.10	0.08	0.17	0.20
C-SW America	55	71	101	0.03	0.08	0.08	0.11	0.16	0.20
Europe	61	197	328	0.12	0.12	0.12	0.16	0.22	0.26
FSU	100	200	200	0.11	0.13	0.13	0.14	0.18	0.26
India	26	55	94	0.03	0.08	0.14	0.10	0.19	0.20
Japan	95	98	93	0.07	0.10	0.10	0.26	0.23	0.23
Maghreb	200 (sm)	81	100	0.04	0.06	0.08	0.17	0.16	0.11
N America	183	362	569	0.09	0.09	0.09	0.23	0.28	0.34
Oceania	45	82	65	0.04	0.07	0.11	0.20	0.23	0.19
SAmSoyRep	138	242	474	0.03	0.04	0.05	0.07	0.18	0.33
SEAsia	26	148	283	0.02	0.02	0.03	0.12	0.16	0.14

sm: soil mining.

economic model (Lotze-Campen *et al* 2008, 2010, Bodirsky *et al* 2012, 2014 Schmitz *et al* 2012). This model predicts the human diet in the different world regions based on economic development (Valin *et al* 2014), which results in future regional diets richer in protein than present ones, and large inter-regional disparities. The two SSED scenarios consider a convergence of human diet in each region towards the equitable diet defined above (see section 2.1).

The distribution of livestock in the BAU scenarios is defined for each region based on the data provided by MAgPIE for the GO/A1 scenario, which assumes that all regions converge towards the European feed rations and productivity. In the SSED scenarios, the distribution of livestock in each region first depends on a full exploitation of grassland by ruminants, together with 20% additional feed, and the efficiency calculated for 2050 (table 2). If the protein-N produced by ruminants does not meet the requirements for an equitable diet, additional animal production consisting of pig or poultry and eggs may be considered. This additional monogastric production only occurs if it can be based on locally produced feed which is in excess over human and ruminant requirements. In regions where the calculated ruminant production meets or exceeds local needs for animal proteins, a minimum monogastric production is nevertheless assumed in order to ensure diversity in animal protein consumption. This monogastric production has been arbitrarily set at a value corresponding to an ingestion rate of crop products by monogastric equal to 5% of that by ruminants.

Regarding cropland production and nutrient use, three different rules were used. In the 'BAU standard' scenario, the proportions of global crop production in each region have been considered identical to those predicted in the GO/A1 Scenario of the MAgPIE model. Thereby, fertilizer application rates have been adjusted based on the yield/fertilization relationship (with its regional Y_{max} value) and taking into account the previously calculated local resources of manure. In the 'SSED local' scenario, the total N input to cropland in each region is adjusted to ensure that the volume of local crop production is as close as possible to the domestic human and livestock protein requirements (in addition to the protein supply in the form of grass); however N input to cropland is limited to a maximum set at 50% of Y_{max} (i.e., $Y_{max}/2$). If the crop production at $Y_{max}/2$ exceeds the local human and livestock protein requirements, extra production takes place for export; export is not allowed to exceed a maximum fraction of local production. This fraction is the same for all regions, and is adjusted so that global crop production equals global consumption. Note that in this work the term 'local' refers to the 12 intrinsic macro regions here defined; we did not explore the effect of intra-regional connections as was done by Zumkehr and Campbell (2015).

Optimal allocation of N inputs between the 12 regions in both BAU and SSED follows the methodology of Mueller *et al* (2014). In this variant, N inputs are optimized in order to maximize the global NUE for the scenario-specific volume of global crop production. Optimal allocation means that global NUE and production is maximized for a given volume of N input. The condition for optimal allocation is a constant dY/dF across all regions, regardless of Y_{max}. To illustrate the mechanism behind this optimization, consider two regions of similar Y_{max} but with low and very high N application rates. Assuming that the total N input over the two regions is the same, production can be maximized by redistributing N fertilizer from the region of high N rates to the region with low N application rates; this can lead to an increase of total production, since the marginal yield response to additional fertilizer (dY/dF) in the low-N region will exceed the marginal yield loss in the high-N region after a reduction in fertilizer application. This is a

Figure 1. Generalized representation of N transfers through the world agro-food system (GRAFS) in 1961 and 2009.

consequence of the asymptotic response of yield to increasing fertilizer inputs (e.g. Paris 1992). Once a constant dY/dF is achieved across both regions, further reallocation will not lead to net production gains. The formal proof that this approach leads to an optimal global NUE is provided in supplementary information S4. The application of this principle of optimum allocation of N input leads to an additional variant of the BAU and SSED scenarios in which N inputs (either as synthetic N fertilizer application or as symbiotic N fixation through inclusion of legumes in the crop rotations) are adjusted in such a way that NUE in each region is equal to the value defined at the global scale for meeting the requirements of crop protein consumption. In the case of the SSED scenario, this additional constraint prevents local crop production to be fully adjusted on local needs.

3. Past trends

3.1. World agricultural and trade system

The N budgets for the 12 world regions and the world total over the past 5 decades (1961–2009) calculated with GRAFS are available as supplementary material S3, S6 and S7. At the global scale, total N inputs to cropland soils increased by a factor of 4.4, while total protein production in croplands increased by a factor of 3.1 (figure 1). These changes imply a reduction of NUE from 66% to 46%, and an increase of N losses from cropping systems from 12 Tg N yr^{-1} in 1961 to 88 Tg N yr^{-1} in 2009 (Tg = teragram; 1 Tg = 10^{12} g). During the same period, international trade between the 12 regions increased eight times from 1.7 to 12.6 Tg N yr^{-1} (from 2.5 to 21 Tg N yr^{-1} when considering flows between all countries). These results are within the range of other global approaches (Bouwman *et al* 2013a, Sutton *et al* 2013).
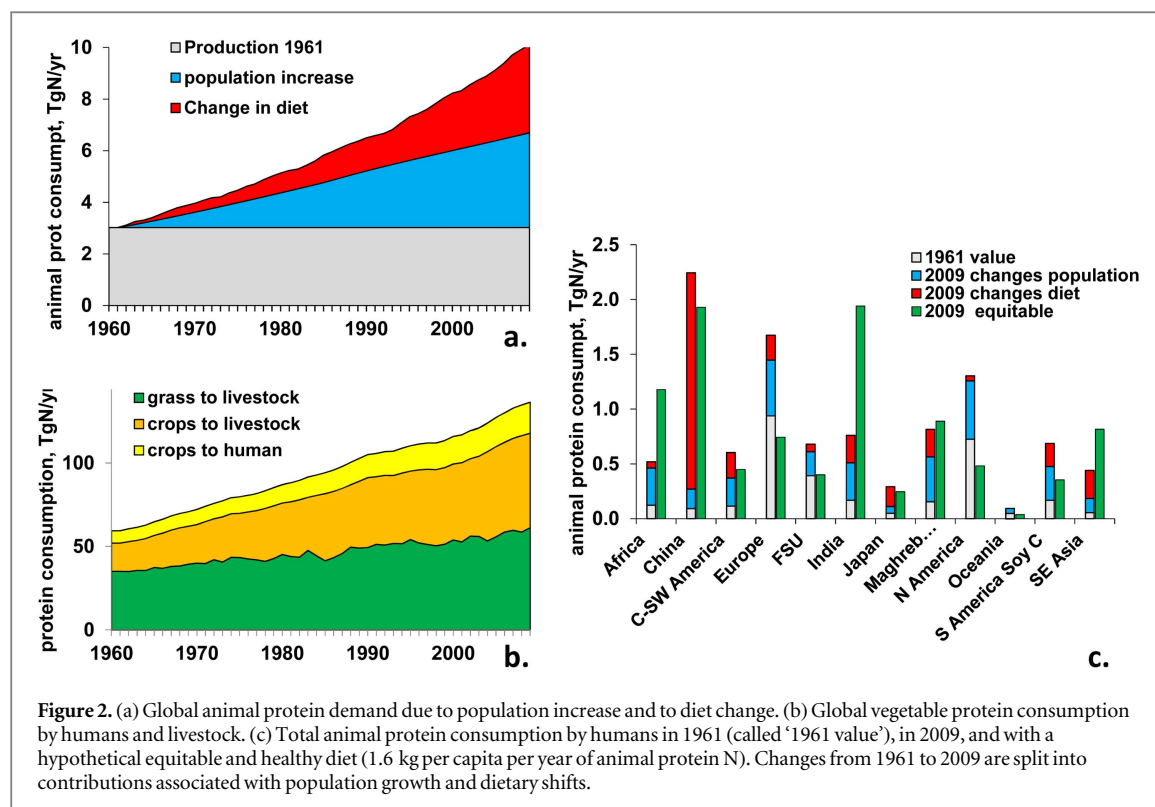
There are strong differences between world regions. Based on both the current organization of the agro-food system in each region and its trends and variations during the last 50 years, we can group the 12

regions as follows: (i) regions with rapidly growing population, decreasing self-sufficiency and increasing dependence on imports of food and feed (Sub-Saharan Africa, Maghreb and Middle East, Central and South West America, China, South East Asia); (ii) regions with stabilizing or moderately growing population, producing excess food and feed for export to deficient countries (North America, South American Soy Countries, Oceania); (iii) regions with stabilizing population and strongly dependent on imports (Japan, Europe, Former Soviet Union); (iv) regions with rapidly growing population, and not depending on international trade (India).

3.2. Human diet

Global average per capita protein consumption increased from 3.6 to 4.5 kg N cap^{-1} yr^{-1} during the past 5 decades, whereby the fraction of animal proteins (including fish) was 31% in the 1960s and 39% in the last decade. About half of the increase in total animal protein N consumption is the result of population growth, the other half results from diet shift (figure 2(a)). The rapid increase in demand for animal proteins has also caused changes in the crop production system due to increased feed crop demand; N in crops used for animal feed increasing from 17 in 1960 to 57 Tg N yr^{-1} in 2009, representing about three quarters of global crop production (figure 2(b)). This proportion is much higher than when it is expressed in calories (Cassidy *et al* 2013), because especially N rich material is used as feed. This value is slightly higher but coherent with the value obtained by calculating the total protein allocated to feed by using the FAO Food Balance Sheets and also including fodder crops (FAO 2012) and distiller grains (DDGS, several sources); small discrepancies can be associated with the indirect way of calculation in our approach of for example wastes, which are considered separately in the FAOSTAT Food Balance Sheets.

The consumption of animal proteins is not equally distributed in the different parts of the world, which is

Figure 2. (a) Global animal protein demand due to population increase and to diet change. (b) Global vegetable protein consumption by humans and livestock. (c) Total animal protein consumption by humans in 1961 (called '1961 value'), in 2009, and with a hypothetical equitable and healthy diet (1.6 kg per capita per year of animal protein N). Changes from 1961 to 2009 are split into contributions associated with population growth and dietary shifts.

clearly illustrated by the share of the increase in animal protein consumption attributable respectively to population increase and change in diet between 1961 and 2009 (figure 2(c)). The Americas, Europe, Former Soviet Union, Japan, China and Oceania have an animal protein consumption that exceeds a diet considered to be equitable in terms of animal products (i.e., 1.6 kg N cap^{-1} yr^{-1}). The other regions are below that level. China, South East Asia and Japan are the regions where diet change towards more animal protein has been the most significant, explaining more than half of the increase in total consumption of animal products in the last 50 years (figure 2(c)). The largest absolute change in consumption of animal proteins is seen in China and Europe and North America are the regions that most surpass the equitable diet limit.
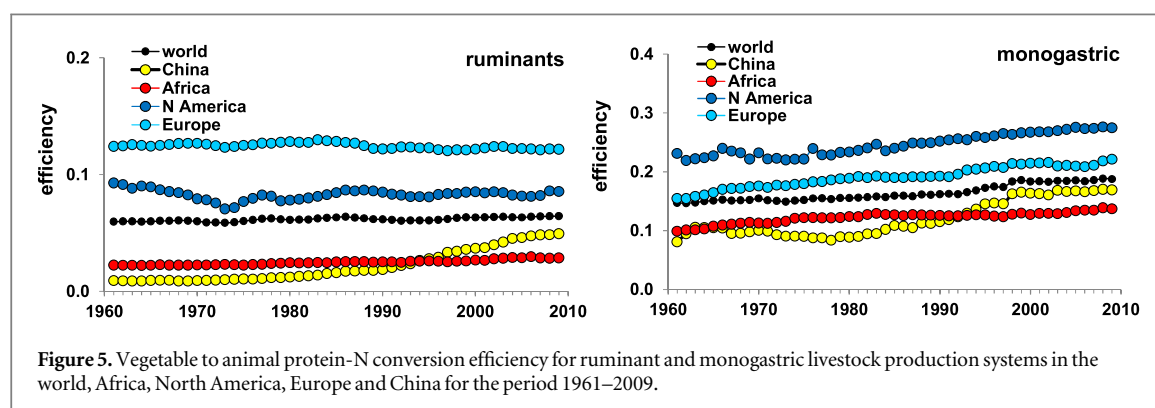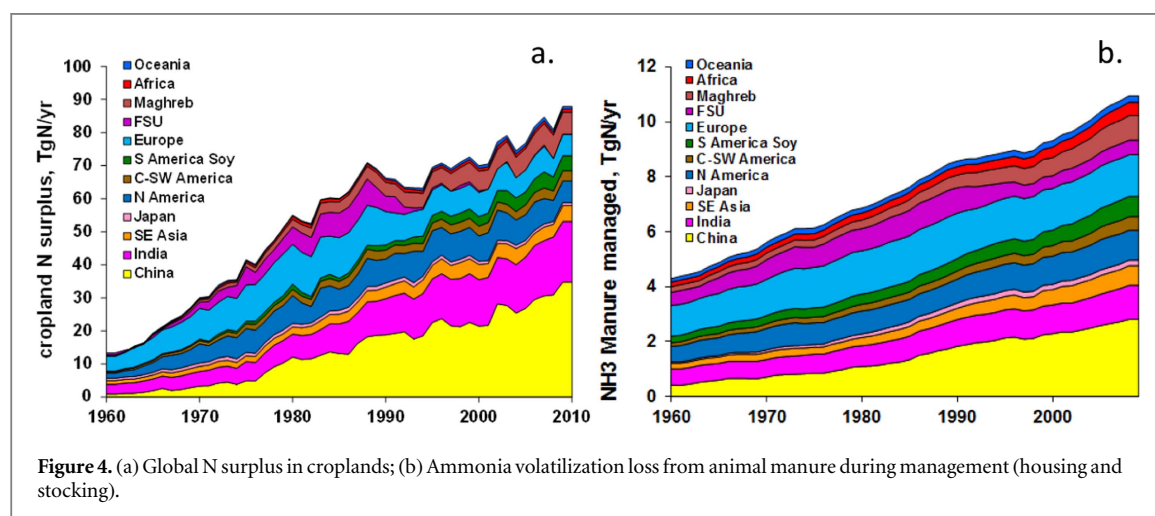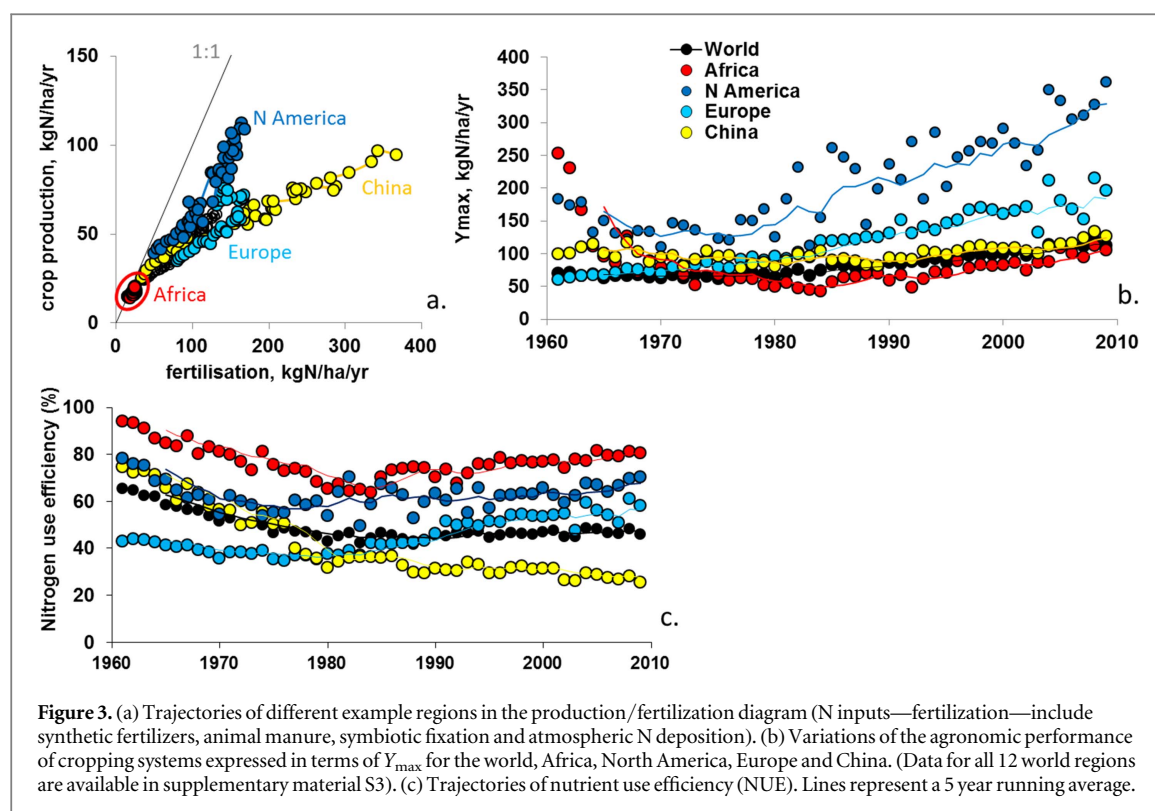
3.3. Agronomic performance and environmental N loss

An overall increase in the agronomic performances of cropping systems, as characterized by increasing Y_{max} (the asymptote of Y(F), equation (1)), is observed in most of the 12 world regions (figure 3, table 2 and supplementary material S3, S6 and S7). However, rates of increase in NUE are much larger in North America and Europe than in the other regions such as China, where the NUE has even dropped (figure 3). While China and Africa have similar Y_{max} levels and trends (figure 3(b)), there are large differences between these two regions in terms of crop productivity and N fertilization (figure 3(a)), with much higher N yields and N inputs in China. Despite increasing efficiency of
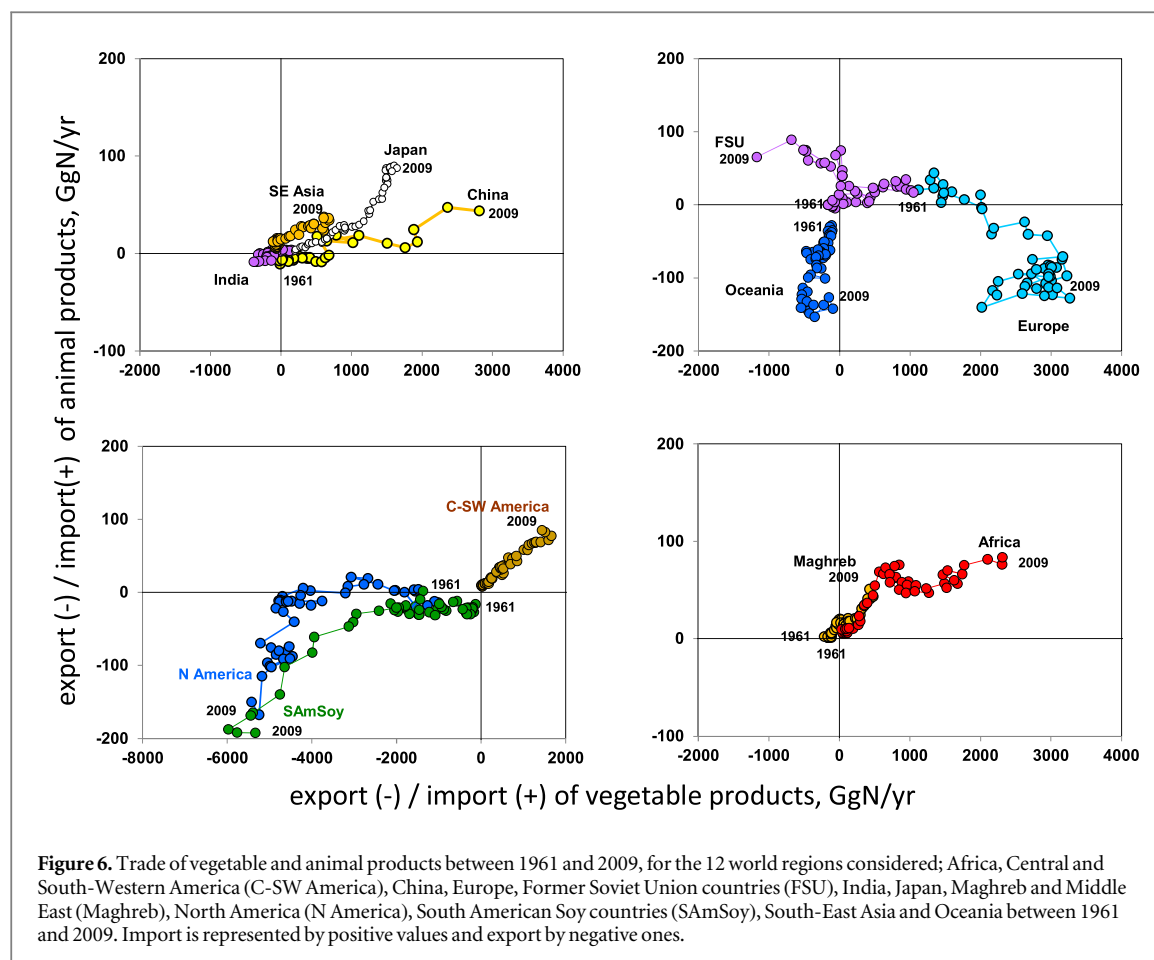
crop production systems in several regions (i.e. the ratio of total N input to cropland to N in harvested products) (figure 3(c)). The absolute N losses to the environment, as calculated by the difference between total N input to cropland and N content of harvested products (N surplus) has increased in past decade (figure 4(a)). This is also true for the N surplus expressed per unit cropland area (supplementary material S7) Gaseous N losses through volatilization from animal manure management more than doubled during the last 5 decades to around 10 Tg N yr^{-1} (figure 4(b)).

N conversion efficiencies in livestock production (figure 5) are much lower than in crop production (figure 3(c)). Ruminants in particular show low efficiencies. In the same way as crops, livestock systems generally have seen an increase in their performance in terms of the efficiency of conversion of vegetable to animal proteins, primarily in monogastric systems (figure 5, table 2). There are also large differences in the N conversion efficiency between world regions for both animal groups, with higher values in Europe and North America than in developing countries.

3.4. Interregional trade

There are major differences in the self-sufficiency and agricultural specialization of the various world regions. In many regions, a significant and growing share of the N in food and feed demand was obtained through imports, while other regions are exporting N in animal and/or vegetable products. Global trade expressed in terms of N exchanged between the 12 regions increased by a factor of 7.5 for vegetable

Figure 3. (a) Trajectories of different example regions in the production/fertilization diagram (N inputs—fertilization—include synthetic fertilizers, animal manure, symbiotic fixation and atmospheric N deposition). (b) Variations of the agronomic performance of cropping systems expressed in terms of Y_{max} for the world, Africa, North America, Europe and China. (Data for all 12 world regions are available in supplementary material S3). (c) Trajectories of nutrient use efficiency (NUE). Lines represent a 5 year running average.

Figure 4. (a) Global N surplus in croplands; (b) Ammonia volatilization loss from animal manure during management (housing and stocking).

Figure 5. Vegetable to animal protein-N conversion efficiency for ruminant and monogastric livestock production systems in the world, Africa, North America, Europe and China for the period 1961–2009.

Figure 6. Trade of vegetable and animal products between 1961 and 2009, for the 12 world regions considered; Africa, Central and South-Western America (C-SW America), China, Europe, Former Soviet Union countries (FSU), India, Japan, Maghreb and Middle East (Maghreb), North America (N America), South American Soy countries (SAmSoy), South-East Asia and Oceania between 1961 and 2009. Import is represented by positive values and export by negative ones.

proteins (from 1.6 to 12.1 Tg N yr^{-1}) and by a factor of 10 for animal protein (from 0.05 to 0.5 Tg N yr^{-1}) from 1961 to 2009.

The regions show contrasting trade patterns for animal and vegetable protein over the course of the study period (figure 6). The protein demand in some regions exceeded domestic production leading to protein-N import, with important increases in China, Japan, South East Asia, Maghreb and Middle East, Africa and Central and South West America. In contrast, other regions are protein-N exporters (North America, South American Soy Countries, Oceania). Europe has an intermediate position as it moves to larger imports of vegetable proteins (mainly soybean from South America) and larger exports of animal proteins. India is a small exporter for both animal and vegetable proteins, with no clear trend in time.

4. Scenarios for the future

The four scenarios offer contrasting views of the world agro-food system in 2050. The different options taken regarding dietary choices and allocation of resources between regions result in large differences between scenarios in terms of interregional trade (figure 7). In the two BAU scenarios, North America is a large exporter of vegetable products and importer of animal products (figure 7). Europe exports animal products and imports vegetable products in the two BAU scenarios, while Europe has minimal trade flows in the SSED ones. Japan is a small importer of all products in the two BAU scenarios, while it is close to neutral with respect to trade in both SSED scenarios. China imports animal products in both BAU scenarios, while it exports vegetable products in the BAU standard scenario and imports vegetable products in BAU with optimized allocation. Africa is a large importer of vegetable products and exporter of animal products in both BAU scenarios, while it is an importer of both product groups in the SSED scenarios. In general, for all regions the trade flows in SSED scenarios are smaller than in BAU.

The scenarios can also be compared in connection with the historical trajectory that we have described in the first part of this letter. The total global N environmental losses between 1961 and 2009 (estimated as the sum of total N surplus from arable soils and ammonia emission associated with manure management) increased by a factor of 4.5 and by a factor of 6.9 when considering cropland surpluses only. Trade dependency (the total amount of agricultural products traded between regions) grew by a factor of 7 in the same period. In the BAU standard scenario, the total N environmental losses would continue to rise by 15% in the period 2009–2050, while trade of agricultural
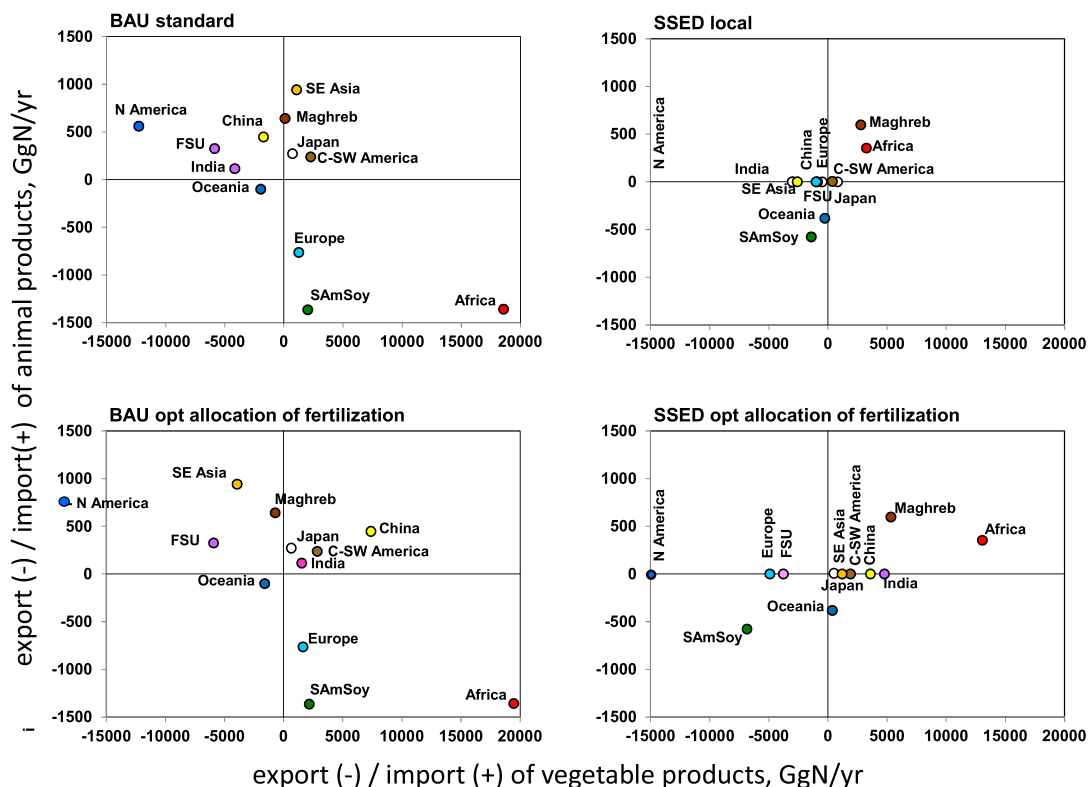
Figure 7. Net import (+) or export (−) of vegetable and animal products between 1961 and 2009, in the 12 regions considered and according to four scenarios considered. All conventions are as in table 1 and figure 6.
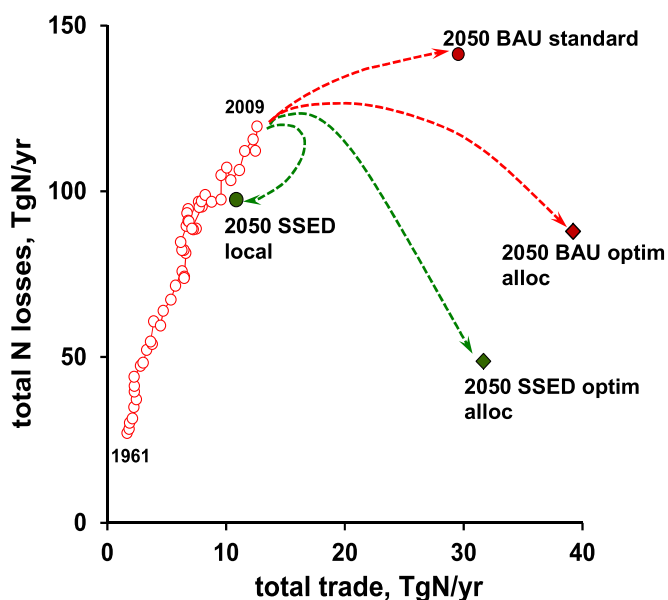

Figure 8. Trajectory of the world agro-food system from 1961 to 2009 (open circles) in terms of total environmental N losses (total N surplus from arable land plus volatilization of livestock excretion) in function of food and feed self-sufficiency (total rate of international trade), for the four scenarios considered. The positions of these scenarios for 2050 are indicated with filled symbols. All conventions are as in table 1.

products would more than double (from 13 to 30 Tg N yr^{-1}) compared to current levels (figure 8).

In contrast, the SSED local scenario in 2050 would succeed in reducing international trade of agricultural products by 40%, and at the same time reducing environmental N losses by 33% between 2009 and 2050. The SSED scenario with optimum allocation of fertilization, which implies a complete redistribution of

fertilization resources between world regions, would allow a quite significant further reduction of environmental losses. However, the optimal allocation would also lead to a large increase in the volume of trade between regions to compensate for a loss of regional self-sufficiency. This increase in N traded globally is larger in the BAU than in the SSED scenario.

The difference between the BAU and SSED scenarios illustrates the strong influence of human diet on both environmental N losses and dependence on international trade. The SSED scenarios, with tendency towards self-sufficiency and equitable diets in all world regions, result in much less environmental N loss and trade. However, even in the SSED local scenario, the N surplus in croplands remains about twice what it could be in case of an optimal allocation of fertilization among regions (figure 8). The comparison between the standard BAU scenario (largest total N loss of all scenarios) and the BAU with optimum allocation scenario shows a major reduction in total N loss with an increase in the international trade volume, similar to the difference between the two SSED scenarios.

5. Discussion

Our analysis of the past (1961–2009) and possible future trends of the world agro-food system in 12 major world regions shows that population growth has not been the only driver of the evolution of the world agro-food system and its disparities between regions, confirming earlier work (e.g., Kastner *et al* 2012, Westhoek *et al* 2015). The change in human diet, particularly the increasing share of animal products in the per capita protein-N ingestion, is the key driver of the agricultural production system, as three quarters of N in crop production (expressed in terms of protein and including bioenergy by-products) is currently devoted to livestock feed production globally.

Improvement of agronomic performance, including maximum attainable N yield and NUE in both cropping and livestock systems was significant over the last 5 decades in most world regions. However, differences between regions are large in terms of both agricultural performance, self-sufficiency, and specialization in crop or livestock production. These differences stem from factors related to the socio-economic context, the environmental policies, the unequal adoption of agronomic improvements, the degree of connection with global markets, and the associated evolution of the crop mix and mix of livestock production systems (monogastrics versus ruminants) (MacDonald *et al* 2011, Lassaletta *et al* 2014a, Davis *et al* 2015, van Grinsven *et al* 2015, Zhang *et al* 2015).

Regarding cropping systems, our approach assumes that N is the main limiting factor of production, but we recognize that there is a range of factors determining N yields. In fact the shape of the

fertilization versus N yield relationship, and the value of the parameter Y_{max}, implicitly account for other limiting factors such as water availability, crop mix, availability of macro and micronutrients and agronomical management. Improvements in management of these factors explain the past trends observed for Y_{max}, and are taken into account in the four scenarios considered by extrapolated Y_{max} values.

We explored four scenarios of possible changes in the world agro-food system. These scenarios are obviously not prescriptive, but provide a frame for further discussion. Several recent papers provided an interesting point of comparison. For instance, Erb *et al* (2016) explore the 'option space'; i.e. the possibilities of feeding the world by varying agricultural intensification and human diet while maintaining unchanged current total agricultural land area and thus avoiding any deforestation. With a different approach, this work provides support for that of Billen *et al* (2015). Both studies demonstrate that a vast range of options exist for feeding the projected world population in 2050, without expanding the agricultural area. Both studies demonstrate that human diet (more specifically the fraction of livestock products in diet) is the strongest determinant of the option space, followed by N yield levels.

The five shared socio-economic pathways (SSPs) constructed as a basis of future climate change research (O'Neill *et al* 2015, van Vuuren *et al* 2016). In these scenarios there is no constraint set to agricultural areas, which varies according to the supply and demand of food and feed. However, dietary change, development of agricultural yields and performance of livestock systems also appears as key elements differentiating the scenarios.

The four scenarios constructed in our study were more specifically designed to compare the N losses from agriculture and dependence to inter-regional trade of food and feed. The BAU scenario with an optimum allocation of fertilization between regions would lead to much lower environmental losses of N, but would imply much more specialization and international trade than in the standard BAU scenario. The SSED local scenario with maximum possible regional food self-sufficiency, leads to international trade and environmental N losses lower than its current volume (similar to environmental N losses under BAU with optimal allocation).

The SSED scenario with optimal allocation of fertilization allows a further reduction in N pollution; however optimal fertilizer allocation conflicts with the objective of self-sufficiency, leading to an increase of the international trade volume by a factor of 3. Increased trade in this scenario results from concentrating N resources and production in regions with high Y_{max}, which does lead to greater nutrient use efficiency at the global scale but has the counter-intuitive effect of concentrating fertilizer in regions that already have high productivity (N yields). More trade would

bring both benefits and drawbacks for the resilience of the global food system. Trade allows access to food for people in those regions where the local production is not sufficient to meet demand (Fader *et al* 2013, Porkka *et al* 2013), and can enhance the resilience of local food supplies by reducing the vulnerability to local weather disruptions (Burgess and Donalson 2010). Trade relationships are thought to be important for economic development in some developing nations (Godfray *et al* 2010), for example in countries where export-oriented crop production is responsible for large monetary transfers (MacDonald *et al* 2015). However, more trade may also reduce the system-wide resilience of the global food system to shocks by enhancing the pressure on natural resources (e.g. D'Odorico *et al* 2010, Rulli and D'Odorico 2014, Suweis *et al* 2015). For example, increased trade openness has been shown to correlate with enhanced pollution in low- and middle-income countries (Le *et al* 2016). More trade also allows an elevated level of meat and milk consumption in some regions, which could create competing claims on imported proteins leading to less overall protein availability (Davis and D'Odorico 2015). Finally, substantial amounts of N pollution is embodied in traded commodities (Oita *et al* 2016), allowing importing countries to avoid the true environmental costs of their consumption (Galloway *et al* 2007, Lassaletta *et al* 2016, de Ruiter *et al* 2016).

6. Conclusions

As a whole, our findings show that improving the agricultural performance of cropping systems including an optimal reallocation of N fertilizers is a promising strategy to reduce environmental N loss. This conclusion is consistent with earlier studies showing that such improvements can have a larger impact on reducing N losses than increasing international trade (e.g., Kastner *et al* 2014). We have also found that the coupling of better agricultural performance with changes in human diet is an even more promising strategy, as was also concluded by Lamb *et al* (2016). Summarizing, our results clearly show that it would be possible to feed the world with much higher levels of regional self-sufficiency while also generating lower N pollution than currently.

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