A vast range of opportunities for feeding the world in 2050: trade-off between diet, N contamination and international trade

Gilles Billen 1,2, Luis Lassaletta 1 and Josette Garnier 1,2

1 Université Pierre et Marie Curie (UPMC), UMR 7619 Metis, 4 place Jussieu, 75005 Paris, France
2 Centre National de la Recherche Scientifique (CNRS), UMR 7619 Metis, 4 place Jussieu, 75005 Paris, France

E-mail: gilles.billen@upmc.fr

Abstract

Through a detailed analysis of the FAO database, we have constructed a generalized representation of the nitrogen transfers characterizing the current agro-food system (GRAFS) of 12 macro-regions of the world in terms of functional relationships between crop farming, livestock breeding and human nutrition. Based on this model, and maintaining the current cropland areas and the performance of cropping and livestock systems in each region, we have assessed the possibilities of meeting the protein requirements of the estimated world population in 2050, according to various combinations of three critical drivers namely human diet (total amount of protein consumed and share of animal protein in this total), regional livestock production and crop fertilization intensity, in each region. The results show that feeding the projected 2050 world population would generally imply higher levels of inter-regional trade and of environmental nitrogen contamination than the current levels, but that the scenarios with less recourse to inter-regional trade generally produce less N losses to the environment. If an equitable human diet (in terms of protein consumption) is to be established globally (the same in all regions of the world), the fraction of animal protein should not exceed 40% of a total ingestion of 4 kgN capita\(^{-1}\) yr\(^{-1}\), or 25% of a total consumption of 5 kgN capita\(^{-1}\) yr\(^{-1}\). Our results show that slightly improving the agronomical performance in the most deficient regions (namely Maghreb, the Middle East, sub-Saharan Africa, and India) would make it possible not only to meet the global protein requirements with much less international trade (hence more food sovereignty), but also to reduce N environmental contamination the most efficiently.

1. Introduction

The world population is projected to exceed 9 billion inhabitants by 2050 (United Nations 2013). The need to feed a growing population with increasing food quality requirements, while preserving biodiversity and environmental resources, including ground and surface water, atmosphere, soils and biodiversity, thus poses a major challenge to global agriculture. This challenge has often been presented as a dilemma between land sparing and land sharing (Phalan et al. 2011, Ramankutty and Rhemtulla 2012): in the former option, intensification of farming on the best agricultural soils would spare areas for preserving biodiversity, while in the latter option, less productive, multifunctional agriculture would reconcile food production and preservation of natural resources on the same or extended agricultural areas. The first option would foster further development of trade exchanges between regional agro-food systems which today already represents as much as 30% of world protein crop production (Lassaletta et al. 2014a), while the second would stress food sovereignty and a better adjustment of local production on local requirements. Since the millennium ecosystem assessment (MEA, Alcamo et al. 2006), a number of studies have established prospective contrasting scenarios of the global food system at horizon 2050 reflecting this dichotomy. The MEA Global Orchestration scenario corresponds to the land sparing option, while the Adapting Mosaic scenario is more along the lines of the land sharing option. The biogeochemical consequences of both scenarios on the world hydrosystem have been calculated (Billen et al. 2010) and show a...
lower global perturbation by the latter than by the former. The two Agrimonde scenarios (Paillard et al 2010) also correspond respectively to land sparing (current trend scenario) and land sharing (agro-ecological scenario). The MAgPIE model (Lotze-Campen et al 2008, 2010, Schmitz et al 2012, Bodirsky et al 2012, 2014), which elegantly couples an economic land use model with a biophysical process model of vegetation growth and nitrogen cycling, was also run to explore different options related to food trade liberalization and to study their effect on various indicators of environmental quality. In this context, a vivid debate has developed concerning the respective merits of land sparing versus land sharing options (Beddington 2010, Godfray et al 2010, Fischer et al 2011, Tilman et al 2011, Phelps et al 2013). Several voices advocate the need for the incorporation of agro-ecological paradigms in future development of agro-ecosystems, as well as a major move towards a new type of regionally embedded agro-food ecological economy, including rethinking market mechanisms and organizations, and a new institutional context (Altieri 2002, Fischer et al 2011, Horlins and Marsden 2011). On the other hand, the mere possibility of further increasing yields in the best agricultural soils at the rate required by many models of land sparing is questioned based on the observation that yield plateaus have been reached for cereals in many regions of the world (Grassini et al 2013).

Many of the previous analyses of the world agro-food system focus on calories, rather on proteins and micronutrients which can be deficient in the diet even when caloric requirements are met ('The Hidden Hunger', Muthayya et al 2013). The present study, as a small number of others, deals with the protein requirements for feeding the human population. It assumes that the adequate protein intake would likely come with adequate total caloric intake (while the reverse is not necessarily true). From a biogeochemical point of view the issue of nitrogen transfers is closely related to the functioning of the agro-food system, both because this element is the main limiting factor of agricultural production and because nitrogen losses from agriculture to the hydrosphere and atmosphere at the successive steps of the agro-food chain are causing severe environmental damages (Billen et al 2013, 2014, Sutton et al 2013, Bodirsky et al 2014). Crop production is the first stage at which a large amount of N is emitted to the environment instead of being incorporated into the harvested crops (Oenema et al 2009). The efficiency of the N applied as fertilizer has evolved differently in world countries during the last decades (Lassaletta et al 2014b). Next, livestock breeding, involving the transformation of vegetal into animal proteins, is a further and significant bottle neck of the system, because of the rather low efficiency of this transformation. Recent papers have also shown how the concentration of animal production in areas completely disconnected from the feed production regions could result in high emissions of N into the environment, by lack of possibility to recycle it within the local cropping systems (Naylor et al 2005, Gerber and Menzi 2006, Herrero et al 2010, Weiss and Leip 2012, Lassaletta et al 2014a, 2014c, 2014d). Finally, at the level of human consumption, the diet patterns play a significant and crucial role in shaping the agro-food system and its associated environmental N losses, as recently showed by Westhoek et al (2014).

Through a detailed analysis of the FAO database, we have proposed a generalized representation of the nitrogen transfers characterizing the current agro-food system (GRAFS) of 12 macro-regions of the world, defined on the basis of their pattern of international trade exchanges and level of self-sufficiency with regard to their local needs for proteins for feeding humans and livestock (Lassaletta et al 2014a, Billen et al 2014). The analysis first highlights the inequality between the different regions in terms of human diet (total protein intake between 3.3 and 6.5 kgN capita$^{-1}$ yr$^{-1}$ with 15–58% animal proteins), as well as considerable differences in the efficiency of vegetal to animal protein conversion by livestock systems (from 2.4 to 21%). For the cropping systems of each region, we established the relationship between total inputs of nitrogen to cropland and crop production expressed in nitrogen content and integrated over the whole rotation cycle (Billen et al 2013, Lassaletta et al 2014b). This relationship characterizes both the agronomical and environmental performance of the agriculture of each region of the world. In terms of food sovereignty, the analysis reveals that a small number of net exporting countries such as Brazil, Argentina, the USA and Canada are closing the gap between production and demand of a large number of deficient, net importing countries. It also shows that over a total of 95 Tg reactive N released annually from cropland at the global scale, 75% is emitted in China, India, North America and Europe, with severe consequences in terms of human health, atmospheric and water pollution, and loss of biodiversity (Sutton et al 2011, 2013).

The purpose of this paper is to systematically explore the possibilities and the limits of some structural changes in the current agro-food system to meet the requirements of feeding the projected world population in the middle of the century, while limiting environmental N contamination. By structural changes, we mean modifications concerning three aspects of the system in each region: (i) human diet, defined by the regional mean per capita total protein ingestion rate, as well as by the proportion of proteins from animal sources in this total; (ii) the amount of livestock and its connexion to cropping systems; (iii) the intensification of cropping systems, measured by the rate of new nitrogen added to cropland, either as synthetic fertilizer or through symbiotic N fixation by cultivated legumes. The extent of long-distance trade of agricultural products is viewed as a direct consequence of
these three characteristics which together define the self-sufficiency of each region of the world. Possible technical agronomical improvements were not taken into account here and we therefore considered that the relationship currently observed between crop yield expressed in protein content and total nitrogen fertilization will remain unchanged. The same conservative assumption is made for the efficiency of vegetal to animal protein conversion by livestock farming systems, as well as for the rate of animal manure recovery. We also consider no change in the area occupied by cropland, grassland and forests.

2. Methods and assumptions

2.1. The GRAFS model

The GRAFS approach is based on functional relationships between crop farming, livestock breeding and human nutrition expressed in terms of transfer of nitrogen (i.e. proteins) (figure 1). The system’s driving variables are (1) the size of the human population; (2) human apparent diet (which includes wastes generated at the different steps of the agro-food chain); (3) the livestock numbers; and (4) the intensity of extra fertilization of cropland either by synthetic fertilizers or symbiotic fixation.

The model calculates crop production assuming for the pedoclimatic and socio-technical context of each region a hyperbolic single parameter relationship between long-term integrated annual yield per ha (Y) and total inputs of nitrogen to cropland (through manure application, atmospheric deposition, symbiotic N fixation and synthetic fertilization) (Fert, kgN ha\(^{-1}\) yr\(^{-1}\)):

\[
Y = Y_{\text{max}} \times \frac{\text{Fert}}{Y_{\text{max}} + \text{Fert}}
\]

with \(Y_{\text{max}}\) (kgN ha\(^{-1}\) yr\(^{-1}\)) representing the protein yield value reached at saturating fertilization.

The justification of this relationship is provided in Lassaletta et al. (2014b). The value of the parameter \(Y_{\text{max}}\) has been calculated for the current situation of each region from the estimated values of \(Y\) and Fert (Billen et al. 2014). The long-term balance between N inputs to cropland and N export through crop harvest (N surplus), calculated according to relation (2) is used as an indicator of N environmental losses (Billen et al. 2013):

\[
\text{N surplus} = \text{Fert} - Y
\]

\[
= \text{Fert} \left[ 1 - \frac{Y_{\text{max}}}{Y_{\text{max}} + \text{Fert}} \right].
\]

Livestock ingestion, excretion and meat and milk production are calculated from livestock numbers (arbitrarily expressed in livestock units (LUs), defined as the number of animals excreting 85 kgN yr\(^{-1}\)) using the conversion efficiency of vegetal to animal protein calibrated for the current situation in each region (Billen et al. 2014). The fraction of total excretion applied to cropland is calculated using the regional coefficients defined by Sheldrick et al. (2003) for the current situation, and considering a loss of 30% during management (Oenema et al. 2003, Liu et al. 2010).

The production of permanent and semi-natural grassland grazed by livestock is considered identical to that estimated in the current situation (Billen et al. 2014). Similarly, the amount of fish eaten by humans in 2050 is considered identical to that estimated for 2009 and is included in the animal protein diet.

Imports or exports of vegetal proteins are calculated by the difference between local crop production and requirements for human nutrition and livestock feeding (taking into account production of permanent grassland). Imports or exports of animal protein are calculated as the difference between livestock production and human requirements (taking into account fish consumption).

2.2. Regional scenarios

In a study of global trade exchanges of agricultural products, Lassaletta et al. (2014a) proposed grouping the world’s countries into 12 macro-regions, defined on the basis of their current level of self-sufficiency with regard to their local protein needs for feeding humans and livestock. These regions are North America, Europe, the Former Soviet Union (FSU), Maghreb and the Middle East, sub-Saharan Africa (SSAf), India and Bangladesh (Ind), South–East Asia (SEAs), China, Japan, Central and South–West America (CSWAm), the South American Soy Countries (SASCs) and Australia/New Zealand (Austr). The current structure of their agro-food system was analysed in detail by Billen et al. (2014).

The population of these 12 regions in 2050, according to UN projections (United Nations 2013), will total 9.2 billion globally. The increase will be particularly high in SSAf (+135%), Maghreb and the Middle East (+61%), India and Australia (+40%); it will be moderate (+20–35%) in all the American regions and SEA, insignificant in Europe and negative in FSU, China and Japan.

For each of the 12 regions, a wide spectrum of scenarios of agro-food system structure has been established, by combining the three levers of change mentioned above, namely apparent human diet (final protein food intake and/or wasting along the agro-food chain), amount of livestock and crop intensification level (figure 1(b)). For diet, we explored the range of total protein consumption comprised between 4 and 7 kgN capita\(^{-1}\) yr\(^{-1}\), with 20–70% animal protein (including fish). LUs varied between a minimum value corresponding to the current carrying capacity of permanent and semi-natural grassland of each region and a maximum set at twice the local requirements of the population for each diet hypothesis. For the gradient of crop intensification, we considered inputs of new
reactive nitrogen (typically synthetic fertilizers) between zero and twice the value of \( Y_{\text{max}} \) (i.e. the range for which yield is still strongly responding to the fertilization rate and excluding situations of extreme inefficiency and associated N contamination), in addition to the application of manure (depending on the livestock numbers), the current atmospheric deposition rate and the current symbiotic N fixation by cultivated legumes. For each value of these three levers, the model calculates total crop and animal production, compares it to local human requirements and calculates the required import, or possible export, of vegetal and animal proteins (figure 1) (note that we expressed export as negative values of import). The characteristics of the 12 macro-regions that are considered invariant across all scenarios in our conservative
Table 1. Main characteristics of the agro-food system of 12 world regions maintained at 2009 levels in the 2050 model. Considered range of variations of control factors and variables calculated by the model.

| Regions                        | Human diet |               |               |                |               |               |                |                |                |                |                |                |                |                |
|--------------------------------|------------|---------------|---------------|----------------|---------------|---------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|                                |            | Africa        | Maghreb and   | Middle East   | Europe        | Former         | India and      | Bangladesh    | China           | Japan          | South–East Asia| North America  | South American  | Soy countries  |
|                                |            | Million       | Million       | Million        | Million       | Soviet         | Million        | Million       | Million         | Million        | Million         | Million         | Million         | Million         |
|                                |            | 1954          | 1034          | 541            | 278           | 1956           | 1356           | 156           | 749             | 447            | 304            | 426            | 37             | 9238           |
| Population                    | Million    | 1034          | 541           | 278            | 1956          | 1356           | 156            | 749           | 447             | 304            | 426            | 37             | 9238           |                |
| kgN capita⁻¹ yr⁻¹             |            | Varied from 4 to 7 kgN capita⁻¹ yr⁻¹ (by intervals of 1 kgN capita⁻¹ yr⁻¹) |            |                |                |                |                |                |                |                |                |                |                |                |
| Fish protein consumption      | kgN capita⁻¹ yr⁻¹ | 0.2            | 0.2           | 0.2            | 0.2           | 0.2            | 0.4            | 1.2           | 0.6             | 0.3            | 0.3            | 0.2            | 0.3            | 0.27           |
| Animal protein cons (incl fish)| %          | Varied from 20 to 70% |            |                |                |                |                |                |                |                |                |                |                |                |
| Cropping systems              | Million ha | 186.0          | 89.0          | 109.9          | 118.0         | 182.8          | 127.1          | 5.7           | 102.3           | 144.3          | 107.9          | 37.7           | 26.0           | 1237           |
| 
Ymax                           | kgN ha⁻¹ yr⁻¹ | 58             | 69            | 142            | 203           | 64             | 127            | 79            | 294             | 290            | 64             | 80             | –              | –              |
| Symbiotic N fixation          | kgN ha⁻¹ yr⁻¹ | 6.7            | 12.0          | 15.2           | 2.8           | 34.2           | 23.8           | 27.1          | 20.1            | 54.8           | 70.1           | 15.6           | 6.6            | –              |
| Atmospheric deposition        | kgN ha⁻¹ yr⁻¹ | 5.6            | 4.1           | 8.5            | 2.6           | 17.9           | 12.4           | 4.9           | 5.7             | 3.7            | 5.6            | 4.4            | 1.8            | –              |
| Effective manure application  | kgN ha⁻¹ yr⁻¹ | Calculated from livestock numbers and cropland area, assuming current rate of animal excrement recycling |            |                |                |                |                |                |                |                |                |                |                |                |                |
| Additional fertilizer         | kgN ha⁻¹ yr⁻¹ | Varied from 0 to 2*Ymax (by intervals of Ymax/5) |            |                |                |                |                |                |                |                |                |                |                |                |
| Crop production               | kgN ha⁻¹ yr⁻¹ | Calculated from total inputs to cropland soil (Fert) according to the relationship Crop prod = Ymax Fert/(Fert + Ymax) |            |                |                |                |                |                |                |                |                |                |                |                |
| Cropland soil N balance       | TgN yr⁻¹    | Calculated as the difference between total N inputs to cropland soils and total crop production |            |                |                |                |                |                |                |                |                |                |                |                |
| Regions                        | Africa | Maghreb and Middle East | Europe | Former Soviet Union | India and Bangladesh | China | Japan and S Korea | South–East Asia | North America | South American Soy countries | Central and SW America | Australia and NZ | World |
|-------------------------------|--------|-------------------------|--------|--------------------|----------------------|-------|------------------|-----------------|---------------|-------------------------------|-----------------------|------------------|-------|
| Permanent grassland           |        |                         |        |                    |                      |       |                  |                 |               |                               |                       |                  |       |
| Grassland area                | Million ha |                         | 832.4  | 359.2              | 73.5                 | 361.8 | 13.2             | 505.9           | 0.1           | 16.9             | 263.5                 | 367.2             | 183.8           | 372.5 | 3350 |
| Used grassland production b   | TgN yr⁻¹ |                         | 18.4   | 7.7                | 2.8                  | 3     | 15.7             | 9.04            | 0             | 1.7              | 0.1                   | 12.4               | 6.4             | 3.0    | 80.3 |
| Livestock systems             |        |                         |        |                    |                      |       |                  |                 |               |                               |                       |                  |       |
| Number of livestock c         | Million LU |                         | Varied from the carrying capacity of current permanent grassland to the value corresponding to 140% of local animal protein needs (by intervals of 20%) |       |        |                  |                 |               |                               |                       |                  |       |
| Conversion efficiency d       | %      |                         | 2.4    | 7.1                | 16.2                 | 12.2  | 4.2              | 11.8            | 21.0          | 7.1              | 17.0                 | 6.4               | 7.0             | 8.4    | 8.4  |
| Trade                         |        |                         |        |                    |                      |       |                  |                 |               |                               |                       |                  |       |
| Net imp/exp of vegetal proteins | TgN yr⁻¹ |                         | Calculated as the difference between local needs for livestock and human nutrition and local production of crop products |       |        |                  |                 |               |                               |                       |                  |       |
| Net imp/exp of animal proteins | TgN yr⁻¹ |                         | Calculated as the difference between local needs of animal proteins (excl fish) for human nutrition and local production of animal protein by livestock |       |        |                  |                 |               |                               |                       |                  |       |

a Projections by United Nations 2013.
b 2009 values, assumed unchanged (italic characters) see Billen et al (2014). Detailed characteristics of the regions can be consulted in Billen et al (2014) and Lassaletta et al (2014a).
c LU is arbitrarily defined here as the amount of livestock excreting 85 kgN yr⁻¹.
d Ratio of the livestock production of animal proteins to ingestion of vegetal protein.
analysis are gathered in table 1, as well as the range of variations considered for the other characteristics, and the relationships linking them to each other.

Each regional scenario is then characterized by a number of indicators. Its degree of self-sufficiency with respect to vegetal protein is measured by the fraction of local requirements of vegetal proteins (for humans and livestock) supplied by local production including semi-natural grasslands. Similarly, animal protein self-sufficiency is defined as the fraction of animal protein consumed by humans supplied by local livestock production and fisheries. Finally, as stated above, the environmental N losses are estimated by the N balance of cropland soils (also referred to as N surplus), and will serve as an indicator of potential agricultural alteration of the N cycle (including nitrate leaching, ammonia and nitrous oxide emissions).

2.3. Global scenarios
A global scenario is defined by the combination of 12 particular scenarios from each of the 12 regions. It is only viable if the sum of all possible exports of vegetal and animal proteins by some regions exceeds the required imports by other regions:

$$\sum_{\text{for all regions}} (\text{net import vegetal proteins}) < 0,$$

$$\sum_{\text{for all regions}} (\text{net import animal proteins}) < 0.$$

A calculation routine was established (as a macro for MS-Excel) to test the viability of all combinations of a selected number of scenarios for all 12 regions.

Viable global scenarios can be characterized by several indicators.

The overall degree of food sovereignty is measured by the amount of inter-regional trade, calculated as half the sum of the absolute value of import or export of animal and vegetal proteins by each region:

$$\text{Interreg. trade} = \frac{1}{2} \times \sum_{\text{for all regions}} [\text{ABS(import vegetal protein) + ABS(import animal protein)}].$$

The overall environmental loss of nitrogen from cropland, expressed in TgN yr$^{-1}$ is a good indicator of the pollution generated by the global agro-food system at the global scale (Billen et al 2013)

$$\text{N Loss} = \sum_{\text{for all regions}} [\text{N balance of cropland soils}].$$

3. Results

3.1. Regional scenarios
3.1.1. Trade of agricultural products and self-sufficiency at the regional scale
A large number of scenarios were generated in each region by varying human diet, livestock number and intensification of cropping systems. For each combination of these three levers, the value of the corresponding calculated required import (or possible export) of vegetal and animal proteins was plotted in figure 2. The current (2009) position of each region in terms of vegetal and animal trade is also shown for comparison. This representation distinguishes several types of regions in terms of their capacity of reaching self-sufficiency (net imports/exports of both animal and vegetal proteins close to zero), of exporting agricultural products or, on the contrary, of requiring imports of either vegetal or animal proteins. Considerable potential for vegetal or animal protein export are predicted to exist in 2050 for North America, FSU and SASC and to a much lower extent Australia. Europe, currently a net importer of vegetal and net exporter of animal proteins, has the capacity of exporting both or being self-sufficient in 2050. China, today a net importer of vegetal and animal proteins, has the capacity of becoming a net exporter of both or being self-sufficient in 2050, depending on human diet, amount of livestock or intensification of cropping systems. For SEAs, CSWAm and Japan, most of the scenarios involve import of either vegetal or animal protein or both, although some self-sufficient or net exporting scenarios exist for these countries, at low protein content in the diet. Africa, India and Maghreb are the three regions for which no self-sufficient or net exporting scenarios were generated by any combination of diet, cropping system intensification or live-stock numbers within the range tested. Many scenarios generated for these regions would require imports of proteins from international trade higher than the maximum cumulated possibilities of export from all the other regions (estimated to 83 TgN yr$^{-1}$ from the data shown in figure 2), indicating that these scenarios are unsustainable. In the case of India and Bangladesh, where the current very low proportion of animal protein in the diet is related to deep cultural matters, the scenarios tested with higher meat and milk consumption might be irrelevant; however, even at the present level of animal protein per capita consumption, this region, currently slightly net exporting proteins, is predicted by our model to become dependent on massive imports in 2050.

Within the scope of our model, the factors explaining the incapacity of Africa, Maghreb and the Middle East, and India of reaching self-sufficiency at any diet and cropping system intensification lie of course in these regions’ high projected population, but also in the low value of the parameter of the yield–fertilization relationship and the low efficiency of live-stock farming (table 1).

A moderate increase of these parameters would allow the three regions to reach self-sufficiency for at least the lowest diet tested (4 kgN capita$^{-1}$ yr$^{-1}$ with 20% animal proteins). For Africa, India and Maghreb, this requires increasing the vegetal to animal protein conversion efficiency from the current values of 2.4, 4.2 and 7.1% to 6, 7.5 and 10%, respectively. Also, the $Y_{\text{max}}$ value characterizing the yield–fertilization relationship of the cropping system should be increased.
from 58, 64 and 58 kgN ha\(^{-1}\) yr\(^{-1}\) to 75 kgN ha\(^{-1}\) yr\(^{-1}\) (figure 2).

3.1.2. Intensification of cropping systems and nitrogen contamination at the regional scale
The capacity of a region to export proteins (or its degree of dependency on protein imports) depends a great deal on the degree of intensification of cropping systems (defined in the GRAFS model by the level of external N fertilization of cropland, i.e. either the application of synthetic fertilizers or the recourse to symbiotic N\(_2\) fixation), as well as on the amount of livestock and the composition of human diet. With increasing fertilization, the environmental contamination generated by cropping systems is also rapidly increasing (figure 3). This contamination is expressed in the model by the regional cropland soil N balance (or surplus), which represents the potential for environmental losses of N, either to the hydrosphere through nitrate leaching, or to the atmosphere as
ammonia or nitrous oxide emissions. While grassland soil can store a large part of the N surplus in their organic matter pool, this is not the case for croplands, which are therefore the most important source of environmental N contamination globally (Billen et al 2013). In many regions, surpluses greater than 150 kgN ha\(^{-1}\) yr\(^{-1}\) are reached for certain scenarios. For an infiltrating water height of 300 mm yr\(^{-1}\), this surplus value corresponds to a sub-root concentration of 50 mgN l\(^{-1}\), which is already five times over the WHO drinking water standard. This criterion thus allows assessing the trade off between capacity of export and environmental contamination.

3.2. Global scenarios
Combining the regional scenarios for the 12 macro-regions creates a large number of global scenarios. A particular combination is eligible on the necessary condition that the cumulated calculated imports (export counted as negative values) of vegetal and animal proteins of all 12 regions are negative or null. We have already mentioned that not all regions have sufficient productive capacities to reach self-sufficiency in 2050, so that some net exchanges of vegetal and/or animal proteins between regions are required for a global scenario to be able to feed the world with the current characteristics of the global agro-food system.

3.2.1. Scenarios with the current and projected diets
In the first step, we combined all scenarios for the 12 regions maintaining the current diet of each of them, i.e. the currently observed total per capita protein consumption rate and the fraction of animal protein in this total, ranging from 4 kgN capita\(^{-1}\) yr\(^{-1}\) with 20% animal protein in India and Africa to 6 kgN capita\(^{-1}\) yr\(^{-1}\) with 60% animal protein in Europe, North America and Australia. The combinations meeting the above requirement all involve higher total trade of vegetal (25–60 TgN yr\(^{-1}\)) and animal (2.3–5.6 TgN yr\(^{-1}\)) proteins compared to current levels (respectively, 24 and 1.0 TgN yr\(^{-1}\)) (figure 4(a)). They also produce much higher levels of environmental N contamination (195–275 TgN yr\(^{-1}\)) compared to the current level of 95 TgN yr\(^{-1}\). Two examples of the possible combinations are represented in figure 4(b), compared with the current situation of inter-regional trade exchanges.

A number of agro-economic models have calculated what the human diet could be in the different regions of the world in 2050 according to the Global Orchestration scenario. The results, gathered by Valin et al (2014), are provided in kcal capita\(^{-1}\) d\(^{-1}\) of crop and livestock products. We converted them into kgN capita\(^{-1}\) yr\(^{-1}\) using a region-specific coefficient derived from FAOstat (45–60 kcal g\(^{-1}\) protein for crop products and 12–17 kcal g\(^{-1}\) protein for livestock products). The projected 2050 diets thus range between 5.5 kgN capita\(^{-1}\) yr\(^{-1}\) with 60% animal protein for OCDE countries and FSU, 5 kgN capita\(^{-1}\) yr\(^{-1}\) with 50% animal protein for Latin America and Asia, and 4 kgN capita\(^{-1}\) yr\(^{-1}\) with 30% animal protein for Africa and the Middle East. These diets are slightly richer that the current ones. Similar to what we did
with the current diet, we combined the regional scenarios of the 12 regions with these projected diets. Over more than 200 million combinations tested, only nine met global needs. As shown in figure 4, all of them require a high level of international trade (50 TgN yr\(^{-1}\)) and result in large N release from cropping systems (257 TgN yr\(^{-1}\)).

### 3.2.2. Scenarios with equitable diet

The diet considered in the two previous scenarios is quite unequally distributed among the world’s regions: as a global average in 2050, the current diet would represent a per capita intake of 4.6 kgN capita\(^{-1}\) yr\(^{-1}\) with 36% animal protein, while the projected diet is slightly higher, 4.6 kgN capita\(^{-1}\) yr\(^{-1}\) with 44% animal protein.

We define an equitable diet as one which can be shared by all regions of the world. Starting from a total protein consumption of 4 kgN capita\(^{-1}\) yr\(^{-1}\) with 20% animal proteins, we gradually increased both figures and looked for the occurrence of eligible combinations of regional scenarios with this diet, varying livestock numbers and cropping system fertilization independently in each region. However, we kept the percentage of animal protein in the Indian diet at 20% as a typical Indian specificity. With these constraints, the richest possible diet was found to be 4 kgN capita\(^{-1}\) yr\(^{-1}\) with 40% animal protein (figure 5). Increasing the total uptake of protein to 5 kgN capita\(^{-1}\) yr\(^{-1}\) limits the percentage of animal protein to 25% in eligible combinations.

A remarkable feature within the possible scenarios plotted in figure 5 is the positive correlation between inter-regional trade and the total surplus of N input to arable soils, which indicates the level of global N environmental contamination. This suggests that among
the scenarios able to feed the world, those requiring less inter-regional trade are also those causing less agricultural pollution globally. The examples illustrated in figure 5(b) indeed show that the scenarios involving the highest specialization of certain regions into either animal or vegetal production, while it increases the capacity for international export, give rise to the highest overall N surplus of cropland. This is related to the link between cropping intensity, N balance and protein export illustrated in figure 3.

3.2.3. Scenarios with improved performance of cropping and livestock systems in Maghreb, Africa and India.

The low performance of both cropping and livestock systems in the three regions where the population increase is predicted to be the highest at the 2050 horizon is a serious hindrance to the capacity of the global agro-food system to meet the requirements of the future world population. With the current characteristics of the agro-food system of these three regions, a considerable fraction of the food consumption will have to be provided by inter-regional trade, even at the highest rate of cropping intensification. We showed above that reasonably improving agricultural performance, i.e. increasing the $Y_{max}$ value of the cropping system as well as the vegetal to animal conversion efficiency of livestock farming, could suffice to make these regions self-sufficient for a diet of 4 kgN capita$^{-1}$ yr$^{-1}$ with 20% animal protein. Including these changes in the above regional scenarios largely increases the number of eligible combinations (figure 6). A first obvious set of combinations shows all 12 regions being self-sufficient, thus with zero net inter-regional trade. Depending on the diet in each of these regions, the corresponding global N contamination level would range from 65 to 104 TgN yr$^{-1}$ (compared with the current value of 95 TgN yr$^{-1}$).

The highest value of equitable diet which could be achieved with these slight improvements of the agronomical performance of the three least productive regions is now 5 kgN capita$^{-1}$ yr$^{-1}$ with 40% animal protein, and the equitable diet of 4 kgN capita$^{-1}$ yr$^{-1}$ with 40% animal protein would be achieved with much lower values of inter-regional trade and cropland soil N surplus contamination. Again, a strong correlation appears between trade and N contamination, reinforced by the low values of global N surplus corresponding to the self-sufficient region scenarios (figure 6).

4. Discussion

The present exercise by no means represents either a prediction or a recommendation of what the global food system would or should be in 2050. Our starting hypotheses are indeed very restrictive. We considered no change in cultivated areas, no change in practices, beyond increasing or decreasing the cropland fertilization, and no change in the efficiency of cropping and livestock farming systems (with the exception of the improvement discussed in Maghreb and the Middle East, India, and Africa). The very simplified model we
used is only intended to explore the interplay of diet, crop intensification and inter-regional trade as constrained by the biophysical potentialities of the agro-food system as it works today.

Most existing models of the future of the global agro-food system are based on economic drivers, linking GDP to human diet (Valin et al. 2014), thus leaving little room for exploring an alternative future for human nutrition. In our approach, human diet appears as a major driver of the future agro-food system. With the strong hypothesis of an equitable diet, we showed that the highest sustainable protein consumption would be 4 kgN capita$^{-1}$ yr$^{-1}$ with 40% animal products or 5 kgN capita$^{-1}$ yr$^{-1}$ with 20% animal protein. This maximum sustainable diet increases to 5 kgN capita$^{-1}$ yr$^{-1}$ with 40% animal protein with a slight improvement of the agronomical performance of Maghreb, India, and Africa. These diets, although well below the current standards in the West, should be compared with the World Health Organization’s dietary recommendations (WHO 2007) of a total per capita protein intake of 2.8 and 3.5 kgN yr$^{-1}$ (for women and men, respectively, with 55–75 kg body weight). The value of 4 kgN capita$^{-1}$ yr$^{-1}$ for total consumption thus already incorporates about 20% of unavoidable losses between crop production and final intake (Gustavsson et al. 2011). A value of 30–40% of animal protein is consistent with the Mediterranean diet, known as a quite healthy one (Saez-Almendros et al. 2013) as well as with the recommendation of the demitarian diet for developed countries (Sutton et al. 2013).

Most published models also assume a general trend of increasing nitrogen use efficiency (NUE) through technical improvement of agricultural practices in developed countries and adoption of Western agricultural characteristics in developing countries (see e.g. Bodirsky et al. 2014). However, other authors show that climate change could negatively affect crop yields in some areas, offsetting the positive effects of improved agricultural practices (Challinor et al. 2014, Trnka et al. 2014). The scenarios explored in the present paper are independent of such assumptions. As a conservative hypothesis, we did not take for granted that NUE would increase or would even remain constant at the current value in all regions of the world; instead we assumed a definite relationship between yield and fertilization of cropping systems in each region, the form of which implicitly implies a reduction of NUE with increasing cropland fertilization.

In our model, the lever of cropping intensification is represented by additional N input to cropland soil with respect to atmospheric deposition (taken as equal to its current rate), manure application (dependent on livestock, with the same recycling ratio as observed today) and the current rate of symbiotic fixation by current legume crops; it thus represents either the application of synthetic fertilizers or further recourse to N$_2$-fixing crops. The model considers both sources of additional N as equivalent in terms of yield response integrated over the whole culture rotation cycle, although the latter source of N might be more efficient than the former as suggested by recent work (Lassaletta et al. 2014b).
The most striking result of our exercise is the positive correlation between inter-regional trade and N contamination measured by the global soil balance of cropland. This might seem surprising, since one might have expected less global pollution in situations where food production is concentrated in efficient regions and redistributed by long-distance trade where the highest populations are concentrated. The contrary is observed as a consequence of the increasing N losses resulting from further intensification even in efficient agricultural regions, which today produce already the major part of global N contamination. This suggests that a moderate intensification throughout the world agricultural systems would be more efficient than a hyper-intensification of the agricultural practices in some favourable areas (or in areas with weaker environmental legislation). On the other hand, several authors have recently described the intense disconnection between crop and livestock that is occurring in many world regions (Naylor et al 2005, Sasu-Boakye et al 2014, Lassaletta et al 2014a). The results of the present work also reflect the loss of global NUE resulting from this disconnection that is exacerbated in the high trade scenarios.

Overall, these results suggest that the objective of food sovereignty is consistent with that of minimizing N contamination. From this respect, the scenarios we run with slightly improved agronomical performance in Maghreb and the Middle East, India, and Africa show that bringing these regions to self-sufficiency (which in many cases would however require to overcome water limitation issues) would be by far the most efficient way to reduce global N contamination (figures 4 and 5).

The lessons from the rather academic exercise presented here is obviously difficult to translate into operational policy recommendations at the regional or global scale. However, at the level of the three levers studied (cropping systems, livestock breeding and human diet), existing policies that could have positive effects can be identified. The application of agricultural and environmental policies in the European Union has produced demonstrated benefits in the reduction of the emissions of N compounds to the environment, from both crop and livestock systems, by increasing NUE (van Grinsven et al 2012, Dalggaard et al 2014, Lassaletta et al 2014b). These efforts can be positive in all the world regions but particularly relevant in Maghreb and the Middle East, India, and Africa. As far as human diet is concerned, a reduction of animal protein consumption in developed countries where this consumption is above health standards is undoubtedly desirable. The socio-political implications of such a diet are particularly difficult to assess, but Westhoek et al (2014) reviewed several options, from public awareness campaigns to taxation policies, that could be implemented.

5. Conclusions

The calculations presented in this paper show that it is possible to supply the proteins required to feed the projected 2050 world population without increasing agricultural areas, and without relying on radical changes in the functional characteristics of current cropping ($Y_{max}$) and livestock farming systems (vegetal to animal conversion efficiency). However, this would imply a considerable increase in inter-regional food and feed trade as well as in N contamination of the environment. If an equitable human diet is to be established globally (the same in all regions of the world), the fraction of animal protein should not exceed 40% of a total ingestion of 4 kgN capita$^{-1}$ yr$^{-1}$, or 20% of a total consumption of 5 kgN capita$^{-1}$ yr$^{-1}$. Scenarios with less potential for recourse to inter-regional trade generally produce less environmental N losses.

Improved agronomical performance ($Y_{max}$, vegetal to animal conversion rate) in the three most deficient regions (namely Maghreb and the Middle East, SSAF, and India) are required to feed the world with less international trade (hence more food sovereignty) and less cropping intensification (hence less N contamination).

Acknowledgments

This work was partly carried out in the scope of the EMoSEM project (ANR-12-SEAS- 0005-01) financed by the French National Research Agency. We wish to thank Professor G de Marsily for the lively discussions which sparked our interest in the topic. The idea of the present study emerged during a Territorial Biogeochemistry course at the University P & M Curie in Paris, where students were asked to imagine a scenario for feeding the world in 2050, starting from the GRAFS analysis of the current situation, and maintaining unchanged the current area and yield/fertilization relationship of cropland, as well as the main functional characteristics of livestock breeding in each of the 12 world regions. From completely vegan to entirely globalized, the scenarios designed by each student differed greatly, reflecting the personality and ideological orientation of their author. The analysis of these numerous possible scenarios demonstrated that feeding the world in 2050 is theoretically possible in many ways, including without relying on the extension of arable surfaces or a strong intensification of cropping systems. We are grateful to all the students of the 2013–2014 graduation class of this course whose enthusiasm and creativity motivated the present study. We also thank B Bodirsky for fruitful discussions.

References

Alcamo J, van Vuuren D and Cramer W 2006 Changes in ecosystem services and their drivers across the scenarios, in ecosystems
and human well-being; scenarios ed S R Carpenter et al (Washington, DC: Island Press) pp 279–354
Altieri M A 2002 Agroecology: the science of natural resource management for poor farmers in marginal environments Agric. Ecosystems Environ. 93 1–24
Beddington J 2010 Food security: contributions from science to a new and greener revolution Phil. Trans. R. Soc. B 365 61–71
Billen G, Beusen A, Bouwman L and Garnier J 2010 Anthropogenic nitrogen autotrophy and heterotrophy of the world’s water-sheds: past, present, and future trends Glob. Biogeochem. Cycles 24 GB0A11
Billen G, Garnier J and Lassaletta L 2013 The nitrogen cascade from agricultural soils to the sea: modelling N transfers at regional watershed and global scales Phil. Trans. R. Soc. B 368 20130123
Billen G, Lassaletta L and Garnier J 2014 A biogeochemical view of the global agro-food system: nitrogen flows associated with protein production, consumption and trade Glob. Food Secur. 3 209–19
Bodirsky B L et al 2014 Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution Nat. Commun. 5 3858
Bodirsky B L, Popp A, Weindl I, Dietrich J P, Rolinski S, Schießle L, Schmitz C, and Lotze-Campen H 2012 N2O emissions from the global agricultural nitrogen cycle—current state and future scenarios Biogeosciences 9 4169–97
Challinor A J, Watson J, Lobell D B, Howden S M, Smith D J R and Chhetri N 2014 A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4 287–91
Dalgaard T 2014 Policies for agricultural nitrogen management—trends, challenges and prospects for improved efficiency in Denmark Environ. Res. Lett. 9 115002
FAO 2001 Food Balance Sheets A Handbook (Rome: FAO)
Fischer J et al 2011 Conservation: limits of land sparing Science 334 593
Gerber P and Menzí H 2006 Nitrogen losses from intensive livestock farming systems in Southeast Asia: a review of current trends and mitigation options Integ. Congr. Ser. 1293 253
Godfray H C J et al 2010 Food security: the challenge of feeding 9 billion people Science 327 812–8
Grassini P, Eskridge K M and Cassman K G 2013 Distinguishing between yield advances and yield plateaus in historical crop production trends Nat. Commun. 5 3858
Gustavsson J, Cederberg C, Sonesson U, van Otterdijk R and Meybeck A 2011 Global Food Losses and Food Waste FAO Report 38 (Rome: FAO)
Herrero M et al 2010 Smart investments in sustainable food production: revisiting mixed crop-livestock systems Science 327 822–5
Horlings L G, Mardesen T K 2011 Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could ‘feed the world’ Glob. Environ. Change 21 441–52
Lassaletta L, Aguilera E, Sanz-Cobena A, Pardo G, Billen G, Garnier J and Grizzetti B 2014d Leakage of nitrous oxide emissions within the Spanish agro-food system in 1961–2009 Mitigation Adaptation Strategy. Glob. Change doi:10.1007/s11027-014-9569-0
Lassaletta L, Billen G, Grizzetti B and Garnier J 2014b The relationship between crop yield and nitrogen input to cropland in 131 countries: 50 years trends Environ. Res. Lett. 9 105011
Lassaletta L, Billen G, Grizzetti B, Garnier J, Leach A M and Galloway J N 2014a Food and feed trade as a factor in the global nitrogen cycle: 50 year trends Biogeochemistry 118 223–41
Lassaletta L, Billen G, Romero E, Garnier J and Aguilera E 2014c How changes in diet and trade patterns have shaped the N cycle at the national scale: Spain (1961–2009) Reg. Environ. Change 14 785
Liu J G, You L Z, Amini M, Obersteiner M, Herrero M, Zehnder A J B and Yang H 2010 A high-resolution assessment on global nitrogen flows in cropland Proc. Natl. Acad. Sci. USA 107 8035–40
Lotze-Campen H, Muller C, Bondeau A, Jachner A, Popp A and Lucht W 2008 Food demand, productivity growth and the spatial distribution of land and water use: a global modeling approach Agric. Econ. 39 325–38
Lotze-Campen H, Popp A, Beringer T, Muller C, Bondeau A, Rost S and Lucht W 2010 Scenarios of global bioenergy production: the trade-offs between agricultural expansion, intensification and trade Ecol. Model. 221 2188–96
Muthayya S et al 2013 The global hidden hunger indices and maps: an advocacy tool for action PLoS One 8 e67860
Naylor R, Steinfeld H, Falcon W, Galloway J, Smith V, Bradford E, Alder J and Mooney H 2003 Losing the links between livestock and land Science 310 1621–2
Oenema O, Kros H and de Vries W 2003 Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies Eur. J. Agron. 20 3–16
Oenema O, Witzke H P, Klimont Z, Lesschen J P and Veldho G L 2009 Integrated assessment of promising measures to decrease nitrogen losses from agriculture in EU-27 Agric. Ecosystems Environ. 133 280
Paillard S, Treyer S and Dorin B 2010 Agrimonie: Scénarios et défis pour nourrir le monde en 2050 (Paris: Quae)
Phalan B et al 2011 Reconciling food production and biodiversity conservation: land sharing and land sparing compared Science 333 1289
Phelps J, Carrasco R L, Webb E L, Koh L P and Pascual U 2013 Agricultural intensification escalates future conservation costs Proc. Natl. Acad. Sci. USA 110 7601–6
Ramanukthi N and Renthumula J 2012 Can intensive farming save nature? Guest editor Frontiers Ecol. Environ. 10 455
Saenz-Almendros S, Obreado B, Bach-Faig A and Serra-Majem L 2013 Environmental footprints of Mediterranean versus Western dietary patterns: beyond the health benefits of the Mediterranean diet Environ. Health 12 118–25
Sasu-Boakye Y, Cederberg C and Wirsenis S 2014 Localising livestock protein feed production and the impact on land use and greenhouse gas emissions Animal Fl 1339–48
Schmitz C et al 2012 Trading more food: implications for land use, greenhouse gas emissions, and the food system Glob. Environ. Change 22 189–209
Sheldrick W, Syers J K and Lingard J 2003 Contribution of livestock excreta to nutrient balances Nutr. Cycl. Agroecosyst. 66 119–31
Sutton M A et al 2013 Our nutrient world: the challenge to produce more food and energy with less pollution Global Overview of Nutrient Management Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International, Edinburgh
Sutton M A, Howard C M, Erisman J W, Billen, G, Bleeker A, G rennfelt A, van Grinsven H J M and Semenov M A 2014 Adverse weather conditions and mitigation options to decrease nitrogen losses from agriculture in EU-27 Agric. Ecosystems Environ. 133 280
Tilman D, Christian Balzer C, Hill J and Befort B 2011 Global food demand and the sustainable intensification of agriculture in 2050 and 2050+ 4
Trnka M, Rotter R P, Ruiz-Ramos M, Kersebaum K C, Olesen J E, Zalud Z and Semenov M A 2014 Adverse weather conditions and mitigation options to decrease nitrogen losses from agriculture in EU-27 Agric. Ecosystems Environ. 133 280
van Grinsven H J M, et al 2014 Localising livestock protein feed production and the impact on land use and greenhouse gas emissions Animal Fl 1339–48
Weiss F and Leip A 2012 Greenhouse gas emissions from the EU dairy sector: a life cycle study of the excreta to nutrient balances Nutr. Cycl. Agroecosyst. 66 119–31
Sutton M A et al 2013 Our nutrient world: the challenge to produce more food and energy with less pollution Global Overview of Nutrient Management Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International, Edinburgh
Sutton M A, Howard C M, Erisman J W, Billen, G, Bleeker A, G rennfelt A, van Grinsven H J M and Semenov M A 2014 Adverse weather conditions and mitigation options to decrease nitrogen losses from agriculture in EU-27 Agric. Ecosystems Environ. 133 280
Tilman D, Christian Balzer C, Hill J and Befort B 2011 Global food demand and the sustainable intensification of agriculture in
PNAS 108 20626–4
Trnka M, Rotter R P, Ruiz-Ramos M, Kersebaum K C, Olesen J E, Zalud Z and Semenov M A 2014 Adverse weather conditions and mitigation options to decrease nitrogen losses from agriculture in EU-27 Agric. Ecosystems Environ. 133 280
United Nations 2013 World Population Prospects: The 2012 Revision vol 1. Comprehensive Tables ST/ESA/SER.A/336 (New York: United Nations)
Valin H et al 2014 The future of food demand: understanding differences in global economic models Agric. Econ. 45 51–67
van Grinsven H J M et al 2012 Management, regulation and environmental impacts of nitrogen fertilization in North-western Europe under the nitrates directive: a benchmark study Biogeosciences 95143
Weiss F and Leip A 2012 Greenhouse gas emissions from the EU livestock sector: a life cycle assessment carried out with the CAPRI model Agric. Ecosystems Environ. 149 124
Westhoek H, Lesschen J P, Rood T, Wagner S, De Marco A, Murphy-Bokern D, Leip A, van Grinsven H, Sutton M A and Oenema O 2014 Food choices, health and environment: effects of cutting Europe’s meat and dairy intake *Glob. Environ. Change* **26** 196

WHO 2007 Protein and amino acid requirements in human nutrition WHO/FAO/UNU *WHO Technical Report Series no 935* (Geneva: WHO)