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LETTER

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

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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 plays 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 losses 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}):

$$Y = Y_{max} {}^{\star} \text{Fert} / \left(\text{Fert} + Y_{max} \right) \qquad (1)$$

with Y_{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_{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):

$$
\begin{aligned}
\text{N surplus} &= \text{Fert} - Y \\
&= \text{Fert} \left[1 - Y_{max} / \left(\text{Fert} - Y_{max} \right) \right].
\end{aligned} \qquad (2)
$$

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 agrofood 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
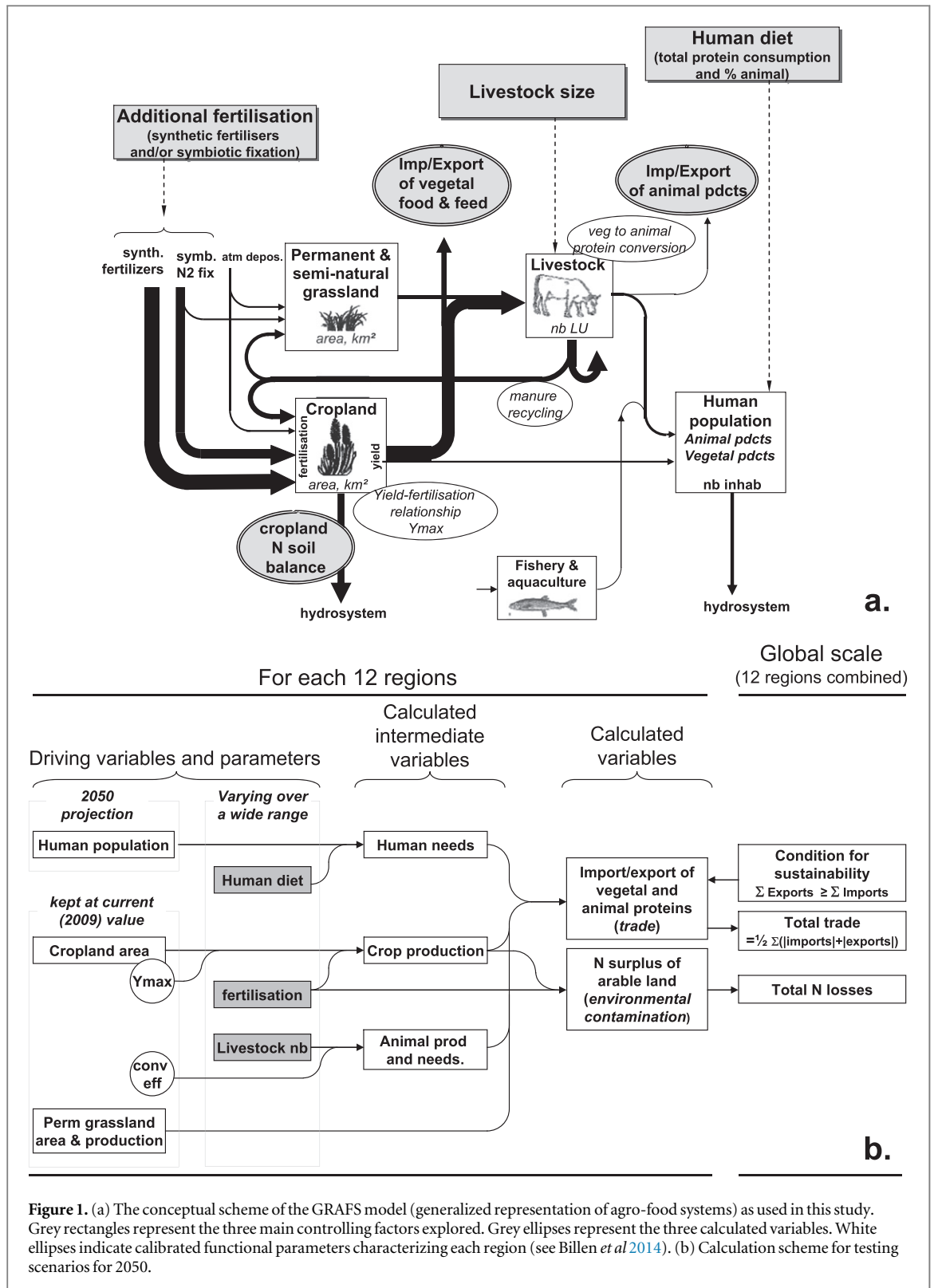
Figure 1. (a) The conceptual scheme of the GRAFS model (generalized representation of agro-food systems) as used in this study. Grey rectangles represent the three main controlling factors explored. Grey ellipses represent the three calculated variables. White ellipses indicate calibrated functional parameters characterizing each region (see Billen *et al* 2014). (b) Calculation scheme for testing scenarios for 2050.

reactive nitrogen (typically synthetic fertilizers) between zero and twice the value of Y_{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		Africa	Maghreb and Middle East	Europe	Former Soviet Union	India and Bangla-desh	China	Japan and S Korea	South–East Asia	North America	South American Soy countries	Central and SW America	Australia and NZ	World
Human diet														
Population[a]	Million	1954	1034	541	278	1956	1356	156	749	447	304	426	37	9238
Total protein consumption[a]	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 consuption	*kgN capita^{-1} yr^{-1}*	*0.2*	*0.1*	*0.2*	*0.2*	*0.1*	*0.4*	*1.2*	*0.6*	*0.3*	*0.1*	*0.2*	*0.3*	*0.27*
Animal protein cons (incl fish)	%	Varied from 20 to 70%												
Cropping systems														
Cropland area	*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*
Y$_{max}$	*kgN ha^{-1} yr^{-1}*	*58*	*69*	*142*	*203*	*64*	*127*	*149*	*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 application	kgN ha^{-1} yr^{-1}	Varied from 0 to 2*Y_{max} (by intervals of Y_{max}/5)												
Crop production	kgN ha^{-1} yr^{-1}	Calculated from total inputs to cropland soil (Fert) according to the relationship Crop prod = Y_{max} Fert/(Fert + Y_{max})												
Cropland soil N balance	TgN yr^{-1}	Calculated as the difference between total N inputs to cropland soils and total crop production												

Table 1. (Continued.)

Regions		Africa	Maghreb and Middle East	Europe	Former Soviet Union	India and Bangla-desh	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 v*alues, 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:

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

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

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:

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

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)

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

3. Results
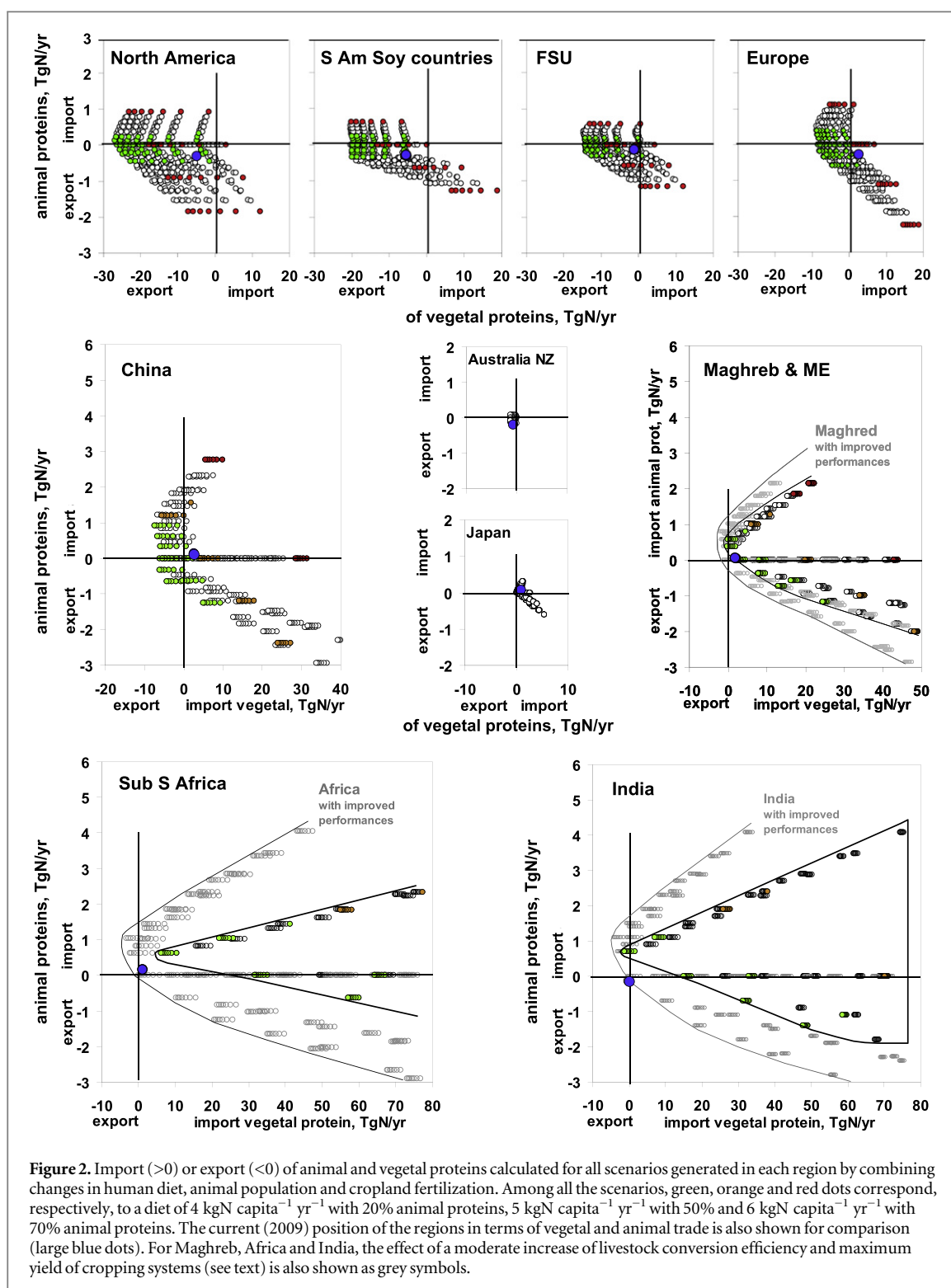
3.1. Regional scenarios

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 livestock 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 livestock 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_{max} value characterizing the yield–fertilization relationship of the cropping system should be increased
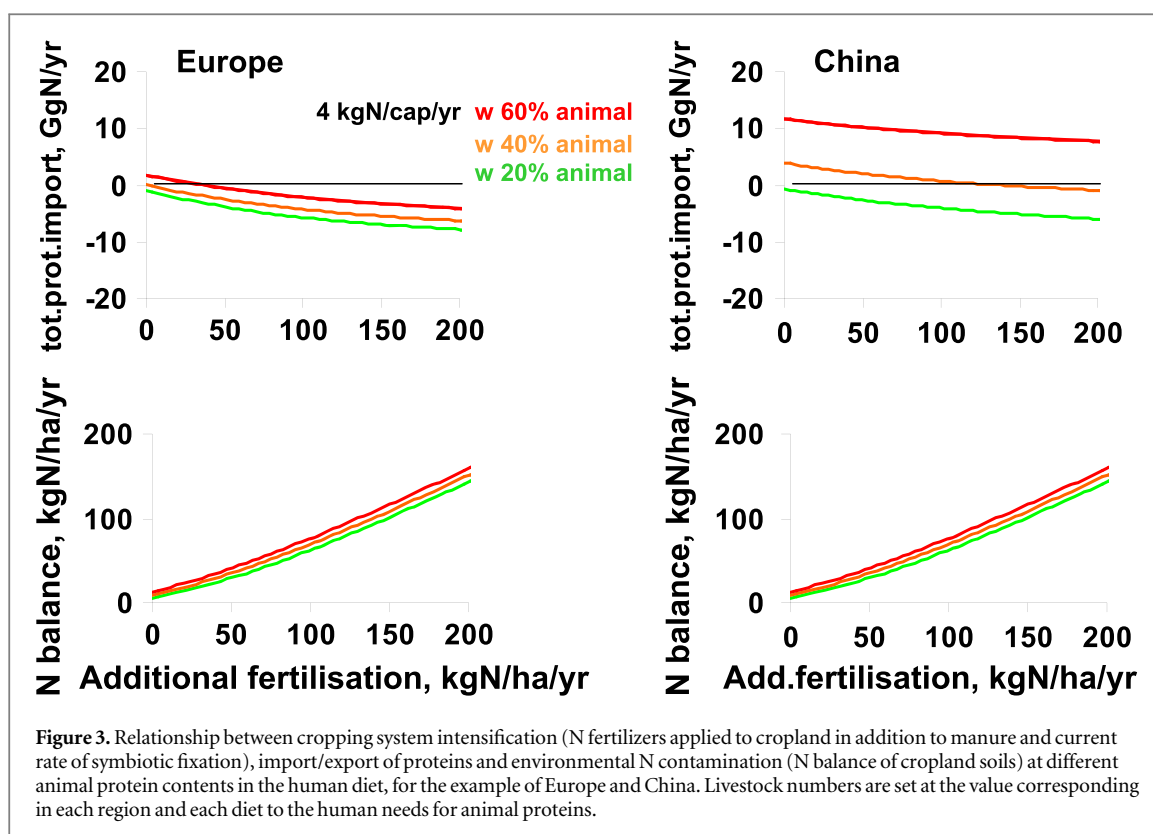
Figure 2. Import (>0) or export (<0) of animal and vegetal proteins calculated for all scenarios generated in each region by combining changes in human diet, animal population and cropland fertilization. Among all the scenarios, green, orange and red dots correspond, respectively, to a diet of 4 kgN capita^{-1} yr^{-1} with 20% animal proteins, 5 kgN capita^{-1} yr^{-1} with 50% and 6 kgN capita^{-1} yr^{-1} with 70% animal proteins. The current (2009) position of the regions in terms of vegetal and animal trade is also shown for comparison (large blue dots). For Maghreb, Africa and India, the effect of a moderate increase of livestock conversion efficiency and maximum yield of cropping systems (see text) is also shown as grey symbols.

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

Figure 3. Relationship between cropping system intensification (N fertilizers applied to cropland in addition to manure and current rate of symbiotic fixation), import/export of proteins and environmental N contamination (N balance of cropland soils) at different animal protein contents in the human diet, for the example of Europe and China. Livestock numbers are set at the value corresponding in each region and each diet to the human needs for animal proteins.

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.
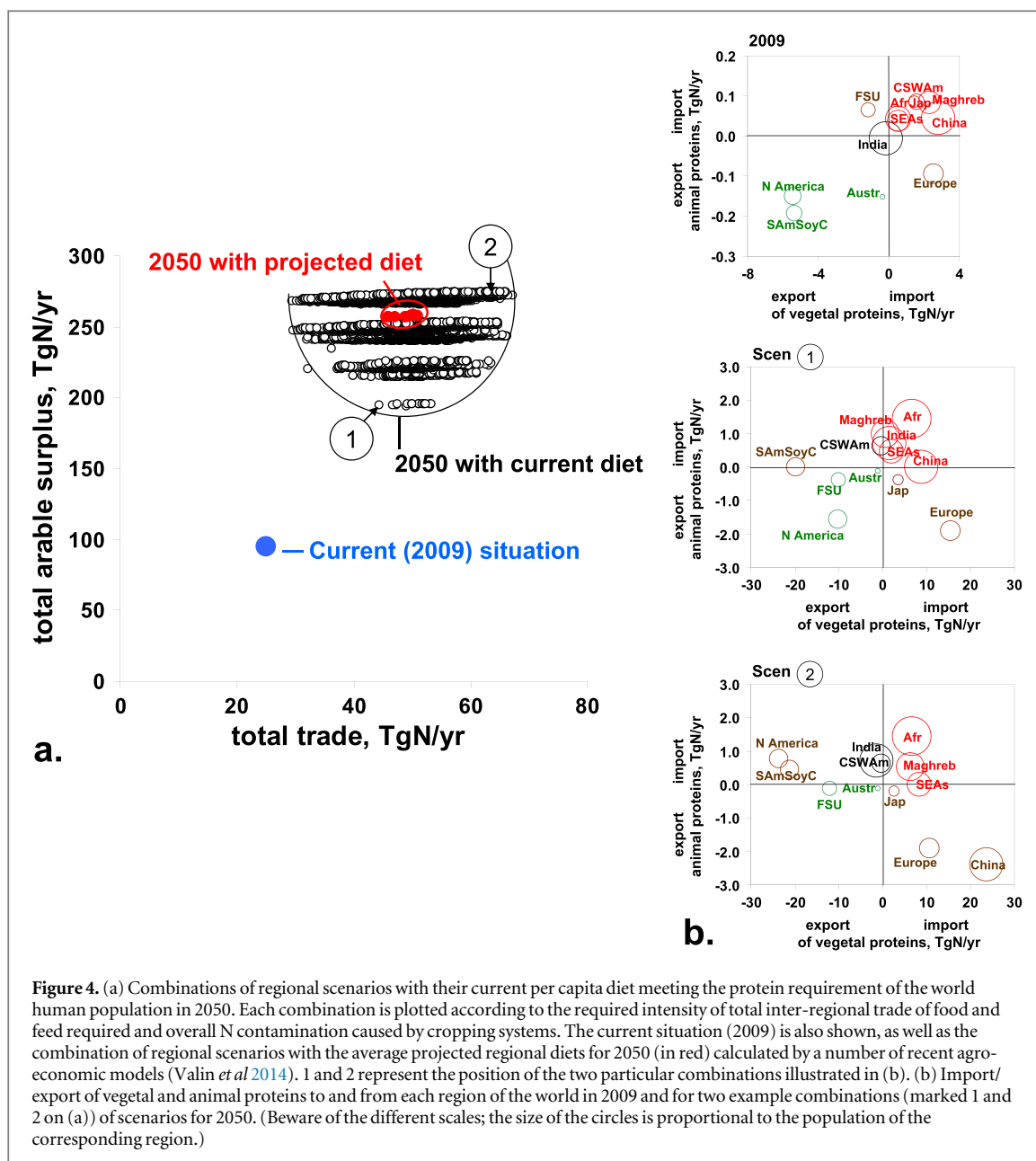
3.2. Global scenarios

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

Figure 4. (a) Combinations of regional scenarios with their current per capita diet meeting the protein requirement of the world human population in 2050. Each combination is plotted according to the required intensity of total inter-regional trade of food and feed required and overall N contamination caused by cropping systems. The current situation (2009) is also shown, as well as the combination of regional scenarios with the average projected regional diets for 2050 (in red) calculated by a number of recent agro-economic models (Valin *et al* 2014). 1 and 2 represent the position of the two particular combinations illustrated in (b). (b) Import/export of vegetal and animal proteins to and from each region of the world in 2009 and for two example combinations (marked 1 and 2 on (a)) of scenarios for 2050. (Beware of the different scales; the size of the circles is proportional to the population of the corresponding region.)

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
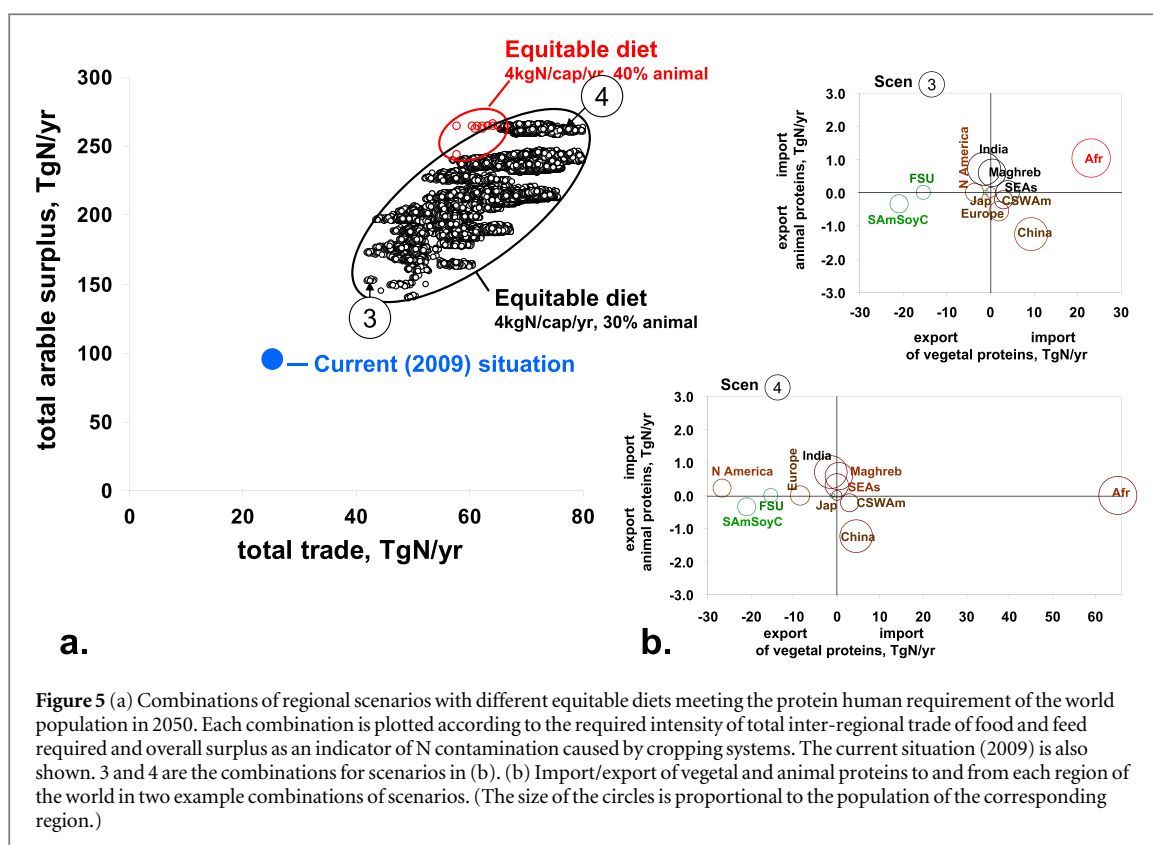
Figure 5 (a) Combinations of regional scenarios with different equitable diets meeting the protein human requirement of the world population in 2050. Each combination is plotted according to the required intensity of total inter-regional trade of food and feed required and overall surplus as an indicator of N contamination caused by cropping systems. The current situation (2009) is also shown. 3 and 4 are the combinations for scenarios in (b). (b) Import/export of vegetal and animal proteins to and from each region of the world in two example combinations of scenarios. (The size of the circles is proportional to the population of the corresponding region.)

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
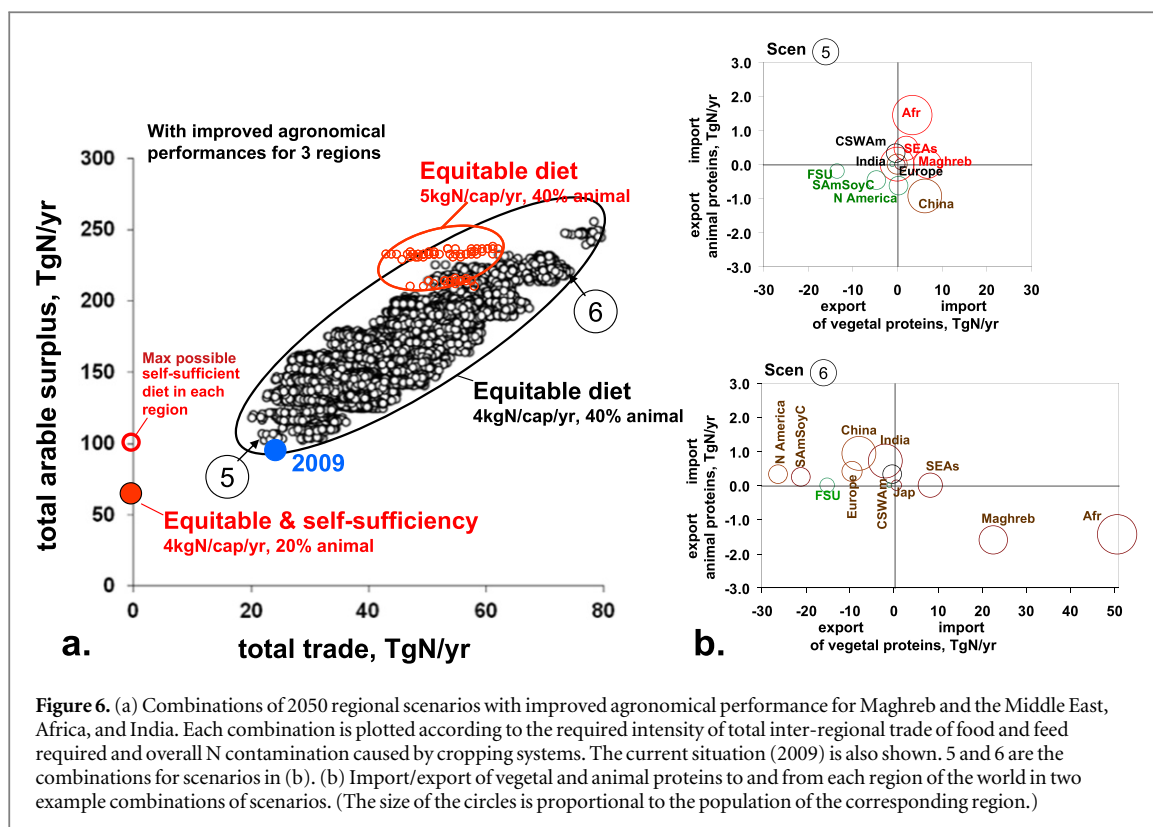
Figure 6. (a) Combinations of 2050 regional scenarios with improved agronomical performance for Maghreb and the Middle East, Africa, and India. Each combination is plotted according to the required intensity of total inter-regional trade of food and feed required and overall N contamination caused by cropping systems. The current situation (2009) is also shown. 5 and 6 are the combinations for scenarios in (b). (b) Import/export of vegetal and animal proteins to and from each region of the world in two example combinations of scenarios. (The size of the circles is proportional to the population of the corresponding region.)

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, Dalgaard *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 campains 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

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