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A biogeochemical view of the global agro-food system: Nitrogen flows associated with protein production, consumption and trade

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ABSTRACT

Through a detailed analysis of the FAO database, we propose a generalised representation of the world's agro-food systems in 2009, based on the description of nitrogen (i.e. proteins) fluxes from fertilisers to crops and from crops to livestock and human nutrition. This description also includes the resulting environmental losses of nitrogen at each stage of the chain. Current trade and production fluxes of food and feed differentiate 12 macro-regions, strongly contrasted in terms of *N* transfer patterns. Three major factors determining the performance of the agro-food system are highlighted: (i) the cropland yield–fertilisation relationship, (ii) vegetal to animal protein conversion efficiency in the livestock farming system, as well as its connection to either semi-natural grassland or cropping systems, and (iii) total protein consumption and proportion of animal protein in the human diet.

1. Introduction

Cropping practices, livestock husbandry and dietary habits are among the most basic features of civilisations, and their diversity across the world is tremendous. Yet, in today's connected world, the exchanges between regional agro-food systems become increasingly significant, not only qualitatively (as they have always been), but also quantitatively (which is a much more recent phenomenon; Schmitz et al., 2012; Lassaletta et al., 2014a,b). The challenge of meeting the food needs of a growing and more demanding global population while protecting the environment obviously requires the diversity of the world's different agro-food systems to be taken into account (Mueller et al., 2012) and safeguarding them insofar that they can meet local human needs (Fader et al., 2013; MacDonald, 2013). At the same time, this makes it necessary to develop a summarizing and unifying view of how the whole system works today. In this paper we propose such an overall view, based on a generic representation of what we believe are common features of all agro-food systems, i.e. the biogeochemical interrelationships between crop farming, livestock husbandry and human nutrition. Based on a thorough analysis of the FAO database (www.fao.org/), we describe the fluxes of agricultural goods across these three components at the scale of the world, split into a limited number of regions with similar features.

The choice of unifying metrics for our description is important. Instead of monetary units, dry matter or dietary energy units (calories), we express fluxes associated with the functioning of the agro-food system in terms of nitrogen (or protein). This choice, previously made by other authors such as Smil (1999), Bouwman et al. (2005, 2009, 2011), Liu et al. (2010) and Bodirsky et al. (2012), is justified not only by the fact that proteins are essential constituents of the human diet (WHO, 2007), but also because it allows one to directly highlight the relationship between food production/consumption and environmental quality (Foley et al., 2011; Tilman et al., 2011). Indeed, at each stage of the agro-food chain, losses of nitrogen occur, which are transferred to all environmental compartments through the so-called nitrogen cascade, with severe consequences in terms of air pollution, groundwater resource alteration, loss of biodiversity both in terrestrial and aquatic environments, coastal eutrophication and greenhouse gas emissions (Galloway and Cowling, 2002; Sutton et al., 2011, Billen et al., 2012).

In this paper, we first explain our division of the world into 12 coherent regions based on their patterns of trade exchanges. We then characterise the human food requirements in each of these 12 regions in terms of vegetal and animal proteins. The analysis of the crop and livestock farming systems of these regions then makes it possible to calculate the internal fluxes between cropland, semi-natural grassland, livestock and human nutrition in addition to international trade exchanges. The principle of the approach is described in Textbox 1. It has already applied at smaller scales, namely the scale of a watershed (Billen et al.,

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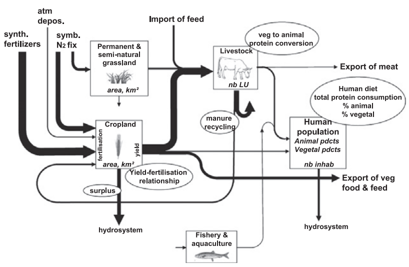
Box 1–Generic representation of an agro-food system from the angle of nitrogen transfers associated with the processes of food production.

The GRAFS Approach (Generic Representation of Agro-Food Systems).

The term "agro-food system" designates the processes and infrastructure intended for feeding the human population of a given territory, including agriculture, livestock husbandry, processing and disposal of associated wastes. From a biogeochemical perspective, agro-food systems can be described by quantifying the fluxes of nutrients between cropland, livestock, humans and the natural environment (Fig. T1).



Because of its major role as a limiting factor of agricultural primary production and as a prominent component of proteins, which are essential to the human diet, as well as because its environmental losses cause severe ecological dysfunction, nitrogen fluxes are particularly pertinent for a representation of agro-food system functioning. The amounts of all food and agricultural commodities produced and traded are provided by the FAO database (see also Lassaletta et al. (2014a) for a comprehensive table of *N* contents).

From the nitrogen cycling perspective, cropping systems can be considered as converting *N* inputs to the soil (as fertilisers, manure, symbiotic *N* fixation, and atmospheric deposition) into harvestable vegetal products. The ratio of total *N* inputs to cropland to the *N* contained in the harvest defines the cropping *N* use efficiency (NUE).

The crop products can be used for meeting the vegetal protein requirement of human nutrition, for being exported or for feeding livestock to the extent that they are not fed by grazing of permanent and semi-natural grassland. The efficiency of feed and grazing conversion into consumable animal proteins (meat, milk and eggs) determines the amount of excreted nitrogen, a part of which can be recycled into cropland as manure, making cropland fertility partly dependent on transfers from semi-natural grassland. The fishery and aquaculture sector also contributes to providing animal proteins for human nutrition.

Losses of *N* to the environment occur at each stage of the chain, particularly through leaching and volatilisation from arable soils, losses of animal excreta not recycled as manure or directly deposited on grasslands, and wastes from food processing and final human consumption.

The diagram in Fig. T1 offers a convenient way to account for the budget of all these interrelated *N* fluxes within the whole system. Note that this analysis does not explicitly distinguish non-food agricultural productions, such as fibre and energy crops. This is explained by the fact that most of the nitrogen associated with these crops is separated from the final products and used as high-protein by-products for animal feeding (cottonseed feed products, cakes of rapeseed grain, gluten and protein preparations from wheat and maize, etc.), thus fully entering the food chain.

2011, 2013; Lassaletta et al., 2012) or a country (Lassaletta et al., 2014b). The approach is developed here with the aim of assessing the current (2009) functioning of the global agro-food system in terms of *N* fluxes within and between the 12 regions. While our approach is based on a much simpler model than the one implemented by other authors (IMAGE, Bouwman et al., 2006, 2009; MAgPIE, Bodirsky et al., 2012), we believe that our assessment, precisely because of its simplicity, offers the way to easily grasp a clear view of how the global agro-food system is working today.

2. International trade patterns between world regions

Lassaletta et al. (2014b) recently analysed the fluxes of agricultural products traded between countries in terms of protein-N. They showed that international trade nowadays concerns as much as 30% of total proteins harvested in the world, and that a small number of net exporting countries such as Brazil, Argentina, the USA and Canada are feeding a large number of deficient, net importing countries. On this basis, they proposed to divide the world into 12 groups of contiguous countries, with similar behaviour as a net importer or net exporter of food and feed in 2009, hence with similar degree of food and feed dependency (here defined as the ratio between net imports of protein with respect to local crop production).

The net importing regions include the seven following regions:

* sub-Saharan Africa, with net imports of 340 GgN/yr) in 2009, i.e. 9.6.% of their total crop production as proteins.

* Maghreb and Middle East (all North African countries from Morocco to Egypt and all West Asian countries including Turkey and Pakistan), net importing 1660 GgN/yr (42% of local crop production).

* Europe (EU27 excluding ex-Soviet Union countries, plus Switzerland, Norway, and the Balkan countries), with a net import of 2340 GgN/yr (30% of crop production).

* China (with Mongolia and North Korea) importing 2900 GgN/yr (24%).

* Japan and South Korea, importing 2300 GgN/yr (474%).

* South-East Asia, importing 530 GgN/yr (11%).

⁎ Central and South-Western America, importing 1330 GgN/yr (83%).

The three main net exporting regions are:

* North America (the USA and Canada), exporting a net amount of 4850 GgN/yr, representing 32% of local crop production.

* South American Soy Countries (Brazil, Argentina, Bolivia, Uruguay, Paraguay), with a net export of 5260 GgN/yr (58% of crop production)

* Oceania (Australia and New Zealand) with a net export of 460 GgN/yr (50%).

Two regions are close to a trade balance:

* Former Soviet Union (FSU) exports 620 GgN/yr (14% of local crop production)

* India exports 190 TgN/yr (2.3%)

Throughout this paper, we use the same divisions to regionalise our description of the world agro-food system. Of particular importance in this regionalisation is the distinction, within Central and South America, of the eastern soy-exporting countries from the rest of the sub-continent, because these two regions experience quite different situations regarding food and feed self-sufficiency. Also, highly contrasted situations exist in Asia between Japan, China, India, South-East Asia and the Middle East (Table 1).

3. Human consumption

Not only the distribution of populations, but also the differences in the composition of human diet between regions are key determinants of the structure and functioning of the whole agro-food system (Kastner et al., 2012). The FAO database provides

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