Biogeosciences, 10, 471–481, 2013
www.biogeosciences.net/10/471/2013/
doi:10.5194/bg-10-471-2013

Biogeosciences

Nitrogen food-print: N use related to meat and dairy consumption in France

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Received: 21 December 2011 – Published in Biogeosciences Discuss.: 20 February 2012
Revised: 15 November 2012 – Accepted: 21 December 2012 – Published: 24 January 2013

Abstract. Human foods typically contain a minor fraction of the nitrogen (N) used in agricultural production. The major fraction is lost to the environment and interferes with all current environmental problems and global change issues. Food is also generally consumed far from its production location and associated N losses remain unknown unless connected to products through consumption-based indicators. We develop the N food-print as an indicator to connect N flows and losses in livestock systems to the consumption of dietary N in the form of beef, pork and fresh milk in France. This N food-print of a product is the N loss associated with its agricultural production. The conversions of N, from field application to recovery in vegetal and animal proteins, are calculated from statistical data on crop and animal production and through modelling of feed rations for cattle and swine. Beef farming to feed an individual in France uses 11.1 kg N cap^{-1} yr^{-1}, out of which 3.8 kg N cap^{-1} yr^{-1} (or 35 %) is the N food-print, 7 % is recovered in retail products, 3 % is slaughter waste and 55 % returns to agriculture as manure. Pork and dairy production use 7.5 and 2.3 kg N cap^{-1} yr^{-1}, respectively, out of which 53 and 48 % is the N food-print, respectively; about 11 % is recovered in retail products and 35 % returns to agriculture as manure. In total, more than 75 % of the N food-print relates to crop cultivation for feed and much of these losses (80 % for dairy and pork production, 20 % for beef production) occur in crop farms far from where the livestock is reared. Regional and national policies to reduce N losses should take into account that trade in feed implies causal relationships among N losses in agrosystems distant from each other.

1 Introduction

Human activities have considerably increased the amount of reactive nitrogen (Nr) in the earth's atmosphere and biosphere. Reactive nitrogen includes all biologically, photochemically and radiatively active compounds of nitrogen as opposed to molecular nitrogen (N_2) – the major component of the earth's atmosphere – which is nonreactive (Galloway et al., 2003).

Global food production is the primary cause for anthropogenic Nr creation and has a major influence on the global N cycle. By the end of the 20th century, about 75 % of global human-driven inputs of Nr were used for agriculture but only 30 % of these inputs were effectively recovered into vegetal proteins to feed humans and livestock (Smil, 2001). The non-recovered fraction is mostly lost to the environment where it contributes to the N cascade, which is defined as "the consequential transfer of Nr through environmental systems and which results in environmental change as Nr moves through or is temporally stored within each system" (Galloway et al., 2003). The N cascade is now recognized as a major cross-cutting theme over all environmental problems and global change issues such as climate change, biodiversity losses, groundwater pollution, eutrophication, tropospheric ozone generation and stratospheric ozone depletion with severe effects on ecosystems and human health (Sutton et al., 2011).

The contribution of agriculture to the N cascade has greatly increased in the second half of the 20th century, since agricultural revolutions made it possible to sustain rapidly growing human populations and livestock production on a moderately expanding agricultural area. Between the late 1960s and the late 1990s, global population increased 70 %,

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the per capita meat and milk consumption 50 % and 5 %, respectively and total arable land and grassland about 6 % and 4 %, respectively (WHO, 2003; US Census Bureau, Population division, 2011; Smil, 2000, Bouwman, 2005).

The breakthroughs in productivity relate to successive increases in both the crop yields and the conversion efficiencies of feed energy and proteins into livestock biomass (Chatzimpiros and Barles, 2010; Chatzimpiros, 2011). High productivity, however, at the scale of individual crops and animals, is often accompanied by high Nr losses over the entire livestock system: first, increases in crop yields usually involve heavy fertilization with diminishing returns in terms of nitrogen use efficiency (Tilman et al., 2002). Second, the production of animal rations with high N recovery into meat and milk may depend on feed crop systems with low nitrogen use efficiency at the field level. Third, high productivity in livestock farming increasingly relies on highly specialized, large-scale, vertically integrated systems, dependent on external and often distant feed sources and resulting in nutrient inefficiencies with respect to manure management (Cowling and Galloway, 2002). Given that about 70 % of global agricultural production is fed to livestock (Smil, 2001) and that most of the ingested nutrients are excreted in manure, studying the environmental impacts of livestock production requires considering the entire livestock system including feed production, feed conversion efficiencies and manure management practices (Bouwman et al., 2011). System boundaries should encompass all feed production agrosystems, whether these are local or external to livestock farms.

N losses from agriculture also depend on human (urban) diets; it is thus relevant to integrate production issues with urban metabolism into consumption-based indicators. Since the mid-1990s, the terms footprint, imprint and food-print have been used in several contexts as generic metaphors to express human interference with natural resources from a consumption perspective. Footprint indicators so far have mainly dealt with appropriation of bioproductive land for biomass supply, housing and carbon sequestration (ecological footprint, expressed in additive global hectare equivalent units e.g. Wackernagel and Rees, 1996), emissions of carbon dioxide and other greenhouse gases (carbon footprint, measured as CO_2 equivalent e.g. Weidmann and Minx, 2008), quantitative and qualitative freshwater use associated with production and consumption of commodities (water footprint, expressed in volume e.g. Chapagain et al., 2006) and, more recently, Nr losses to the environment in relation to food and energy consumption and to sewage treatment efficiencies in the US and the Netherlands (nitrogen footprint, Leach et al., 2012). In a similar way and by allusion to the physical traces left in the environment by a living organism, the term imprint has been used to express the environmental influence of urban metabolism on the resource supply hinterlands of cities (Billen et al., 2012a, b). In this context and specifically for food, the term food-print has also been used to express, in real hectares, the agricultural area used to supply food to a city (Billen et al., 2009).

We develop in this paper the N food-print as a consumption-based indicator of Nr inputs and losses from spatially scattered livestock systems. We measure N use efficiency in these systems per unit of N supply in products and per unit of land requirements involved in the production. The relevance for integrating production and consumption into a N food-print is reflected by the following four objectives: (i) assess long-distance implications of food choices on Nr losses, (ii) obtain insights on where Nr emissions occur along the production chain, (iii) put inhabitant N pollution loads in urban wastewater in perspective with N discharge from agriculture; and (iv) identify opportunities to reduce N losses through changes in production systems and human diets.

We apply the N food-print on the supply of fresh milk, beef and pork to an average consumer in France. Those three products are chosen due to their traditionally high shares in French diets, but such an analysis is relevant for any product/production system. We summarize here the major steps of our bottom-up approach: first, average consumption of fresh milk, pork and beef is expressed in terms of nitrogen. Then we calculate the feed equivalent of this consumption and evaluate feed deficits in livestock farms. We do so by modelling feed rations for swine, beef and dairy cows to meet their energy and protein requirements, then, by comparing these requirements with the feed production capacity of the livestock farms. Feed deficits in livestock farms are made up for by imports of feeds produced in external (domestic and global) crop systems. We identify the producing locations from national and international data on feed production and trade. The N food-print is then calculated as total nitrogen losses from entire livestock systems using data on total N fertilization, atmospheric deposition and manure management per crop and livestock farm. The N food-print is expressed per capita ($\mathrm{kg\,N\,cap^{-1}\,yr^{-1}}$) and per unit of agricultural land ($\mathrm{kg\,N\,ha^{-1}}$) in order to make results comparable with other products, consumers and production systems. Emissions of Nr in consequence of feed, milk and carcass transportation and processing are not accounted for. Nr is hereafter referred to as N.

2 Methods and data

2.1 Meat and fresh milk consumption

We used data on national average apparent consumption. Apparent consumption (also known as food availability) is calculated from national food supply balances as domestic production, plus imports, minus exports and it includes, therefore, retail and household food waste. Apparent food consumption (hereafter referred to as consumption) links resource use in agriculture with total food production. In France, consumption of milk, pork and beef is respectively

Table 1. Composition of fresh milk, beef and pork and corresponding annual energy (Mcal cap^{-1} yr^{-1}) and protein (kg N cap yr^{-1}) consumption. Data sources: see in the text.

	Fresh milk	Beef	Pork
Water (%)	87.5	57.0	57.0
Proteins (%)	3.3	18.0	15.0
Lipids (%)	3.6	24.0	25.0
Lactose (%)	4.6	–	–
Minerals/ash (%)	1.0	1.0	3.0
Total (%)	100	100	100
Annual per capita consumption (including offal)			
Proteins (kg N cap yr^{-1})	0.27	0.75	0.82
Gross Energy (Mcal cap^{-1} yr^{-1})	36.5	85.1	109.4

52 L cap yr^{-1}, 34 kg cap^{-1} yr^{-1}, 26 kg cap^{-1} yr^{-1} (Agreste, 2006). Table 1 shows the chemical composition of milk (CNVA, 2006), beef (NRC, 2000; Wulf, 1999; Hoch and Agabriel, 2004) and pork (Lange et al., 2003; NRC, 1998) and the annual per capita consumption of each product in terms of nitrogen (kg N cap yr^{-1}) and gross energy (Mcal cap^{-1} yr^{-1} – energy in lipids, proteins and lactose is 9.4, 5.6 and 4.0 Mcal kg^{-1}, respectively). The three products account for about 25 % of the dietary nitrogen intake of an individual.

The N food-print locates where the feed crops are grown and where the livestock are reared. We assume that average meat and dairy consumption in France originate from all French administrative regions proportionally to their share in the national gross meat and milk production, and from foreign countries proportionally to their share in national trade balances. Domestic production of pork and beef, each one, stands for 82 % of domestic consumption and the remaining 18 % originates from a small number of EU countries: Spain, the Netherlands, Germany and Belgium together account for 85 % of the pork and beef imports and Italy, Ireland, Luxembourg and Austria provide another 12 % (Agreste, 2006, 2010; FAOSTAT, 2004, 2006). The spatial distribution of pork and beef production in France is shown in Fig. 1. Milk production is shown in Fig. 2. Milk imports from abroad are negligible. Milk consumption in France is therefore practically entirely sustained by domestic production.

2.2 Animal rations, feed origin and land requirements

We model animal rations for milk, beef and pork production to derive the feed equivalent of each product and the associated manure production rates. The composition of animal rations plays a pivotal role in the structure and functioning of livestock systems, and it largely determines N inputs to and N losses from these systems. We base all calculations on data for French farms where most of the meat and milk come

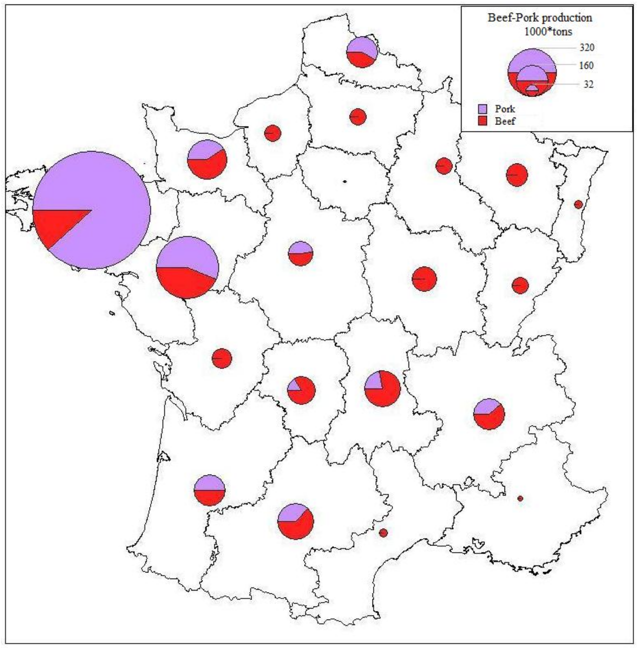

Fig. 1. Beef (red) and pork (purple) production per French administrative region. Data sources: Statistique agricole annuelle, 2006.

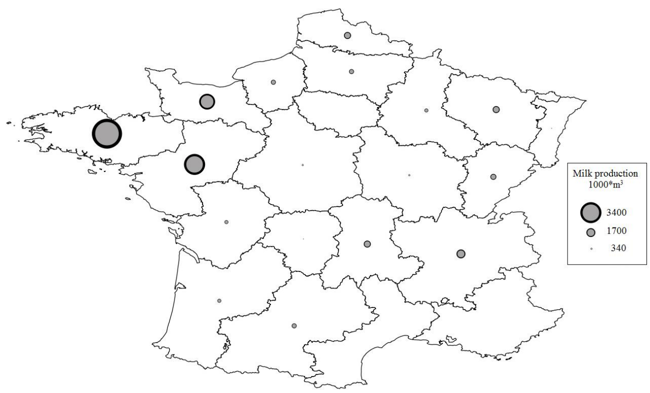

Fig. 2. Milk production per French administrative region. Data sources: Statistique agricole annuelle, 2006.

from. No differentiation is made for pork and beef imported from abroad.

For standard ambient conditions and animal biomass composition, the nutrient requirements of livestock depend on physical and metabolic characteristics and on rates of biomass production. Biomass production concerns body accretion rates for growing animals and milk yields for dairy cows. The feed energy system used in the simulation of rations for pork production is metabolic energy and for beef and dairy production net energy, according to data availability in major literature sources (NRC, 1998, 2000, 2001).

We model beef and dairy rations per French administrative region using a dynamic ration formulation model (NRC, 2001, CNCV, 2006). We follow the approach developed in Chatzimpiros and Barles (2010) in which the growing and milking phases of cows are modelled separately in order to obtain rations that are specific to meat and milk production. This is relevant because the nutrient requirements for lactation differ from those for body biomass accretion. Consequently, the feeds used in milk and meat production are not necessarily the same. The environmental influence of farms is therefore related to their specialization in production.

For milk production, we assume annual lactation cycle of 305 days and constant live-weight (LW) for both the lactation and non-lactation periods. Milk yields per lactation day vary from 13 to 22 L d^{-1} at the regional scale in France (Statistique agricole annuelle, 2004). Dairy rations are simulated with respect to this variation for LW of 630 kg (Statistique agricole annuelle, 2004). For cattle meat production, rations are simulated for final LW at slaughter of 800 kg and for average steady growth rate of 1.1 kg d^{-1} (Statistique agricole annuelle, 2006). Regional data on the slaughter age of animals that would allow calculating regional variability of growth rates are not available in the agricultural statistics.

Swine rations only produce meat and are modelled on the basis of the energy and protein requirements of growing pigs (NRC, 1998) for average steady growth rate of 0.6 kg d^{-1} and final LW at slaughter of 110 kg (Statistique agricole annuelle, 2006). As for cattle, we simulate swine rations for average growth rate of pigs in France.

The diet of an animal represents a nutrient balance between the nutrient requirements for maintenance and growth and the nutrient supply of feed. The term feed is used to include roughage, grazed biomass and feed concentrates. Data on the nutrient composition of feeds are derived from NRC (2000, 2001) for cattle and from NRC (1998) and ITAB (2001) for swine.

Beef and dairy cattle in France are mainly fed roughages from perennial crop systems such as grasses and legumes, annual fodder such as maize-whole-crop and beetroots and concentrate feeds such as cereals and protein meals from soybean and rapeseed crops (Agreste, 2008a; Chatzimpiros and Barles, 2010). Pigs are in contrast exclusively fed concentrate feeds, mainly cereal grains (wheat, barley and maize) and protein meals (Agreste, 2007, 2008a).

Roughages (including annual fodder) are typically produced on livestock farms because they are bulky and therefore difficult to transport. The type of roughages used in cattle farming is derived from agricultural statistics for each region (Statistique agricole annuelle, 2006, Ministry of Agriculture, www.agreste.agriculture.gouv.fr). In general, natural and semi-natural grasslands and meadows are dominant in regions specialized in beef meat production while maize-forage is dominant in regions specialized in dairy production (Agreste, 2008c).

As opposed to roughages, concentrate feeds are often purchased by the livestock farms. The ingredients used in the production of concentrate feeds are derived from datasets of agro-industries per livestock sector. Major ingredients are cereal grains, cereal by-products and soy and rape meals (Agreste, 2008a).

Soy meal is mainly imported from Brazil, Argentina, the USA and other countries at respective shares of 80 %, 12 %, 3 % and 5 % (FAOSTAT, 2004). Rapeseed is on the other hand produced in specialized monocultures in France and the European Union (France is a net exporter of rapeseed) and is traded among countries for industrial processing. For instance, much of the French production of rapeseed is exported to oil extraction industries abroad (Germany and the United Kingdom among others) to be then re-imported to France in the form of meals to feed livestock (Agreste, 2005, FAOSTAT, 2006). Potential losses of N in feed processing are not accounted for.

Soy and rape meals account for the bulk feed inputs to beef and dairy farms. In contrast, pig farms face in addition severe deficits of cereals, the magnitude of which varies among regions. Cereal deficits appear when the stocking rates exceed the feed production capacity of livestock farms. We computed cereal deficits per French region by comparing data on the stocking rates of swine recorded in the agricultural censuses of a given year (Agreste, 2007) with the stocking rates possible to sustain upon local cereal production at the same year given the cereal intake of pigs and the agricultural yields of cereal crops. We assume that the cereals imported to swine farms in the form of concentrate feeds are produced in French regions, according to their shares in the national gross production.

We calculate land requirements per livestock production by applying agricultural yields per region and country of feed production to the feed intake of the livestock (Statistique agricole annuelle, 2006, FAOSTAT, 2006). For crop by-products – such as soy and rape meals – the corresponding land requirements are fractions of the land required to grow the respective mother-crops. These fractions are calculated as the ratios of energy in each by-product compared to the energy content of the processed seed (Chatzimpiros and Barles, 2010). As noted in Chatzimpiros and Barles (2010), there is agreement between energy-based and monetary-based allocations for soybean but not for rapeseed, for which the meal is given a market value that is proportionally lower to its energy value in rapeseed.

2.3 N budgets of livestock systems and the N food-print of products

Figure 3 gives a generic representation of a livestock system and of input and output N flows among its segments.

The N inputs per livestock system are computed per region and feed crop from statistical data except for soybean. Data on soybean fertilisation in the countries exporting to

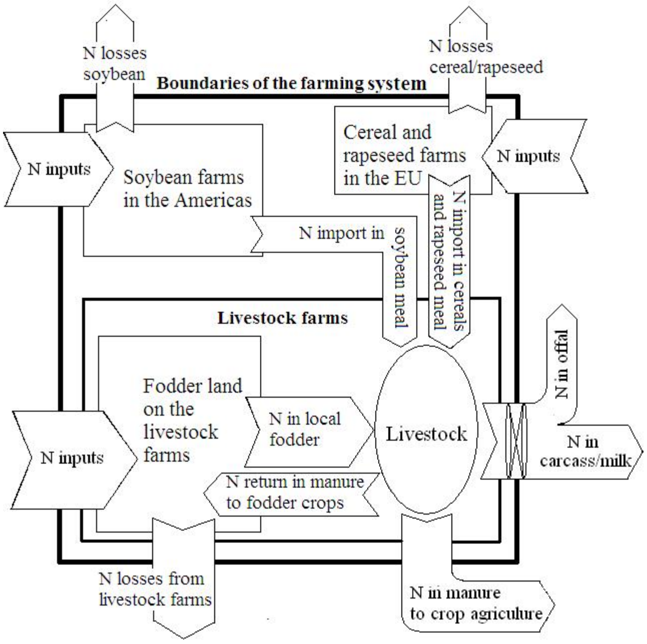

Fig. 3. The N cycle in spatially scattered livestock systems.

France were not available. N inputs in soybean agrosystems are estimated indirectly, assuming global average NUE of 50 % (Cassman et al., 2002). Agricultural yields for soybean are taken from FAO (2004) and average (in terms of nitrogen content) 125 kg N ha^{-1} in Brazil, 120 kg N ha^{-1} in Argentina, 155 kg N ha^{-1} in the USA and 120 kg N ha^{-1} on global average.

For crops other than soybean, we calculate N inputs and nitrogen use efficiencies (NUE) from specific data on total fertilization and crop yields (expressed in nitrogen) per region and crop (Agreste, 2006). All data are for 2006. Data on chemical fertilizer application per region and crop are taken from Agreste (2008b). For atmospheric deposition we used simulation data from EMEP (2006). N deposition rates for France vary between 3 to 6 kg N ha^{-1}/y. For BNF, we used commonly accepted values from literature: 250 kg N ha^{-1} yr^{-1} for alfalfa, 35 kg N ha^{-1} yr^{-1} for pasture (assuming 15 % legumes) and 5 kg N ha^{-1} yr^{-1} for fallow (Smil, 1999, Peoples et al., 1995). In crop rotations, green fertilizers are mainly used in association with maize in half-year rotations. We assume an annual BNF rate of 125 kg N ha^{-1} in these rotations. For manure application, we assume a uniform rate of 170 kg N ha^{-1}, which is the prevailing upper limit for manure application in the European Commission Nitrate Directive, 1991/676/CEE. Certainly, not all crop farmers fertilize at the allowance rate, but, lacking precise data obliged us to adopt this simplification. We note that on livestock farms, manure N is an internal N flow but additional N is imported as feed (cf. Fig. 3). N inputs in feed are calculated in the previous step. N inputs to farming systems are calculated per livestock product and sum up to the gross N food-print of that product.

N leaves the farming systems in the form of manure towards crop agriculture, in the form of live animals and milk, in the form of N_2 through denitrification, and in oxidized and reduced forms through volatilization and leaching, which directly enter the N cascade. N output in the form of animal biomass sums the N in fresh milk, pork and beef (cf. Table 1) plus the N in slaughter waste for beef and swine. For beef, N in slaughter waste is 30 % of N in live weight (Hoch and Agabriel, 2004). For pork, slaughter waste is 10 % of N in live weight because offal, intestines, blood and most other cuts of pig are put on the market.

N output to crop agriculture in the form of manure is calculated top-down in four steps. First, we multiplied data on fertilized area per region and crop (Agreste, 2008b) with the allowance fertilisation rate of organic N on cropland. Then, we allocated the regional flows of manure N to specific livestock species using livestock units (LU) as an "exchange ratio" for manure production. By definition, one LU is the number of livestock of any species equivalent to one dairy cow in terms of manure production. Livestock in France mainly consists of dairy cows, beef cattle, swine, chicken and sheep. LU for chicken and sheep are derived from literature (Vilain et al., 2008). LU for dairy cows, beef cattle and swine are computed in this study. Equivalences are: 1 LU = 1 dairy cow = 1.6 beef = 6.6 growing pigs = 125.0 chicken = 10.4 sheep. Based on these factors, manure production per administrative region is allocated among the five livestock species at the regional scale. The results obtained are compared to the modelled N excretion per species to derive potential manure N availability for export to crop agriculture. If for a given species available N is lower than calculated, the area allocated to that species is reduced to fit manure N availability and the difference is reallocated to another species. Gaseous N emissions during housing and storage of manure are assumed to be re-deposited on surrounding cropland; they are thus accounted for as N output to crop agriculture.

Potential N losses to the cascade are calculated as total N inputs minus N export in the form of livestock products and in the form of manure for each segment of the farming systems. By subtracting from total N losses those relating to feed crop cultivation (already calculated as total N fertilisation minus N in crop harvest) we obtain an approximation of N losses from manure excretion.

Figure 4 summarizes the components of the N food-print. The gross N food-print corresponds to total N inputs in the livestock system. The net N food-print corresponds to N inputs minus N recovered in animal biomass and shows the fertilisation capacity of livestock production in mixed agrarian systems. The net N food-print is then partitioned between N export to crop agriculture in the form of manure and potential direct N loss to the N cascade (Fig. 4).

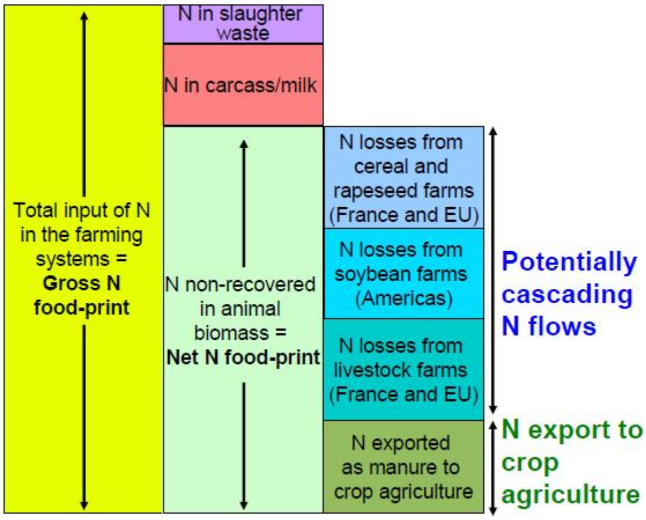

Fig. 4. The components of the N food-print

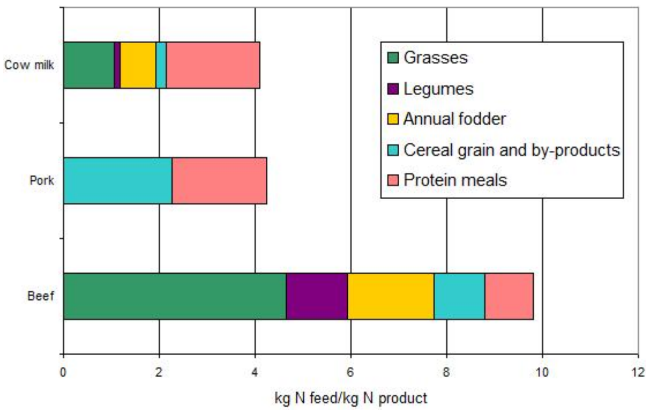

Fig. 5. Average composition of animal rations for the production of fresh milk, pork and beef (kg N in feed/kg N in animal products).

3 Results

Figure 5 shows the nitrogen composition of animal rations per unit of nitrogen output in the form of milk, pork and beef. On average, about 80 % of the protein intake of beef cattle is supplied by roughages (about 60 % is from grasses and legumes and 20 % from annual fodder). Roughages average 50 % (in terms of N) in dairy production (25 % from grasses and legumes and 25 % from annual fodder) and is nil in pig production, where protein is half supplied by cereal grains and by-products and half by soy and rape meals. For each production, the nitrogen conversion efficiency (NCE) is calculated with respect to the share of N in retail products. For milk, it is 100 %, for beef 70 % and for pork 90 %.

Figures 6, 7 and 8 show the N cycle and the land requirements associated with the annual consumption of fresh milk, pork and beef in France. N inputs are calculated per N source (except for soybean agrosystems). Land requirements are expressed per capita (ha cap^{-1} yr^{-1}) and N flows both per capita (kg N cap yr^{-1}) (bold type) and per unit of land (kg N ha^{-1}) (numbers in brackets). Figure 9 shows the results for the three products together.

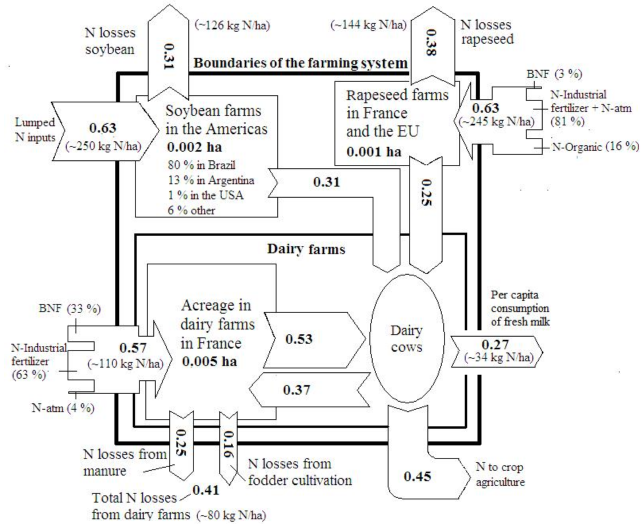

Fig. 6. Nitrogen and land requirements associated with the production of fresh milk. Arrows (bold type) refer to per capita N flows (kg N cap yr^{-1}) and rectangles to per capita land requirements (ha cap^{-1} yr^{-1}) per country of feed production. N input and output per hectare are given in brackets (kg N ha^{-1}).

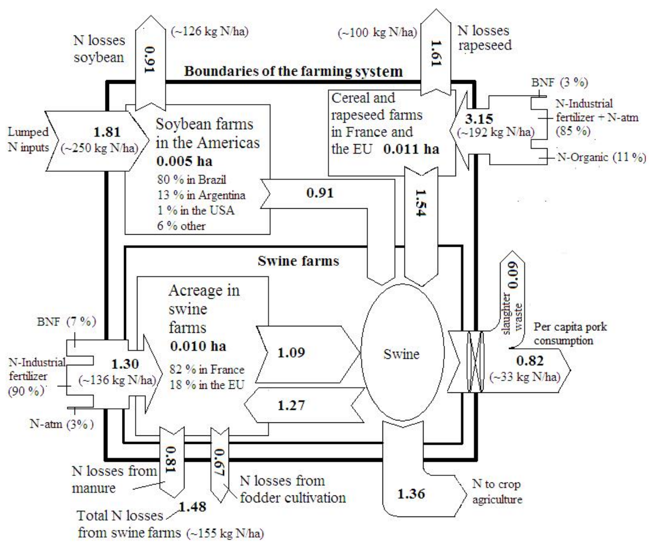

Fig. 7. Nitrogen and land requirements associated with the production of pork. Arrows (bold type) refer to per capita N flows (kg N cap yr^{-1}) and rectangles to per capita land requirements (ha cap^{-1} yr^{-1}) per country of feed production. N input and output per hectare are given in brackets (kg N ha^{-1}).

Land requirements to supply fresh milk, beef and pork total 0.1 ha cap^{-1} yr^{-1}, out of which 75 % is located in France. The remaining fraction is located in other EU countries and

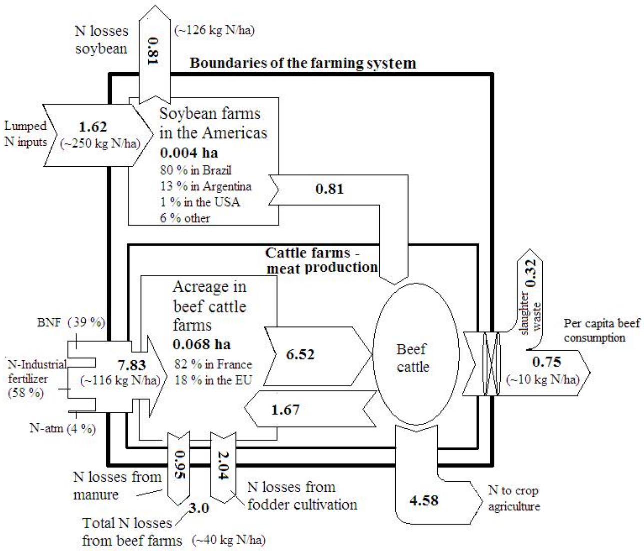

Fig. 8. Nitrogen and land requirements associated with the production of beef. Arrows (bold type) refer to per capita N flows ($kg\,N\,cap\,yr^{-1}$) and rectangles to per capita land requirements ($ha\,cap^{-1}\,yr^{-1}$) per country of feed production. N input and output per hectare are given in brackets ($kg\,N\,ha^{-1}$).

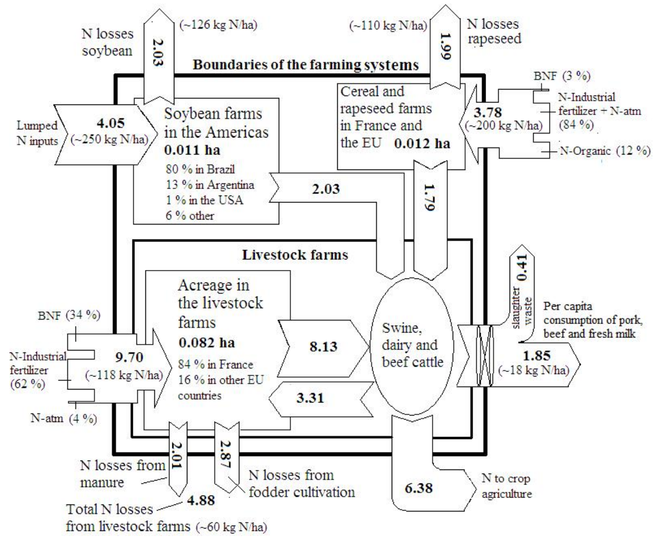

Fig. 9. Nitrogen and land requirements associated with the production of fresh milk, pork and beef. Arrows refer to per capita N flows ($kg\,N\,cap\,yr^{-1}$) and rectangles to per capita land requirements ($ha\,cap^{-1}\,yr^{-1}$) per country of feed production. N input and output per hectare are given in brackets ($kg\,N\,ha^{-1}$).

in America (especially in Brazil). Accordingly, out of the 0.5 ha of agricultural area available per person in France, about 15 % is used to supply fresh milk, pork and beef, three products accounting for 25 % of the dietary nitrogen consumption per capita.

Table 2 summarizes the NUE (%) per crop agrosystem and the NCE (%) of livestock for milk, pork and beef production. The bottom line shows the overall NUE (total N in retail products/total N inputs, %) per livestock system.

Beef production uses 10 units of feed protein per unit of protein output; the ratio is about 4 in pork and dairy productions. Hence, respectively about 90 and 75 % of the protein intake of livestock ends up in manure. Whether the contained N returns to agriculture or is lost to the environment greatly depends on availability of surrounding cropland for manure application. Our system analysis shows that massive imports of feed N in swine and dairy farms are responsible for almost 20 % of total N loss from these farms (Figs. 6, 7). In both dairy and pig farms, about two thirds of the N content of manure excretion is lost to the environment. In beef farms, manure recovery is higher (N loss equals 55 % of manure excretion, Fig. 8) because N imports in feed are lower.

For the current N budgets of the farms, manure export to crop agriculture is 65 000 tons of N for 19 000 tons of N in retail products. Admitting a NUE of 50 % for crops receiving this manure, the consumption of livestock products currently sustains the production of about 1.7×10^6 tonnes of wheat equivalent (1.92 % N). This is roughly $0.17\,kg\,N\,cap^{-1}\,yr^{-1}$ and implies that the consumption of 1 unit of animal proteins sustains the production of 1.7 units of vegetal proteins. This ratio underlies the fertilisation capacity of livestock farming within a context of mixed (crop + livestock) agrarian systems.

The ratio between N losses and N in animal products indicates overall efficiency of livestock systems in terms of N use. We refer to this ratio as “N loss factor”. Table 3 summarizes per capita N consumption in the form of fresh milk, beef and pork, the N losses from crop and livestock farms and the N loss factors per farming system.

4 Discussion and conclusions

We develop and apply the N food-print as an indicator of N flows and losses from livestock systems in relation to fresh milk, pork and beef consumption in France. Consumption and production are analysed from a system perspective that provides insights on where the N emissions occur along the production chain and on where to focus to reduce them. Uncertainties with respect to numerical values mainly concern the use of average biomass accretion rates in French farming, average literature-derived BNF rates (different values used for grasslands, meadows and cropland) and uniform rates for manure spreading on cropland. Total fertilization and feed deficits in livestock farms are calculated per farming region. Feed deficits are derived from crop productivity and stocking rates. We focus the discussion on differences in N flows and N losses per type of livestock production in relation to differences in fertilization, feed inputs and feed trade.

Table 2. NUE in feed production per crop and livestock farm and NCE of the livestock for beef, milk and pork production. All numbers are in %.

	Beef production	Milk production	Pork production
NUE in feed crop cultivation on the livestock farms	76	76	62
NUE in rapeseed farms	–	40	
NUE in cereal farms	–	–	63
NUE in soybean farms	50		
Overall NUE in ration production	72	56	53
NCE of livestock	10	24	24
Overall NUE per livestock system	7.2	13.4	12.7

Table 3. N consumption per product, N loss and N loss factors for pork, beef and milk production. All units are in kg N cap^{-1} yr^{-1} unless otherwise stated.

Farming type	N in products	N losses from feed crop cultivation on the livestock farms	N losses from feed crop cultivation on associated crop farms	N losses from manure	Total N losses	N loss factors (N losses per unit of N in products) (as ratio)
Milk	0.27	0.16	0.69	0.25	1.10	4.1
Beef	0.75	2.04	0.81	0.95	3.79	5.1
Pork	0.82	0.67	2.52	0.81	4.00	4.9
Total	1.85	2.87	4.02	2.01	8.90	4.8

In all three livestock systems, crop cultivation for feed is the major cause of N loss (more than 75 % of total N loss). Accordingly, losses from manure account for less than 25 % of total N losses. Each production system uses different feed inputs which affect the share of feed trade per sector and the geographical pattern of N losses. For feed trade to occur, feed surpluses with high nutritional-value must be generated in low-cost producing agrosystems. This makes it possible to raise livestock in regions where the production of the same or an equivalent feed would be more expensive and/or constrained by biophysical and socio-economic conditions. Because not all feeds are subject to trade, there are large differences among livestock production sectors. Roughages for instance have lower nutritional density and are, therefore, bulkier and more expensive to transport than energy and protein concentrates. As a consequence, feed trade is more important for livestock systems with monogastrics than with ruminants. However, the use of feed concentrates in cattle production also depends on the nutritional value and, more precisely, on the balance among nutrients in roughages. Roughages with relatively high energy and relatively low protein contents, like maize, must be balanced in rations with feeds, like soy and rape meals, which are rich in protein and relatively poor in energy. The energy to protein ratio in grasses is better balanced than in maize fodder. Milk production in France uses higher shares of maize and lower shares of grasses than beef production, which results in higher dependency on protein-rich feed concentrates in milk than in beef production. As a result, feed trade from crop monocultures to livestock facilities and – the other way round – the degree of physical externalization of N-related impacts from livestock farms to crop monocultures are higher for pork and dairy than for beef production. Our system analysis shows that French swine farms import on average 70 % of the protein requirements of pigs. The N losses associated with these imports occur on other, sometimes far away, arable farms that cultivate the cereals, rapeseed and soybean and account for 80 % of total N losses associated with the production of a pig's ration. For dairy production, the share of feed proteins produced on farms other than where the cows are reared is 50 % and the associated N losses 80 %. For beef production, the share of imported feed proteins is 10 % and the corresponding N losses 30 %. In all three production systems, the ratio of N losses to the protein value of feeds is higher for the feeds grown in external crop farms than for those produced on the livestock farms. This relates to differences in NUE. As shown in Table 2, the cultivation of rapeseed has lower NUE than the cultivation of cereals and roughages, which are partly or entirely produced on livestock farms. The NUE of 50 % assigned to the cultivation of soybean is an assumption.

Trade in feed is in addition an important explanatory factor for the geographical distribution of livestock farms. This geographical distribution is currently governed by the distribution of feed markets more than of food demand to reduce costs on the input side (Steinfeld et al., 2006). A main reason is that the feed-to-food conversion efficiency of livestock is inherently lower than 100 % and typically lower than 25 %, which means that feed inputs per head are much bulkier than livestock products. Accordingly, reducing trade distances for feed is more efficient than for food. In addition, land prices usually decrease with distance from big cities. Other factors such as land availability, infrastructures, soil type, labour etc. may also affect the geographical distribution of livestock production among and within countries (Steinfeld et al., 2006). In France, most pork and dairy production is located in regions on the northwest coast (cf. Figs. 1 and 2) which have easy access to cheap feed, in particular soy meal, shipped from America to Europe and are at the same time relatively close to big consumption centres like Paris. The influence of trade in soy meal on the geographical pattern of French livestock production highlights the importance of this feed in livestock productivity. The trade of soy meal has impacts both at the locations of soybean cultivation and at the locations of soy meal use. On the one hand, soybean farms suffer N losses resulting from soybean cultivation. These losses depend on field NUE. For NUE of 50 % (the value we assumed in calculations), they account for about one third of total N losses associated with feed production. For this NUE value, N loads to the environment in America and especially in Brazil are substantially affected by French consumption of dairy and meat. On the other hand, massive imports of soybean in France contribute to sustaining high stocking rates in the regions which are specialized in livestock farming. In these regions, manure is often produced at rates that exceed the nutrient requirements of locally grown crops. Manure thus turns from resource to waste and affects water and air quality with consequences, at various scales, on ecosystems and humans. N loss from manure can be reduced if stocking rates are tied to availability of surrounding land for manure application (Cowling and Galloway, 2002; Galloway et al., 2007). In the case of milk, pork and beef consumption such a measure could at maximum yield a 25 % reduction of the N food-print.

Although appreciable, a reduction by 25 % suggests that strategies to reduce N losses should focus more on increasing field NUE. Best management practices to improve field NUE include better timing of fertilizer application, reduced tillage and the use of cover crops (Tilman et al., 2002). In addition, preferential planting of feed crops with high NUE is an option, which may imply changes in the nutrient composition of animal rations and affect, therefore in return, the NCE of livestock. Adjustments in ration composition should be designed systemically so that the overall NUE of livestock systems is improved, otherwise, reduction of N losses in one place may result in increases elsewhere. Moreover, a net reduction in fertilization rates is also an option. However, without a simultaneous increase of NUE, this option will be accompanied by a reduction in crop yields. A yield reduction would imply an increase in total land requirements if the same amounts of milk and meat were to be produced. The most robust strategy to decrease N losses and pressure on agricultural land would be a choice for food products with relatively low land requirements. A decrease in the share of animal proteins in human diets can reduce total feed production with a concomitant decrease in N losses. Similarly, a switch to diets with higher shares of dairy and lower shares of beef products can also reduce N losses. Dairy production is more efficient in converting vegetal into animal proteins than body biomass accretion in beef cattle. This implies lower land requirements, lower N loss from fodder cultivation and less manure excretion per unit of milk compared to beef production.

We stress the importance of the correct choice of system boundaries in assessing N pollution effects of food consumption. Only by including all external feed production locations can the total N loss (or the N food print) be assessed. N loss factors calculated from a farm-gate perspective are only meaningful for individual farms and are not applicable to products. In a recent review on livestock systems across Europe, Jarvis et al. (2011) report N loss factors from a farm-gate perspective. As expected, the reported factors are much lower than the ones calculated in this study, especially for pork production, which relies on massive flows of feed from various regions and countries.

Our N loss factors for France are comparable to those calculated by Leach et al. (2012) for average US production systems. For pork production, those factors are quite similar (4.7 in the Leach et al. paper versus 4.9 in this paper) but for milk and beef production, they are notably higher in US systems: 5.7 for milk and 8.5 for beef versus 4.1 and 5.1 in this paper, respectively. The expected agreement for pork production confirms that French and US systems are similarly industrialized. Swine are raised in feedlots and most of their requirements are met by cereals and protein concentrates produced in agrosystems where NUE is typically lower than 60 %. High rates of feed imports in pig farms typically lead to low rates of manure recovery into further crop production. Inversely, the disagreement of results for cattle production between the two studies implies different N use efficiencies with respect to feed crop cultivation and manure management between US and French systems.

N use and loss in agricultural production can be put in perspective with respect to N pollution load in urban wastewater due to human excretion. Total N inputs in farming systems are roughly ten times higher than the dietary N in products. Potential N losses to the N cascade are about half these inputs (so about 8.9 kg N $\mathrm{cap}^{-1}\,\mathrm{yr}^{-1}$). This figure is almost two times higher than the typical per capita annual N discharge in urban wastewater, while fresh milk, beef and pork provide 25 % of the dietary nitrogen intake of an individual. Given that livestock production is inherently more wasteful in nutrients than crop production, we estimate that N pollution from agriculture is about three to four times higher than the urban N discharge (we assume that half of the N loss from agriculture will be retained in the landscape, which may be an optimistic assumption for landscapes poor in wetlands;

Saunders and Kalff, 2001). Obviously, this insight does not deny the necessity of urban sewage treatment, but it rather stresses the significant implications of food consumption on upstream (rural and global) resources.

Acknowledgements. We would like to thank the reviewers for their valuable comments and suggestions that helped us improve the manuscript substantially. The study has been financially supported by the PIRVE program and AnR program "Villes Durables" contract number 08-VILL-0008.

Edited by: H. van Grinsven

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