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Nitrogen food-print: N use and N cascade from livestock systems in relation to pork, beef and milk supply to Paris

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Abstract

A bottom-up approach is constructed to determine N losses from livestock farming systems and to relate these losses to the supply of fresh milk, pig and beef to Paris. First, the three products are expressed in terms of their nitrogen content; then, their fodder equivalent is determined by modelling feed formulas for swine, beef and dairy cows to meet their energy and protein requirements. Fodder deficits in livestock farms are determined by comparing the nutrient requirements of the livestock with the fodder production on the livestock farms. This allowed determining the geography of the livestock systems according to the imports of fodder to the livestock farms from external crop farms. Then we assessed the "farm-gate" N budgets in all crop and livestock farms of the entire livestock systems using data on total N fertilization, atmospheric deposition and manure management practices to finally derive N losses in relation to fodder cultivation and to manure management. Measured in N, the supply of milk, beef and pig to Paris sum 1.85 kg N/cap and the corresponding N losses from the farming systems total 8.9 kg N/cap. N losses per unit of product differ among the three livestock systems according to where and how the fodder is grown and to what densities the livestock is reared.

1 Introduction

Global food production is the primary cause for anthropogenic inputs of reactive nitrogen into the biosphere. By the end of the 20th century, about 75 % of global human driven inputs of N were destined to 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 for the majority lost in the environment and 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). With more than

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half of the world population now living in cities and with most agricultural production occurring outside cities, urban food demand drives at distance most impacts relating to the alteration of the global N cycle.

Behind the alteration of the global N cycle lay agricultural revolutions of the second half of the 20th century which made it possible to sustain rapidly growing human populations and livestock production on moderately expanding agricultural area. Indeed, between the late 1960s and the end of 1990s, global population increased 70 %, 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).

This breakthrough in productivity relates to successive increases in both the crop yields and the conversion efficiencies of fodder energy and proteins into livestock biomass (Chatzimpiros and Barles, 2010; Chatzimpiros, 2011). However, high productivity at the scale of individual crops and animals does not guarantee low N losses over the entire livestock systems: first, increases in crop yields are often accompanied by 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 fodder 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 the global agricultural production is fed to livestock (Smil, 2001) and that most of the ingested nutrients are excreted in manures, 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).

In this paper we develop the N food-print as a tool for linking urban consumption of specific animal products with the above-mentioned structural aspects of the livestock systems that generate these products. We use as case study the supply of fresh milk, beef and pig biomass to Paris, the capital of France, in the early 21st century. We follow an analytical "bottom-up" approach summarized here in four steps: first, the supply of fresh milk, pig and beef to Paris is estimated from average consumption data and expressed in terms of nitrogen. Due to insufficient transportation data, assumptions had to be made about the spatial origins of the urban imports. In a second step, we calculate the fodder equivalent of the imports of pig, beef and fresh milk to Paris and evaluate the fodder deficits of the livestock farms. We do so by modelling feed formulas for swine, beef and dairy cows to meet their energy and protein requirements, then, by comparing these requirements with the fodder production of the livestock farms. Feed deficits in livestock farms are met through feed imports from external crop farms and result in livestock systems being spatially clustered. In a third step, we specify these systems in terms of size and geography using data on feed trade and crop yields. This is the spatial food-print of Paris (Billen et at., 2009). The N food-print is calculated in a fourth step as total N losses from the livestock systems. We assess "farm-gate" N budgets in all crop and livestock farms of the entire livestock systems using data on total N fertilization, atmospheric deposition and manure management practices to derive N losses in relation to fodder cultivation and manure management. These N losses are potential cascading N flows in consequence of the supply of fresh milk, pig and beef to Paris. Emissions of N relative to feed and livestock transportation and transformations are not accounted for in this paper.

2 Methods and data

2.1 Meat and milk supply to Paris

The geography of a consumer's food-print depends on the spatial origins of the urban imports and the geography of the fodder supply to farms. Billen et al. (2011) localised the Paris food supply areas for cereals, animal products and fruits and vegetables at three dates over a period of two centuries (1786, 1886 and 2006) based

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on data from transportation and production statistics for human food and animal feed. Unfortunately, transportation data for meat do not allow for such a localisation. Indeed, transportation records aggregate beef, pork, chicken, lamb and all other carcasses into a single carcass-equivalent weight unit (French Ministry of Environment, www.statistiques.developpement-durable.gouv.fr/). This aggregation conflicts with the objectives of this paper in which we seek to establish the N food-print of individual animal products because of the fundamental differences in production practices among different livestock sectors. Indeed, most – if not all – of the factors that underlie environmental change in animal agriculture – e.g. the type of crops used as fodder, the nitrogen conversion efficiencies of livestock, animal densities in feedlots, trade in feed etc. – differ dramatically between the current beef, dairy and swine sectors, meaning that accounting for such discrepancies is central in N food-printing. To do so, we assumed that the 265×10^3 tonnes of beef (0.75 kg N/cap/y) and the 350×10^3 tonnes of pig products (0.82 kg N/cap/y) imported to Paris in 2006 to feed the capital's 10 143 000 population originated from all French administrative regions proportionally to their share in national gross production (Fig. 1) and from foreign countries proportionally to their share in the national trade balances. In total, national production stands for 82 % of the pig and 82 % of the beef consumed in France and the remaining 18 % originates from EU countries exclusively (Spain, the Netherlands, Germany and Belgium together account for 85 % of pig and beef imports) (Agreste, 2006, 2010; FAOSTAT, 2006).

The origins of milk imports are derived from the above mentioned transportation database. Those data, though, report the places of last loading of products which are not necessarily the production sites. The latter can be traced back by combining the transportation data with production statistics on the ground of simplifying assumptions, such as the "perfect mixing principle" which assumes no regional preferences for locally grown food (Billen et al., 2011). In the case of milk, interregional trade before retail is expected to be low. Given that determining the exact geography of the N food-print is not the research question that we address in this paper, we used the data as they appear in the database except for the regions where milk exports exceeded

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local production. In that case, we assumed that the tonnage in excess originates from all French regions proportionally to their respective productions. Figure 2 shows this distribution for the $524 \times 10^3\,m^3$ of milk (0.27 kg N/cap/y) imported to Paris in 2006.

Table 1 shows the chemical composition of milk (CNVA, 2006), beef (NRC, 2000; Wulf, 1999; Hoch and Agabriel, 2004) and pork carcasses (Lange et al., 2003; NRC, 1998) and the annual "per capita" supply of pork, beef and fresh milk to Paris in terms of proteins (kg N/cap) and energy (Mcal/cap – energy in lipids, proteins and lactose is 9.4, 5.6 and 4.0 $Mcal\,kg^{-1}$ respectively). According to national statistics, those three products account for about 25 % of total protein intake of Parisians.

2.2 Animal rations and feed origins

The next step consists in modelling the animal rations. Their composition plays a pivotal role in the structure and functioning of the livestock systems and it largely determines the N inputs and losses to and from these systems.

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. This concerns body accretion rates for growing animals and milk yields for dairy cows. The energy system we used in ration simulations is metabolic energy for swine rations and net energy for beef and dairy rations according to data availability in major literature sources (NRC, 1998, 2000, 2001).

We modelled beef and dairy rations per French administrative region using a dynamic ration formulation model (NRC, 2001, CNCV, 2006). We followed the approach developed in Chatzimpiros and Barles (2010) in which the growing and milking phases of cows are modelled separately in order to disconnect the nutrient requirements relating to lactation from those relating to weight accretion in body biomass and vice-versa. This is necessary in order to obtain rations that are specific to milk and meat production respectively which is relevant because milk and meat output of single dairy animals or entire livestock farms are two independent variables.

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For milk production, we admitted annual lactation cycle of 305 days and constant liveweight (LW) in both the lactation and non-lactation periods of the cows. Milk yields per lactation day vary from 13 to 22 l day^{-1} (Statistique agricole annuelle, 2006). For cattle meat production, we admitted steady growth rates from birth to slaughter, which averages 1.1 kg day^{-1} in France (Statistique agricole annuelle, 2006).

Swine rations only produce meat and are modelled on the basis of the energy and protein requirements of growing pigs (NRC, 1998) for steady growth rate of 0.6 kg day^{-1} which is the average rate in French pig farms (Agreste, 2006). Table 2 summarizes average values of biomass production and the live-weights of the livestock that we used to simulate nutrient requirements.

The diet of an animal represents a nutrient balance between the requirements for maintenance and growth and the nutrient supply of fodder.

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

The type of roughages used in cattle farming is derived from agricultural statistics for each farming 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 the production of beef meat while maize-forage is dominant in regions specialized in dairy production (Agreste, 2008c).

The ingredients used in the fabrication of concentrate feeds are derived from datasets of agro-industries per livestock sector (Agreste, 2008a). Data on the nutrient composition of feeds are derived from NRC (2000, 2001) for cattle and from NRC (1998) and ITAB (2001) for swine.

Trade in fodder only concerns energy and protein concentrate feeds as opposed to roughages which are typically produced on the farms because they are bulky and therefore expensive to transport (Agreste, 2006). Trade in feed generally makes up for

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deficits in the fodder production of livestock farms, either due to high animal densities or to overspecialization of agriculture. In France, "on-farm" production of concentrate feeds is typically limited to cereals while practically all soybean and rapeseed meals are imported.

Soybean is imported to France mostly in the form of meals and originates 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) 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) and is then partially re-imported to France in the form of meals to feed livestock (Agreste, 2005; FAOSTAT, 2006). Emissions of N relative to feed transport and transformation are not accounted for in this paper.

Imports of soybean and rapeseed meals account for the bulk fodder inputs to beef and dairy farms. In contrast, pig farms face in addition severe deficits of cereals, the magnitude of which vary among regions. Cereal deficits appear when swine are reared at densities that exceed the carrying capacity of "on-farm" land. We computed deficits by comparing data on swine densities recorded in the agricultural censuses of a given year (Agreste, 2007) with the pig densities possible to sustain from "on-farm" cereal production at the same year given the cereal intake of pigs and the agricultural yields of the cereal crops in that year.

In overall, the livestock acreage and therefore the food-print are spatially clustered among the livestock farms and the crop agrosystems that supply the soybean, rapeseed and cereal feeds. For pig and beef imported from abroad, we considered identical structure for the livestock systems.

The land requirements per livestock system are computed using agricultural yields per region and country of fodder production (Statistique agricole annuelle, 2006; FAOSTAT, 2006). For crop by-products – such as soybean and rapeseed meals – the corresponding land requirements are fractions of the land required to grow the respective

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mother-crops. These fractions equal the energy content of by-products as percentage of the energy content of the processed seeds (Chatzimpiros and Barles, 2010).

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

Figure 3 indicates the N fluxes within and from the livestock systems that supply beef, pig and fresh milk to Paris. These flows as well as the land requirements of the production will be accounted for separately for pig, beef and fresh milk supply to Paris.

The N inputs per livestock system are computed per region and fodder crop except for the locations where data are unavailable. This was the case in soybean producing countries for which N inputs are estimated indirectly assuming global average nitrogen use efficiency (NUE) of 50 % (Cassman et al., 2002). This implies that the N losses through leaching and/or denitrification processes equal the amount of N removed in soybean harvest. Agricultural yields for soybeans are taken from FAO (2004) and average (in terms of nitrogen content) 125 kg N/ha in Brazil, 120 kg N/ha in Argentina, 155 kg N/ha in the USA and 120 kg N/ha on global average.

For crops other than soybean, we calculated N inputs and Nitrogen Use Efficiencies (NUE) from specific data on total fertilization and crop yields (expressed in nitrogen) per region of crop production (Agreste, 2006). Data concern the year 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). Deposition rates in France typically vary from 3 to 6 kg N ha yr^{-1}. For BNF, we used common values from literature: 250 kg N ha yr^{-1} for alfalfa, 35 kg N ha yr^{-1} for pasture (assuming 15 % legumes) and 5 kg N ha yr^{-1} for fallow (Smil, 1999; Peoples et al., 1995). Green fertilizers are mainly used in association with maize in half-year rotations, we assumed an annual BNF rate of 125 kg N/ha. For manure application, we admitted uniform rate of 170 kg N/ha which is the prevailing upper limit for manure application in the European Commission Nitrate Directive, 1991/676/CEE. Certainly, not all crop farmers necessarily stick with the allowance rate, but in lack of precision data we were obliged to this simplification. We note that on livestock farms, manure N is an internal N flow but additional N is imported as feed (cf. Fig. 1). In overall, 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 live animals and milk, in the form of manures towards crop agriculture and in the form of nitrogen compounds through volatization and leaching which potentially contribute to the N cascade.

Total N output in the form of animal biomass equals N export to Paris in the form of fresh milk, pig and beef products (cf. Table 1) plus N in slaughter waste for beef and swine. N in slaughter waste is about 30 % of total N in live weight for beef (Hoch and Agabriel, 2004) and 10 % of total N in live weight for pig because tripe, blood and most other cuts of swine are edible as charcuterie.

N output to crop agriculture in the form of manures are calculated for all livestock species from data on manured area per region and crop (Agreste, 2008b) and is then allocated to specific livestock species using livestock units (LU) as "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, the manured area (ha) per administrative region can be allocated among the five livestock species at the regional scale and then be downscaled for the pig, beef and milk supply to Paris. Export of manure per species is then calculated for the allowance application rate of 170 kg N/ha. Finally, we must check that manure export is not overestimated for any species. To do so, exportable N is compared to excreted N minus the manure that is applied on the livestock farms. Potential gaseous N losses during housing and storage of manures are not subtracted because they are assumed returning on surrounding cropland. If for a given species available N is deficient, then the area allocated to that species is reduced to fit N availability and the difference is reallocated to another species.

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At last, environmental N losses are derived as total N inputs minus N export in products and manure for each fragment of the farming systems (i.e. livestock farms, soybean farms in Americas and cereal and rapeseed farms in the EU – cf. Fig. 3). Indeed, N losses specific to fodder cultivation are already known from the N balance between total fertilisation and harvest, thus, N losses specific to manure management can be also calculated separately.

Figure 4 summarizes the N flows to and from the farming systems as components of the urban N food-print. The Gross N food-print corresponds to total N inputs. The net N food-print corresponds to total N inputs minus N recovered in animal biomass and is thus a measurement of potential primary production in agriculture or natural ecosystems left behind secondary production. The net N food-print is partly exported to crop agriculture and partly lost in the environment with potential direct contribution to the N cascade.

3 Results

Animal rations and the components of the N food-print are established per French administrative region. Results are presented for the total supply of each product to Paris. Figure 5 shows the average simulated composition of the rations of swine, beef and dairy cows in terms of nitrogen intake per unit of nitrogen output in the form of animal products. In beef production, the nitrogen conversion efficiency (NCE) is calculated with respect to carcasses which generally contain 70 % of total live-weight protein (Hoch and Agabriel, 2004). In swine production, the NCE is calculated with respect to carcasses plus all other edible cuts imported to Paris as charcuterie (including tripe, blood etc) totalling 90 % of live-weight protein.

On average, about 80 % of the protein intake of beef cattle is supplied by roughages (about 60 % is from grasses and legumes). The share of roughages averages 50 % in dairy production (25 % from grasses and legumes) and is nil in pig production where protein is half supplied by cereal grains and by-products and half by soybean and rapeseed meals.

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Figures 6, 7 and 8 show the N cycle and the land requirements associated with the annual supply of fresh milk, pig and beef to Paris. The land requirements are expressed per capita (ha/cap) and the N flows both per capita (kg N/cap) and per unit of land (kg N/ha, numbers in brackets). Figure 9 shows the results for the three products together.

Land requirements to supply fresh milk, beef and pig to Paris total about 0.1 ha/cap of which about 75 % is located in France. The remaining fraction is located in other EU countries and in the Americas (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, pig and beef, three products that stand for 25 % of the "per capita" protein consumption.

N losses due to fodder cultivation are spatially scattered among livestock and crop farms according to the structure of the livestock systems. Indeed, the quantities of fodder imports to the livestock farms differ considerably among the three livestock sectors. For every unit of protein imported to Paris in the form of fresh milk, two units of protein are imported to the livestock farms in the form of feed, so a ratio of 1:2 (cf. Fig. 6). This ratio exceeds 1:3 in the production of pig (cf. Fig. 7) and is about 1:1 in the production of beef (cf. Fig. 8).

The higher the ratio of fodder imports to the livestock farms, the greater the degree of physical externalisation of N-related impacts to crop agrosystems other than the livestock farms. The rate of N losses depends on the Nitrogen Uptake Efficiencies (NUE) in field agriculture. Table 3 summarizes NUE (%) in association with the production of swine, beef and dairy rations. The two bottom lines of Table 3 show the Nitrogen Conversion Efficiencies of the livestock (NCE,%) and the combined Nitrogen Use Efficiency (cNUE,%) in each farming system.

N losses in the production of current beef rations are almost 40 % lower than in the production of swine rations and 30 % lower than in the production of dairy rations. Differences are partially due to the fact that no rapeseed-derived feeds are used in the beef cattle rations – the NUE in rapeseed cultivation being particularly poor. Differences also relate to the fact that the N input/output intensity in fodder cultivation

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is higher in swine systems (253/133 kg N/ha) than in dairy (190/106 kg N/ha) and beef cattle (137/100 kg N/ha) systems. However, for a given fertilisation rate, N losses in cropping systems with permanent land cover (the case of grasslands and meadows producing cattle rations) are usually lower than in cropping systems with long periods of soil in fallow (the case of annual fodder, cereals and rapeseed crops used in dairy and swine rations).

Beef production uses about 10 units of feed-protein per unit of carcass-protein against 4 units in the case of pig and dairy productions. Hence, respectively about 87, 73 and 75 % of the protein intake of livestock ends up in manures. Nonetheless, whether this organic nitrogen returns to agriculture or is lost to the environment depends on manure management practices in livestock farms and on the availability of surrounding cropland for manure application. In swine and dairy farms, massive imports of N in feeds contribute in manure being produced at rates that exceed the availability of surrounding land for manure disposal. According to our model, 25 % of the N intake of swine and cows is lost in the environment that way. In contrast, N losses from excreted manures equal 13 % of N intake in beef farms because of the notably lower animal densities and therefore the lower share of imported fodder in beef cattle diets.

For the current N budgets of the farms, manure export to crop agriculture is estimated at 65 000 tonnes of N. Admitting nitrogen uptake efficiency (NUE) of 50 % in crops receiving this manure, the urban consumption 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 yr^{-1} and means that the consumption of 1 unit of animal protein sustains the production of 1.7 units of vegetal protein. Ideally, if all produced manure was sent back to crop agriculture as organic fertilizer, the consumption to production ratio of protein would increase 20 % and the cascading N flows would shrink to losses from fodder cultivation, so about 6.9 kg N cap yr^{-1}.

The ratio between total N losses and N in animal products can be defined as the agroenvironmental efficiency of livestock systems. Table 4 summarizes in "per capita" terms the N imports to Paris in the form of fresh milk, beef and pig, total N losses in

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the farming systems and the agroenvironmental efficiency per farming system. The agroenvironmental efficiency turns to be very similar between the pig and beef farming systems and 20 % lower than in the dairy farming.

4 Discussion and conclusions

We show that total N inputs in farming systems supplying beef, pig and milk to Paris roughly sums ten times the urban imports of N in products. N in agrosystems is mostly supplied by industrial fertilizer. In swine farms, BNF from green fertilizers and free-living bacteria amounts 7 % of N inputs. In dairy farming, BNF supplies 30 % of N inputs and in beef cattle farming about 40 % of N inputs.

Nonetheless, total N losses with potential contribution to the N cascade are about half of the N inputs (so about 8.9 kg N cap yr^{-1}). As a comparison, this is almost two times the "per capita" annual N discharge in urban wastewater. According to national statistics, fresh milk, beef and pig meat provide together about 25 % of the protein intake of Parisians. Given that livestock production is à priori more wasteful in nutrients than primary production, we estimate that total indirect N related water pollution from Parisians is about six times the direct N discharge. This ratio means that wastewater treatment plants only handle about 15 % of total food-related direct and indirect urban N emissions. Indeed, this analysis reveals the extent at which cities affect the environment of territories on which they depend for food. We argue that linking diffuse agricultural N emissions to specific products and consumers may contribute in mitigating N-related environmental impacts in regional and global scales.

For milk, beef and pig supply together, N losses on the livestock farms average 60 kg N/ha (cf. Fig. 9). This is very consistent with the Figure of 68 kg N ha yr^{-1}, which corresponds to aggregate N losses for all meat and dairy products to Paris from main farming regions (Billen et al., 2012) based on a computation using transportation and production data. Nonetheless, as shown above (cf. Figs. 6, 7, 8), N losses differ much among products. Measured in kg N/ha, N losses on the livestock farms are more than

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3 times greater for swine than for beef production (45 kg N/ha and 155 kg N/ha respectively) and average 80 kg N/ha in dairy farming.

N losses from livestock systems are spatially scattered due to trade in fodder. For the sum of milk, beef and pig supply to Paris about 45 % of total N losses are on crop farm other than where the livestock is reared and, as shown above, this ratio is as high as 65 % in milk and pig productions and 20 % in beef production (cf. Figs. 6, 7, 8). This underlies huge discrepancies in terms of physical externalisation of impacts in relation to all resources involved in the production, directly or indirectly. For instance, respectively 6, 19 and 21 % of the spatial food-print of beef, swine and dairy supply to Paris is located in soy producing countries – especially in Brazil: more this dependence is high and more the French diets are likely to contribute to the Amazon's deforestation with environmental implications at the global scale.

Farm dependency on imported protein is most generalised in pig production and concerns in particular the region of Brittany (western France) which accounts for almost 60 % of total French pig production (Statistique agricole annuelle, 2006). Protein dependency in Brittan pig farms is estimated at 60 % for cereals alone and at 80 % in total. In overall, less than 10 % of total national French pork production comes from farms self-sufficient in cereals while no farms at all are completely autonomous in feed.

Yet, in order to effectively account for spatially scattered impacts of specific products, consumption-based indicators must follow trade beyond administrative or geographical frontiers. Otherwise assessments are incomplete and results may be misleading. For instance, a recent study (Jarvis et al., 2011) assesses N losses of dairy, beef and swine farming per unit of milk, beef and pig meat production without accounting for N losses in the crop systems that supply "ready-to-feed" protein to the livestock farms. As a result, the "losses to product" ratios in that study are underestimated (equal 2.55, 2.7 and 0.85 for milk, beef and pig respectively against 4.1, 5.1 and 4.9 in our study) and results must be interpreted with caution.

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Tying livestock densities to availability of surrounding land for waste application is an efficient means for improving nutrient cycling in agro-systems (Cowling and Galloway, 2002; Galloway et al., 2007). In the case of milk, pork and beef supply to Paris such a measure can at maximum result in 25 % reduction of the cascading N food-print. Although appreciable, the figure suggests than even under optimal management of manure, about 75 % of N losses would pertain because relating to fodder cultivation. Improved fertilization practices and/or changes in the composition of animal rations (by shifting for instance towards fodder crops with higher nitrogen uptake efficiency-NUE) can be used as mitigation strategies with respect to entire livestock systems. Beef cattle have the greatest potential for such a reduction. In spite of its low efficiency in the conversion of vegetal into animal protein (NCE), beef cattle can be exclusively fed roughages from grasslands and meadows with high NUE. Indeed, the substantially lower N losses per unit of primary production in such agrosystems are an asset in cattle farming and may substantially counterbalance low conversion rates. For instance, in a scenario with beef rations of 90 % NUE and swine rations of 50 % NUE (corresponding to current average N efficiency in cereal and rapeseed agrosystems), the cascading N food-print of beef and pig consumption would be identical. Of course, this scenario assumes very high rates of manure recycling after excretion, which may be considered too optimistic. Nonetheless, losses from manure greatly depend on management practices. For instance, N losses from volatization can be substantially reduced with the separation of liquid from solid wastes in animal husbandry facilities (Kaspers et al., 2000; Cowling and Galloway, 2002). In addition, low emission of volatile particles may also be achieved by shortening time intervals between production and disposal of manures. Indeed, under good management practices of manures, pasture-based cattle farming may have lower N food-prints than other livestock systems using grain as main feed source.

Our analysis underlines the fact that animal rations of different composition can provide identical livestock products with different environmental outcome. This is an asset for secondary production where N losses can be reduced by shifting towards fodder

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crops with higher NUE. High quality proteins for human diets can thus be obtained on agrosystems of low impact on the N cycle. The cascading N food-print is a relevant tool for assessing potential environmental change of food consumption in spatially scattered agrosystems and according to management practices and human diets.

The results presented in this paper include uncertainties that mainly relate to the quality of the datasets on N fertilisation, to values used for biological nitrogen fixation (BNF), to nitrogen uptake efficiency (NUE) assumed equal to 50 % in soybean producing agrosystems in the Americas and to the uniform manure spreading rate in crop agriculture assumed equal to 170 kg N/ha. Indeed, manure distribution modelling is a complex issue because various factors may intervene in the choice of farmers on manure use and application rates. For instance, except for social factors, taste for manure use may also depend on soil type, agricultural machinery, tilling practices, “least cost method disposal” etc. potentially resulting in variable application rates among neighbouring farms. Uncertainties in relation to such variables are particularly difficult to assess.

Other uncertainties are easier to seize. We used for instance uniform rates of BNF for grasslands and meadows with variable yields. In most cases we associated relatively high BNF rates to relatively low yielding systems which is likely to result in slightly overestimated N losses from fodder cultivation in cattle farms. Inversely, our results on NUE in cereal systems suggest that total fertilisation and therefore the N losses in these systems may have been underestimated. Indeed, NUE in cereal cultivation was found to exceed 60 % in many cases and 70 % in some cases meaning that N losses associated with the production of swine rations in particular are likely to have been underestimated. Accordingly, the overall nitrogen use efficiency in swine and beef cattle farming would be pretty much equivalent. Swine is indeed more efficient than beef in converting vegetal into animal proteins but beef farming seems to be more efficient than swine in recovering N before and after the nutrition as well as it results in less spatially scattered impacts. This reflects why livestock production should be always studied through systemic approaches including feed production, feed conversion efficiencies

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and manure management practices, which are evidently opposed to classical economic perspective in which maximization of profits is disconnected from nutrient use efficiencies.

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Table 1. Chemical composition of the fresh milk, beef and pork carcasses and of the corresponding annual energy and protein supply to Paris (Mcal/cap, kg N/cap). Data sources: see in the text.

	Fresh milk	Beef carcass	Pork carcass
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" supply to Paris (including charcuterie, tripe etc)			
Proteins (kg N/cap)	0.27	0.75	0.82
Gross Energy (Mcal/cap/year)	36.5	85.1	109.4

Table 2. Typical live weights (LW) at slaughter, annual biomass accretion rates (and milk yields of the swine, beef and dairy cattle supplying meat and fresh milk to Paris. Data sources: Statistique agricole annuelle, 2006.

	Dairy cows	Beef cattle	Swine
LW (kg)	630	800	110
Annual production rate (lt milk yr^{-1} for cows, kg LW yr^{-1} for beef cattle and swine)	18	1.1	0.6

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Table 3. Average nitrogen uptake efficiency in fodder cultivation (NUE), average nitrogen conversion efficiency of the livestock (NCE) and combined nitrogen use efficiency per livestock system (cNUE).

	Cattle farming		Swine farming
	Meat production	Milk production	
NUE (%) in fodder 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 the livestock (%)	10	24	24
cNUE per livestock system (%)	7.2	13.4	12.7

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Table 4. Imports to Paris, N losses and environmental efficiency for pig, beef and milk.

Farming type	N in products to Paris	N losses from fodder cultivation on the livestock farms	N losses from fodder cultivation on crop farms	N losses from manures	Total N losses	N losses per unit of N in animal products
Units			(kg N cap yr^{-1})			(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
Pig	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

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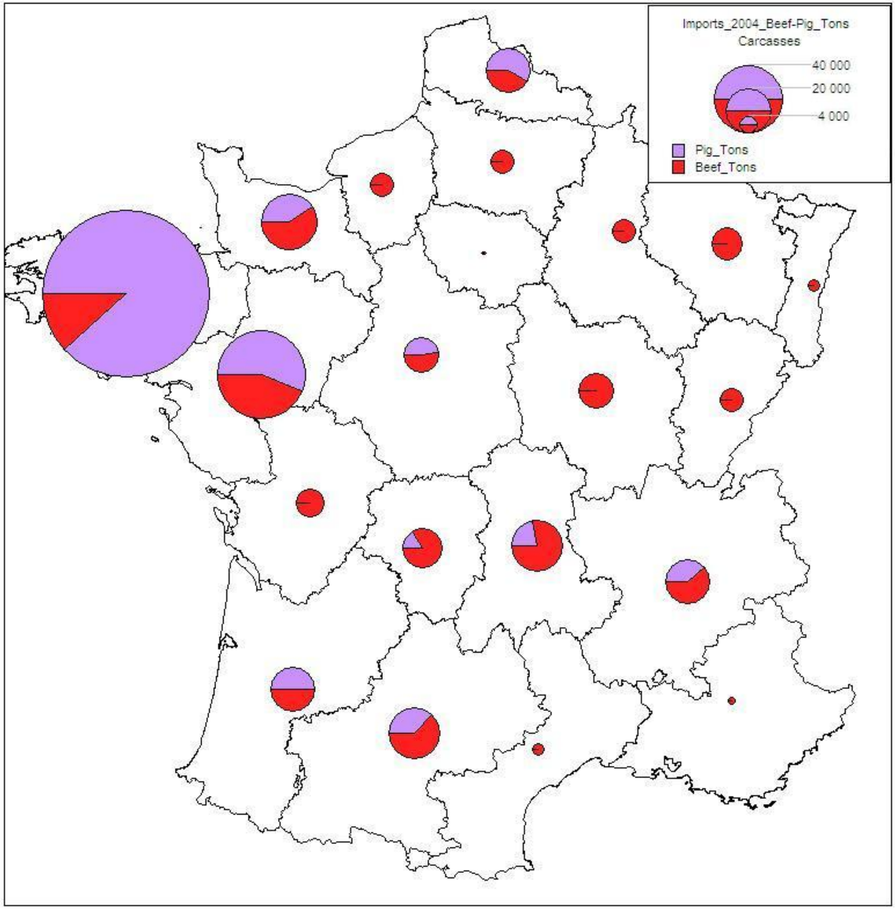

Fig. 1. Imports of beef (in red) and pork (in purple) products to Paris in the early 21st century per French administrative farming region. Data sources: Statistique agricole annuelle, 2006.

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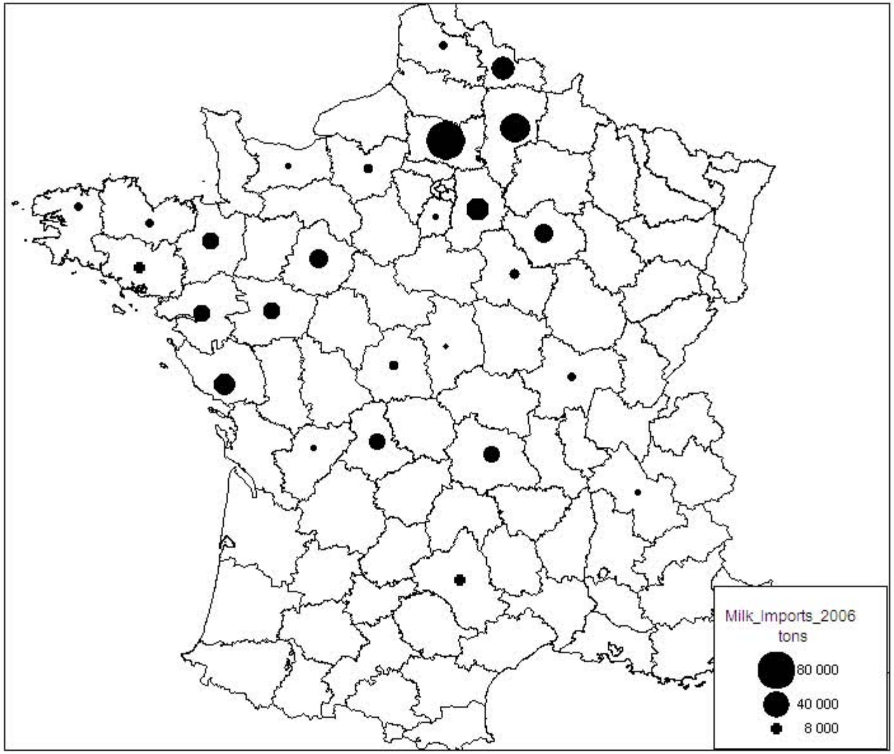

Fig. 2. Imports of fresh milk to Paris in the early 21st century per administrative French department. Data sources: French Ministry of Environment, www.statistiques.developpement-durable.gouv.fr/.

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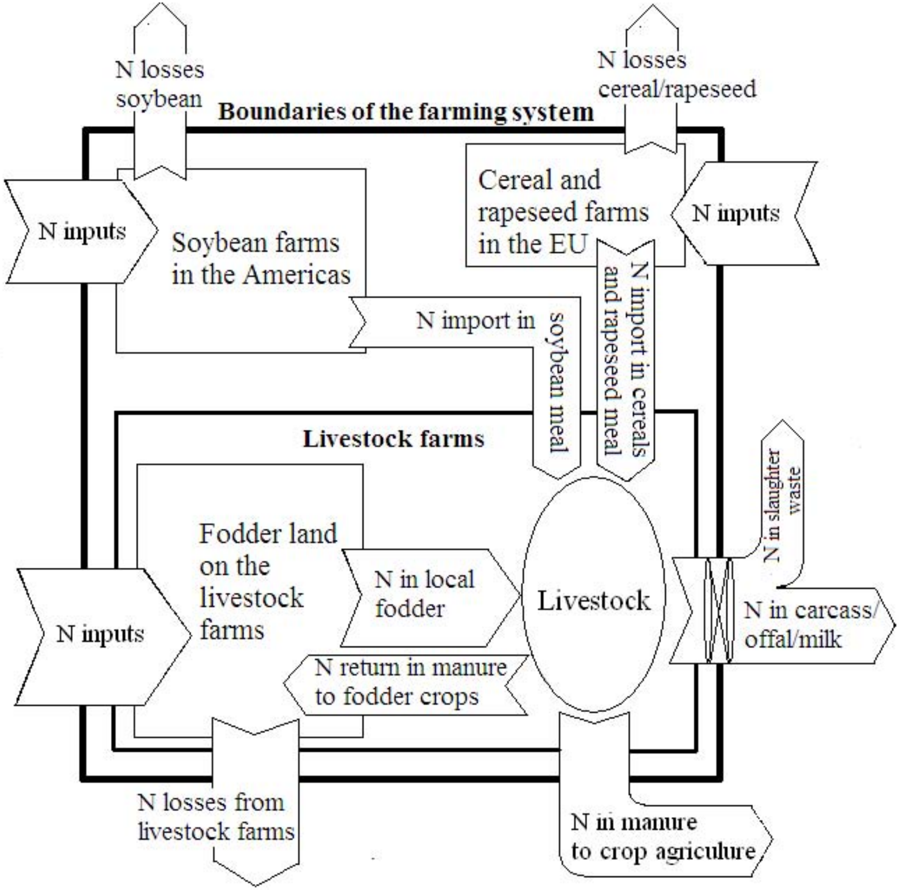

Fig. 3. The N cycle in spatially clustered livestock systems.

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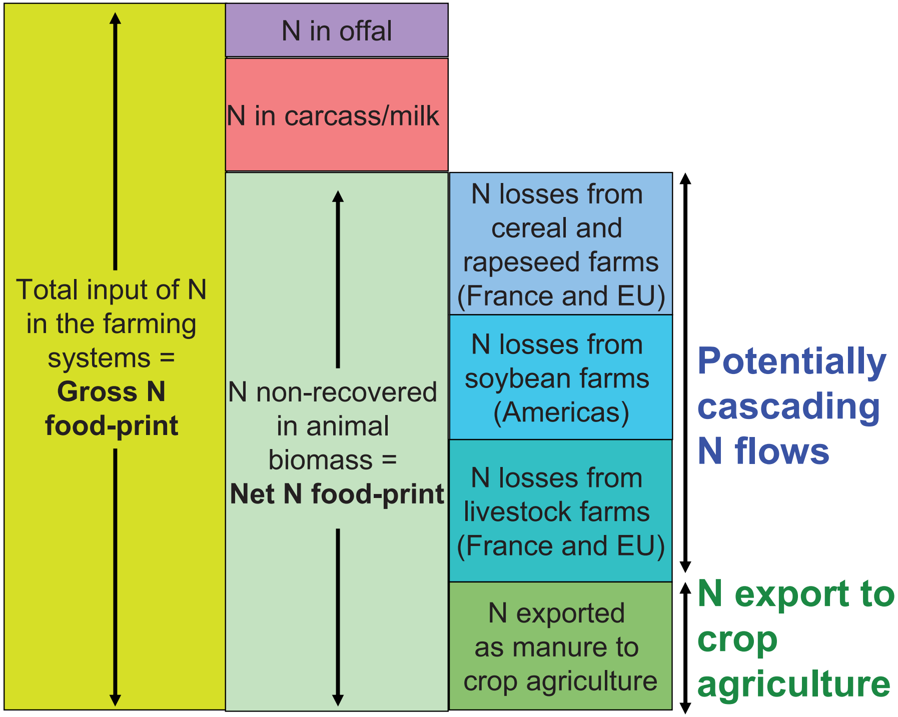

Fig. 4. The components of the urban N food-print of meat and milk consumption.

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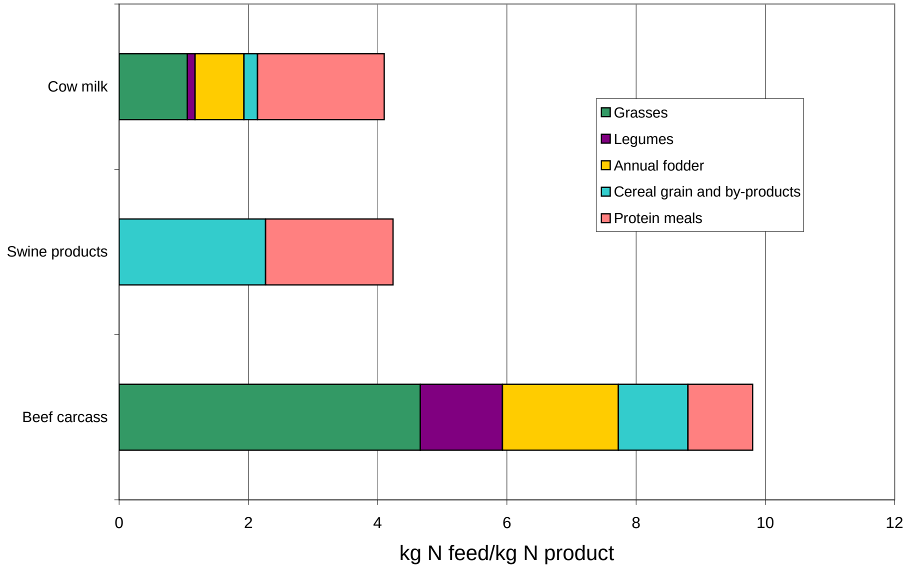

Fig. 5. Average composition of animal rations for the production of fresh milk, pig and beef (kg N in feed/kg N in animal products).

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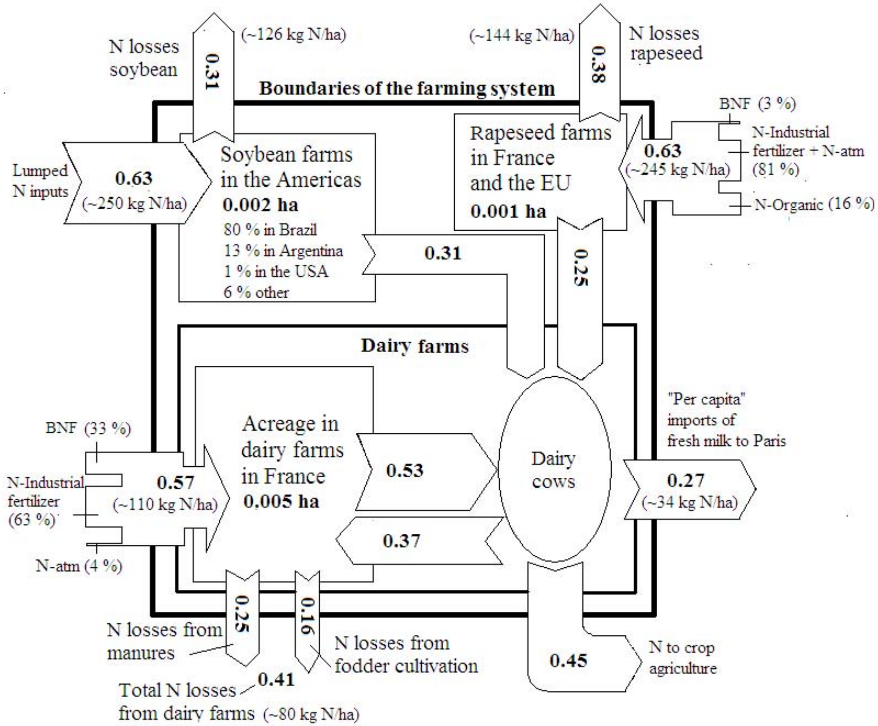

Fig. 6. Land requirements (ha/cap) and N flows (kg N/cap and kg N/ha) to supply fresh milk to Paris.

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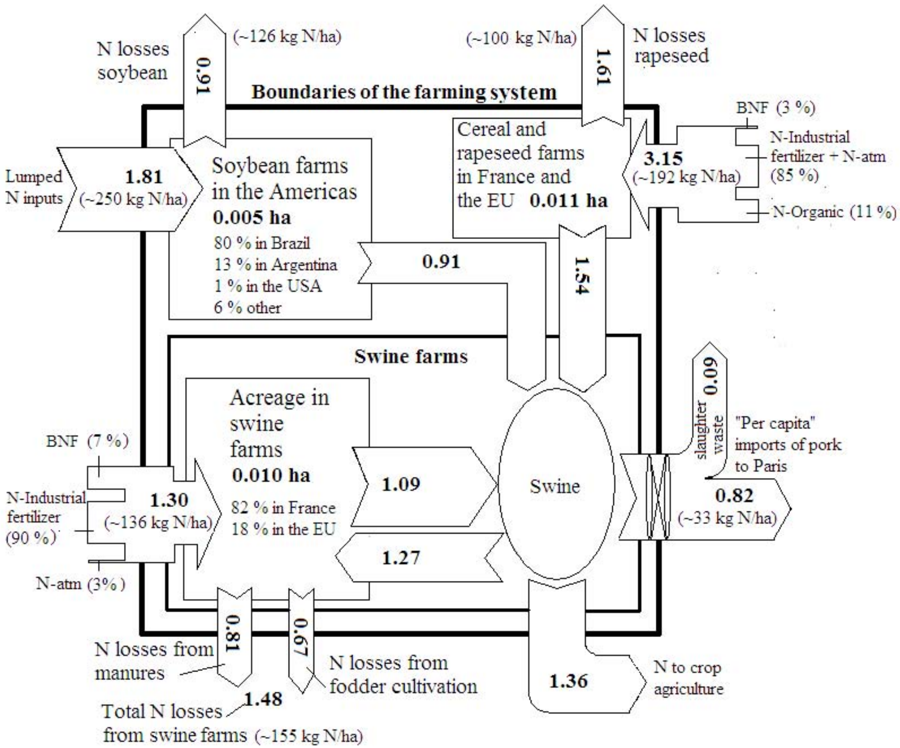

Fig. 7. Land requirements (ha/cap) and N flows (kg N/cap and kg N/ha) to supply pig to Paris.

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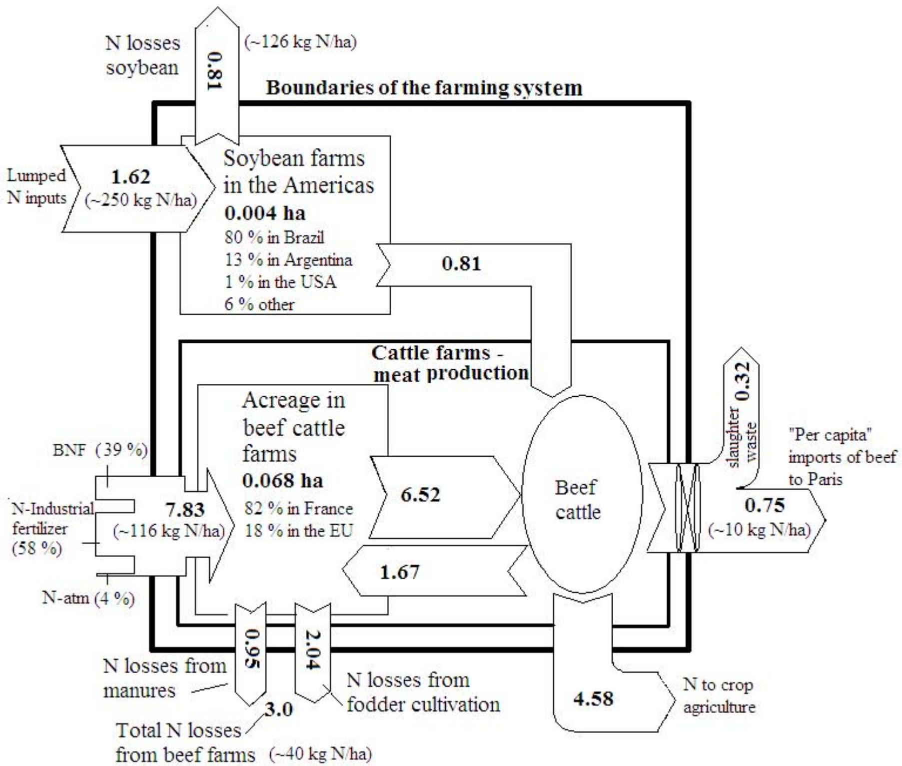

Fig. 8. Land requirements (ha/cap) and N flows (kg N/cap and kg N/ha) to supply beef to Paris.

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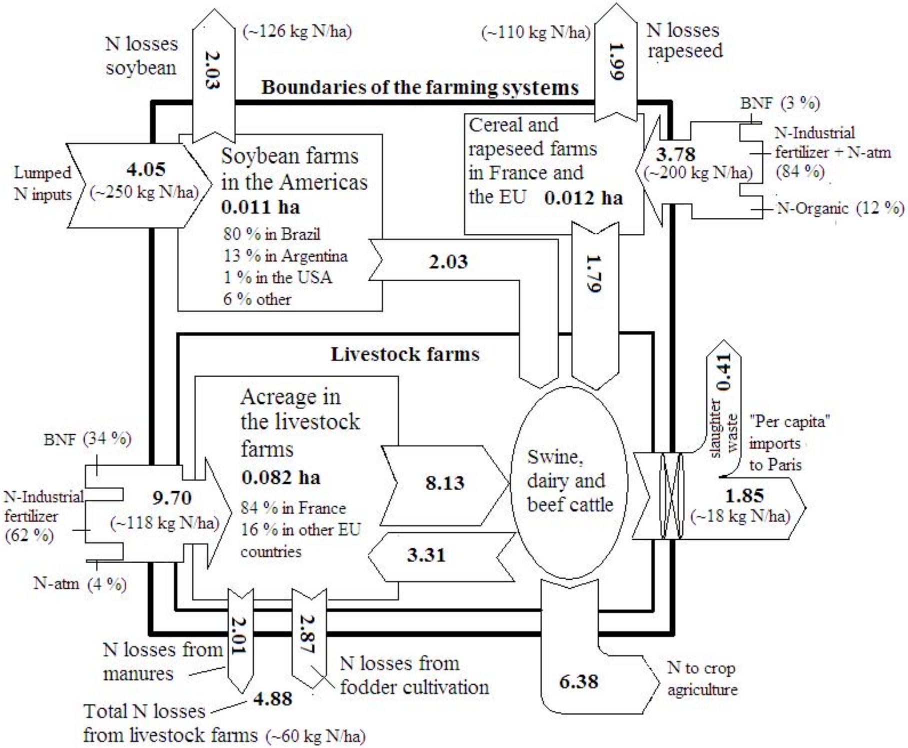

Fig. 9. Land requirements (ha/cap) and N flows (kg N/cap and kg N/ha) to supply pig, fresh milk and beef to Paris.

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