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How the structure of agro-food systems shapes nitrogen, phosphorus, and carbon fluxes: The generalized representation of agro-food system applied at the regional scale in France

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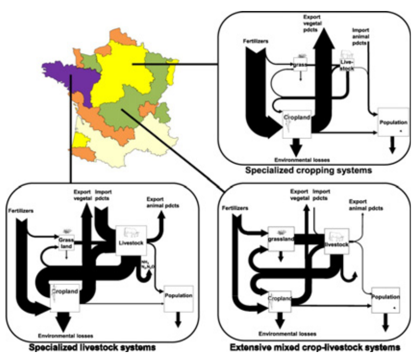
HIGHLIGHTS

- The circulation, losses and storage of N, P and C in agro-food systems is documented.
- A typology of the main agro-food systems in France is established.
- We quantify their environmental and agronomic performances.
- Increasing specialization and intensification increase losses from crop- and grassland.
- Increasing specialization and intensification decrease losses per unit of production.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of the study was to develop a conceptual framework to analyze the agro-food system of French agricultural regions from the angle of N, P and C circulation through five major compartments (cropland, grassland, livestock biomass, local population and potential environmental losses). To reach that goal we extended the Generalized Representation of Agro-Food System approach to P and C and applied it to French regions. Using this methodology we analyzed the relation between production pattern and N surplus, P budget, and efficient organic carbon inputs (OC_{eff}), assuming these three indicators to be good proxies for (i) N losses to waterbodies and the atmosphere, (ii) P accumulation or depletion in soils, and (iii) potential additional C sequestration in soils, respectively.

A typology was then established, allowing for comparison between five types of agricultural systems. This made it possible to highlight that intensive specialized agricultural systems generate high environmental losses and resource consumption per unit of agricultural surface and present a very open nutrient cycle due to substantial trade flows. Conversely, mixed crop and livestock farming and extensive cropping systems had more limited N and P consumption and led to lower potential water and air contamination. However, this trend was reversed when expressing resource consumption and N and P budget on a pro rata basis of vegetal and animal product unit, reflecting the better nutrient use efficiency of specialized regions in their respective field of specialization. This study demonstrates the systemic impact of production patterns on environmental and agronomic performances at the regional scale.

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1. Introduction

Resource management in agricultural systems is a key issue from both agronomic and environmental perspectives since it is a matter of feeding people in a sustainable way and preserving terrestrial and coastal environments from pollution. The trade-off between food production and environmental impacts is reflected in the duality of elements such as nitrogen (N), phosphorus (P), and carbon (C). They are essential for plant growth and soil fertility but with harmful effects for the environment when resulting in eutrophication (O'Higgins and Glibert, 2014; Passy et al., 2013) or when emitted to the atmosphere as greenhouse gases (GHG, Martikainen, 1985; Rodrigues Soares et al., 2012) or other compounds, considered as a major environmental risk to human health. Over the twentieth century, the impact of crop and livestock production on a global scale became the major cause of global N- and P-cycle alteration as a result of agriculture intensification, increasing use of fertilizers, and manure excretion stemming from intensified livestock production (Bouwman et al., 2013). Agricultural soils also play a major role in the C cycle, as agricultural practices have the potential to mitigate GHG emissions through additional C storage in the soil (Seguin et al., 2007; Smith, 2012), which in turn is beneficial to biodiversity and soil fertility, reducing erosion through structural improvement.

In this context, analyzing the functioning of the agro-food system from the angle of nutrient cycles is greatly needed. Several approaches have been developed for that purpose at different scales, from local to global. At the farm scale, nutrient budgets have been used as a tool for management of soil fertility with different accounting procedures from farm gate to system budgets (Watson and Atkinson, 1999; Watson et al., 2002). Humus balance is also a commonly used method to predict SOM shifts in the soil from an agronomic perspective (Hénin and Dupuis, 1945; Quenum et al., 2004). On a regional scale, several approaches have been developed with various objectives, but generally focusing on one single nutrient (e.g., Nesme, 2015; Garnier et al., 2016). At national and global levels, several methodologies have been developed to account for nutrient cycling in agro-food systems with different objectives, giving rise to an extensive literature (e.g., Senthilkumar et al., 2011, 2014; Garnier et al., 2015). A Generalized Representation of the Agro-Food System (GRAFS) on a global scale was developed by Billen et al. (2014) for analyzing the N biogeochemical cycle. The GRAFS method was initially developed to assess both food sufficiency and environmental N contamination at the scale of 12 macro-regions of the world (Lassaletta et al., 2014a; Billen et al., 2014, 2015). This approach has also been applied to regional and local scales, in study cases of river basins (Seine and Ebro basins, Lassaletta et al., 2012; Billen et al., 2013b), small catchments (Orgeval basin, Garnier et al., 2016), and individual farms (Anglade et al., 2015a; Bonaudo et al., 2015). Briefly, the GRAFS approach describes the agro-food system of a given geographical area by considering four main compartments exchanging nutrient flows: cropland, grassland, livestock biomass, the local population, and potential losses to the environment associated to these exchanges. It provides key indicators for analyzing an agro-food system from both environmental and agronomic perspectives. One important feature of this approach lies in the separation of utilized agricultural surface between permanent grassland and cropland (the latter including leys and temporary grassland), while most previous analyses consider agricultural surfaces overall. In this paper, we adopt the GRAFS methodology to investigate N, P, and C flows in the French agro-food system at a regional resolution scale. The case of France is of particular interest because it is a major agricultural country. Over the 2006–2013 period, France held a strategic position in the world for cereal production as the second largest world exporter and the seventh world producer (FAO, 2016, http://faostat3.fao.org/home/E). Therefore, understanding the agro-food system of French regions has both theoretical and practical value. This choice is also based on the existing literature on N flows embedded in the food and feed trade between French regions themselves and with foreign countries (Le Noë et al., 2016). In addition, this study seeks to gain a more holistic understanding of the agro-food system by extending the GRAFS approach from a N focus to a multi-nutrient vision, integrating the P and C flows described herein. Applying the GRAFS approach at the regional scale also enables to draw a particular picture for each regional unit and show the diversity of the agro-food systems existing at the national level. As suggested by several studies, the regional scale is well suited for studying socio-ecosystems through quantitative and qualitative analysis of material or nutrient flows (Buclet et al., 2015).

The final objectives of this study were to (i) identify agricultural patterns from the biogeochemical point of view, (ii) draw a typology of the main farming systems encompassed at the national scale, and (iii) highlight the relation between production pattern, trade pattern, and environmental and agronomic performance.

2. Methods

We describe here the data and assumptions used to establish the detailed budget of N, P, and C fluxes across the French agro-food system at the scale of its agricultural regions. The base year of the data set used in the GRAFS model is 2006, for the sake of comparison with the data assembled on interregional trade throughout France by Le Noë et al. (2016). Analyzing the trends of several important indicators of agricultural production over the last few decades shows that 2006 is reasonably representative of the 2000–2013 period (Fig. 1a–c).

2.1. Definition of homogeneous regional units

As proposed by Le Noë et al. (2016), France was divided into 33 agricultural areas defined by grouping *départements* (French NUTS 3 administrative units) based on their geographical proximity and the similarity of their agricultural system in terms of (i) the proportion of permanent grassland over the utilized agricultural area and (ii) livestock density. We assumed these criteria to be good proxies for describing the system specialization into livestock versus crop production. A similar grouping of world countries into 12 macro-regions was defined at the global scale by Lassaletta et al. (2014a).

2.2. Human food consumption and excretion

Data on the availability of food commodities, based on the analysis of national accounts, are provided by the French National Institute for Statistics and Economical Studies (INSEE, 2004). These data correspond to the apparent food consumption of the French population as a whole, including wasted or discarded parts at the retail and domestic level. We considered that national data on food consumption could be appropriately applied to each regional unit, as confirmed by more detailed inquiries on dietary habits in France (INCA 2, 2009), which also provide figures of effective ingestion. The conversion coefficients used to translate consumption figures in fresh weight of each food item into C, N, and P were taken from several databases and are provided in Supplementary material (SM1, Section 2). Human excretion and waste production were assumed to be equal to consumption. Waste recycling through the application of wastewater treatment plant sludge or solid waste composts to agricultural land was estimated from the French Ministry of the Environment, Energy and the Sea (MEEM, 2002) (see SM1, Section 5).

2.3. Livestock metabolism

The livestock production for 2006 is provided by national agricultural statistics (Agreste, 2006) in terms of fresh weight units. Milk and egg production in terms of N, P, and C were calculated from these figures, using the conversion coefficients provided in SM1 (Section 3).

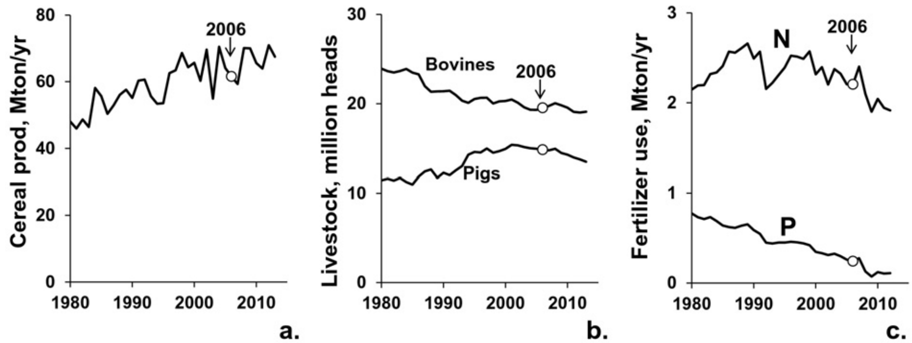


Fig. 1. Evolution of: a. total cereal production (mega-tons/yr), b. number of livestock (10^6 head/yr) and, c. N and P synthetic (mega-tons N and P/yr) fertilizers for the 1980–2013 period in France.

Meat production, provided by the statistics in terms of carcass weight, were broken down into edible and inedible production, the latter including the unavoidable losses occurring at the slaughter and cutting stage (Benhalima et al., 2015). The detailed hypothesis, calculation and coefficients used are described in SM1 (Section 3).

Total excretion was calculated from livestock numbers using N and P emission factors specific to each age class of each animal category (see SM1, Section 3). Note that we defined a livestock unit (LU) as the number of animals of any species annually excreting 85 kgN/yr, as previously adopted by Billen et al. (2014). In the case of N, a certain percentage of the N embedded in the excreted manure is lost by direct volatilization in the form of ammonia depending on manure management (farmyard manure, slurry, or direct excretion while grazing). Data on manure management practices for each animal category at the NUTS 3 level as well as volatilization coefficients from manure, slurry and direct excretion at different stages (indoor, storage and spreading on field) were taken from the Commissariat Général au Développement Durable (CGDD, 2013). The C content of manure and slurry was calculated from their C/N ratio for different animal categories as provided by MEEM (2002) taking into account gaseous losses and/or C straw addition during processing. Regarding P content in excretion, it was assumed that no loss occurred between excretion and application of manure to the soil.

Total ingestion in terms of N and P was defined as the sum of the total production and total excretion. In terms of C, since a large part of the C ingested is emitted as CO_2 through respiration, this approach could not be used and the amount of C ingested was calculated from the corresponding N figure by applying the C/N ratio in animal feed, specific for each agricultural region (see below). The livestock conversion efficiency (vegetal to animal product conversion, based on N, P or C) was calculated as the ratio of edible production to ingestion.

2.4. Crop- and grassland fertilization

Fertilization refers here to all inputs of N and P to cropland and permanent grassland including synthetic fertilizers, atmospheric deposition, manure and urban sludge application and symbiotic N_2 fixation. Inputs of organic carbon were taken into account by C captured through photosynthesis and returned to the soil after harvest as crop or root residues, or brought with manure and urban sludge.

N and P synthetic fertilizer application rates were taken from Unifa (2016) (Union des Industries de la Fertilisation) at the administrative regional scale for 2006. The partition from administrative to agricultural regions, and between cropland and permanent grassland was calculated based on specific data on cropland and grassland fertilization provided by CGDD (2013) and Agreste (2006) (see SM1 Section 5). A fraction of N embedded in synthetic fertilizers was considered as lost by ammonia volatilization depending on the form of fertilizers (e.g., ammonium nitrate, urea, NPK compound fertilizers, etc.). N volatilization coefficient data from synthetic fertilizer application on a regional scale (NUTS 2) were taken from CGDD (2013).

For atmospheric deposition, we used the values provided by the European Monitoring and Evaluation Programme (EMEP, 2016) and by Némery and Garnier (2007), respectively, for N and P deposition, assuming deposition rates to be evenly distributed across landscapes and geographical areas (see SM1, Section 5).

N, P, and C inputs through urban sludge spreading were estimated from data provided by MEEM (2002), assuming fixed values for their content in urban sludge, and distributed between regions pro rata to their urban population (see SM1, Section 5).

Symbiotic N_2 fixation was estimated according to the relationships developed by Anglade et al. (2015b) linking N fixation to yields for forage and grain legumes. For permanent grassland, we assumed legumes to be responsible for 25% of the total production.

C inputs from crop residues were deduced for 36 crop categories from their harvest indexes (HI) provided by Guzmán et al. (2014), who characterized the harvested fraction with respect to the total aboveground production. In the case of straw cereals, as the HI refers to grain, the harvested straw was subtracted from the inputs to soil corresponding to the straw actually exported. Similarly, C inputs from roots were calculated by applying their root/shoot ratio (Guzmán et al., 2014), characterizing the underground production with respect to aboveground production. Details of the calculation are provided in SM1 (Section 4).

N, P, and C inputs to the soil as animal manure were calculated in the following way. Knowing the total nutrient content after volatilization and according to manure management practices, we assigned N, P, and C in the excreted manure either to the managed stock (i.e., emitted indoor) or to direct excretion on temporary or permanent grasslands while grazing, depending on the fraction of time spent indoors specific to each of the four animal categories. We assumed that the excreted manure while grazing was allocated between temporary and permanent grasslands in proportion to their respective surface areas. The managed manure was assumed to be evenly distributed on cropland (thus including temporary grassland) (see SM1, Section 6.3).

2.5. Cropland and grassland harvested (or grazed) production

Crop- and grassland production are taken as the mass harvested (or grazed) provided by Agreste in wet weight or dry weight, at the *département* scale for the year 2006. Vegetal production was converted from mass unit to ktN/yr, ktP/yr and ktC/yr based on coefficients gathered in SM1 (Section 4) for 36 categories of vegetal products (For N and P contents: Lassaletta et al., 2014a, compiling FAO data; for C: Guzmán et al., 2014; Niedertscheider et al., 2016).

2.6. N, P, and C budget in cropland and grassland

The GRAFS approach quantifies the annual N, P, and C budget between inputs to soil and output through harvest. For N, inputs include N-synthetic fertilizers and N in manure after all NH_3 volatilization has occurred, N contained in sludge, symbiotic N fixation by legumes, and N atmospheric deposition. N surplus was defined as the sum of these N inputs minus N output through crop harvesting. The N surplus represents a potential for losses from the soil to the environment, either as N_2, N_2O, and NO emissions essentially owing to denitrification, or as N leaching for a major amount (Benoit et al., 2015); part of the N surplus can also be stored in the SOM pool.

The annual soil P budget was calculated using a similar approach accounting for P inputs through manure, sludge, synthetic fertilizers, and atmospheric deposition, and P output through harvest. Contrary to N, P tends to accumulate in soils because P is strongly adsorbed onto soil particles, therefore lixiviation is not significant. A positive P budget would thus indicate potential P accumulation in soils and possible subsequent P losses through erosion. A negative P budget would indicate P removal from the soil (Bouwman et al., 2013; Garnier et al., 2015).

By analogy, the annual C budget could be established as the difference between net primary production (including underground parts and residues) and harvest. However, most of inputs are mineralized in less than 1 year, before being really incorporated into the different SOM pools. The budget of *efficient* organic carbon (OC_{eff}) inputs was therefore considered more relevant. Efficient C input is defined as the fraction of fresh material (including crop residues, manure and sludge) added to soil remaining after 1 year (Soltner, 2005; Sleutel et al., 2006, 2007) and was estimated using humification coefficients reported in the literature, ranging from 0.08 to 0.2/yr depending on the type of material and the type of soil (see SM1, Section 4).

2.7. Allocation of local production: internal flows and extraregional exchanges

To keep all nutrient flows consistent with each other, allocation of the agricultural production was first established in terms of N flows and then translated into P and C flows based on the C/N and P/N ratios of grassland and crop production. These ratios varied across regions depending on the dominant types of crop and animal production (see SM2). For each region, the import and export of animal feed were obtained from the complete matrix of the fluxes of agricultural commodities exchanged between the 33 French agricultural areas established by Le Noë et al. (2016) from the analysis of the SitraM (2006) database on commodity transport of the French Ministry of Environment and according to Silvestre et al. (2015).

Considering local human consumption as the most essential function of local agricultural production, we assumed vegetal and livestock production to be largely dedicated to meeting the local human demand. If the local vegetal or animal production was not sufficient to feed the local population, the gap was then assumed to be filled by importation from foreign regions. In this case, we subsequently examined whether crops and vegetables or meat and dairy product imports, as provided by the analysis of the SitraM database, were coherent with the population's requirements. In a similar way, the livestock was assumed first to be fed by direct grazing or by grass as silage or hay from local grassland production, and by net feed imports, as provided by SitraM. If the livestock N requirement was not entirely met by these two local and imported sources, then the remaining animal needs were considered to be completed at the expense of local cropland production not already dedicated to the local population. The remainder of local crop production was considered exported outside the region. The coherency of these estimations was checked by comparing the calculated fluxes of import or export to or from each agricultural region with the fluxes recorded in the SitraM database (see SM1, Section 7).

When N flows were translated in terms of P, it often occurred that the livestock P demand was not met; this discrepancy between N and P budgets is based on the differences in the N:P ratio of vegetal and animal biomass. We assumed this gap to be filled by imports of feed additives used in livestock nutrition. Mineral additives, including phosphates, are indeed regularly used in livestock feeding, as indicated by feeding recommendations (Meschy and Ramirez-Perez, 2005; Soltner, 2008; Agreste, 2014). Meschy and Ramirez-Perez (2005) suggested that 20 to 40% of the P requirement for a suckler cow should be provided through mineral P additives, either directly or incorporated in feed compounds. According to Senthilkumar et al. (2012), mineral P feed accounts for as much as 42% of the total P import through food and feed in France.

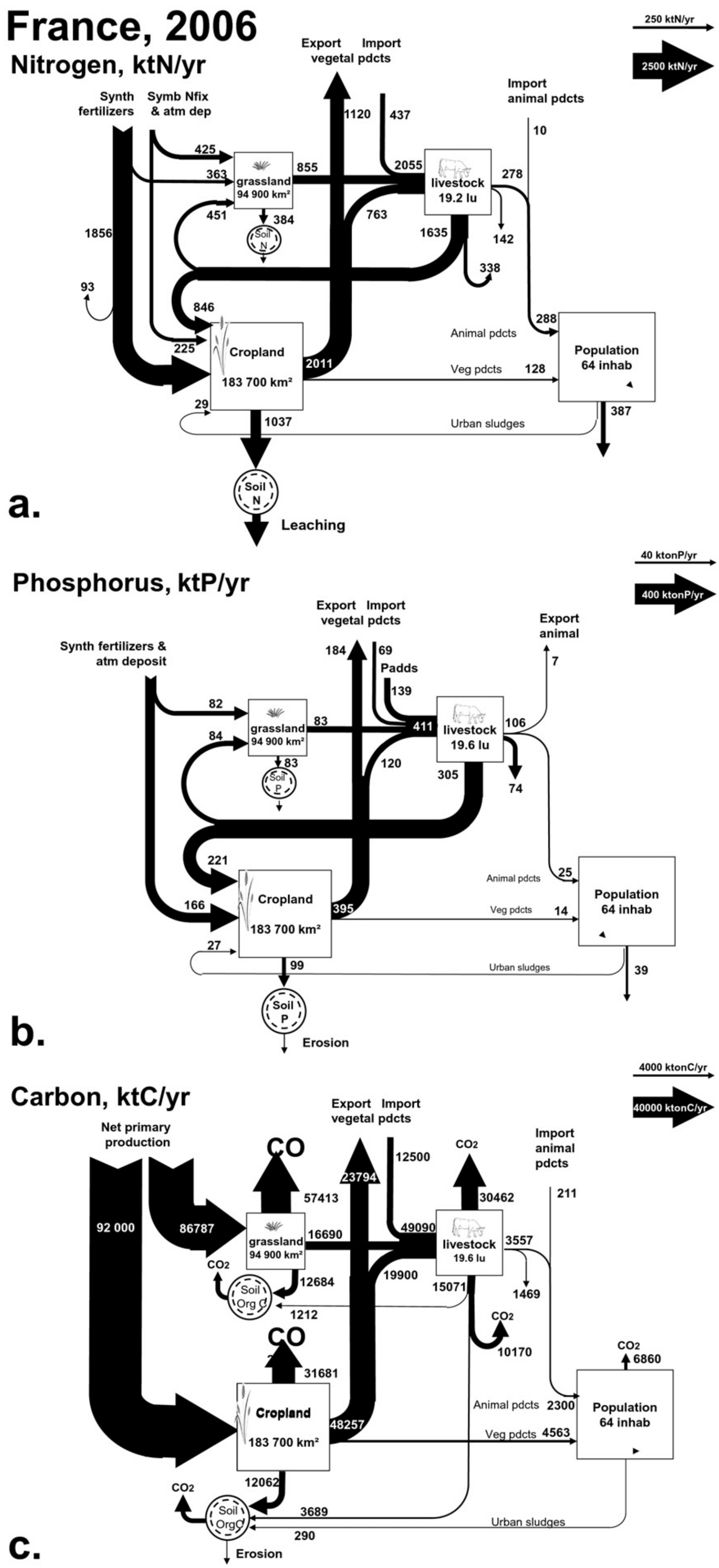
2.8. N and P imprints of agricultural production

Once assembled into a coherent representation of the agro-food system, the GRAFS data can assess the agronomical and environmental performance associated with a certain type of production pattern, in terms of the resources required and the environmental nutrient losses. From a regional perspective (the scale of agricultural areas as described above and in line with the definition provided by Buclet et al., 2015), the environmental imprint of agricultural production was expressed pro rata to the surface of crop- and grassland, i.e., in kgN and kgP per hectare and per year. To assess the N and P resources and the losses attributable to regional production, not only those associated with direct inputs (synthetic fertilizers, N symbiotic fixation, atmospheric deposition, sludge) must be accounted for, but also those related to the fraction of imported feed ending up as manure applied on cropland and grassland. The latter are referred as *new* N and P in manure. To calculate this, the manure fraction derived from local crop and grass ingestion by livestock was excluded from the calculation, given that it represents internally recycled nutrients.

With regard to agronomic performance, resource consumption and environmental losses were expressed per unit of vegetal and animal production, which required partitioning resource consumption and environmental losses between animal and vegetal production, respectively. We considered resource consumption and environmental losses attributable to crop production to be prorated to the proportion of crop production that was not dedicated to local livestock, i.e., production exported from the region or directly dedicated to the local population. Once the vegetal production imprint had been calculated, the animal production imprint was deduced by subtracting resource consumption and environmental losses attributable to vegetal production from the total resource consumption and environmental losses within the agro-food system on the regional scale. The details of the calculations carried out to calculate the inputs of new resources and nutrient losses attributable to crop and livestock production, respectively, are provided in detail in SM1, Section 8.

2.9. Accuracy of the results and uncertainty analysis

As discussed by Oenema et al. (2003), uncertainties in the model results may originate both from structural uncertainties about the construction of the model itself and from operational uncertainties in the data and parameters. Structural uncertainties concern the rules for allocating nutrients flows between arable land, grassland, livestock and human population pools. As an example, the simplifying assumptions regarding the order of preference for allocating arable crop production to local human consumption or livestock feeding make logical sense but would require empirical investigation, and might be a source of bias in our results. For instance, the part of the arable crop production allocated to local human population or livestock could be possibly exported, and local human population or livestock could be fed with more imported vegetal products than estimated with the GRAFS approach. It is rather difficult to quantitatively assess this kind of uncertainty.


France, 2006
Nitrogen, ktN/yr
250 ktN/yr
2500 ktN/yr
Export Import
vegetal pdcts
Import
animal pdcts
Synth
fertilizers
Symb Nfix
& atm dep
1120
437
10
425
363
855
2055
278
grassland
94 900 km²
livestock
19.2 lu
451
384
763
1635
142
1856
Soil
N
338
93
846
288
Animal pdcts
225
Cropland
183 700 km²
2011
Population
64 inhab
Veg pdcts
128
29
1037
387
Urban sludges
Soil
N
Leaching
a.
40 ktonP/yr
400 ktonP/yr
Phosphorus, ktP/yr
Export Import
vegetal pdcts
Export
animal
Synth fertilizers &
atm deposit
184
69
7
Padds
139
82
grassland
94 900 km²
83
411
livestock
19.6 lu
106
84
83
120
305
Soil
P
74
221
Animal pdcts
25
Cropland
183 700 km²
395
Population
64 inhab
166
Veg pdcts
14
27
99
Urban sludges
39
Soil
P
Erosion
b.
4000 ktonC/yr
40000 ktonC/yr
Carbon, ktC/yr
Export Import
vegetal pdcts
Net primary
production
CO
23794
12500
CO2
Import
animal
pdcts
57413
30462
211
92 000
86787
grassland
94 900 km²
16690
49090
livestock
19.6 lu
3557
CO2
12684
19900
15071
1469
Soil
Org C
1212
CO2
CO
10170
CO2
6860
31681
Cropland
183 700 km²
48257
Animal pdcts
2300
Population
64 inhab
Veg pdcts
4563
CO2
12062
3689
Soil
Org C
Urban sludges
290
Erosion
c.

On the other hand, to assess operational uncertainties, we used the Monte Carlo method to generate random samples of values for each primary data (such as animal production in kton carcass or atmospheric deposition) and each parameter (such as %N of each crop or animal product), considering their own level of uncertainty. We considered that primary data such as surface area, crop and animal production figures, originating from official agricultural census are known within a confidence interval of 1, 5 and 15% respectively; data from other sources with 5 to 20% uncertainty. Accuracy of the parameters was estimated between 10 and 30% depending on the source of information. Model intermediate variables (such as vegetal or animal production in N, P or C) and outputs (such as N or P surpluses) were computed in accordance to the Monte Carlo simulation of the primary data (Loucks et al., 2005). We thus generated a distribution of the main variables and outputs of the model by bootstrapping the Monte Carlo simulation with replacement (1000 replicates). The uncertainty for each variable and parameter were given by the standard error of the mean of the 1000 replicates. All statistical analyses were performed using Microsoft Excel and associated VBA macros.

3. Results and discussion

The GRAFS analysis, as described above, provides a comprehensive picture of the N, P, and C fluxes across the agro-food system of each of the 33 regions considered in France in 2006, a year that can be considered reasonably representative of the situation of French agriculture during the first decade of the 21st century (Fig. 1). The detailed account of these fluxes is shown in the Excel file provided in SM2. The interconnection of these fluxes is represented at the scale of all of France for N, P, and C (Fig. 2a–c). These data can be used to highlight various aspects of the biogeochemical functioning of the agro-food system, including soil nutrient budgets and their environmental consequences. It can also distinguish different patterns of production systems among the regional units and assess their agronomical and environmental performance.

3.1. Soil nutrient budget

3.1.1. Nitrogen

N surplus in cropland (after N-NH_3 volatilization had occurred) ranged from 16 (±2.0) to 171 (±26) kgN/ha/yr, showing the large variability in N use across the 33 French agricultural regions (Fig. 3a). Empirical data demonstrate that N surplus in cropland is a robust indicator of N losses, mostly through lixiviation, which generally accounts for 30–80% of losses (Billen et al., 2013a; Anglade, 2015c), leading to ground- and surface water contamination and coastal eutrophication (Passy et al., 2016). Generally the highest N surplus over cropland was found in regions with high livestock density (e.g., Brittany, Loire Aval). Regions showing high N inputs and high crop production, such as Champagne-Ardenne-Yonne, Nord-Pas-de-Calais, and Eure-et-Loire, did not show very high surplus values.

Nitrogen surplus for grassland ranged from 8.3 (±0.8) to 108 (±22) kgN/ha/yr (Fig. 3b), but unlike in cropland, N surplus in grassland does not result in high leaching below a threshold of about 100 kgN/ha/year (Watson and Foy, 2001; Billen et al., 2013a). Accordingly, the surplus observed in grassland might not be necessarily viewed as indicating a negative environmental impact. In some cases it is indeed likely to increase the SOM level. High surplus on grassland reflected a mismatch between grazing intensity and grassland surfaces, leading to overfertilization of N from animal excretion in excess over grass production (e.g., in Brittany).

Ammonia emission is the second leading pathway of environmental N losses from agricultural areas (Fig. 3c). Ammonia volatilization owing to synthetic fertilizer application in regions dominated by crops, and to animal excretion depending on livestock density, were counted together, although the proportion of both emission pathways greatly differed between regions. Ammonia losses from N synthetic fertilizer volatilization reached 83% of emissions in Ile-de-France, while 95% originated from manure management in Brittany. However, it is notable that the highest NH_3 emissions rose from regions with important livestock density and where animal excretion is stored and transformed into manure or slurry. NH_3 emissions thus primarily reflected manure management and livestock density.

3.1.2. Phosphorus

On cropland, the P budget ranged from −6.4 (±2.5) to 41 (±6.6) kgP/ha/yr, showing large disparities between regions (Fig. 3d). Extreme P budget values resulted from an imbalance between P inputs to the cropland and P uptake by crop. In the case of P-removing regions (e.g., in the central Paris basin), the imbalance resulted from very intensive crop production with inputs of P fertilizers lower than the requirements of crop growth. As discussed by Senthilkumar et al. (2011) and Garnier et al. (2015), this is made possible without severe crop growth limitation owing to the legacy of huge accumulated stocks of P resulting from past excessive P fertilization. The rate of P application to cropland in these regions has indeed been reduced by a factor of 3.5 since the 1970s (Unifa, 2016). By contrast, regions presenting the highest P accumulation in cropland also had significant mismatches between herd size and cropland area (e.g., Brittany). The positive P budget in these regions should be attributed to the very high inputs of P on cropland through manure application that is not absorbed by crops.

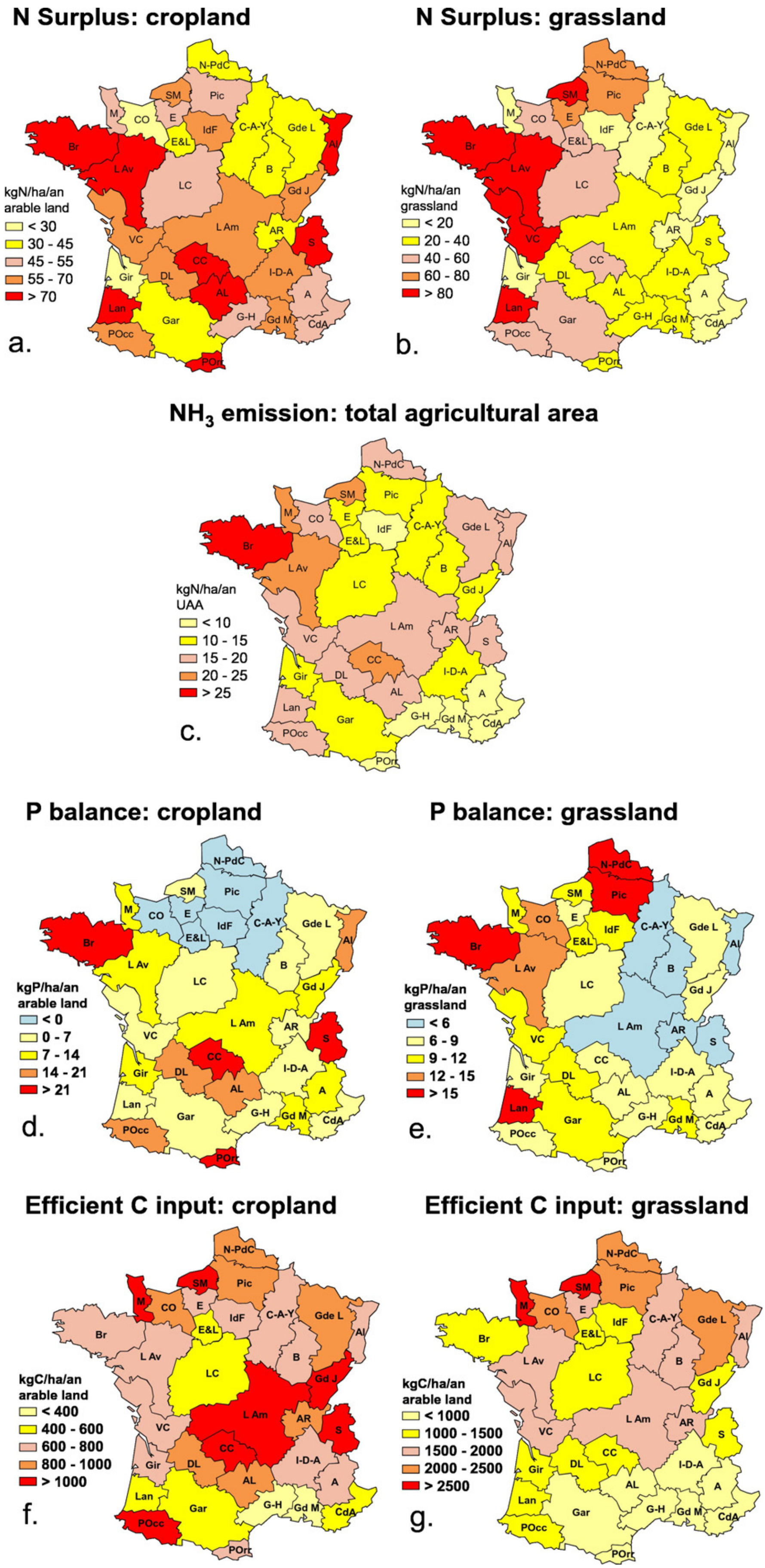
Very high P accumulation rates (together with high N surplus) were also observed in regions such as Cantal-Corrèze, Savoie and Pyrénées Orientales with intermediate herd size, but a very low arable land proportion of the total agricultural area (Fig. 3e). In these regions, the fertilization of cropland with manure produced during the period of livestock in barn stay is in large excess over the requirements of a rather low crop production.

The phosphorus budget in grassland, with much lower variability, ranged from 3.8 (±2.7) to 22 (±4.6) kgP/ha/yr. It is notable that the Picardie and Landes regions showed the highest positive P budget in grassland, whereas their P budget in cropland was among the lowest (Fig. 3d and e). This result could reflect an artifact due to the very small grassland areas of these regions. The remaining regions, with a quite high P budget, were characterized by high livestock density; therefore P accumulation on grassland was due to an excess of P inputs through direct excretion, which would also be in excess if recycled on cropland due to high livestock density. This is in accordance with the study reported by Sharpley et al. (2007), which reported that regional specialization patterns and intensification of livestock production led to reduced opportunities for P recycling over the surrounding cropland. The transfer of fertility from grassland to crop land (Ohm et al., 2015; Barataud et al., 2015; Sattari et al., 2016) can be illustrated here at the regional scale (e.g., Loire Amont, Alsace, and Cantal-Corrèze) where P accumulation on cropland is higher than on grassland with a similar fertilizer input. This probably resulted from higher export of P through cattle grazing than P inputs through direct excretion, implying a P transfer from grassland to cropland through manure application.

3.1.3. Carbon

A large number of studies indicate that SOC content at steady state is controlled by OC_{eff} inputs (Jenkinson and Rayner, 1977; Kong et al.,

Fig. 2. Representation of nitrogen (a), phosphorus (b) and carbon (c) fluxes, expressed in kt/yr at the national scale for France in 2006. Squares represent transformation processes occurring in the corresponding environmental compartments. The width or black arrows are proportional to the intensity of the fluxes involved in these processes. Circles represent storage pools of N, P or C in the soil compartments; the dotted circle figures the initial state, the solid circle the final stage.


N Surplus: cropland
kgN/ha/an
arable land
< 30
30 - 45
45 - 55
55 - 70
> 70
a.
N Surplus: grassland
kgN/ha/an
grassland
< 20
20 - 40
40 - 60
60 - 80
> 80
b.
NH3 emission: total agricultural area
kgN/ha/an
UAA
< 10
10 - 15
15 - 20
20 - 25
> 25
c.
P balance: cropland
kgP/ha/an
arable land
< 0
0 - 7
7 - 14
14 - 21
> 21
d.
P balance: grassland
kgP/ha/an
grassland
< 6
6 - 9
9 - 12
12 - 15
> 15
e.
Efficient C input: cropland
kgC/ha/an
arable land
< 400
400 - 600
600 - 800
800 - 1000
> 1000
f.
Efficient C input: grassland
kgC/ha/an
arable land
< 1000
1000 - 1500
1500 - 2000
2000 - 2500
> 2500
g.
N-PdC
SM
Pic
M
CO
E
E&L
IdF
C-A-Y
Gde L
Al
Br
L Av
LC
B
Gd J
L Am
AR
S
VC
CC
DL
AL
I-D-A
Gir
A
Lan
Gar
G-H
Gd M
CdA
POcc
POr

2005; Sleutel et al., 2006, 2007; Vitro et al., 2012; Chenu et al., 2014), although humus mineralization is also dependent on climatic conditions as well as the soil's biophysical features and management (Stockmann et al., 2013). However, the quite recent emergence of a soil C saturation concept as a limit above which SOC can become saturated (Stewart et al., 2007) has led to re-examining the paradigm that prevailed before, e.g., a linearity between C input levels and C stocks at steady state (as first proposed by Jenny, 1941), implying that SOC content could continuously increase with increasing OC_{eff} inputs. Since concepts such as “maximum C sequestration” or “effective stabilization capacity” are still under debate (Six et al., 2002; Stewart et al., 2007; Schmidt et al., 2011), we considered OC_{eff} inputs to be a good proxy for potential additional storage assuming that croplands are, in most cases, far from their C saturation limit and have not yet reached their steady state. This assumption is in line with the results from the Rothamsted long-term experiment, which showed that even after 150 years of identical agricultural practices; soil C stocks have not yet reached their steady state (Jenkinson and Rayner, 1977).

Carbon efficient inputs mainly depend on the type of crop roots and residues returning to the soils, crop productivity, and manure management. Regions with substantial manure spreading over cropland but average crop production (e.g., Loire Amont, Cantal-Corrèze) had the highest scores of C efficient inputs (Fig. 3f). Regions with intermediate C efficient inputs to cropland were mostly characterized by low manure supply and high crop productivity (e.g., Ile-de-France, Loire Centrale, Eure) or the reverse (e.g., Brittany, Loire Aval). A recent study by Tosser et al. (2014) reported a positive progression of SOC stocks in croplands in France over the 1990–2010 period; this supports the idea that cropping systems keep accumulating C in France. If this remains true at the regional scale, regions with the highest OC_{eff} inputs are likely to enhance their SOC stocks at best. At the national level, C efficient inputs derived from crop residues were on average three times as large as inputs derived from animal excretion. However, the latter varied much more (84% variation coefficient around the mean value) than the former (34% variation). This indicates that crop residue efficient inputs to the SOM pool are crucial, but the quantity and quality of animal excretion management are also very influential for potential C storage improvement, as highlighted by Vleeshouwers and Verhagen (2002) and Kong et al. (2005).

Carbon efficient inputs on grassland were much higher than on cropland (Fig. 3g). This is coherent with the study by Soussana et al. (2004), who demonstrated that grassland soil always behaves as a C sink. In the case of grassland, OC_{eff} inputs mainly reflected the grassland productivity; indeed, OC_{eff} inputs derived from plant residues accounted for, on average, 91% of the total efficient inputs.

3.2. A typology of production patterns

The analysis of the data provided by the GRAFS approach on a regional scale highlights the various production patterns characterizing the different agricultural systems in France. A typology was established based on the N fluxes, although the following analysis also accounted for P and C management in each of the typical regions defined and will subsequently be discussed as well. The establishment of a typology of agricultural regions implies the introduction of criteria and thresholds that necessarily involved arbitrariness, yet such an approach has the benefit of providing clearer insight into the diverse types of production patterns. Fig. 4a represents the decision tree leading to the proposed typology represented in Fig. 4b and discussed hereafter.

3.2.1. Specialized crop farming regions

Regions with stocking density below 0.5 livestock units per hectare of utilized agricultural area (LU/UAA) were considered marginal for their animal husbandry activity and were defined as specialized in crop production. These crop farming regions were further discriminated based on their production per hectare taking a threshold of 100 kgN/ha/year, thus distinguishing intensive specialized crop farming regions from extensive ones (Fig. 4b). More specifically, yields clearly differed between the two regions, reaching average production of 120 ($\pm$4.7) and 83 ($\pm$7.5) kgN/ha/yr, respectively.

3.2.2. Livestock farming regions

Conversely, the regions with stocking density above 0.5 LU/UAA were considered as areas with substantial breeding activity. From this, three agricultural patterns were distinguished based on their feeding practices.

First, the share of grass in total ingestion is indicative of the adequacy between livestock size and available grassland surface for cattle grazing. At the regional scale, grass feeding was estimated from the permanent grassland production (SM1, Sections 4 and 7). We denominated regions where livestock is fed by more than 60% grass as “extensive mixed crop and livestock farming” regions, assuming this threshold to fairly discriminate between intensive and extensive breeding systems. The “extensive mixed crop and livestock farming” regions are also characterized by very low recourse to importation to support their cattle production. With the exception of Cantal-Corrèze, Calvados-Orne, Savoie and Loire Amont, which feed their livestock with 21, 16, 11, and 9% of imported feed, respectively, all other “extensive mixed crop farming” regions imported less than 2% of feed consumption.

Second, the share of animal feed import was considered to reflect the level of specialization in a livestock production region and, accordingly, to reveal the degree of disconnection of its livestock and crop farming and its dependency on foreign production to sustain livestock. In line with this last criterion, we made a distinction between regions relying on importation for more or less than 50% of their livestock N-protein requirements. The latter were defined as “intensive mixed crop and livestock farming” regions, since cattle are fed with less than 60% N ingested on permanent grassland but imports are kept below 50% of their diet. In other words, the cattle breeding system of these regions is often close to self-sufficient, but local crop production is needed to sustain the livestock since between 27 and 70% of the local crop production is used as feed. Finally, the agricultural regions whose livestock is fed for less than 60% through grassland grazing and more than 50% through imported feed were grouped in the type called “intensive specialized livestock farming.” This typology of agricultural production patterns based on N fluxes can be compared with the one by Ryschawy et al. (2015) who proposed an interesting typology of animal breeding practices based on the analysis of ecosystem services with a similar scale resolution in France. The five regions grouped together in their study superimposed rather well onto the types of regions we defined in the present study, suggesting that production patterns we defined on a biogeochemical basis could be linked with certain ecosystem services as described by these authors.

3.3. Coherency between production and trade patterns

The classification of regions based on their production patterns led to the definition of five types of agricultural region, with distinct regional N metabolism. Fig. 5(a–f) shows the representation of N, P, and C

Fig. 3. Distribution across the 33 French agricultural areas of (a) N surplus for cropland (kgN/ha/yr); b. N surplus for grassland (kgN/ha/yr); c. NH_3 emissions for utilized agricultural area accounting for NH_3 emissions derived from livestock manure and synthetic fertilizer spreading (kgN/ha/yr); d. P budget in cropland (kgP/ha/yr); e. P budget in grassland (kgP/ha/yr); f. OC_{eff} inputs to cropland (kgC/ha/yr); g. OC_{eff} inputs to cropland (kgC/ha/yr). A: Alpes; Al: Alsace; AL: Aveyron-Lozère; AR: Ain-Rhône; B: Bourgogne; Br: Bretagne; C-A-Y: Champagne-Ardennes-Yonne; CC: Cantal-Corrèze; CdA: Côte d'Azur; CO: Calvados-Orne; DL: Dordogne-Lot; E: Eure; E&L: Eure-et-Loire; Gar: Garonne; Gd J: Grand Jura; Gd M: Grand Marseille; Gde L: Grande Lorraine; G-H: Gard-Hérault; Gir: Gironde; I-D-A: Isère-Drôme-Ardèche; IdF: Ile de France; L Am: Loire Amont; L Av: Loire Aval; Lan: Landes; LC: Loire Centrale; M: Manche; N-PdC: Nord Pas-de-Calais; Pic: Picardie; Pocc: Pyrénées Occidentales; POr: Pyrénées Orientales; S: Savoie; VC: Vendée-Charentes.

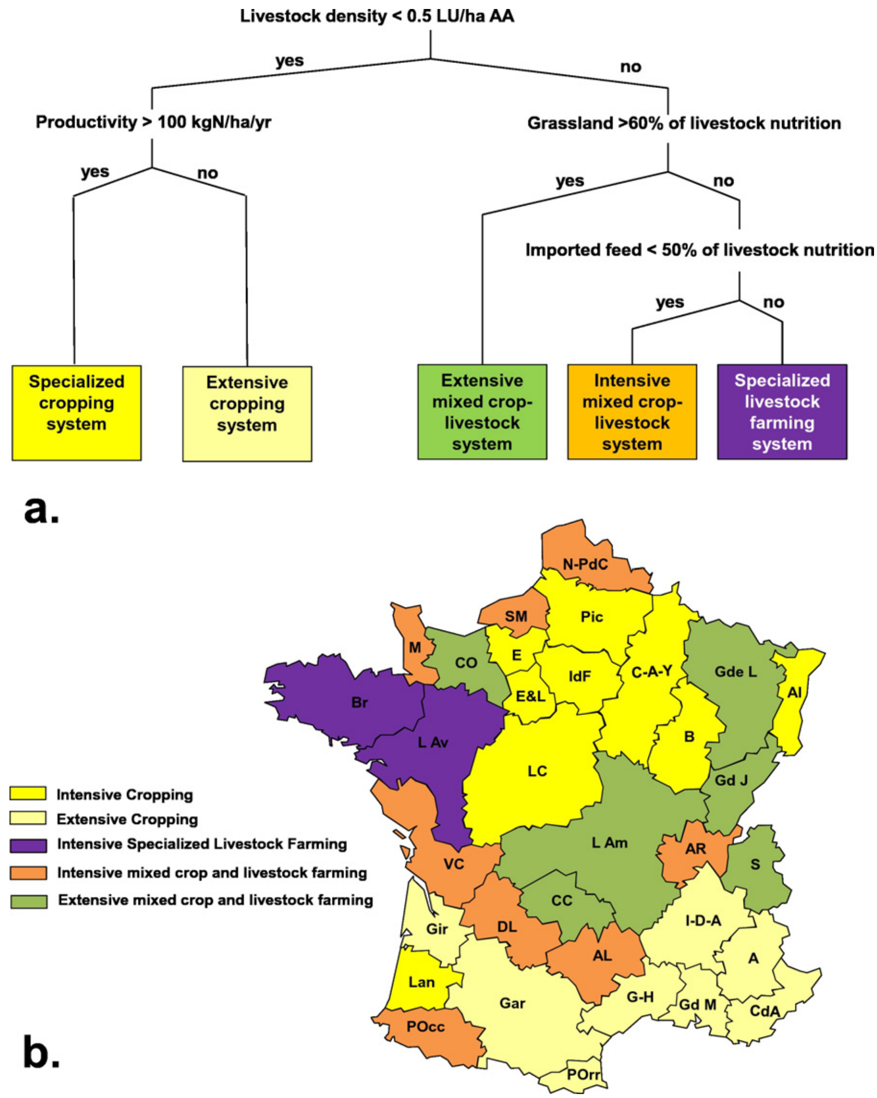


Fig. 4. a. Decision tree for the establishment of the typology of the main representative agricultural systems in France. b. Spatial distribution of the five main representative agricultural systems as defined according to the criteria set out in Fig. 4a, the French regions on the map are those defined by Le Noë et al. (2016).

flows through the agro-food system of two of the five typological zones defined for France (See SM3 for the three remaining agricultural patterns). These different production patterns are also associated with different trade patterns (see SM2 and SM3).

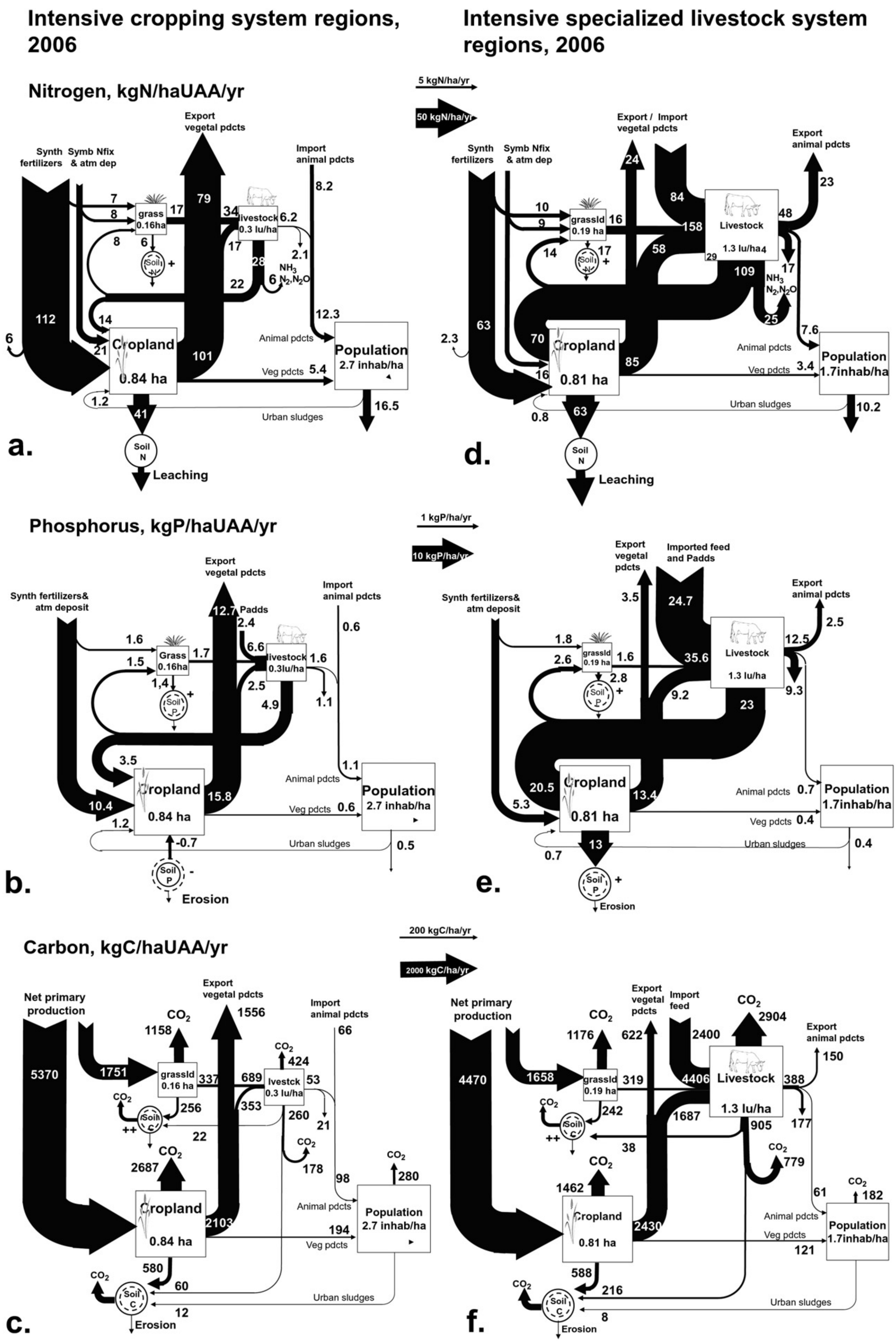
Regions characterized by an "intensive cropping" system and "intensive specialized livestock farming" patterns represent two extremes of agricultural specialization. Both are very productive and highly involved in agricultural trade. The so-called "specialized intensive livestock farming" areas were the largest net exporters of animal products with 91 ($\pm$9.0) ktN/yr of edible products. However, the "intensive specialized livestock farming" regions imported much more in vegetal products (net import of 233 ($\pm$23) ktN/yr), mainly from South American countries. Conversely, the "intensive cropping" regions together exported massive amounts of vegetal products (net export of 646 ($\pm$29) ktN/yr), but imported a high quantity of animal products (net import of 67 ($\pm$4.5) ktN/yr of edible products).

Regions defined as "extensive cropping" systems constituted an intermediate type of trade pattern: although the production regime was far less intensive, the specialization was nonetheless high. Consequently, all regions included in this production pattern were net exporters of vegetal products (83 ($\pm$10) ktN/yr), but net importers of animal products (48 ($\pm$1.9) ktN/yr of edible products).

Finally, regions of "intensive mixed crop and livestock farming" and "extensive mixed crop and livestock farming" systems can be distinguished by a lower degree of specialization: they were net exporters of vegetal and animal proteins. Net exportation of vegetal products confirmed their autonomy for livestock production.

Analyzing the agricultural trade patterns in French regions in light of the various production patterns revealed the influence of regional specialization over the shape of agricultural trade. In that respect, the case of France is very similar to the global trend of growth in international trade of agricultural products promoted by increasing concentrations

Fig. 5. Representation, in 2006, of the N, P, and C fluxes across the agro-food system, expressed in kg per ha of utilizable agricultural area of (a, b, c) the "intensive cropping" system region and (d, e, f) the "intensive specialized livestock" system. Squares represent transformation processes occurring in the corresponding environmental compartments. The width or black arrows are proportional to the intensity of the fluxes involved in these processes. Circles represent storage pools of N, P or C in the soil compartments; the dotted circle figures the initial state, the solid circle the final stage.


Intensive cropping system regions, 2006
Intensive specialized livestock system regions, 2006
Nitrogen, kgN/haUAA/yr
5 kgN/ha/yr
50 kgN/ha/yr
Synth fertilizers
Symb Nfix & atm dep
Export vegetal pdcts
Import animal pdcts
Export / Import vegetal pdcts
Export animal pdcts
grass 0.16ha
livestock 0.3 lu/ha
grassld 0.19 ha
Livestock 1.3 lu/ha
Soil N
NH_3 N_2,N_2O
Cropland 0.84 ha
Cropland 0.81 ha
Population 2.7 inhab/ha
Population 1.7inhab/ha
Animal pdcts
Veg pdcts
Urban sludges
Leaching
a.
d.
Phosphorus, kgP/haUAA/yr
1 kgP/ha/yr
10 kgP/ha/yr
Synth fertilizers& atm deposit
Imported feed and Padds
Padds
Grass 0.16ha
livestock 0.3lu/ha
Soil P
Erosion
b.
e.
Carbon, kgC/haUAA/yr
200 kgC/ha/yr
2000 kgC/ha/yr
Net primary production
Import feed
CO_2
grassld 0.16 ha
lvestck 0.3 lu/ha
Soil C
c.
f.

of livestock production and the subsequent decoupling between livestock and feed production (Schipanski and Bennett, 2002; Lassaletta et al., 2014a, 2014b).

3.4. Environmental and agronomical performance of production patterns

3.4.1. Environmental performance

The production patterns observed in the five typological regions were also associated with differing environmental effects in terms of the N and P resources mobilized, with P and C stored in the soil and N lost to the atmosphere and the hydrosphere. Table 1 illustrates the value of these environmental indicators expressed per hectare of crop- and grassland, inferring the environmental performance from a regional perspective. Looking first at the environmental imprint for crop production, it appears that regions included in the “intensive cropping” system type were by far the largest consumers of N and P synthetic fertilizers (133 (±6.5) kgN/ha cropland/yr and 13.3 (±1.1) kgP/ha cropland/yr). The large quantity of synthetic fertilizers in this type of region came from the almost total lack of organic inputs combined with the high demand for N and P to support the high productivity of cropland with high nutrient use efficiency, leading to intermediate N surplus and negative P budget (56.2 (±8.5) kgN/ha cropland/yr and −0.85 (±0.90) kgP/ha cropland/yr). Furthermore, the negative P budget in cropland indicates that some regions with this production pattern have begun to mine their soil P reserve. The opposite pattern occurred in “specialized intensive livestock farming” systems where the use of synthetic fertilizers over cropland was among the lowest, but the *new* N and P inputs through manure application (as defined above) were the highest. Lower crop production, however, led to an imbalance between total N and P inputs and outputs, resulting in the highest N surplus and P budget (77 (±10) kgN/ha cropland/yr and 16.1 (±2.3) kgP/ha cropland/yr). Both “mixed crop and livestock farming” systems presented intermediate trends, since these types of region had intermediate N and P inputs and budgets over cropland. It is remarkable that for N, synthetic fertilizers remained the largest input (about 50% of total N inputs in both systems), while P input through manure was the largest contributor to cropland fertilization (more than 60% in both systems). Finally, the lowest total N and P inputs and budgets were found in “extensive cropping” systems. This result is consistent with the extensive and specialized nature of this system, marked by a quasi-absence of organic fertilizers and low synthetic fertilizer leading to very moderate surplus.

The environmental imprint regarding grassland production followed similar trends to that described above for cropland. The main difference was the far larger contribution of N fixation for grassland fertilization (between 18 and 28% of the total N inputs) than for cropland (between 2 and 13% of the total N inputs).

Overall, we showed that, from a regional point of view, “specialized agricultural systems” (either cropping or livestock farming systems) were clearly associated with the highest environmental losses and resource consumption, whereas the “mixed crop and livestock” and “extensive cropping” systems were characterized by lower N and P consumptions leading to moderate N and P budget. These findings are in good agreement with the several studies by Lassaletta et al. (2014a, 2014b, 2014c, 2014d), revealing that the increasing specialization of the agro-food systems' production on global and sometimes national (as in Spain) scales has led to a complete reshaping of the N cycle as well as increased water pollution and GHG emissions.

3.4.2. Agronomical performance

The environmental performance indicators discussed above can be put into perspective for agronomical performance evaluation by expressing them per unit of vegetal and animal production, which reflects the nutrient use efficiency of the production process. Table 2 illustrates the resources and the environmental cost per unit of vegetal and animal production, respectively, thus indicating the agro-environmental performance. The calculation accounted for total N and P input and N and P budget in cropland and grassland areas in each region attributable to its animal and vegetal production, respectively; N and P consumption and loss generated for imported feed production in the source region were also taken into account.

On the whole, the production of one unit of vegetal product used up to 1.5–4.5 times less N and P input than one unit of animal product. Similarly, vegetal production generated N surplus and P budget up to four times less than one unit of animal product (Table 2). By comparing the agronomic performance of the different types of production pattern for their vegetal production, it appears that nutrient requirement was the lowest for “intensive cropping” systems, e.g. 1.42 $_{(\pm 0.07)}$ kgN required per kgN of vegetal products and 0.97 $_{(\pm 0.06)}$ kgP per kgP of vegetal products. This corresponds to NUE of 70% $_{(\pm 3)}$ and PUE of 106% $_{(\pm 6)}$. The particularly low requirement of P per unit of vegetal product may reflect the negative P budget for cropland in this typological region (Fig. 4d above). Low requirement of P was physically possible only because of the utilization of a huge P legacy resulting from intensive fertilizer application over the past few decades (Fig. 1c) (Rowe et al., 2016; Sattari et al., 2012). For “extensive cropping” regions, the lower NUE possibly resulted from the Mediterranean climate that prevails in this type of region. For the “intensive specialized livestock farming” regions, low NUE of cropping systems could be explained, to a certain extent, by the high stocking size generating excessive N inputs through manure application on cropland.

Regional nutrient requirement for animal production was lower for “intensive specialized livestock farming” systems with 3.31 (±0.63) kgN and 1.79 (±0.25) kgP of new resources required per unit of N and P of animal product, respectively. This corresponds to NUE of 31% (±3) and PUE of 56% (±6). By contrast, “extensive mixed crop and livestock farming” systems had higher nutrient requirement with 5.23 (±0.99) kgN/kgN and 3.26 (±0.60) kgP/kgP of animal products, respectively. This corresponds to NUE of 19% (±3) and PUE of 31% (±4) (Table 2). In “intensive specialized livestock farming” systems, with a high animal production rate per hectare (48.4 kgN/ha UAA/yr or 12.5 kgP/ha UAA/yr), the high NUE and PUE was partly due to a high proportion of monogastric animals with a much higher conversion coefficient of vegetal into animal proteins compared to ruminants (conversion coefficients were 0.20 (±0.01) vs 0.09 (±0.00), respectively, for “specialized intensive livestock” and “extensive mixed crop and livestock farming” systems, calculated from SM2). Finally, while looking at N surplus and P budget in grassland generated per unit of animal production, “extensive mixed crop and livestock farming” regions presented the strongest impact followed by “intensive mixed crop and livestock farming” and finally by “intensive specialized livestock farming” regions (Table 2); however, this ranking actually reflected the time spent on grassland.

These results suggest an inverse relationship between environmental and agronomic performance of agro-food systems. This anti-symmetry between the environmental footprint per area unit versus per agricultural production unit has already been highlighted by Chatzimpiros and Barles (2013), who stressed that high productivity at individual animal and crop levels in specialized intensive systems is often associated with high nutrient loss over the whole agricultural system. The improvement of crop yields generally involves heavy fertilization with lower NUE (Tilman et al., 2002), while intensive livestock farming give rise to an overconcentration of livestock, resulting in a high amount of manure excretion with a low opportunity for recycling in the agricultural system.

4. Conclusion

We enlarged the GRAFS approach with a multi-nutrient vision for the case of the French agro-food system. Nitrogen and phosphorus budgets and OC_{eff} input over grassland and cropland were calculated from a system perspective linking fertilization levels, yields, and livestock density together with environmental losses. In this framework, analyzing

Table 1
Environmental indicators expressed per unit of agricultural surface within each of the five main agricultural systems in France. Numbers in parenthesis indicate uncertainties.

	Intensive cropping systems	Extensive cropping systems	Specialized intensive livestock farming	Intensive mixed crop livestock farming	Extensive mixed crop livestock farming
Nitrogen					
N synth fertilizers to cropland (kgN/ha/yr)	133 (±6.5)	78 (±6.7)	77.8 (±6.6)	94.6 (±4.9)	74.0 (±5.0)
N fixation to cropland (kgN/ha/yr)	13.3 (±1.1)	16.4 (±1.5)	4.1 (±0.4)	8.2 (±0.6)	6.3 (±1.6)
New N manure to cropland (kgN/ha/yr)	0.31 (±0.07)	1.13 (±0.34)	45.6 (±12.1)	6.9 (±1.8)	7.1 (±1.8)
N synth fertilizers to grassland (kgN/ha/yr)	45.2 (±3.0)	25.8 (±2.6)	57.0 (±7.4)	44.9 (±2.9)	38.5 (±3.5)
N fixation to grassland (kgN/ha/yr)	40.3 (±3.6)	13.5 (±1.4)	56.7 (±4.1)	35.3 (±2.7)	37.9 (±4.3)
New N manure to grassland (kgN/ha/yr)	0.7 (±0.2)	0.68 (±0.21)	38.7 (±6.4)	5.5 (±1.5)	4.7 (±1.2)
Surplus from cropland (kgN/ha/yr)	56.2 (±8.5)	49.4 (±8.3)	80.0 (±10.4)	58.5 (±7.0)	58.7 (±7.3)
Surplus from grassland (kgN/ha/yr)	35.7 (±6.8)	31.7 (±3.6)	89.6 (±13.9)	47.4 (±65.9)	32.3 (±8.6)
NH3 emission from total UAA (kgN/ha/yr)	12.3 (±0.4)	9.2 (±0.4)	27.7 (±2.4)	18.3 (±0.7)	16.2 (±1.1)
Phosphorus					
P-synth fertilizers to cropland (kgP/ha/yr)	12.0 (±0.2)	7.1 (±0.6)	6.2 (±0.5)	8.1 (±0.4)	4.9 (±0.4)
P-synth fertilizers to grassland (kgP/ha/yr)	9.5 (±0.7)	7.3 (±0.5)	9.1 (±1.1)	9.1 (±0.6)	7.7 (±0.6)
New P-manure to cropland (kgP/ha/yr)	1.5 (±0.1)	2.3 (±0.2)	17.6 (±2.7)	6.1 (±0.6)	9.1 (±1.6)
New P-manure to grassland (kgP/ha/yr)	3.3 (±0.6)	1.5 (±0.2)	9.3 (±1.8)	4.0 (±0.5)	4.0 (±0.9)
P budget in cropland (kgP/ha/yr)	−0.85 (±0.90)	3.7 (±1.0)	16.1 (±2.4)	7.1 (±1.3)	8.0 (±1.3)
P budget in grassland (kgP/ha/yr)	8.6 (±1.2)	8.2 (±0.7)	14.6 (±2.6)	10.0 (±0.9)	7.0 (±1.4)
Carbon					
Efficient org C input to cropland (kgC/ha/yr)	688 (±56)	555 (±59)	724 (±92)	907 (±85)	1144 (±160)
Efficient org C input to grassland (kgC/ha/yr)	1760 (±353)	603 (±131)	1480 (±377)	1670 (±318)	1660 (±358)

the agro-food systems for the 33 regions of France defined here led to the establishment of an innovative typology based on production orientation, crop yields, and breeding practices, revealing the diversity of agricultural systems found at the national scale. This typology made it possible to distinguish five main agricultural production patterns referred to as: (i) intensive cropping system, (ii) extensive cropping

Table 2
Environmental indicators expressed per unit of animal or vegetal product within each of the five main agricultural systems in France and nutrient use efficiency for vegetal and animal production. Numbers in parenthesis indicate Uncertainties.

	Intensive cropping systems	Extensive cropping systems	Specialized intensive livestock farming	Intensive mixed crop livestock farming	Extensive mixed crop livestock farming
Nitrogen					
Synthetic fertilizer					
kgN/kgN vegetal products	1.16 (±0.06)	1.17 (±0.12)	1.21 (±0.23)	1.24 (±0.09)	0.98 (±0.9)
kgN/kgN animal products	2.42 (±0.24)	3.53 (±0.38)	0.82 (±0.17)	2.31 (±0.19)	2.24 (±0.47)
Symbiotic fixation					
kgN/kgN vegetal products	0.26 (±0.01)	0.44 (±0.04)	0.33 (±0.06)	0.35 (±0.02)	0.47 (±0.05)
kgN/kgN animal products	1.06 (±0.07)	2.15 (±0.13)	0.33 (±0.05)	1.25 (±0.07)	2.18 (±0.24)
N inputs invested for imported feed[a]					
kgN/kgN vegetal products	0.00 (±0.00)	0.01 (±0.00)	0.71 (±0.15)	0.06 (±0.02)	0.08 (±0.04)
kgN/kgN animal products	0.10 (±0.02)	0.42 (±0.11)	2.16 (±0.41)	0.69 (±0.15)	0.81 (±0.20)
N surplus, arable land[b]					
kgN/kgN vegetal products	0.43 (±0.05)	0.63 (±0.09)	1.25 (±0.49)	0.65 (±0.08)	0.53 (±0.17)
kgN/kgN animal products	0.74 (±0.17)	1.46 (±0.45)	1.34 (±0.15)	1.32 (±0.13)	1.21 (±0.16)
N surplus, grassland					
kgN/kgN animal products	0.91 (±0.18)	2.29 (±0.30)	0.35 (±0.0)	1.09 (±0.19)	1.75 (±0.49)
N volatilization UAA					
kgN/kgN animal products	0.93 (±0.06)	1.12 (±0.10)	0.52 (±0.09)	0.87 (±0.05)	1.31 (±0.13)
Overall N use efficiency of vegetal production (%)	70% (±3)	62% (±5)	44% (±6)	60% (±4)	65% (±6)
Overall N use efficiency of animal production (%)	27% (±2)	17% (±2)	31% (±3)	23% (±1)	19% (±3)
Phosphorus					
Synthetic fertilizer					
kgP/kgP vegetal products	0.86 (±0.05)	1.15 (±0.09)	0.84 (±0.22)	1.02 (±0.10)	0.85 (±0.14)
kgP/kgP animal products	1.10 (±0.09)	2.70 (±0.23)	0.34 (±0.06)	1.29 (±0.11)	1.48 (±0.27)
P inputs invested for imported feed[a]					
kgP/kgP vegetal products	0.09 (±0.01)	0.17 (±0.05)	1.27 (± 0.47)	0.39 (±0.09)	0.50 (±0.20)
kgP/kgP animal products	0.73 (±0.11)	1.19 (±0.20)	1.45 (±0.19)	1.22 (±0.14)	1.78 (±0.33)
Soil P surplus in arable land					
kgP/kgP vegetal products	−0.04 (±0.04)	0.20 (±0.07)	0.37 (±0.12)	0.17 (±0.05)	0.22 (±0.08)
kgP/kgP animal products	−0.01 (±0.06)	0.49 (±0.11)	0.65 (±0.12)	0.62 (±0.11)	0.69 (±0.2′)
Soil P surplus in grassland					
kgP/kgP animal products	0.84 (±0.12)	2.41 (±0.24)	0.22 (±0.04)	0.92 (±0.10)	1.61 (±0.35)
Overall P use efficiency of vegetal production (%)	106% (±6)	75% (±7)	51% (±26)	71% (±11)	74% (±20)
Overall P use efficiency of animal production (%)	55% (±4)	26% (±2)	56% (±6)	40% (±3)	31% (±4)

[a] N inputs invested for imported feed are calculated assuming that regions providing animal feed are of the 'intensive cropping system' type. This corresponds to 1,42 ktN per ktN of imported feed. Similarly, P inputs invested for imported feed are calculated as P in feed additives plus P required for imported feed assuming that regions providing animal feed are of the 'intensive cropping system' type. This corresponds to 0,97 ktP per ktP of imported feed.

[b] N surplus in arable land is calculated as the N surplus from arable land in each region type plus the N surplus generated outside the territory for imported feed, again assuming that regions providing animal feed are of the 'intensive cropping system' type. This corresponds to 0.43 ktN per ktN of imported feed.

system, (iii) intensive specialized livestock farming, (iv) intensive mixed crop and livestock farming, and (v) extensive mixed crop and livestock farming.

Overall, this study demonstrates the value of the GRAFS approach in an attempt to articulate a vision of how production patterns, trade patterns, as well as environmental and agronomic performance are related. Trade and production patterns appear to be closely related. The assessment of the environmental effects in view of the established typology revealed that "intensive specialized agricultural" systems are clearly associated with the highest environmental loss and resource consumption per unit of agricultural surface, whereas for "extensive and intensive mixed crop and livestock farming" and "extensive cropping" systems, total N and P consumption and water and air contamination appear much lower. However, this trend was reversed when resource consumption and N and P budgets were expressed on a pro rata basis of vegetal or animal product units, reflecting the better agronomic performance of specialized regions in their respective field of specialization. To sum up, applying the GRAFS approach at the regional scale enables to show the systemic impacts of production patterns on environmental and agronomic performances.

In future studies, the GRAFS approach could be well suited to studying the long-term evolution of agricultural production patterns at nested scales and the associated changes in N and P budgets and OC_{eff} inputs over grassland and cropland, as well as to building possible alternative scenarios of the agro-food systems with a similar biogeochemical perspective. The GRAFS methodology can therefore be a useful tool to link structural changes in the agro-food system to their environmental effects.

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Appendix A. Supplementary data

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