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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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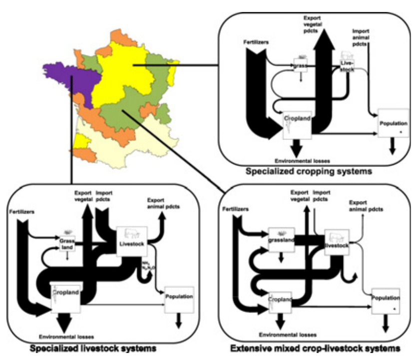
HIGHLIGHTS

- 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).