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Long-term socioecological trajectories of agro-food systems revealed by N and P flows in French regions from 1852 to 2014

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ABSTRACT

We present a quantitative description of the N and P flows characterizing the agro-food system metabolism of 33 agricultural regions in France and their time evolution since the middle of the 19th century. The data were interpreted in terms of connection between crop production, livestock breeding, human nutrition and trade of agricultural goods, and were linked to their historical background. Until the early 20th century, the integrated crop and livestock farming model dominated everywhere, and the slow increase in crop production was only possible because of an increase in livestock density. Specialized cash crop farming systems appeared in the central Paris basin only in the first half of the 20th century together with the increase in the use of industrial fertilizers. Only after WWll, under the pressure of strong interventionist policies, did specialization of French territories lead to five types of systems, favoring their openness and integration into the international market, with harmful environmental impacts. The 1980s were marked by a policy shift towards more liberalism, which reinforced specialization. However, greater environmental concern stabilized or decreased nutrient losses, while maintaining largely open biogeochemical cycles.

1. Introduction

Today, agriculture is largely responsible for disturbing the nitrogen (N) and phosphorus (P) cycles, which Steffen et al. (2015) pointed out as one of the nine earth-system limits. These perturbations are mainly due to the shift from an organic agriculture closely coupling livestock and vegetal production to an industrial agriculture based on mineral fertilization and specialization that has separated crop and livestock farming. The transition from organic fertilization toward mineral-based fertilization was initially made possible by two historical discoveries: (i) the existence of phosphate deposits, in the form of guano in Peru first, and as phosphorus rock in Florida and Morocco thereafter (Clark and Foster, 2009; Pluvinage, 1912) and (ii) the invention of the Haber-Bosh process in 1913 (Smil, 2001). By the end of the 19th century, these new farming techniques responded to the problem of soil exhaustion, which had already raised concerns among scientists (e.g., Liebig) as early as 1840 (Foster, 2000). It also made it possible to better integrate agriculture into the market economy as yields increased with these new means of fertilization, while the need for closing the nutrient loop locally became less stringent. In many places, this implied the progressive specialization of agro-food systems over the course of the 20th century in order to remain competitive and maximize profits (Mazoyer and Roudart, 1998). In return, decoupling animal and vegetal production resulted in ever-increasing trade flows of agricultural products (Lassaletta et al., 2014a). The consequences for N and P cycles were a complete opening at the global scale (Smil, 2000; Galloway and Cowling, 2002) leading to the eutrophication of water streams (Carpenter, 2005), an increase in NH_3 emissions, which have dangerous side effects for both ecosystems and human health (Bouwman et al., 1997), and emission of N_2O, a powerful greenhouse gas (Bouwman, 1996). Furthermore, the opening of the P cycle also raised the issue of its exhaustion over the more or less long term (Elser and Bennett, 2011) given that it is a limited and nonrenewable resource over the human time scale. As an indispensable element to plant growth, restricted accessibility to P is likely to jeopardize the capacity of agro-food systems to produce enough food for a growing world population, which may generate geopolitical conflicts (Cordell et al., 2009).

In this context, a number of recent studies have focused on the socioecological metabolism of agro-food systems, applying material, nutrients or energy flow analysis approaches from local to global scales (Güldner and Krausmann, 2017; Guzmàn et al., 2017; Garnier et al., 2015, 2016; Soto et al., 2016; Billen et al., 2012). Analyses of

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socioecological metabolism conducted within a long-term perspective can shed light on the interrelation between human and natural history in the evolution of agro-ecosystems. Material and energy flows embedded in the functioning of agro-food systems are shaped by human activities of extraction, processing and consumption of biomass, but are also mediated by complex and dynamic natural processes such as ammonia volatilization, nitrate leaching and P sorption. Therefore, as stated by Gizicki-Neudlinger et al. (2017), agricultural systems, perhaps more than any other human activity, need to be considered as "historical phenomen[a] at the intersection of economy and ecology, as a hybrid between nature and culture."

However, to our knowledge few studies within this perspective have examined the case of France, with the exception of the recent article of Harchaoui and Chatzimpiros (2017), which analyzed the transformation of livestock breeding and its consequences over land use and agricultural trade in France over the 1961–2010 period. Yet, the national scale adopted in their study is blind to regional disparities and to the structural link between livestock breeding, arable land and grassland production. The case of France is noteworthy because this country is currently one of the main agricultural powers in Europe, the first exporter of cereals in 2014 (FAO, 2017), although the modernization of French agriculture had long lagged behind other Western European countries such as the United Kingdom, The Netherlands, Belgium and Germany (Ruttan, 1978). The late modernization of agriculture in France has been studied in great depth by historians (Jollivet, 2007; Duby and Wallon, 1993; Muller, 1984; Ruttan, 1978; Duby and Wallon, 1977) who highlighted the political and economic reasons for this delay. Nevertheless, the consequences of the particular evolution of French agriculture in terms of N and P cycles and environmental and agronomic performance are still lacking in the analysis. Therefore, the present research explored the co-evolution of the different patterns of agro-food systems in terms of N and P cycles in their historical context, applying the Generalized Representation of Agro-Food System (GRAFS) as developed by Billen et al. (2014) and Le Noë et al. (2017).

Studying the trajectories of agro-food systems from the perspective of N and P flows is an original prism for such analysis because at the same time it provides information on their degree of openness, their agronomic and environmental performance in terms of N and P use efficiency (NUE and PUE, i.e. the fraction of all N and P inputs that is effectively harvested), and the N and P balances. What are the trajectories that have led to the current agro-food systems at the regional scale? What were the main drivers of these trajectories? What are the environmental consequences? What are the legacies from the previous history on the current state of the system? Answering these questions contributes to responding to the general challenge for future sustainable agricultural production because (i) lessons can be drawn from the past given that traditional agricultural systems relied mainly on nutrient recycling at the farm and regional scale and (ii) designing future patterns of production will require accounting for the effect of agriculture development based on soil fertility, particularly P.

We therefore studied the period from 1852 to 2014. The mid-19th century corresponds to the very beginning of mineral fertilization in France (Boulaine, 2006) and also to the beginning of the Napoleonian Second Empire and the documentation of regular and detailed agricultural statistics. In this paper, some concrete findings regarding the evolution of agro-food system for three typical and contrasted French regions are first analyzed in order to capture the main characteristic of these systems. Based on this first analysis, a typology is then developed in order to objectify main types of agro-food system and to further systematize the analysis of regional trajectories. Finally, based on this typology, we investigate the evolution of agro-food systems toward the different types identified, the consequences of these evolutions in terms of N and P fluxes and some interpretations regarding the drivers of these evolutions are proposed based on literature review.

2. Concepts of the method, data collection and hypothesis

2.1. Concepts of the GRAFS approach

The GRAFS approach (Generalized Representation of Agro-Food Systems, Billen et al., 2014) is a generic biogeochemical approach for describing the agro-food system of a given territory, from the farm (Garnier et al., 2016) to the global scale (Lassaletta et al., 2016), by quantifying nutrient fluxes between cropland, permanent grassland, livestock, humans and the natural environment. From the GRAFS perspective, cropping systems are considered to convert nutrient inputs (such as fertilizers, manure, symbiotic N fixation, and atmospheric deposition) into harvestable vegetal products. Crop products can be used (i) to meet the vegetal protein requirements of human nutrition, (ii) to be exported or (iii) to feed livestock, to the extent that they are not fed by grazing on permanent and semi-natural grassland or by imported feedstuffs. The difference between nutrient inputs and outputs informs on the nutrient balance of either crop or grassland soils. More detailed information is provided in Supplementary material SM 1.

The efficiency of feed and grazing conversion into consumable animal proteins (meat, milk and eggs) determines the amount of excreted N, a part of which can be recycled into cropland as manure, making cropland fertility partly dependent on transfers from permanent grassland. The fishery and aquaculture sector also contributes, providing animal proteins for human nutrition, but is considered in our analysis as a separate system for the sake of simplicity. Nutrient losses to the environment occur at each stage of the chain, particularly through leaching and volatilization from cropland, loss from animal excreta and waste from food processing and, finally, from human excretion. Storage in the soil pool is also a possible fate for nutrients.

The GRAFS representation enables to draw direct links between different aspects of the agro-food system, e.g., the link between livestock breeding, grassland areas, and forage crops and the link between fertilization of cropland and grassland and environmental nutrient losses. GRAFS also provides some key indicators for analyzing agro-food systems from both the environmental and agronomic perspectives. A full description of the GRAFS methodology has been provided by Le Noë et al. (2017). Hereafter, we only provide a synthetic description of the main hypotheses and data sources to establish GRAFS for past and current times. A more detailed description of the method is provided in SM1. In this study, we applied the approach to 33 regions defined by Le Noë et al. (2016) for 22 dates from 1852 to 2014.

2.2. Data collection for past and present

2.2.1. Human population and consumption

Total, urban and rural population figures at the "département" (Nuts 3) level are provided by the French National Institute for Statistics and Economic Studies (INSEE, 2017) for the census years, every 5 years from 1852 to 2014, interpolated to the years of the survey. The changes in the human diet in France over the last two centuries were investigated from different data sources and archives (Philippe, 1961; Toutain, 1971; Barles, 2007; AFSSA, 2009; Chatzimpiros, 2011; INSEE, 2017). The conversion coefficients used to translate consumption of each food item into N and P were taken from several databases including CIQUAL (https://pro.anses.fr/tableciqual/), Diet Grail (http://dietgrail.com) and USDA (http://ndb.nal.usda.gov). These coefficients were provided in detail by Le Noë et al (2017).

2.2.2. Livestock metabolism

Animal production and livestock numbers for different age classes and animal categories were provided in carcass weight equivalent by annual agricultural statistics, available online at http://agreste.agriculture.gouv.fr/la-statistique-agricole/, starting in 1970. For earlier periods, data were obtained from nondigitized official registers (available from Gallica.bnf.fr). Meat, milk and egg production in terms