The phosphorus legacy offers opportunities for agro-ecological transition (France 1850–2075)

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Abstract

Management of the non-renewable resource phosphorus (P) is critical to agricultural sustainability. The global P cycle is currently disturbed beyond planetary boundaries, mostly due to large excess P use in the agriculture of industrialized countries, while P is lacking in the Global South. The trajectories of P management and their effects on future sustainable agriculture were investigated for the case of France from 1850 to 2015 based on empirical data and simulations of two coupled biogeochemical models. Here we show that while French cropland soils have accumulated significant amounts of P, mainly sourced from former colonies or protectorates, P reserves in grassland soils have been depleted. Scenario calculations indicate that current P reserves may on average allow for another 60 years of agricultural production without mineral P application. In the light of a possible upcoming P scarcity, this time frame offers an opportunity for a transition towards regionally closed P loops and enhanced sustainability, allowing for fairer international distribution of P resources in the future.

1. Introduction

Over the last 150 years, agricultural activities have strongly altered the global P cycle, mainly by exploiting lithospheric reserves of P ore for application as mineral fertilizer in industrialized agricultural systems (Elser and Bennett 2013). Most of the globally extracted mineral P has been mined in Morocco, China and the United States (Cordell et al 2009). While there is a yet unresolved debate about the actual scarcity of mineral P reserves due to uncertainties related to the actual size and quality of remaining deposits (Elser and Bennett 2013, Nanda et al 2019, Scholz and Wellmer 2019), the perturbation of the P cycle caused by modern agriculture is considered to exceed planetary boundaries (Carpenter and Bennett 2011). Globally, the declining grades of mineral P (Mew 2016, Scholz and Wellmer 2019) and the large and growing disparities between world regions in terms of access to vital P resources raises concern about international and intergenerational justice (Potter et al 2010, Macdonald et al 2012, Elser and Bennett 2013, Cordell and Neset 2014, Nanda et al 2019).

P accumulated in agricultural soils has become an important reserve of P, which has been denoted as P legacy (Sharpley et al 2013, Haygarth et al 2014). Significant P legacies can be found in industrialized countries with a long history of high input agriculture based on access to P fertilizers at low cost (Cordell et al 2009, Mogollón et al 2018). However, only a small fraction of the P accumulated in soils is actually available for plant nutrition, because P can be strongly bound to soil particles. In the context of the global disparities regarding the access to P resources (Cordell and Neset 2014, Nanda et al 2019), the potential role of the P legacy in agricultural soils for sustaining crop production and for a transition towards more sustainable agriculture needs to be further assessed. Considering that P is an essential and limited resource, also the origin of the soil P legacy needs to be elucidated in order to address questions of intra- and intergenerational justice, related to the search for a fairer distribution of P resources in the future.
Previous studies on P legacies have been constrained by limited spatial resolution (Ringeval et al 2014), lack of consideration for the geographic origin of P accumulated in soils (Ringeval et al 2014, Mogollón et al 2018, Wironen et al 2018) or ignoring the issue of plant availability of P (Wironen et al 2018). Here, we overcome these limitations by investigating the long-term trajectories of P management in French agriculture at the regional level. Our empirical analysis spans from 1850 to 2015 and covers the trajectory from traditional organic to high-input industrialized agriculture including more recent attempts towards agro-ecological practices, and is linked to two scenarios analyses up to 2075. We (i) quantify the P legacy in cropland and grassland in 33 French regions as defined by Le Noë et al (2016), (ii) simulate the dynamics of soil P stocks, (iii) trace back the geographical origin of soil P and (iv) test two scenarios exploring the potential role of these reserves for agricultural production in the next 60 years. The aim of this study is to assess the extent of the French P legacy and its implications for a transition towards more sustainable farming systems.

2. Material and methods

2.1. Model description

In order to calculate the long-term evolution and geographical origin of cropland and grassland soil P stocks, we coupled the GRAFS approach (Le Noë et al 2018) and the DPPS model (by Wolf et al 1987, Sattari et al 2012, Zhang et al 2017). Hereafter, we briefly describe the hypotheses, input data and coupling of the two models (figure 1); further details are provided in supplementary online material 1 and 2 (SOM 1, 2) (stacks.iop.org/ERL/15/064022/mmedia) and the whole model calculations are available in the form of an excel workbook in SOM 3.

The GRAFS model enables to assess the annual P budget on cropland and grassland respectively, accounting for P inputs from mineral fertilizer, manure, urban sludge, atmospheric deposition, and for P outputs from harvest and erosion. All P inputs and output through harvest were taken from Le Noë et al (2018) while P outputs from erosion were derived from the results of the modelling approach by Borelli et al (2018). The DPPS model simulates the soil P dynamic, considering two soil P pools (stable and labile). The coupling of the two models yields the long-term evolution of stable and labile soil P stocks both in cropland and grassland.

The initial value of the total soil P pool, representing the pre-industrial P stock (before 1850), is adjusted in each region to the value required to correctly simulate the average measurements of current total P in cropland and grassland soils (Delmas et al 2015). Internal processes of P exchange between the labile and stable P pools are represented by first order rate kinetics for both processes. The constant rate for the transfer from labile to stable P ($k_{S,L}$) is fixed at 0.2 yr$^{-1}$ (Wolf et al 1987, Zhang et al 2017), while the rate constant for stable P conversion into labile P ($k_{L,S}$) is one order of magnitude higher, and is calibrated for each region based on observed values of Olsen P for the 1995–2004 and 2005–2014 periods reported by Gouny et al (2016). The best fit values of $k_{S,1}$ of each region ranges between 0.005 and 0.1 yr$^{-1}$, with a mean value of 0.02 yr$^{-1}$. The initial value of the labile pool in each region is calculated considering that a steady state was reached with respect to the inputs and outputs documented for the middle of the 19th century.

The same calculation procedure is then carried out considering the share of geographical origins of the P fluxes and stocks. For mineral fertilizers, the geographical origins considered are domestic French mineral resources (including P derived from basic slag from the iron industry), mineral resources imported from the former French colonies or protectorates (Maghreb and sub-Saharan countries), from the former USSR, the USA and the Middle East (including Egypt and minor imports from other Asian countries). These origins have been estimated through a detailed analysis of the French P supply structure since the end of the 19th century (see SOM 2, figures S5 to S10), using a range of different historical trade data. The rate of P fertilizer application at the department scale is documented since the early 1970s by UNIFA. Data from 1929 to 1965 were compiled from annual agricultural statistics of the Ministry of Agriculture. Prior to 1929, they were obtained only at the national level from Pluvinage (1912) and Duby and Wallon (2004) and distributed across regions (Le Noë et al 2018). For manure inputs, the decomposition by origin is established by considering the share of manure derived from: grassland grazing, regionally produced fodder, imported feed (either soybean from North and South America, other French regions, or other origins) and P additives.

2.2. Scenarios

Based on previous research by Billen et al (2018), we developed two simple agro-food scenarios in order to explore how the soil P reserves could be supportive for a transition towards a more sustainable low input agriculture in France and a fairer distribution of remaining global P resources: a low input (LI) scenario and an autonomous/reconnected/demitarian (A/R/D) scenario. The LI scenario assumes that mineral P fertilization is given up completely from 2015 onward, while all other parameters of French agriculture remain the same. The A/R/D scenario assumes autonomy of agricultural systems in terms of inputs (including P fertilizer and animal feed), reconnection of cropping and breeding activities at regional scale, and a reduction by half (c. 35%) of the amount of animal protein in the human diet (http://www.ninesf.org; Billen et al 2018). Similar to the LI scenario,
mineral P fertilization ceases in 2015, but additionally this scenario assumes a closing of P loops at the regional scale based on a deep reconfiguration of the regional agro-food systems. This reconfiguration is assumed to take place gradually from 2015 until 2050. In previous research, this scenario has been shown to enable a level of agricultural production high enough to feed the French population while still a significant share of crops would be available for export; it would also reduce the nitrogen losses to hydrosystems as well as the direct and indirect emissions of greenhouse gases from agriculture (Billen et al. 2018, Le Noë et al. 2019, Garnier et al. 2019). The value of implementing this scenario in the present study is to explore how more efficient P recycling at the regional scale could further reduce the dependency on mineral P fertilizer inputs considering the current level of P legacy in cropland soils.

3. Results and discussion

3.1. P management in cropland and grassland (1850–2015)

The analysis of long-term historical P flows through France’s agricultural soils reveals a pronounced peak in P inputs in the 1970s, particularly on cropland (figure 2), accompanied by continuously increasing crop yields (see SOM3). Analysis at the regional scale reveals contrasting trajectories, as shown in figure 2 using the example of three of the 33 French regions. These trajectories can be related to different paths of agricultural specialization in French regions (Le Noë et al. 2018), such as intensive livestock production (e.g. Brittany since the 1980s), stockless crop farming, i.e. regions where crop production prevails and livestock husbandry is insignificant, (e.g. Eure-et-Loir since the 1920s), and integrated crop and livestock production.
farming (e.g. Loire Amont over the whole study period).

Until the end of the 19th century, animal manure remained the major P input to arable soils in all three regions which then were all characterized by integrated crop and livestock farming (figure 2). P inputs in that period were hardly sufficient to compensate for P export by crop harvest and the soil P balance both on cropland and grassland was negative throughout much of the 19th century, similar to other European countries (e.g. Spain, González De Molina et al 2015). This indicates a slow mining of the natural soil P reserve, in spite of significant transfers of plant nutrients from permanent grassland to cropland through livestock manure (Sattari et al 2012). Guano fertilizer and phosphate rock were introduced in French agriculture only at the turn of the 20th century. They were initially applied in small quantities only in regions of the Paris Basin (e.g. in the Eure-et-Loir, figure 2(b)), where they facilitated the gradual specialization in stockless crop farming, from the early 1930s onwards. In the first half of the 20th century, the soil P balance for cropland soils became enduringly positive in most regions owing to increasing but still moderate inputs of industrial fertilizers. After World War II, with increasing agricultural specialization (Le Noë et al 2018), the application of industrial fertilizers surged up to the point of becoming the main source of P inputs to cropland, even in regions which remained in the mixed crop and livestock farming system (see e.g. Loire Amont in figure 2(d)). During the post-war boom of

Figure 2. P inputs and outputs on cropland (left panel) and grassland (right panel) in France (2a) and three French regions from 1850 to 2015. The regions have been selected following Le Noë et al (2018) as representative for trajectories of specialization in intensive crop farming (2b Eure-et-Loir), intensive livestock farming (2c Brittany) and a continuously integrated crop and livestock farming (2d Loire Amont).
agricultural modernization, the cropland P balance increased whatever the type of specialization of the region, with annual excess of fertilization reaching 40 to 50 kg P ha$^{-1}$ y$^{-1}$ in the early 1970s (figure 2). The first oil price shock of 1973 and the concomitant dramatic increase of the price of mineral P fertilizers (Cordell et al 2009) marked a sudden turning point in P management, resulting in the severe drop of the application of industrial P fertilizers visible in figure 2(a). This caused a rapid decrease of the annual P balances in all French regions, which was in later years reinforced by the implementation of environmental policy following the successive European Common Agricultural Policy reforms in 1992, 1999 and 2003 as well as the European Water Framework directive in 2000. From the 1980s onward, the importance of P in manure increased, particularly in regions specializing in intensive livestock farming (see e.g. Brittany in figure 2(c)). Since livestock production increasingly relied on imported feed, a considerable share of this P input originated from distant regions. At the national scale (figure 2(a)), owing to the shift towards specialized stockless crop farming in many regions, the P balance became negative around the turn of the 21st century, indicating the depletion of soil P reserves. Indeed, in specialized stockless crop farming regions, the lower input through mineral P fertilizer was not compensated by P input through livestock manure, leading to negative P balance (see e.g. Eure-et-Loir, figure 2(b)). Only regions that have turned towards intensive livestock farming, like Brittany (figure 2(c)), maintained a positive P balance on both cropland and grassland. This regional analysis indicates the systemic interlinkage between P management in agriculture and the subsequent soil P balance on the one hand, and the level of agricultural specialization and the subsequent dependence on mineral fertilizers and imported concentrated feed on the other hand.

3.2. Assessing the P legacy
The trajectories of P fertilization had a long-lasting cumulative effect on soil P stocks. At the national level, the P reserve in cropland soils has increased by c. 24% compared to the pre-industrial level of 1850 (figure 3). By contrast, the level of total soil P in grassland decreased by c. 8% from 1850 to 2015 as a result of sustained soil P mining until the 1960s. As shown by Sattari et al (2012), this stark contrast between P legacies in cropland and grassland soils is the result of the combined effect of P transfers from grassland to cropland via livestock in traditional organic farming in early periods and a much lower level of mineral P fertilization on grassland in more recent decades (figure 3). On average, 33% (7% to 80% across all regions) of the current P stocks in French cropland soils originate from excess fertilization (including P derived from both mineral fertilizers and imported feed embedded in manure), mainly from P inputs during the period from 1955 to 1985 (figure 3). By contrast in grassland soils, the P legacy is only 13% of total P reserves, and more than 2/3 of regions show a negative cumulative P budget on grasslands. Note, however, that in many regions permanent grasslands represent only a rather low fraction of total agricultural area.

However, while the total P stocks in agricultural soils resulting from both pre-industrial soil P and the accumulation of excess fertilizer application are considerable, only 5%–10% of these stocks are actually labile enough to be available for plants. Based on regional agronomical experiments, COMIFER (1995) and Arvalis (1995) have determined Olsen-P concentration thresholds below which P inputs are required to sustain optimal crop production and above which additional fertilization does not result in enhanced plant growth. The calculated labile soil P can then be compared with these reference Olsen-P thresholds to assess the trajectory of crop- and grassland available P (figure 4(a)).

We found that the labile soil P slowly decreased until the 1910s in cropland and until the 1940s in grassland soils (figure 4(a)). Beginning after World War II and at a rapid pace in the 1950s and 1960s, labile soil P contents increased to reach in the 1980s a level c. two times above the upper threshold identified by COMIFER, indicating that the application of P fertilizers could be completely abandoned in most French regions. Owing to a high pre-industrial P level, possibly due to significant long-term P transfers from forest soils through animal manure (Gimmi and Bürgi 2007, Mcgrath et al 2015), or, in some regions, due to alteration over geological time of bedrock rich in phosphate, P availability for plant nutrition was apparently always sufficient in cropland and grassland soils at the regional scale in the study period.

However, a simple hypothetical and counterfactual scenario, assuming no mineral P fertilizer inputs over the whole period, all other things remaining equal, reveals that French agriculture would have continuously depleted soil P reserves to a level below the scarcity threshold, in regions specialized in stockless crop production (figure 4(b)). Therefore, mineral P imports did indeed prevent French agriculture from facing P scarcity as they were of critical importance for enabling the specialized and highly productive agriculture in the late 20th century.

3.3. Origins of soil P
The inputs of P into French soils stem mainly from two types of sources: animal manure and mineral fertilizers. Animal manure inputs are either related to recycling of P from regionally grown crops, the local transfer of P from grassland to cropland in mixed farming systems or the long-distance transfer of P via feed from arable land in other French regions or foreign countries (Le Noé et al 2016, 2017, Nesme et al 2018). Our findings suggest that the
Figure 3. Total soil phosphorus (P) stock, P content and P legacy in French cropland (left) and grassland (right) soils. Current total P stock of the 30 cm top soil (from Delmas et al. 2015) (3a); current total P content of the 30 cm top soil (from Delmas et al. 2015) (3b) and fraction of the current P stock derived from the cumulated P additions to soils since 1850 (legacy stock) (3c). Only the name of the three aforementioned regions are indicated on the map (E: Eure-et-Loir, Br.: Brittany and L. Am.: Loire Amont); for other region names see SOM 3.

Continuous transfer of P from grassland to cropland soils has contributed to a depletion of P reserves in grasslands (figure 3) while the massive export of soybeans from Latin America to France and other countries with intensive livestock production is a matter of increasing concern for soil fertility in these regions (Pengue 2005). The by far largest fraction of current legacy P stocks in cropland and grassland soils in all French regions, however, originates from mineral fertilizers applied in the past century (on average 32% and 12% of current cropland and grassland P stocks, respectively). This mineral P originated from different sources in different periods of the 20th century (see SOM 2, figure S10). The import of P rock from French colonies or protectorates in North and West Africa began in the first decades of the 20th century to provide considerable amounts of P for French agriculture, and continues today. The French super-phosphate industry, relying on P rock imports from Africa, peaked in the 1970s. After the first oil price shock and the decline of the French steel industry in the 1970s and 1980s, direct
import of processed phosphates gradually displaced domestic production, as the countries operating to phosphate mines began to develop their own fertilizer industries.

At the national scale, 20% and 7% of current soil P reserves in cropland and grassland respectively originate from the Maghreb and sub-Saharan countries (former French colonies or protectorates, figure 5). By contrast, the pre-industrial soil P reserves, i.e. the P stocks originating from 1850, before mineral fertilization was introduced, constantly decreased over the 1850–2015 period. In regions with intensive livestock farming also the P contained in imported feed from Latin America presents a significant contribution to the current soil reserve (c. 6% in Brittany, see SOM 2 figure S11). The high significance of imports of P resources from countries of the Global South makes the P legacy also an issue in the debate about ecologically unequal exchange, which is concerned with unbalanced flows of biophysical resources between countries and the subsequent externalization of environmental burdens associated with extraction and production of these resources (Hornborg 2009, Roberts and Parks 2009). Our analysis of the significance of imports of P resources echoes findings from studies which analyzed ecologically unequal exchange patterns of the trade between France and its former colonies and protectorates (Magalhães et al 2018, Infante-Amate and Krausmann 2019), and hints at issues of environmental (in)justice related to phosphorus distribution and use.

Figure 4. (a) Olsen-P content of cropland and grassland soils in France and three French regions from 1850 to 2015, as calculated by the DPPS model, compared with average Olsen-P values observed in cropland soils (orange dots; 10-year averages for 1994–2004 and 2005–2015 sourced from Gouny et al 2016), and with the recommended threshold values for P fertilization by COMIFER (1995) and Arvalis (1995). The red line indicates the threshold value of Olsen P content in soil below which fertilization should be intensified while the green line indicates the threshold value of Olsen P content in soil above which fertilization could be abandoned. (b) Same calculation for a counterfactual scenario assuming no input of mineral fertilizer, but the same crop or grass production, since the beginning of the period.
3.4. P legacy and the transition towards low input agriculture

Exploring two contrasted scenarios of agricultural trajectories at the 2075 horizon enables to assess how the soil P stocks—largely inherited from mineral P resources imported from former French colonies and protectorates—could contribute to improving agriculture sustainability and a fairer distribution of global P resources. Results from model simulation reveal that in the low input scenario, P inputs through manure (figure 6(a)) and the release of plant available P from the accumulated legacy would be large enough to sustain crop requirements at least until 2075 (figure 6(c)). However, the pursuit of significantly negative P budgets (figure 6(a)) would ineluctably lead to a declining level of soil available P until it would eventually fall below the lower threshold at which fertilization is required to avoid crop limitation. The first regions in which the P level would fall below the minimum Olsen P threshold as defined by COMIFER (1995) are those with stockless and intensive cropping systems between 2030 and 2065 (see SOM3), indicating that the replenishment of the available soil P pool would not be rapid enough to sustain crop requirements in these regions. In order to prevent a decline of crop yields, fertilizer application would have to resume. Our calculations indicate that over the whole period from 2016 to 2075, an average mineral P fertilizer input of 60 ktP yr$^{-1}$ would be required to keep all regions above the minimum threshold. This requirement would increase over time from c. 42 ktP yr$^{-1}$ over the 2016–2026 period to 87 ktP yr$^{-1}$ over the 2065–2075 period, i.e. the dependency would grow. While in the low input scenario the legacy benefit would gradually be used up, the average mineral P input requirement is still 60% lower than the current average P application rate. Adjusting P inputs to actual crop requirements by making use of the P legacy, could, therefore, contribute to further decrease the dependency on imported mineral P fertilizers while maintaining an adequate level of available soil P without a loss of agricultural productivity in all French regions.

Our analysis of the Autonomous/Reconnected/Demitarian scenario indicates even more promising results. At the scale of France, the total cropland soil P reserves would slightly decrease until the 2060s before stabilizing at a new equilibrium, while they remain at a constant level on grassland (figures 6(b) and (c); see also data depository). In spite of the initial decline, cropland P reserves would not fall below a level critical for production since the level of labile soil P simulated by the DPPS model always remains above the lower P-Olsen threshold in all but two and three regions for cropland and grassland, respectively. Furthermore, in the vast majority of regions, labile P in cropland and grassland even remains above the upper threshold. While the regional results may conceal P scarcity at the farm/parcel level in cases where the P legacy is unevenly distributed at the intra-regional scale, our simulation of average labile soil P at the regional level suggests that in general it should be
possible to abandon mineral P fertilization and fully replace it by closing local P loops through the use of manure and human excreta. These results indicate that a restructuring of the agro-food system is feasible with respect to P availability.

4. Conclusion: lessons from the French case

Our analysis of the P legacy in French agricultural soils corroborates findings from other studies, which indicate that accumulated reserves of P can sustain crop production even in the absence of additional mineral P fertilization (Blake et al. 2003, Ringeval et al. 2014, Wither et al. 2015, Rowe et al. 2016, Mogollón et al. 2018). France can be viewed as a paradigmatic example for industrialized countries with a long history of high-input agriculture. The comprehensive analysis of this case can inform the debate about improving P management in European countries with similar trajectories (Mogollón et al. 2018) but it is also relevant for developing countries with opposite trajectories (Garnier et al. 2015). Considering the depletion of global P stocks, the degradation of ore grades and the polluting effect of overfertilization, we argue that industrialized countries like France should consider to stop relying on imported P fertilizers. Our calculations show that making use of the P legacy in agricultural soils offers time required for a transition towards sustainable low input agriculture that allows to reduce or even abolish P imports. Such a transition would reduce the draw on limited lithospheric P resources and leave them for improving agriculture in the Global South. Therefore,
it is both a challenge and chance for France and other industrialized countries, to reduce pressure on demand for mineral P resources, as well as to avoid the depletion of their own soil P resources. Overall, our results highlight the extent of the soil P legacy, as it not only contributed to past yields improvement but could also be a serious advantage to fulfill a transition towards a more sustainable low-inputs agriculture in the future.

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