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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.

Keywords: Phosphorus, Legacy, Agriculture, Modelling, Trajectories, Scenario

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 2011). 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 2011; 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; Steffen et al 2015). 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; Elser and Bennett 2011; MacDonald et al 2012; 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 (Haygarth et al 2014; Sharpley et al 2013). 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 bounded 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,

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3 49 related to the search for a fairer distribution of P resources in the future.
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5 50 Previous studies on P legacies have been constrained by limited spatial resolution (Ringeval et al
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7 51 2014), lack of consideration for the geographic origin of P accumulated in soils (Ringeval et al
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9 52 2014; Mogollón et al 2018; Wironen et al 2018) or ignoring the issue of plant availability of P
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11 53 (Wironen et al 2018). Here, we overcome these limitations by investigating the long-term
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13 54 trajectories of P management in French agriculture at the regional level. Our empirical analysis
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15 55 spans from 1850 to 2015 and covers the trajectory from traditional organic to high-input
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17 56 industrialized agriculture including more recent attempts towards agro-ecological practices, and is
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19 57 linked to two scenarios analyses up to 2075. We (i) quantify the P legacy in cropland and grassland
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21 58 in 33 French regions as defined by Le Noë et al (2016), (ii) simulate the dynamics of soil P stocks,
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23 59 (iii) trace back the geographical origin of soil P and (iv) test two scenarios exploring the potential
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25 60 role of these reserves for agricultural production in the next 60 years. The aim of this study is to
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27 61 assess the extent of the French P legacy and its implications for a transition towards more
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29 62 sustainable farming systems.
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38 64 **2. Material and Methods**

39 40 41 65 *2.1. Model description*

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43
44 66 In order to calculate the long-term evolution and geographical origin of cropland and grassland
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46 67 soil P stocks, we coupled the GRAFS approach (Le Noë et al 2018) and the DPPS model (by Wolf
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48 68 et al 1987; Sattari et al. 2012; Zhang et al 2017). Hereafter, we briefly describe the hypotheses,
49
50 69 input data and coupling of the two models (figure 1); further details are provided in Supplementary
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52 70 Online Material 1 and 2 (SOM 1, 2) and the whole model calculations are available in the form of
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54 71 an excel workbook in SOM 3.
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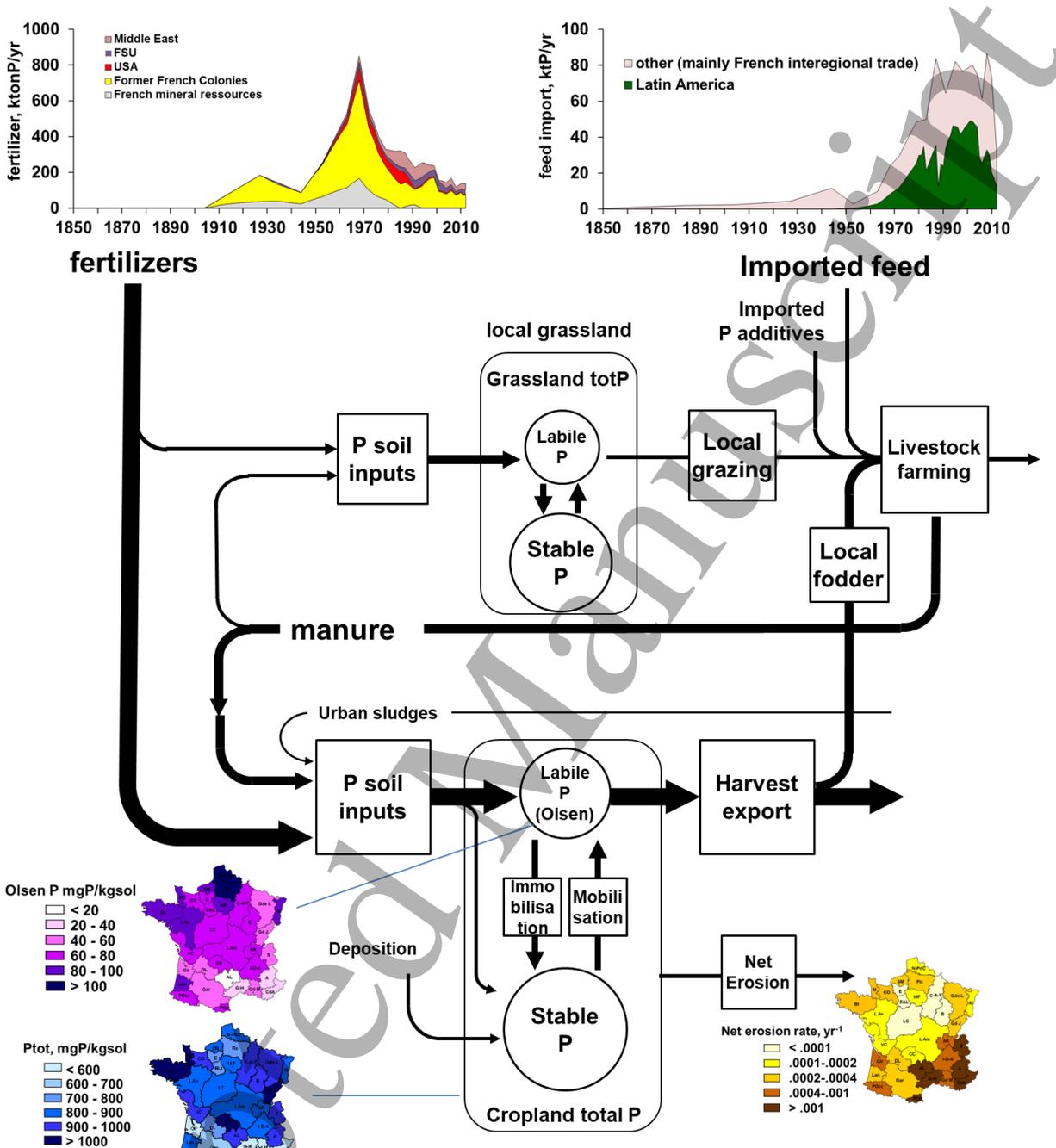


Figure 1. Schematic description of annual P fluxes in the agro-food system (arrows) and of P stocks in agricultural soils (boxes) based on the GRAFS and DPPS model respectively (see SOM1 for more details).

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

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3 79 Le Noë et al (2018) while P outputs from erosion were derived from the results of the modelling
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5 80 approach by Borelli et al (2018). The DPPS model simulates the soil P dynamic, considering two
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7 81 soil P pools (stable and labile). The coupling of the two models yields the long-term evolution of
8
9 82 stable and labile soil P stocks both in cropland and grassland.

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11
12 83 The initial value of the total soil P pool, representing the pre-industrial P stock (before 1850), is
13
14 84 adjusted in each region to the value required to correctly simulate the average measurements of
15
16 85 current total P in crop- and grassland soils (Delmas et al 2015). Internal processes of P exchange
17
18 86 between the labile and stable P pools are represented by first order rate kinetics for both processes.
19
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21 87 The constant rate for the transfer from labile to stable P (k_{L-S}) is fixed at 0.2 yr^{-1} (Wolf et al 1987;
22
23 88 Zhang et al 2017), while the rate constant for stable P conversion into labile P (k_{S-L}) is one order
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25 89 of magnitude higher, and is calibrated for each region based on observed values of Olsen P for the
26
27 90 1995-2004 and 2005-2014 periods reported by Gouny et al (2016). The best fit values of k_{S-L} of
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29 91 each region ranges between 0.005 and 0.1 yr^{-1} , with a mean value of 0.02 yr^{-1} . The initial value of
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31 92 the labile pool in each region is calculated considering that a steady state was reached with respect
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33 93 to the inputs and outputs documented for the middle of the 19th century.

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37 94 The same calculation procedure is then carried out considering the share of geographical origins
38
39 95 of the P fluxes and stocks. For mineral fertilizers, the geographical origins considered are domestic
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41 96 French mineral resources (including P derived from basic slag from the iron industry), mineral
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43 97 resources imported from the former French colonies or protectorates (Maghreb and sub-Saharan
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45 98 countries), from the former USSR, the USA and the Middle East (including Egypt and minor
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47 99 imports from other Asian countries). These origins have been estimated through a detailed analysis
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51 100 of the French P supply structure since the end of the 19th century (see SOM 2, figures S5 to S10),
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53 101 using a range of different historical trade data. The rate of P fertilizer application at the department

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3 102 scale is documented since the early 1970's by UNIFA. Data from 1929 to 1965 were compiled
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5 103 from annual agricultural statistics of the Ministry of Agriculture. Prior to 1929, they were obtained
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7 104 only at the national level from Pluvinage (1912) and Duby and Wallon (1993) and distributed
8
9 105 across regions (Le Noë et al 2018). For manure inputs, the decomposition by origin is established
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11 106 by considering the share of manure derived from: grassland grazing, regionally produced fodder,
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13 107 imported feed (either soybean from North and South America, other French regions, or other
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15 108 origins) and P additives.
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21 110 2.2. Scenarios

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25 111 Based on previous research by Billen et al (2018), we developed two simple agro-food scenarios
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27 112 in order to explore how the soil P reserves could be supportive for a transition towards a more
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29 113 sustainable low input agriculture in France and a fairer distribution of remaining global P
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31 114 resources: a low input (LI) scenario and an autonomous/reconnected/demitarian (A/R/D) scenario.
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34 115 The LI scenario assumes that mineral P fertilization is given up completely from 2015 onward,
35
36 116 while all other parameters of French agriculture remain the same. The A/R/D scenario assumes
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38 117 autonomy of agricultural systems in terms of inputs (including P fertilizer and animal feed),
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40 118 reconnection of cropping and breeding activities at regional scale, and a reduction by half (c. to
41
42 119 35%) of the amount of animal protein in the human diet (<http://www.nine-esf.org>; Billen et al
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44 120 2018). Similar to the LI scenario, mineral P fertilization ceases in 2015, but additionally this
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46 121 scenario assumes a closing of P loops at the regional scale based on a deep reconfiguration of the
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48 122 regional agro-food systems. This reconfiguration is assumed to take place gradually from 2015
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50 123 until 2050. In previous research, this scenario has been shown to enable a level of agricultural
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52 124 production high enough to feed the French population while still a significant share of crops would
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3 125 be available for export; it would also reduce the nitrogen losses to hydrosystems as well as the
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5 126 direct and indirect emissions of greenhouse gases from agriculture (Billen et al 2018; Le Noë et al
6
7 127 2019; Garnier et al 2019). The value of implementing this scenario in the present study is to explore
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9 128 how more efficient P recycling at the regional scale could further reduce the dependency on
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11 129 mineral P fertilizer inputs considering the current level of P legacy in cropland soils.
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17 131 **3. Results and discussion**

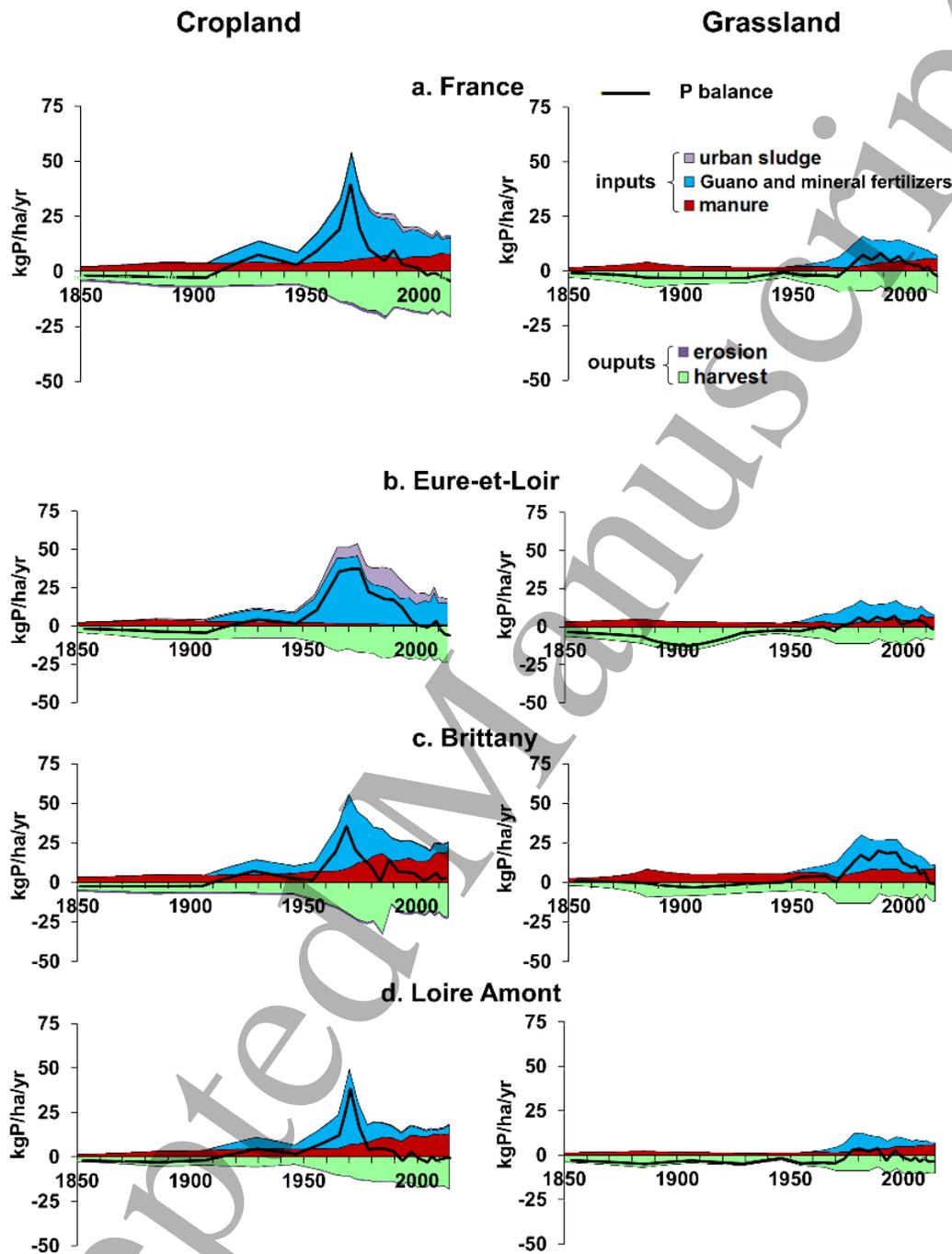
19 132 *3.1. P management in cropland and grassland (1850-2015)*

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23 133 The analysis of long-term historical P flows through France's agricultural soils reveals a
24
25 134 pronounced peak in P inputs in the 1970's, particularly on cropland (figure 2), accompanied by
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27 135 continuously increasing crop yields (see SOM3). Analysis at the regional scale reveals contrasting
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29 136 trajectories, as shown in figure 2 using the example of three of the 33 French regions. These
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31 137 trajectories can be related to different paths of agricultural specialization in French regions (Le
32
33 138 Noë et al 2018), such as intensive livestock production (e.g., Brittany since the 1980's), stockless
34
35 139 crop farming, i.e., regions where crop production prevails and livestock husbandry is insignificant,
36
37 140 (e.g., Eure-et-Loire since the 1920's), and integrated crop and livestock farming (e.g., Loire Amont
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39 141 over the whole study period).
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42

43 142 Until the end of the 19th century, animal manure remained the major P input to arable soils in all
44
45 143 three regions which then were all characterized by integrated crop and livestock farming (figure
46
47 144 2). P inputs in that period were hardly sufficient to compensate for P export by crop harvest and
48
49 145 the soil P balance both on cropland and grassland was negative throughout much of the 19th
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51 146 century, similar to other European countries (e.g., Spain, González de Molina et al 2015). This
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54 147 indicates a slow mining of the natural soil P reserve, in spite of significant transfers of plant
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3 148 nutrients from permanent grassland to cropland through livestock manure (Sattari et al 2012).
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5 149 Guano fertilizer and phosphate rock were introduced in French agriculture only at the turn of the
6
7 150 20th century. They were initially applied in small quantities only in regions of the Paris Basin (e.g.,
8
9 151 in the Eure-et-Loire, figure 2b), where they facilitated the gradual specialization in stockless crop
10
11 152 farming, from the early 1930's onwards. In the first half of the 20th century, the soil P balance for
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13 153 cropland soils became enduringly positive in most regions owing to increasing but still moderate
14
15 154 inputs of industrial fertilizers. After World War II, with increasing agricultural specialization (Le
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17 155 Noë et al 2018), the application of industrial fertilizers surged up to the point of becoming the main
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19 156 source of P inputs to cropland, even in regions which remained in the mixed crop and livestock
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21 157 farming system (see e.g., Loire Amont in figure 2d). During the post-war boom of agricultural
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23 158 modernization, the cropland P balance increased whatever the type of specialization of the region,
24
25 159 with annual excess of fertilization reaching 40 to 50 kgP ha⁻¹ y⁻¹ in the early 1970's (figure 2). The
26
27 160 first oil price shock of 1973 and the concomitant dramatic increase of the price of mineral P
28
29 161 fertilizers (Cordell et al 2009) marked a sudden turning point in P management, resulting in the
30
31 162 severe drop of the application of industrial P fertilizers visible in Figure 2a. This caused a rapid
32
33 163 decrease of the annual P balances in all French regions, which was in later years reinforced by the
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35 164 implementation of environmental policy following the successive European Common Agricultural
36
37 165 Policy reforms in 1992, 1999 and 2003 as well as the European Water Framework directive in
38
39 166 2000. From the 1980's onward, the importance of P in manure increased, particularly in regions
40
41 167 specializing in intensive livestock farming (see e.g., Brittany in figure 2c). Since livestock
42
43 168 production increasingly relied on imported feed, a considerable share of this P input originated
44
45 169 from distant regions. At the national scale (figure 2a), owing to the shift towards specialized
46
47 170 stockless crop farming in many regions, the P balance became negative around the turn of the 21st

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3 171 century, indicating the depletion of soil P reserves. Indeed, in specialized stockless crop farming
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5 172 regions, the lower input through mineral P fertilizer was not compensated by P input through
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7 173 livestock manure, leading to negative P balance (see e.g., Eure-et-Loir, Fig. 2b). Only regions that
8
9 174 have turned towards intensive livestock farming, like Brittany (figure 2c), maintained a positive P
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11 175 balance on both cropland and grassland. This regional analysis indicates the systemic interlinkage
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13 176 between P management in agriculture and the subsequent soil P balance on the one hand, and the
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15 177 level of agricultural specialization and the subsequent dependence on mineral fertilizers and
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17 178 imported concentrated feed on the other hand.
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181 **Figure 2.** P inputs and outputs on cropland (left panel) and grassland (right panel) in France (2a) and three French
 182 regions from 1850 to 2015. The regions have been selected following Le Noë et al. (2018) as representative for
 183 trajectories of specialization in intensive crop farming (2b Eure-et-Loir), intensive livestock farming (2c Brittany) and
 184 a continuously integrated crop and livestock farming (2d Loire Amont).

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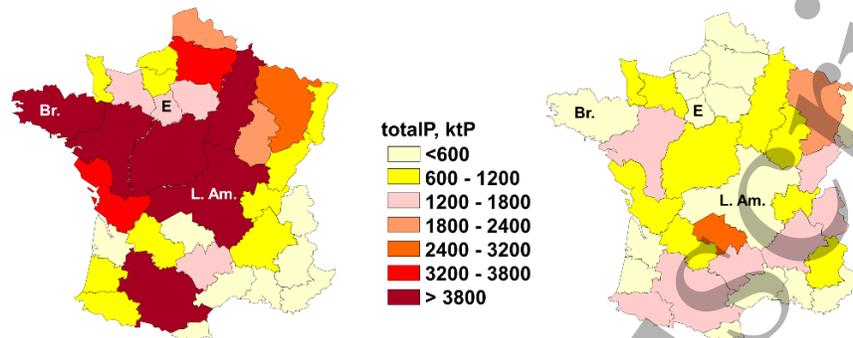
186 3.2. *Assessing the P legacy*

187 The trajectories of P fertilization had a long-lasting cumulative effect on soil P stocks. At the
188 national level, the P reserve in cropland soils has increased by c. 24% compared to the pre-
189 industrial level of 1850 (figure 3). By contrast, the level of total soil P in grassland decreased by
190 c. 8% from 1850 to 2015 as a result of sustained soil P mining until the 1960's. As shown by Sattari
191 et al (2012), this stark contrast between P legacies in cropland and grassland soils is the result of
192 the combined effect of P transfers from grassland to cropland via livestock in traditional organic
193 farming in early periods and a much lower level of mineral P fertilization on grassland in more
194 recent decades (figure 3). On average, 33% (7% to 80% across all regions) of the current P stocks
195 in French cropland soils originate from excess fertilization (including P derived from both mineral
196 fertilizers and imported feed embedded in manure), mainly from P inputs during the period from
197 1955 to 1985 (figure 3). By contrast in grassland soils, the P legacy is only 13% of total P reserves,
198 and more than 2/3 of regions show a negative cumulative P budget on grasslands. Note, however,
199 that in many regions permanent grasslands represent only a rather low fraction of total agricultural
200 area.

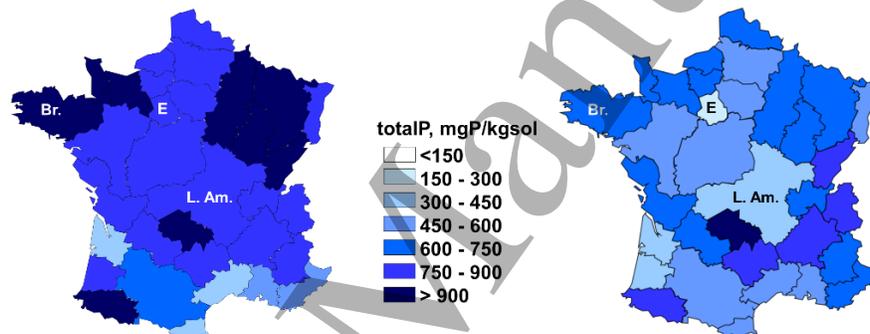
Cropland

Grassland

a. Observed 2015 total P stock



b. Observed 2015 total P content



c. % of total soil P legacy since 1850

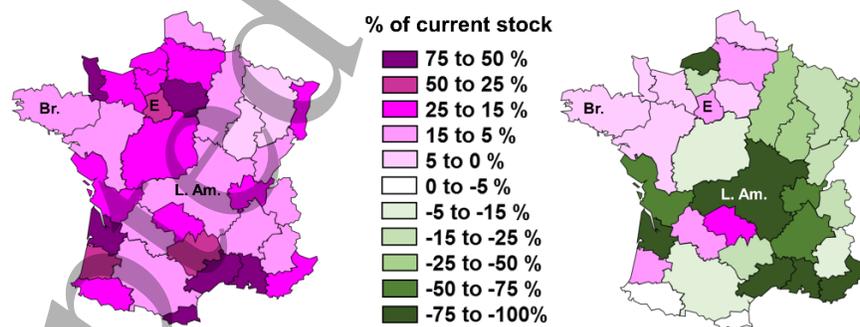
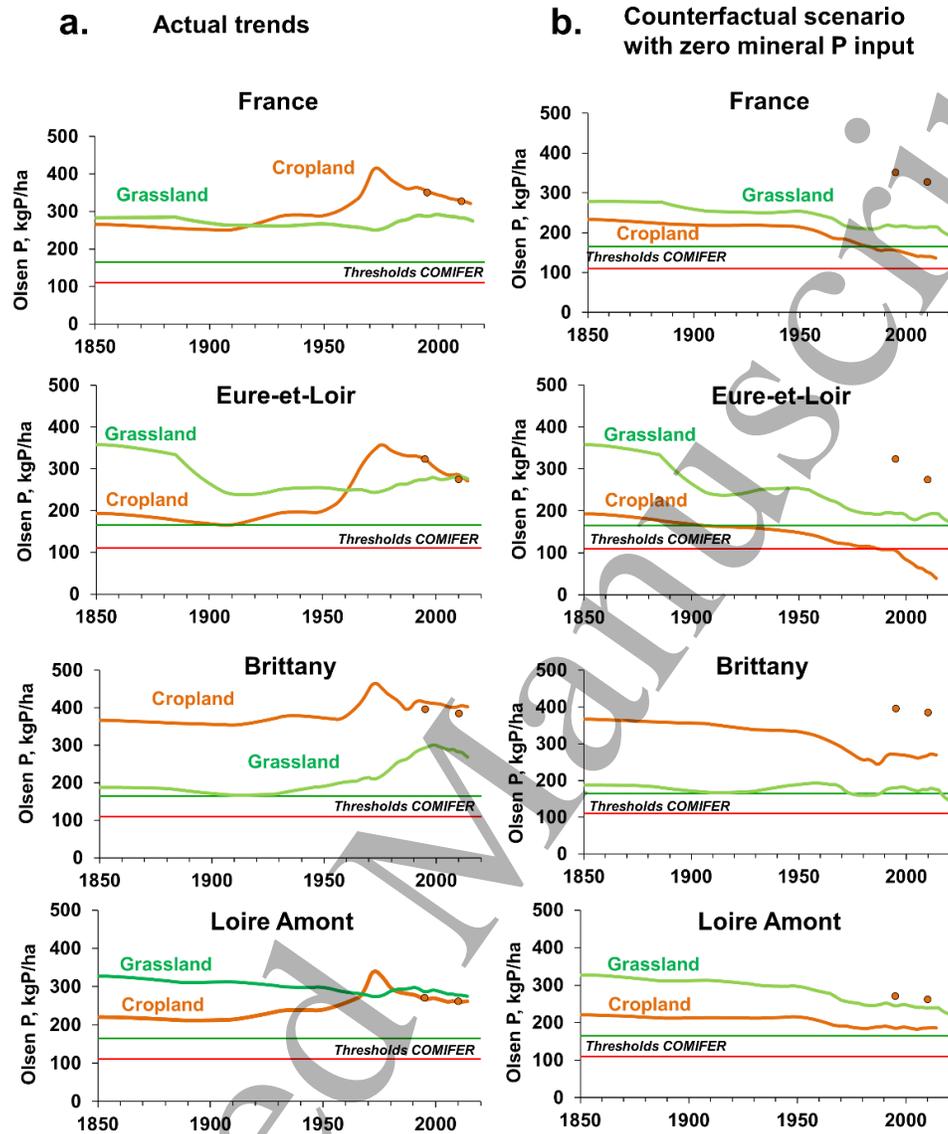


Figure 3. Total soil phosphorus (P) stock, P content and P legacy in French cropland (left) and grassland (right) soils. Current total P stock of the 30cm top soil (from Delmas et al, 2015) (3a); current total P content of the 30cm top soil (from Delmas et al, 2015) (3b) and fraction of the current P 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.

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3 208 However, while the total P stocks in agricultural soils resulting from both pre-industrial soil P and
4
5 209 the accumulation of excess fertilizer application are considerable, only 5 to 10% of these stocks
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7 210 are actually labile enough to be available for plants. Based on regional agronomical experiments,
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9
10 211 COMIFER (1995) and Arvalis (2009) have determined Olsen-P concentration thresholds below
11
12 212 which P inputs are required to sustain optimal crop production and above which additional
13
14 213 fertilization does not result in enhanced plant growth. The calculated labile soil P can then be
15
16 214 compared with these reference Olsen-P thresholds to assess the trajectory of crop- and grassland
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18 215 available P (figure 4a).

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20
21 216 We found that the labile soil P slowly decreased until the 1910's in cropland and until the 1940's
22
23 217 in grassland soils (figure 4a). Beginning after World War II and at a rapid pace in the 1950s and
24
25 218 1960's, labile soil P contents increased to reach in the 1980s a level c. two times above the upper
26
27 219 threshold identified by COMIFER, indicating that the application of P fertilizers could be
28
29 220 completely abandoned in most French regions. Owing to a high pre-industrial P level, possibly due
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31 221 to significant long-term P transfers from forest soils through animal manure (McGrath et al 2010;
32
33 222 Gimmi and Bürgi 2007), or, in some regions, due to alteration over geological time of bedrock rich
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35 223 in phosphate, P availability for plant nutrition was apparently always sufficient in cropland and
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37 224 grassland soils at the regional scale in the study period.

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40 225 However, a simple hypothetical and counterfactual scenario, assuming no mineral P fertilizer
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42 226 inputs over the whole period, all other things remaining equal, reveals that French agriculture
43
44 227 would have continuously depleted soil P reserves to a level below the scarcity threshold, in regions
45
46 228 specialized in stockless crop production (figure 4b). Therefore, mineral P imports did indeed
47
48 229 prevent French agriculture from facing P scarcity as they were of critical importance for enabling
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50 230 the specialized and highly productive agriculture in the late 20th century.
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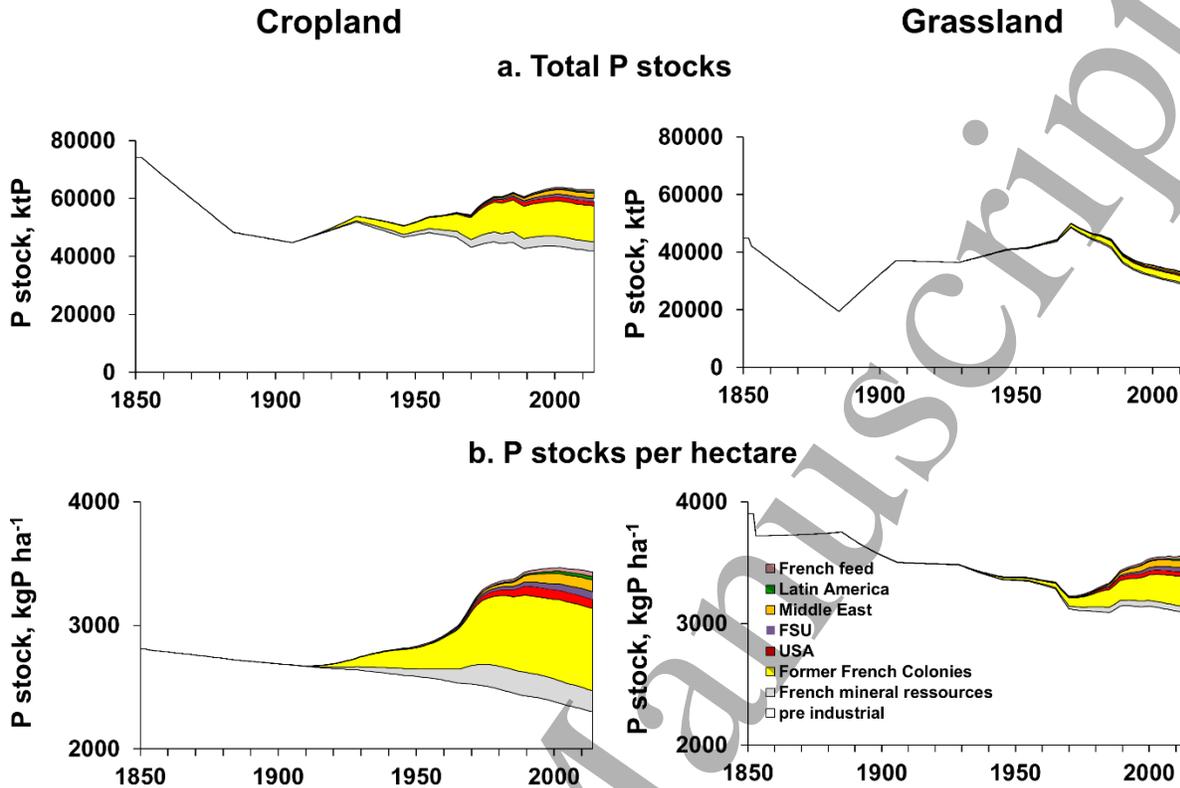
231
232 **Figure 4a.** Olsen-P content of cropland and grassland soils in France and three French regions from 1850 to 2015, as
233 calculated by the DPPS model, compared with average Olsen-P values observed in cropland soils (orange dots; 10-
234 year averages for 1994-2004 and 2005-2015 sourced from Gouny et al 2016), and with the recommended threshold
235 values for P fertilization by COMIFER (1995) and Arvalis (2009). The red line indicates the threshold value of Olsen
236 P content in soil below which fertilization should be intensified while the green line indicates the threshold value of
237 Olsen P content in soil above which fertilization could be abandoned. **4b.** Same calculation for a counterfactual
238 scenario assuming no input of mineral fertilizer, but the same crop or grass production, since the beginning of the
239 period.

241 3.3. *Origins of soil P*

242 The inputs of P into French soils stem mainly from two types of sources: animal manure and
243 mineral fertilizers. Animal manure inputs are either related to recycling of P from regionally grown
244 crops, the local transfer of P from grassland to cropland in mixed farming systems or the long-
245 distance transfer of P via feed from arable land in other French regions or foreign countries (Nesme
246 et al 2018; Le Noë et al 2016, 2017). Our findings suggest that the continuous transfer of P from
247 grassland to cropland soils has contributed to a depletion of P reserves in grasslands (figure 3)
248 while the massive export of soybeans from Latin America to France and other countries with
249 intensive livestock production is a matter of increasing concern for soil fertility in these regions
250 (Pengue 2005). The by far largest fraction of current legacy P stocks in cropland and grassland
251 soils in all French regions, however, originates from mineral fertilizers applied in the past century
252 (on average 32% and 12% of current cropland and grassland P stocks, respectively). This mineral
253 P originated from different sources in different periods of the 20th century (see SOM 2, figure S10).
254 The import of P rock from French colonies or protectorates in North and West Africa began in the
255 first decades of the 20th century to provide considerable amounts of P for French agriculture, and
256 continues today. The French super-phosphate industry, relying on P rock imports from Africa,
257 peaked in the 1970's. After the first oil price shock and the decline of the French steel industry in
258 the 1970s and 1980s, direct import of processed phosphates gradually displaced domestic
259 production, as the countries operating to phosphate mines began to develop their own fertilizer
260 industries.

261 At the national scale, 20% and 7% of current soil P reserves in cropland and grassland respectively
262 originate from the Maghreb and sub-Saharan countries (Former French colonies or protectorates,
263 figure 5). By contrast, the pre-industrial soil P reserves, i.e., the P stocks originating from 1850,

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3 264 before mineral fertilization was introduced, constantly decreased over the 1850-2015 period. In
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5 265 regions with intensive livestock farming also the P contained in imported feed from Latin America
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7 266 presents a significant contribution to the current soil reserve (c. 6 % in Brittany, see SOM 2 figure
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9 267 S11). The high significance of imports of P resources from countries of the Global South makes
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11 268 the P legacy also an issue in the debate about ecologically unequal exchange, which is concerned
12
13 269 with unbalanced flows of biophysical resources between countries and the subsequent
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15 270 externalization of environmental burdens associated with extraction and production of these
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17 271 resources (Hornborg 2009; Roberts and Parks 2009). Our analysis of the significance of imports
18
19 272 of P resources echoes findings from studies which analyzed ecologically unequal exchange
20
21 273 patterns of the trade between France and its former colonies and protectorates (Infante-Amate and
22
23 274 Krausmann 2019; Magalhães et al 2018), and hints at issues of environmental (in)justice related
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25 275 to phosphorus distribution and use.
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278 **Figure 5.** Geographical origins of total P stocks (5a) and P stocks per hectare (5b) of cropland (left panel) and
279 grassland (right panel) soils in France from 1850 to 2015. The geographical origins concern mineral fertilizer and
280 imported feed. Pre-industrial soil P origin refers to the total P stocks estimated for 1850 (Note that in 5b that the Y-
281 axis of the graphs does not start at zero).

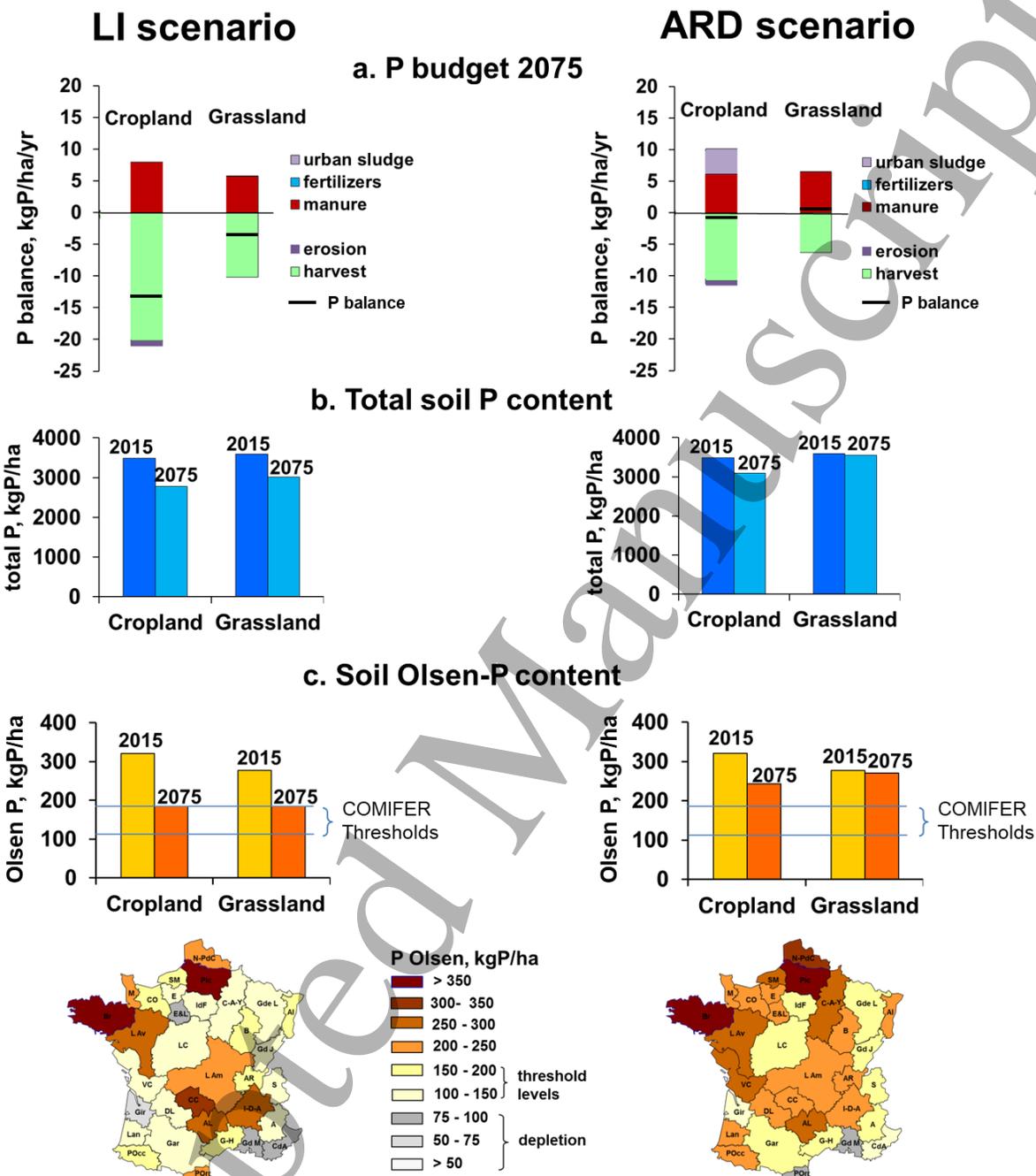
282 3.4. P legacy and the transition towards low input agriculture

284 Exploring two contrasted scenarios of agricultural trajectories at the 2075 horizon enables to assess
285 how the soil P stocks – largely inherited from mineral P resources imported from former French
286 colonies and protectorates – could contribute to improving agriculture sustainability and a fairer
287 distribution of global P resources. Results from model simulation reveal that in the low input
288 scenario, P inputs through manure (figure 6a) and the release of plant available P from the
289 accumulated legacy would be large enough to sustain crop requirements at least until 2075 (figure

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3 290 6c). However, the pursuit of significantly negative P budgets (figure 6a) would ineluctably lead to
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5 291 a declining level of soil available P until it would eventually fall below the lower threshold at
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7 292 which fertilization is required to avoid crop limitation. The first regions in which the P level would
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9 293 fall below the minimum Olsen P threshold as defined by COMIFER (1995) are those with stockless
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11 294 and intensive cropping systems between 2030 and 2065 (see SOM3), indicating that the
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13 295 replenishment of the available soil P pool would not be rapid enough to sustain crop requirements
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15 296 in these regions. In order to prevent a decline of crop yields, fertilizer application would have to
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17 297 resume. Our calculations indicate that over the whole period from 2016 to 2075, an average
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19 298 mineral P fertilizer input of 60 ktP yr⁻¹ would be required to keep all regions above the minimum
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21 299 threshold. This requirement would increase over time from c. 42 ktP yr⁻¹ over the 2016-2026 period
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23 300 to 87 ktP yr⁻¹ over the 2065-2075 period, i.e. the dependency would grow. While in the low input
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25 301 scenario the legacy benefit would gradually be used up, the average mineral P input requirement
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27 302 is still 60% lower than the current average P application rate. Adjusting P inputs to actual crop
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29 303 requirements by making use of the P legacy, could, therefore, contribute to further decrease the
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31 304 dependency on imported mineral P fertilizers while maintaining an adequate level of available soil
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33 305 P without a loss of agricultural productivity in all French regions.

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35 306 Our analysis of the Autonomous/Reconnected/Demitarian scenario indicates even more promising
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37 307 results. At the scale of France, the total cropland soil P reserves would slightly decrease until the
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39 308 2060's before stabilizing at a new equilibrium, while they remain at a constant level on grassland
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41 309 (figure 6b and c, see also data depository). In spite of the initial decline, cropland P reserves would
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43 310 not fall below a level critical for production since the level of labile soil P simulated by the DPPS
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45 311 model always remains above the lower P-Olsen threshold in all but two and three regions for
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47 312 cropland and grassland, respectively. Furthermore, in the vast majority of regions, labile P in
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3 313 cropland and grassland even remains above the upper threshold. While the regional results may
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5 314 conceal P scarcity at the farm/parcel level in cases where the P legacy is unevenly distributed at
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7 315 the intra-regional scale , our simulation of average labile soil P at the regional level suggests that
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9 316 in general it should be possible to abandon mineral P fertilization and fully replace it by closing
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11 317 local P loops through the use of manure and human excreta. These results indicate that a
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13 318 restructuring of the agro-food system is feasible with respect to P availability.
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 321 **Figure 6.** P inputs and outputs in 2075 (6a); Total soil P in 2015 and 2075 (6b); Soil P-Olsen in 2015 and 2075 (6c)
 322 in cropland and grassland for two prospective scenarios assuming (i) Low Inputs (LI) with zero mineral P fertilization
 323 (left panels); and (ii) deep reconfiguration of the food system towards Autonomy, Reconnexion and Demitarian diet
 324 (ARD) from 2015 onwards (right panels).

326 **4. Conclusion: lessons from the French case**

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

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17 355 **Data availability statement**

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19 356 The data that support the findings of this study are openly available at DOI.
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23 358 **References**

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