



Phosphorus plant removal from European agricultural land

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Abstract

Phosphorus (P) is an important nutrient for all plant growth and it has become a critical and often imbalanced element in modern agriculture. A proper crop fertilization is crucial for production, farmer profits, and also for ensuring sustainable agriculture. The European Commission has published the Farm to Fork (F2F) Strategy in May 2020, in which the reduction of the use of fertilizers by at least 20% is among one of the main objectives. Therefore, it is important to look for the optimal use of P in order to reduce its pollution effects but also ensure future agricultural production and food security. It is essential to estimate the P budget with the best available data at the highest possible spatial resolution. In this study, we focused on estimating the P removal from soils by crop harvest and removal of crop residues. Specifically, we attempted to estimate the P removal by taking into account the production area and productivity rates of 37 crops for 220 regions in the European Union (EU) and the UK. To estimate the P removal by crops, we included the P concentrations in plant tissues (%), the crop humidity rates, the crop residues production, and the removal rates of the crop residues. The total P removal was about 2.55 million tonnes (Mt) (± 0.23 Mt), with crop harvesting having the larger contribution (ca. 94%) compared to the crop residues removal. A Monte-Carlo analysis estimated a $\pm 9\%$ uncertainty. In addition, we performed a projection of P removal from agricultural fields in 2030. By providing this picture, we aim to improve the current P balances in the EU and explore the feasibility of F2F objectives.

Keywords Phosphorus budget · Plant uptake · Farm to Fork · Nutrients · Crop production · Phosphorus removal · Food security

1 Introduction

Nitrogen (N), phosphorus (P), and potassium (K) are essential nutrients for plant growth. They are uptaken by the crops from soil and have to be replenished by mineral or organic fertilisers to meet crop demand (Schoumans et al. 2015). Without the fertilization of those nutrients, the agricultural crop production would be limited and soil mined.

The food production in Europe is dependent on imported P fertilizers, but is often inefficient and its losses to the

environment are high (Ott and Rechberger 2012). The farmers in the EU were using more P fertilizers than the crop needs until the first decade of 21st century (Schoumans et al. 2015). Western Europe was the largest consumer of P fertilizers per unit of agricultural land during the period of 1961–2012 (Schoumans et al. 2015). However, there has been a decline in P fertilizer use rate in Europe during the last years compared to the 1980's (Lu and Tian 2017). A P surplus in agricultural soils can lead to environmental pollution like the eutrophication of freshwaters (Dupas et al. 2015). Therefore, it is important to reduce excessive use of mineral and organic fertilizers while ensuring enough food production.

However, depending on soil properties (pH, soil organic carbon, etc.) and the weathering processes, the added P undergoes various reactions (e.g. precipitation, adsorption), transforming it into increasingly less soluble forms that reduce its availability to plants (Roberts and Johnston, 2015). This sorbed P fraction is subsequently vulnerable to be lost from the soil due to soil erosion by water (Carpenter and Bennett 2011) as it is transported by sediments.

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The European Commission Joint Research Centre (JRC) is managing the largest pan-European topsoil survey named Land Use/Cover Area frame Survey (LUCAS) by collecting more than 20,000 samples every three years and analysing them for physical and chemical properties (Orgiazzi et al. 2018). Soil nutrients are among the analysed parameters of LUCAS allowing to assess their spatial distribution in European soils (Ballabio et al. 2019). Therefore, the LUCAS topsoil surveys and the modelled assessments allow to better monitor the status and trends of soil nutrients and identify hotspots in the EU.

P is uptaken by plants and is removed from soils when crops are harvested or grass is grazed (OECD 2007). Understanding and quantifying the phosphorus needs in agriculture at large scales (e.g. country, continent) is important for better management of fertilization, phosphate market requests and identification of the potential risk of eutrophication (Carpenter 2008).

Therefore, the objectives of this study are to (a) investigate the main outputs of P budget in the European agricultural soils; (b) map the P removal both by crop harvesting and residues and (c) develop a framework to ingest statistical crop data and produce a regional (spatial explicit) P output dataset. Finally, we consider scenarios of nutrients reduction relevant to recent policy developments in the EU legislation, such as the F2F Strategy.

1.1 Policy framework

The F2F Strategy is at the heart of the EU Green Deal, aiming at making food systems fair, healthy and environmentally friendly (European Commission 2020). The F2F Strategy addresses the challenges of sustainable food systems and recognizes the inextricable links between healthy people, healthy societies and a healthy planet (European Commission 2020). One of the objectives of the F2F Strategy is to reduce the excess of nutrients (nitrogen and phosphorus) in the environment and limit the excessive use of fertilizers. The aim is to reduce nutrient losses by at least 50% while ensuring no deterioration in soil fertility (Montanarella and Panagos 2021). The strategy proposes to reduce the use of fertilizers by at least 20% by 2030.

To reach this objective, the EU Member States will identify nutrient load reductions and apply balanced fertilization and sustainable nutrient management. Therefore, an integrated nutrient management action plan is necessary to achieve such ambitious objectives without limiting food security and soil fertility. In this policy context, it is important to investigate whether such ambitious targets will influence food security and agricultural production in the EU. Some first results show that reduced agricultural inputs (fertilizer, pesticides, land, and antimicrobials) could reduce agricultural production by 12% (Beckman et al. 2021) in the EU.

2 Materials and methods

2.1 Study area

The study area includes all agricultural lands in the EU and the UK. These cover about 41.5% of the total land area, estimated to be about 180 million hectare (Mha). About 9.3 Mha of agricultural land are set aside (agricultural land which is not cultivated for conservation purposes); therefore, the area of investigation is about 170 million ha (Fig. 1).

The fraction of the total area occupied by agricultural land is not equally distributed among European countries. For example, in Ireland, the Netherlands, and Denmark more than ¾ of total land is occupied by agriculture (Fig. 1), while this share is less than ¼ in Malta, Finland and Sweden (Fig. 1), showing substantial variations between countries (Panagos et al. 2021).

2.2 Available phosphorus in EU agricultural soils

Based on 20,000 samples of LUCAS topsoil survey, we modelled the spatial distribution of P available in EU agricultural soils (Fig. 1).

There is a high variability of P available in the EU agricultural topsoils with the Mediterranean basin having low availability ($< 25 \text{ mg P kg}^{-1}$), while the North-western part of the EU showing saturation ($> 50 \text{ mg P kg}^{-1}$). According to literature findings (Bai et al. 2013; Fischer et al. 2017; Sharpley et al. 2012), the critical Olsen-P for crop production could be in the range of $18\text{--}25 \text{ mg kg}^{-1}$, the optimal level in the range of $25\text{--}50 \text{ mg kg}^{-1}$, while saturation over 50 mg kg^{-1} . Agricultural soils saturated with P ($> 50 \text{ mg kg}^{-1}$) are about 13% of the study area (Fig. 1), where farmers should apply fertilization and manure inputs with care. For the agricultural soils with a P deficit (28% of the study area), it is important to preserve soil fertility with P inputs balancing the crop uptakes and exportation.

2.3 Empirical model for phosphorus balance

We have developed an accounting framework through an empirical model for phosphorus balance (EMPBa), which is based on the Eq. (1):

$$\text{Phosphorus budget} = \text{P_Fert} + \text{P_Man} + \text{P_Atm} - \text{P_Grain} - \text{P_Res} - \text{P_Eros} \quad (1)$$

where.

- P_Fert is the input of fertilizer;
- P_Man is the input from manure application;
- P_Atm is the input from atmospheric deposition;
- P_Grain the output from crop harvesting;

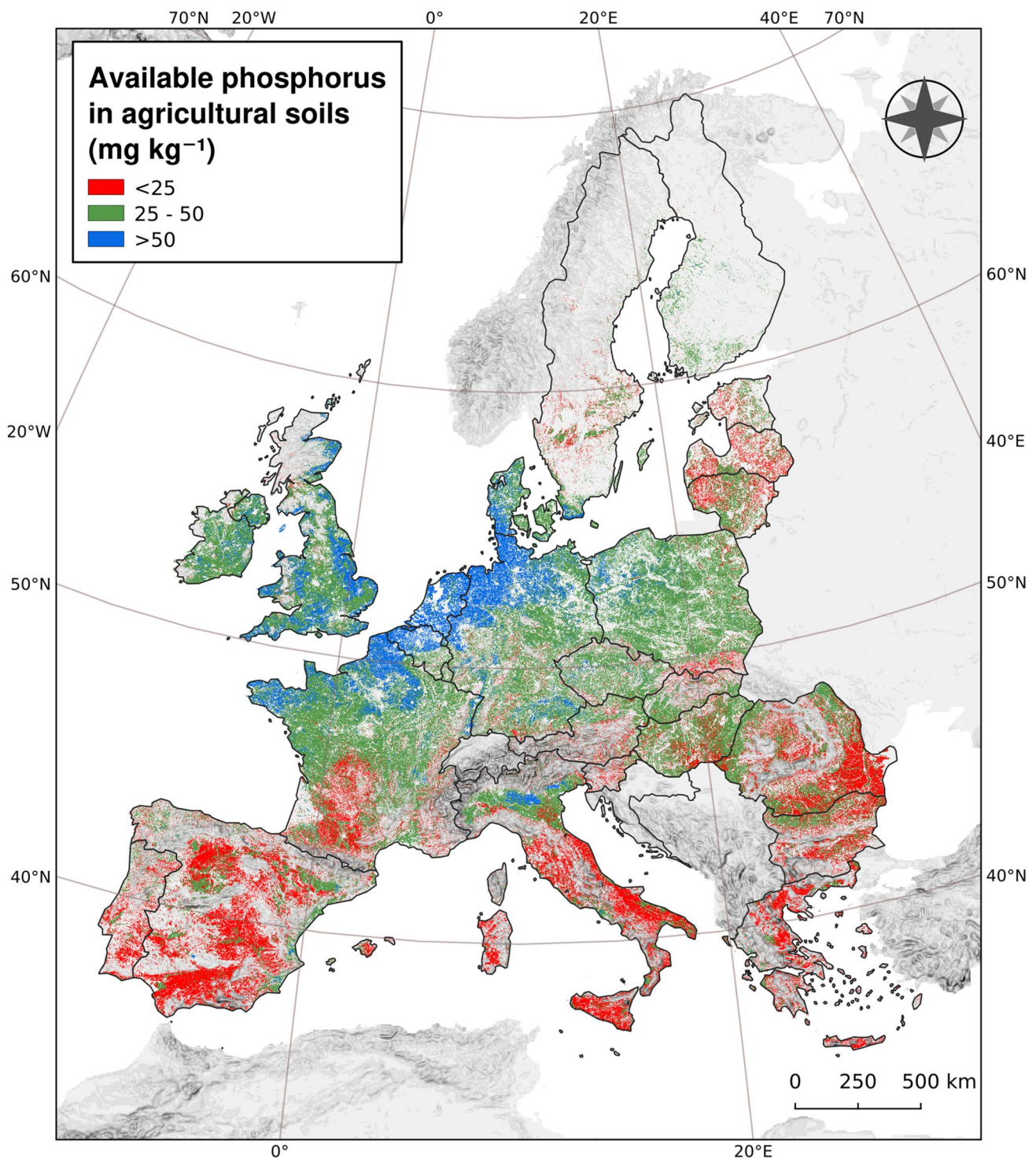


Fig. 1 Available phosphorus in agricultural soils of the EU and UK (modified from Ballabio et al. 2019)

- P_Res the output with crop residues removal;
- P_Eros the phosphorus losses due to water erosion.

The unit in Eq. (1) is in tonnes. The EMPBa takes into account the more disaggregated datasets at the EU level that

may differ in scales (from a regional to country level and to continental [European]). In the current study, we illustrate the P outputs by crop harvesting and by residues removal. Therefore, we estimate the P_Grain and the P_Res terms of the Eq. (1) since they are the main P outputs (Smil 2000).

The rest of the variables in Eq. (1) and the P balance are not addressed in this study. The P inputs in the Empirical Model for Phosphorus Balance (EMPBa) comes from are the fertilizer and manure inputs and the atmospheric deposition as well.

At the technical level, the EMPBa implementation is based on Free and Open Source Software (FOSS). We have used the GNU/Linux, which is hosted by the Big Data Analytics Platform (BDAP-JEODPP) of the European Commission JRC infrastructure (Soille et al. 2018). The R programming language is adopted for data analysis, harmonization, statistical computing, and graphics visualization. Mapping of research results was conducted with QGIS. As some of the results will be presented at regional scale, here we refer to the 220 EU regions which are regularly named as NUTS2 (Nomenclature of the Territorial Units for Statistics), where regional EU policies are applied (Panagos et al. 2013).

As data come from multiple sources (EUROSTAT, modelling, literature), their harmonization is an important step to make them interoperable. The results are obtained through a scripts sequence in order to achieve the reproducibility of the research. In addition to the harmonization by crop category, the spatial matching of different source datasets is necessary. As the input data are available for the most detailed level (regional level—NUTS2), data aggregation into higher hierarchical spatial statistical units (countries, continental) can be realized.

2.4 Modelling crop P outputs with harvesting

Phosphorus is essential for plant growth and development, especially in the early growing phases (White and Hammond 2008). P is removed from soils by harvesting the biomass and mowing the pastures (MacDonald et al. 2011). Each crop has a different P removal depending on P tissue concentration and the fraction of biomass harvested (Ohm et al. 2017). However, values may a broad range in scientific and technical literature. Therefore, we used consistent databases and assimilated JRC products, combined with literature findings to estimate the P removal of crops in agricultural soils (Table 1).

Common Agricultural Policy Regional Impact Analysis (CAPRI) includes a detailed database with production statistics for 37 cropping activities in circa 220 EU regions (Panagos et al. 2021). In a first step, we calculated the regional crop production by multiplying the mean crop production rates (Cpr) with the Agricultural utilized area (AUA) per crop. In a second step, we calculated the P removal by multiplying the total production (in tonnes), the dry matter content, and P concentration by each specific crop.

To estimate this removal, we developed a script that combines:

- Crop type
- Crop production ($t\ ha^{-1}$ as fresh matter) (**Cpr**)
- Agricultural Utilized Area (ha) (**AUA**)
- Humidity rate (%) (**Hum**)
- P concentration (%) in plant tissue as dry production (**Pc**)

$$P_CropUptake\ (tonnes) = Cpr \times AUA \times (1 - Hum) \times Pc \quad (2)$$

$$P_Grain = \sum_{n=1}^{37} (P_CropUptake) \quad (3)$$

The mean crop production rates (Cpr) originates from the Common Agricultural Policy Regional Impact Analysis (CAPRI) model, with reference year 2016. However, the crop production rates were also compared with those from Eurostat and data from the Crop Growth Monitoring System (CGMS) used in Monitoring Agricultural Resources (MARS) (Biavetti et al. 2014). In addition, we used the Agricultural utilized area (AUA) per crop and region from CAPRI.

The humidity rates, used to convert the total production to dry matter, were retrieved from Eurostat statistics (Supplementary material Table S1). Cereals, oilseeds, dry pulses, and protein crops have a moisture content generally ranging between 10% and 14%, while the plants harvested green have a high moisture content (55–80%) (Eurostat 2020a).

It is important that farmers have a good knowledge of plant nutrient requirements in order to apply the necessary P fertilization. According to the literature, the P concentrations in well-fertilized plants approximate 0.4–1.5% of the dry matter (Broadley et al. 2004).

The P concentration for the different crops (Pc in Table 1) stems from a non-exhaustive literature review of field experiments (Fageria et al. 2013; Gallet et al. 2003; Rideout and Gooden 2000; Piccoli et al. 2021; Morari et al. 2008; Giardini 2002), compiled data from national research institutions (e.g. INRA) (Ehlert et al. 2009; Sauviant et al. 2004) and regional nutrient regulations and fertilizer recommendations (Palese et al. 2012; Veneto Agricoltura 2020). Most P concentration are derived from crops grown in Europe (Italy, France, Netherlands, and Switzerland), nevertheless, crop specific literature from the US (tobacco) and Brazil (rice, corn, soy, beans) was also included due to otherwise limited information for these crops. The crop concentration coefficients are expressed on the dry matter. Where multiple values were available, the weighted average is calculated with the number of samples serving as weights (eq. 4).

Table 1 Phosphorus concentration of marketable crop products (based on literature reviews)

	P concentration (%) on dry matter yield (P _c)	Standard deviation (SD of P _c)	No of samples	References	Comment
<i>Cereals</i>					
Soft wheat	0.3559	0.0594 ^a	332	Gallet et al. (2003), Sauv- vant et al. (2004), Piccoli et al. (2021) and Ehlert et al. (2009)	
Durum wheat	0.3881	0.0571 ^b	1	Sauvant et al. (2004)	
Rye and meslin	0.3597	0.0023 ^a	52	Sauvant et al. (2004) and Ehlert et al. (2009)	
Barley	0.4058	0.0245 ^a	289	Gallet et al. (2003), Sauvant et al. (2004) and Ehlert et al. (2009)	
Oats	0.4392	0.0076 ^a	102	Sauvant et al. (2004) and Ehlert et al. (2009)	
Grain maize	0.2380	0.0484 ^a	317	Sauvant et al. (2004), Fage- ria et al. (2013), Piccoli et al. (2021) and Giardini (2002)	
Other cereals	0.3559	0.0594 ^a	332	Gallet et al (2003), Sauv- vant et al. (2004) and Ehlert et al. (2009)	Similar to wheat
Paddy rice	0.2072	0.0144 ^a	4	Sauvant et al. (2004) and Fageria et al. (2013)	
<i>Oilseeds</i>					
Rape	0.7030	0.0121 ^a	169	Gallet et al. (2003), Sauvant et al. (2004) and Ehlert et al. (2009)	
Sunflower	0.5806	0.0968 ^b	1	Sauvant et al. (2004)	
Soya	0.5842	0.0493 ^a	174	Gallet et al. (2003), Sauvant et al. (2004) and Fageria et al. (2013)	
Other oils	0.58				
<i>Other arable</i>					
Pulses	0.4970	0.0466 ^a	52	Sauvant et al. (2004), Ehlert et al. (2009) and Fageria et al. (2013)	
Potatoes	0.2375	0.0312 ^a	349	Gallet et al. (2003), Sauvant et al. (2004) and Ehlert et al. (2009)	
Sugar beet	0.1742	0.0279 ^a	263	Gallet et al (2003), Ehlert et al. (2009) and Legnaro (2009)	
Flax and hemp	0.6913	0.071 ^c	7	Ehlert et al. (2009)	
Tobacco	0.2489	0.01 ^c	8	Rideout and Gooden (2000)	
Other industrial crops	0.6				
Other crops	0.4				
<i>Vegetables</i>					
Tomatoes	0.4				
Other vegetables	0.4874	0.104 ^c	190	Ehlert et al. (2009)	Based on the values for cabbage, cabbage turnip, onion, broccoli, ice lettuce, spinach
Nurseries	0.1457	0.04 ^c	38	Ehlert et al. (2009)	

Table 1 (continued)

	P concentration (%) on dry matter yield (Pc)	Standard deviation (SD of Pc)	No of samples	References	Comment
Flowers	0.2142	0.03 ^c	271	Ehlert et al. (2009)	Based on Anemone, Dahlia, Fritillaria, Gladiolus, Hyacinth, Iris, Crocus, Lily, Tulip, Tantedeschia
New energy crops (ligneous)	0.48				
<i>Fodder</i>					
Fodder maize	0.2111	0.1205 ^a	18	Ehlert et al. (2009) and Legnaro (2009)	
Fodder root crops	0.2185	0.042 ^b	19	Ehlert et al. (2009)	Based on forage beet
Fodder other on arable land	0.2111			Ehlert et al. (2009) and Gallet et al (2003)	Similar to fodder maize (found in Legnaro experimental site)
<i>Permanent crops</i>					
Apples pears Peaches	0.185			Emilia et al. (2018)	
Other fruits	0.185				
Citrus fruits	0.185				
Grapes	0.220			Veneto Agricoltura (2020)	
Olives	0.104			Palese et al. (2012)	
<i>Pastures</i>					
Intensive	0.3616	NA	152	Gallet et al. (2003)	We used the same SD as the extensive pastures
Extensive	0.2613	0.0553 ^a	198	Gallet et al. (2003) and Sauvant et al. (2004)	

^aWeighed standard deviation (stdev) based on the numbers of samples from the sources. Values from Sauvant et al. (2004) were treated as one sample

^bSD provided by the reference

^cAverage stdev calculated from the stdv of the crops considered

$$\text{Formula for the weighted mean } \bar{x} = \frac{\sum_{i=1}^n w_i x_i}{\sum_{i=1}^n w_i} \quad (4)$$

w = number of observations as weights, x = value of observation, \bar{x} = weighted average.

For these weighted averages, the standard deviations are also weighed based on the formula:

$$\text{Formula for the weighted standard deviation } sd_w = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x}_w)^2}{\frac{(N'-1) \sum_{i=1}^n w_i}{N'}}} \quad (5)$$

w = number of observations as weights, x = value of observation, \bar{x} = weighted average, N' = number of non-zero observations.

The P concentrations (%) on dry matter vary from high values as oilseeds (ca. 0.58–0.70%) to lower ones as in fruits (0.07%) or fodder crops (0.21%).

2.5 Modelling P removal with crop residues

Crop residue is defined as the non-edible plant parts that are left in the field after harvest (Lal 2005). Crop residues include straw, head leaves and stems. Part of the residues remain in agricultural field enhancing soil organic carbon (Lugato et al. 2014) and protecting against soil erosion (Borrelli and Panagos 2020). Part of the crop residues are removed from the field for livestock feeding or bioenergy production (Scarlat et al. 2010). The removal of crop residues contributes to P uptake from soils (Erinle et al., 2018), but this is rarely taken into account when estimating the P budget (Damon et al. 2014). The P uptake with crop residues removal was calculated as:

$$P_Res \text{ (Tonnes)} = Rres \times (Cpr \times AUA) \times (1 - Hum) \times Rrem \times Pcr \quad (6)$$

where.

- **Rres** is the ratio of residue production per tonne of crop production
- **Rrem** is the ratio of residues removal from the field
- **Pcr** is the P concentration of residues (%)
- **Cpr** is the crop production (t ha^{-1} as fresh matter)
- **AUA** is the Agricultural utilized area (ha)
- **Hum** is the Humidity rate (%)

The ratio of residue production per tonne of crop production (**Rres**) (Table 2) is derived from experimental sites and works (García-Condado et al. 2019; Scarlat et al. 2010) and it shows a high variation between crops (Table 2). The **Rres** was also compared with other literature studies (Aboudrare et al. 2006; Johnosn et al. 2006; Kadam and McMillan 2003).

Similar to other research reviews on this topic (Cherubini and Ulgiati, 2010; Scarlat et al. 2010; Kadam and McMillan 2003), we also estimated that roughly half of the annual amount of crop residues (mostly cereal straw) is removed from agricultural soils. Therefore, the ratio of residues removal from agricultural fields is around 50% for cereals and 20% for oilseeds (with a SD of 10% for both). We also assumed that the mean P concentration from plant residues is around 0.11% with a standard deviation of $\pm 0.4\%$.

2.6 Uncertainty

The estimated P crop removal has uncertainty due to the variability in crop production, humidity rates, and the P concentration of plant tissues. The SD of P uptake (Table 1), the variability in humidity ($\pm 10\%$) (Supplementary material, Table S1), and the standard deviation in crop production,

obtained from time-series statistics, were used as inputs for the uncertainty analysis.

We ran Monte-Carlo simulations (1000 drawings) within region and crop type to estimate the standard deviation for P crop uptake. As Monte-Carlo is an important method for uncertainty analysis, this serves to put some confidence in the output results (Janssen 2013).

The Monte-Carlo analysis estimated the uncertainty of plant harvesting based on the following probability density functions (SD stands for standard deviation of each parameter):

$$\begin{aligned} \text{Uncertainty} = & \text{rnorm}(n, \text{Cpr}, \text{SD_Cpr}) \\ & \times \text{rnorm}(n, \text{Pc}, \text{SD_Pc}) \\ & \times \text{rnorm}(n, 1 - \text{Hum}, \text{SD_1} - \text{Hum}) \\ & \times \text{rnorm}(n, \text{Area}, \text{Area} \times 0.1) \end{aligned} \quad (7)$$

3 Results

3.1 Crop production in the EU

The crop production in the European Union (EU) and the UK in 2016 added up to approximately 300 Mt of cereals cultivated in 57 Mha (mean 5.3 t ha^{-1}), 33 Mt oilseeds cultivated in 12.5 Mha (mean 2.6 t ha^{-1}), 185 Mt of other arable crops, 93 Mt of vegetables cultivated in 2.6 Mha, 665 Mt of fodder crops (mean 31.4 t ha^{-1}), 70 Mt of fruits (mean 6 t ha^{-1}) and 1,280 Mt of grass production (Figs. 2, 3).

In the EU and the UK, 80% of the area where cereals are grown is covered by soft wheat, barley, and grain maize (Fig. 3), with total production of 140 Mt, 60 Mt and 62 Mt, respectively. Potatoes and sugar beets (category

Table 2 Ratios of residue production and residue removal used for calculating P removal with crop residues

	Ratio of residue production per tonne of crop production (Rres)	Ratio of residues removal from the field (Rrem)	% P on dry matter of residues (Pcr)
<i>Cereals</i>			
Soft wheat	0.96	0.5	0.11
Durum wheat	0.96	0.5	0.11
Rye and meslin	1.13	0.5	0.11
Barley	0.94	0.5	0.11
Oats	1.08	0.5	0.11
Grain maize	0.99	0.5	0.11
Other cereals	0.96	0.5	0.11
Paddy rice	1.52	0.5	0.11
<i>Oilseeds</i>			
Rape	1.74	0.2	0.11
Sunflower	2.47	0.2	0.11
Soya	1	0.2	0.11

Other outputs such as the soil loss by water and wind erosion are not yet taken into account in this study

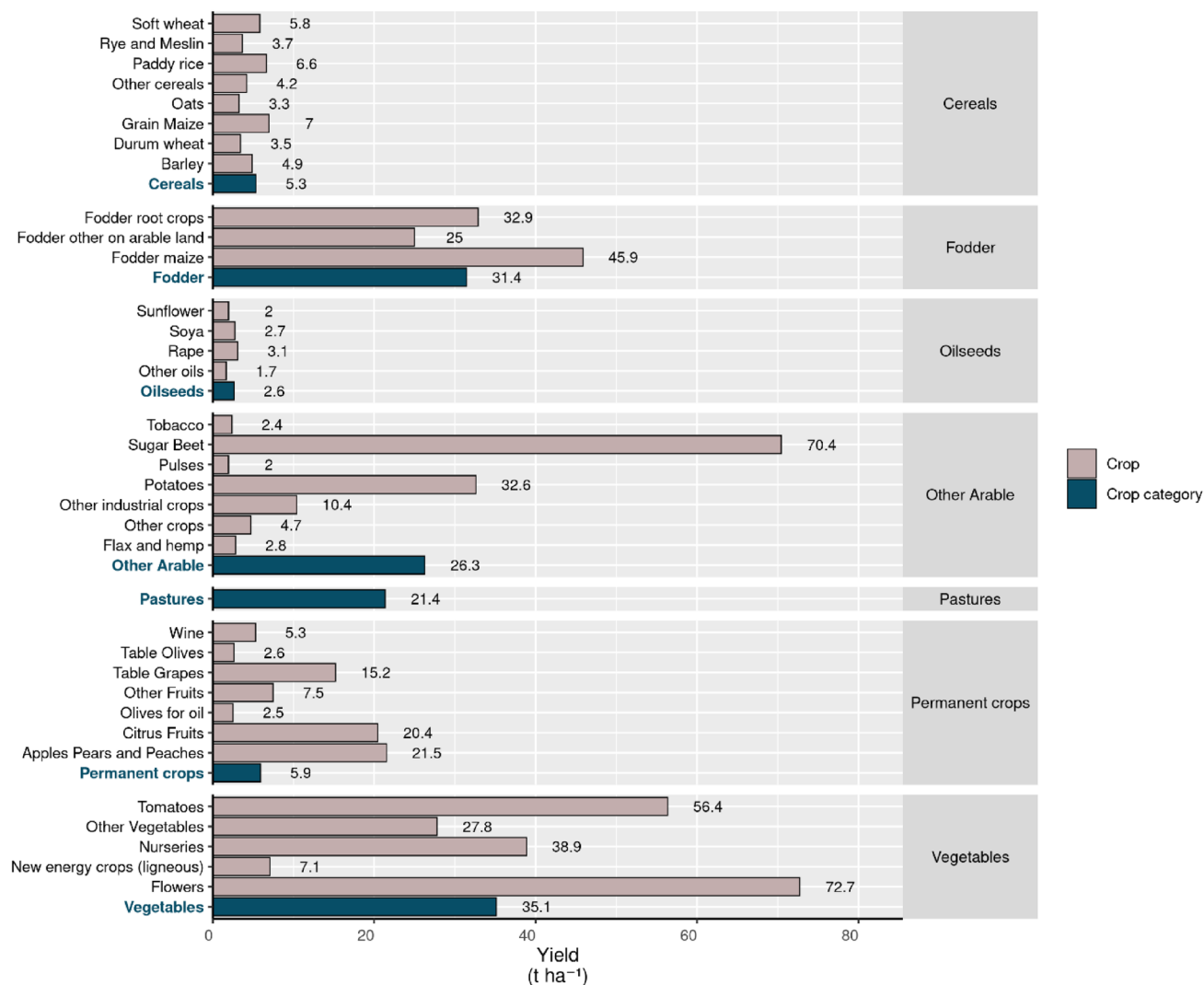


Fig. 2 Mean annual crop productivity (t ha⁻¹ as standard humidity) for major crop categories (cereals, fodder, other arable, oilseeds, permanent crops, vegetables and pastures) and the main crops in the EU and the UK

“other arable”) are harvested on 3 Mha (Fig. 3). The EU and the UK produced 120 Mt of sugar beets (mean 70 t ha⁻¹), and 53 Mt of potatoes (mean 32 t ha⁻¹). More than half of the oilseed category is represented by rape (Fig. 3) with a production of ca. 21 Mt, followed by sunflowers (9 Mt). As for fruits, we estimate a production of 38 Mt (pome fruit 12 Mt; citrus 11 Mt). In addition, the EU produced ca. 18 Mt and 13 Mt of grapes and olives, respectively. Among the vegetables, tomatoes harvest add up to approximately 16 Mt.

3.2 Phosphorus removal with crop harvesting

At the global scale, the P input from inorganic fertilizers is estimated at 14.2 Mt year⁻¹, the P input from manure is

about 9.6 Mt, while the P removal from harvested crops is about 12.3 Mt year⁻¹ (MacDonald et al. 2011). In the EU and the UK, the total P removed with harvested crops is about 2.4 Mt year⁻¹ with an uncertainty of $\pm 8.8\%$ at a 90% confidence level. The quantity of P removed with harvesting crops varies in the range of 2.19–2.6 Mt. The mean removal with crop harvesting is about 14 kg P ha⁻¹ year⁻¹ with an uncertainty of 1.2 kg P ha⁻¹ year⁻¹. The P removal per region or country depends mainly on the amount of agricultural land, crop productivity, and crop composition.

In absolute terms, the three countries with the highest agricultural production (Germany, France, and the UK) cover ca. 1/3 of the 180 Mha of agricultural lands, while their P plant removal is 47% of the total (ca. 1.11 Mt of P).

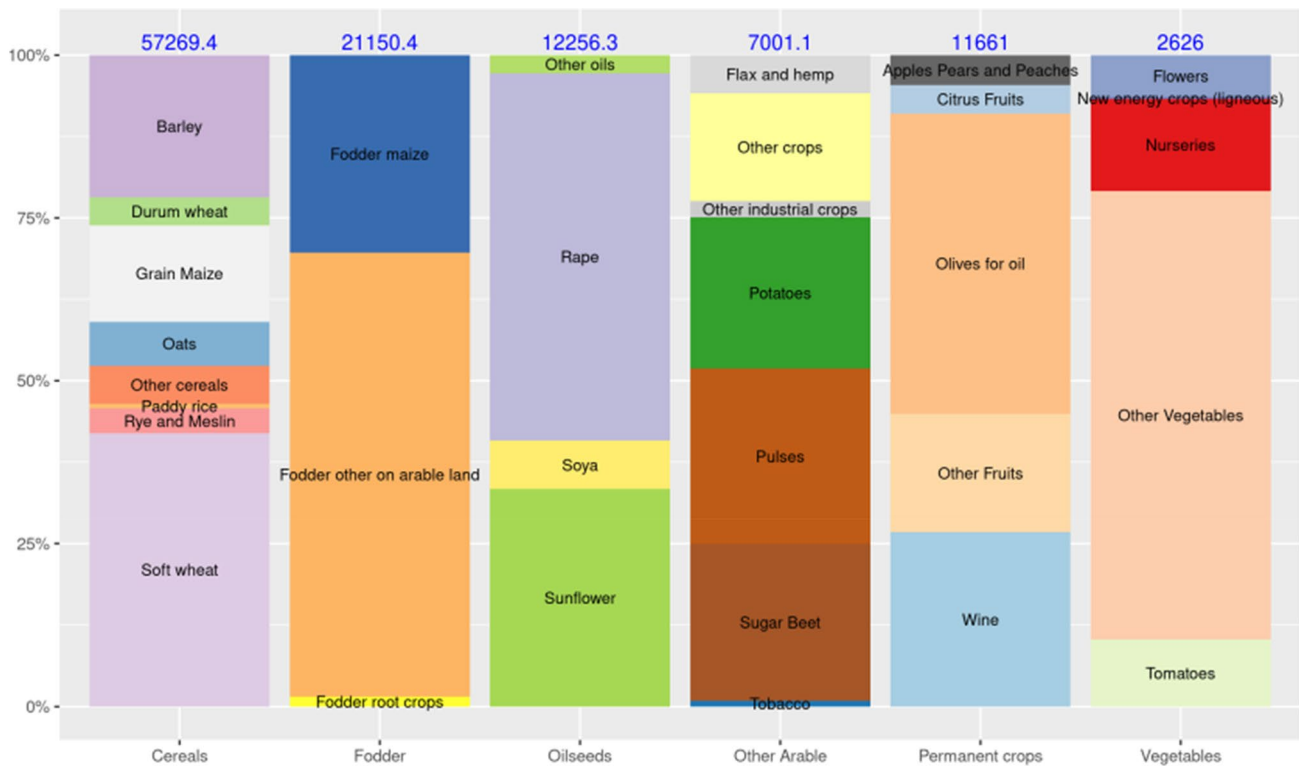


Fig. 3 Area shares (%) per each crop in major crop categories (cereals, fodder, oilseeds, other, permanent crops, vegetables). The figures on the top represent the cultivated/harvesting area (1000 ha)

On the contrary, the larger Mediterranean countries (Spain, Italy, Portugal, and Greece) occupy $\frac{1}{4}$ of the total agricultural land but have a P removal of just around 15% of the total. As a result of differences in both crop productivity and crop composition, the P removal has a high variability per country (Fig. 4) and region (Supplementary material, Fig. S1). Ireland, the Netherlands, Belgium and Denmark have the highest mean P removal with crop harvesting (> 19 kg P ha⁻¹ year⁻¹) while the Mediterranean countries have the lowest one (< 10.5 kg P ha⁻¹ year⁻¹) (Fig. 4).

The mean P removal by crop harvesting is 16 kg ha⁻¹ year⁻¹ in cereals, 15.2 kg ha⁻¹ year⁻¹ in oilseeds, 38 kg ha⁻¹ year⁻¹ in vegetables, 13 kg ha⁻¹ year⁻¹ in fodder crops and pastures, and 2 kg ha⁻¹ in fruits (Fig. 5). Those values may vary per region and country as well as among the corresponding crops categories. For instance, in case of cereals, the soft wheat P removal is 18 kg ha⁻¹ year⁻¹, while rye removes only 11 kg ha⁻¹ year⁻¹. As for oilseeds, the P removal of rape is 18.9 kg ha⁻¹ year⁻¹ compared to 10 kg ha⁻¹ year⁻¹ for sunflowers. The root crops have also a high P uptake. Sugar beets, for example, remove 25 kg ha⁻¹ year⁻¹ and potatoes 15.7 kg ha⁻¹ year⁻¹. In the fruits category, pomes (apples, peaches, etc.), harvest is removing ca. 7.5 kg ha⁻¹ year⁻¹, the citrus 8 kg ha⁻¹ year⁻¹, while olive groves and vineyards have much lower P rates

(2 kg ha⁻¹ year⁻¹). The boxplots represent the standard deviation of P removal per crop (Fig. 5).

Of the 2.4 Mt of P removal by crop harvesting, cereals contribute the major part (38%), followed by pastures (33%), and fodder crops (12%) (Fig. 4). Fruit trees, vegetables, oilseeds, and other arable crops contribute 1%, 4%, 8% and 4% of total P removal, respectively. In most crop categories (pastures, fodder crops, other arable and oilseeds), the total P removal is analogous to the share of agricultural land. For example, pastures occupy 33% of agricultural land and contribute to 33% of P removal. However, fruits occupy around 6.5% of the total agricultural area and have a low share of P removal (1%) due to their low dry matter content (Fig. 4 and Fig. 5). On the contrary, the vegetables occupy only 1.4% of the agricultural land and contribute 4% of P removal. The cereals are cultivated in 31.7% of the EU and the UK and contribute to 38% of total P removal with harvesting (Fig. 5).

The share of each crop category in uptake removal shows high variability (Fig. 4). While the fruits have an overall 1% share of the EU agricultural area, most of the Mediterranean countries (Cyprus, Greece, Spain, and Italy) have more than 5% of total P removed by fruits (Fig. 4a). Pastures contribute to most of the P exportation in Ireland (80%), Slovenia (60%), and the UK (59%). Vegetables have a substantial P removal share in the Netherlands (20%), Malta, Italy and Portugal.

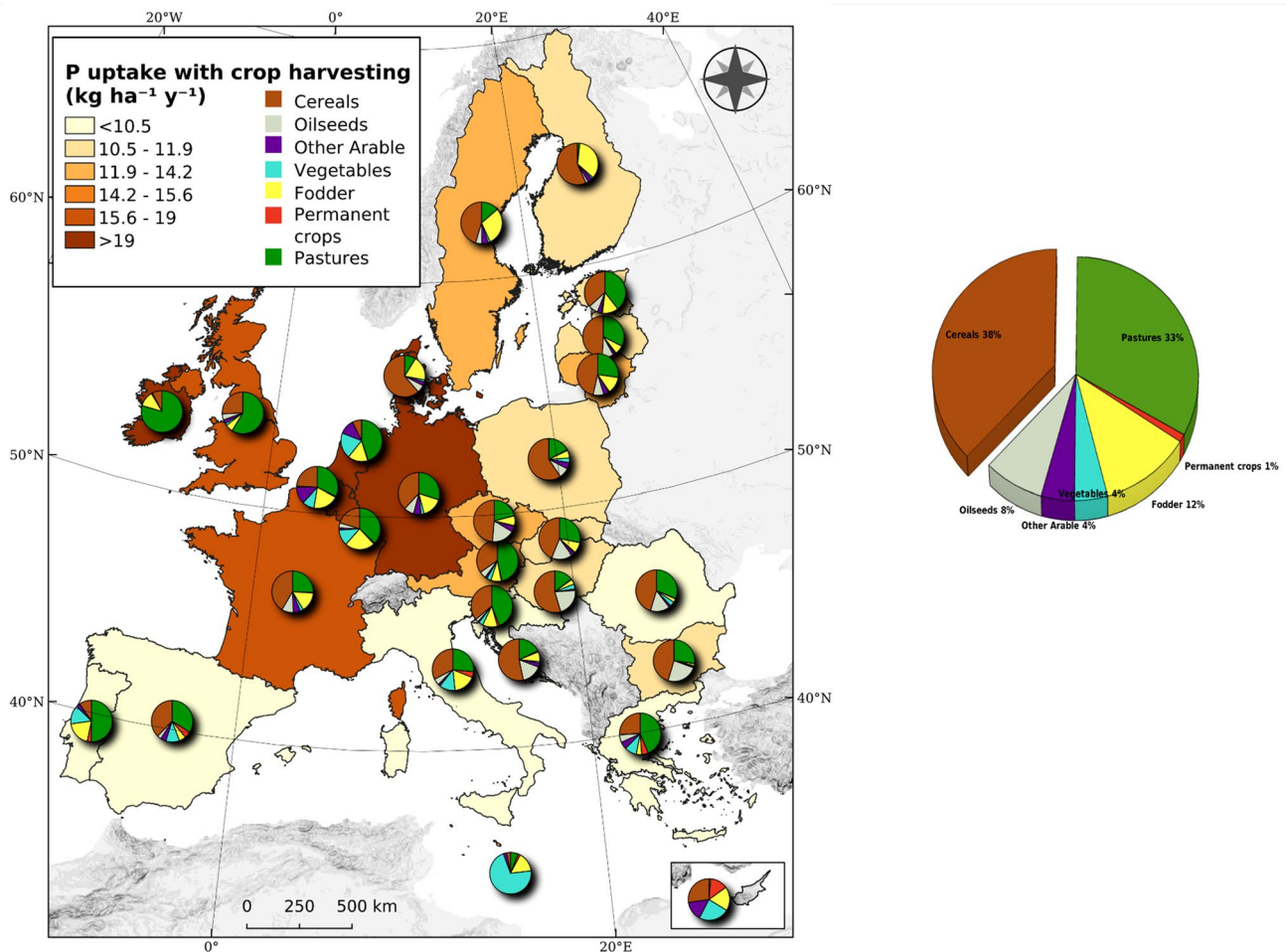


Fig. 4 The mean P removal by crop harvesting per country (kg ha⁻¹). The pies are showing the share of the P exportation per crop category for each country (left) and per crop category for the whole study area (right)

3.3 Phosphorus removal with crop residues

The total crop residues produced from agricultural lands are estimated to be about 353 Mt (max. 395 Mt) with the cereals producing the major part of it (ca. 292 Mt ± 25 Mt). The results show that 130 Mt of dry matter crop residues per year are removed each year in the EU27 and UK.

The total P removal by crop residues is about 151,000 t with ± 14% uncertainty at a 90% confidence level. In regions and countries where cereals have the highest contribution to the agricultural production, P removal by plant residues was above 1 kg ha⁻¹ year⁻¹ (Fig. 6). Around 78% of P removal with crop residues is due to the three main cereals cultivated in the EU (soft wheat, barley, grain maize). Those percentages are in agreement with studies of crop residues availability in the EU (Scarlat et al. 2010). In absolute terms, France has the largest amount of P removal by crop residues (ca. 30 kt), followed by Germany (20 kt), Poland, Spain, and Romania (brown bars in Fig. 7).

4 Discussion

By summing up the P removal with crop harvesting and residues, we estimate a total P uptake of 2.55 Mt with an uncertainty of ± 0.23 Mt. Most of the North–West EU regions (North France, Ireland, Belgium, Germany, Netherlands and Denmark) have a mean P removal higher than 22 kg ha⁻¹ year⁻¹ (Fig. 7). In Mediterranean countries this rate is less than 11 kg ha⁻¹ year⁻¹ while the Eastern EU countries have rates in the range of 13–17 kg ha⁻¹ year⁻¹. Detailed data per country are available in the Supplementary material (Table S2).

At the EU level, the P removal with residues is about 6.3% of that of crop harvesting. As the P removal with crop residues is higher in agricultural lands with a higher share of cereals, Poland, Hungary, Romania, and Bulgaria remove more than 10% of total P by crop residues (Fig. 7).

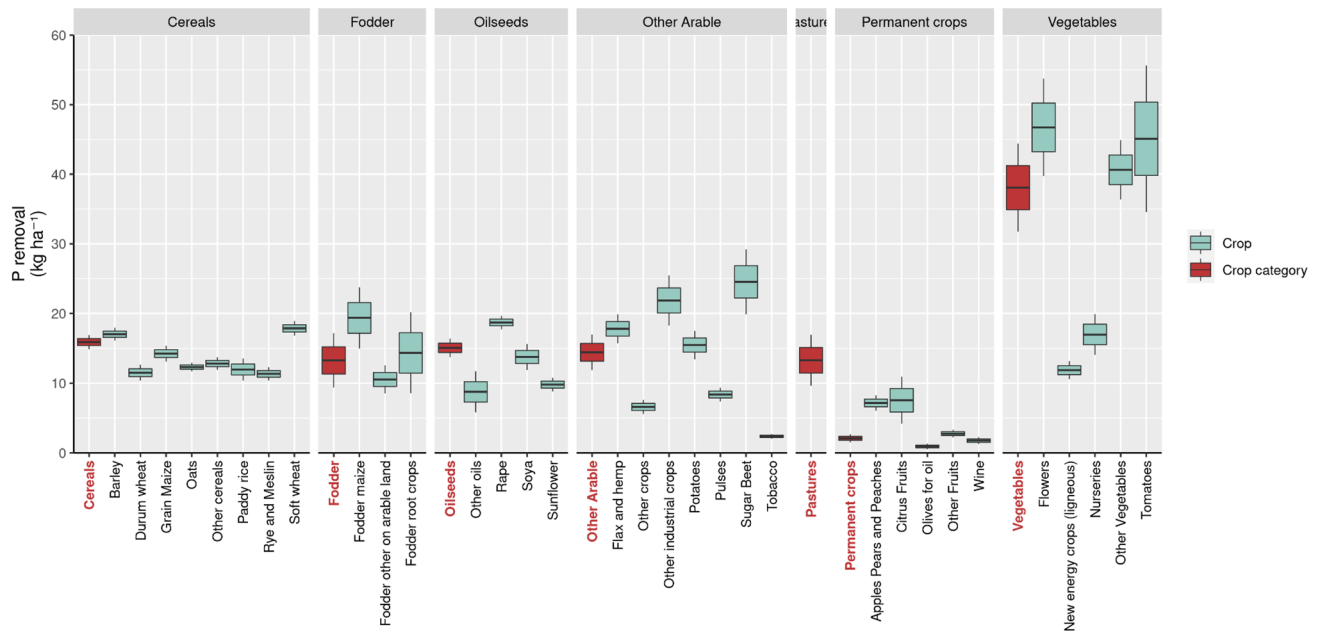


Fig. 5 Mean P removal due to crop harvesting (kg ha^{-1}) for major crop categories (cereals, fodder, other arable, oilseeds, permanent crops, vegetables, and pastures) and the main crops. The boxplots represent the range of values (\pm stdev)

The 2.55 Mt of P exportation by crop harvesting gives a useful indication of the amount of P that should be added through fertilizer (organic/inorganic) per year. However, this may not be the case as suggested by the different P availability in EU agricultural soils (Fig. 1). Therefore, a detailed input/output P budget is necessary for sustainable nutrient management and policy recommendation. In such decisions, both farmers and policy makers should take into account P outputs by crop harvesting, also in combination with the P availability in topsoils (Ballabio et al. 2019) and phosphorus fertilization needs in each region (Tóth et al. 2014). Therefore, P fertilizers could be reduced under optimal values on saturated agricultural fields to avoid P losses to the environment (Garske et al. 2020). On the opposite, P fertilization could be increased under soil mining condition and lower P availability. This is useful from both an economic and an ecological point of view.

This is the first attempt to estimate P removal by crops and residues at European scale using detailed crop production data for 37 crops at a regional scale (220 regions). This will contribute to compile the P budget at the European scale and identify P surplus or deficit areas. Therefore, it is important to have a conservative nutrient management plan in areas with P surplus and implement a more efficient fertilizer and manure use in areas with P deficit. However, the policy interventions should also address the targets at farm scale depending on soil quality and the status of soil physical and chemical properties of the agricultural field.

The estimate of total P removed from soils does not yet include the losses by water erosion. It is known that the mean soil loss due to water erosion in the EU is about $2.45 \text{ t ha}^{-1} \text{ year}^{-1}$ (Panagos et al. 2020), with agricultural soils having higher losses at $3 \text{ t ha}^{-1} \text{ year}^{-1}$. Integrating soil erosion into the P budget framework will be addressed in a future research targeting the whole P budget. In a recent global assessment done at coarse resolution, the P removed through soil erosion in Europe is estimated to be about $1 \text{ kg ha}^{-1} \text{ year}^{-1}$ (Alewell et al. 2020).

In addition, we aim at providing a data management platform for P budget on a regular basis. Our plan is to provide annual updates based on updated crop production and fertilizer consumptions statistics in the EU. This would allow monitoring the nutrient uptake and the sustainable use of fertilizers in accordance with the EU Green Deal policy targets. In addition, as the CAPRI model includes a trend projection module for future agriculture production and commodity markets, future trends in land use and cropping systems can be assessed (Himics et al. 2018; Wirzke et al. 2012).

The land occupied per each cropping system and the productivity trends for 2030 estimated by CAPRI is shown in Fig. 8. In 2030, the agricultural land in EU-27 and UK will be 168.4 Mha, which is 1.7% less compared to the 2016 baseline mainly due to cereals and oilseeds reduction. Areas for fodder crops and pastures will remain rather stable. According to CAPRI, the area of cereals will be reduced by 0.5 Mha (-1%) followed by a reduction in pastures and permanent crops (Fig. 8). However according to the CAPRI projections,

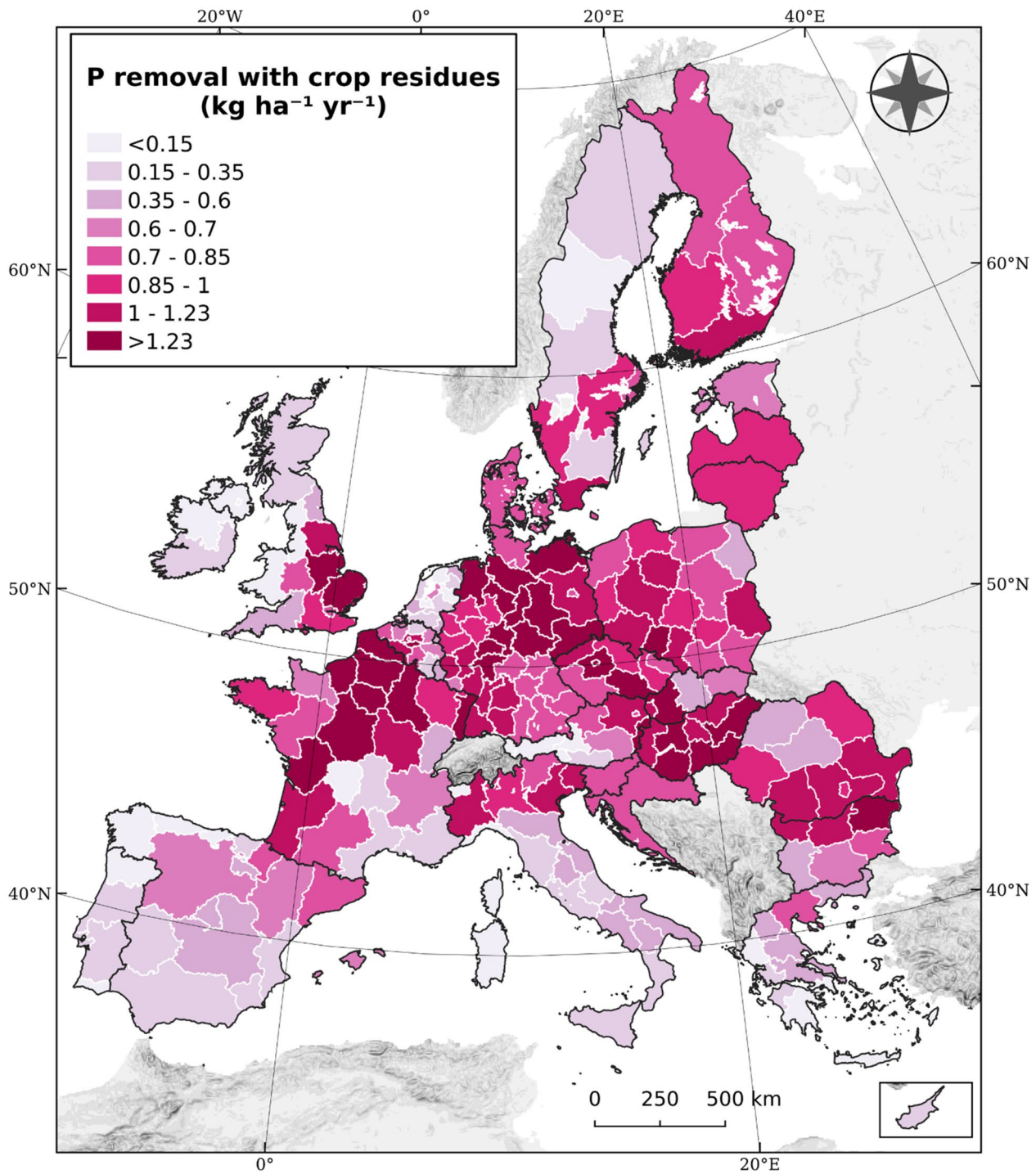


Fig. 6 Phosphorus removal ($\text{kg ha}^{-1} \text{ year}^{-1}$) by crop residues at the regional scale

the productivity rates will be higher resulting in higher crop production. For example, the cereal production may reach 325 Mt, in line with the projections of the EU Agricultural outlook 2018. In the oilseeds category, the rapeseed will show a decline, while the soya and sunflower an increasing trend.

As the production of crops will be higher in 2030 (compared to 2016), the P removal with crop harvesting is expected to increase by 4% (Fig. 8), totaling circa 2.52 Mt in 2030 (compared to 2.4 Mt in 2016). Therefore, it is important to take into account the implications of land use changes, crop systems changes and productivity increases in

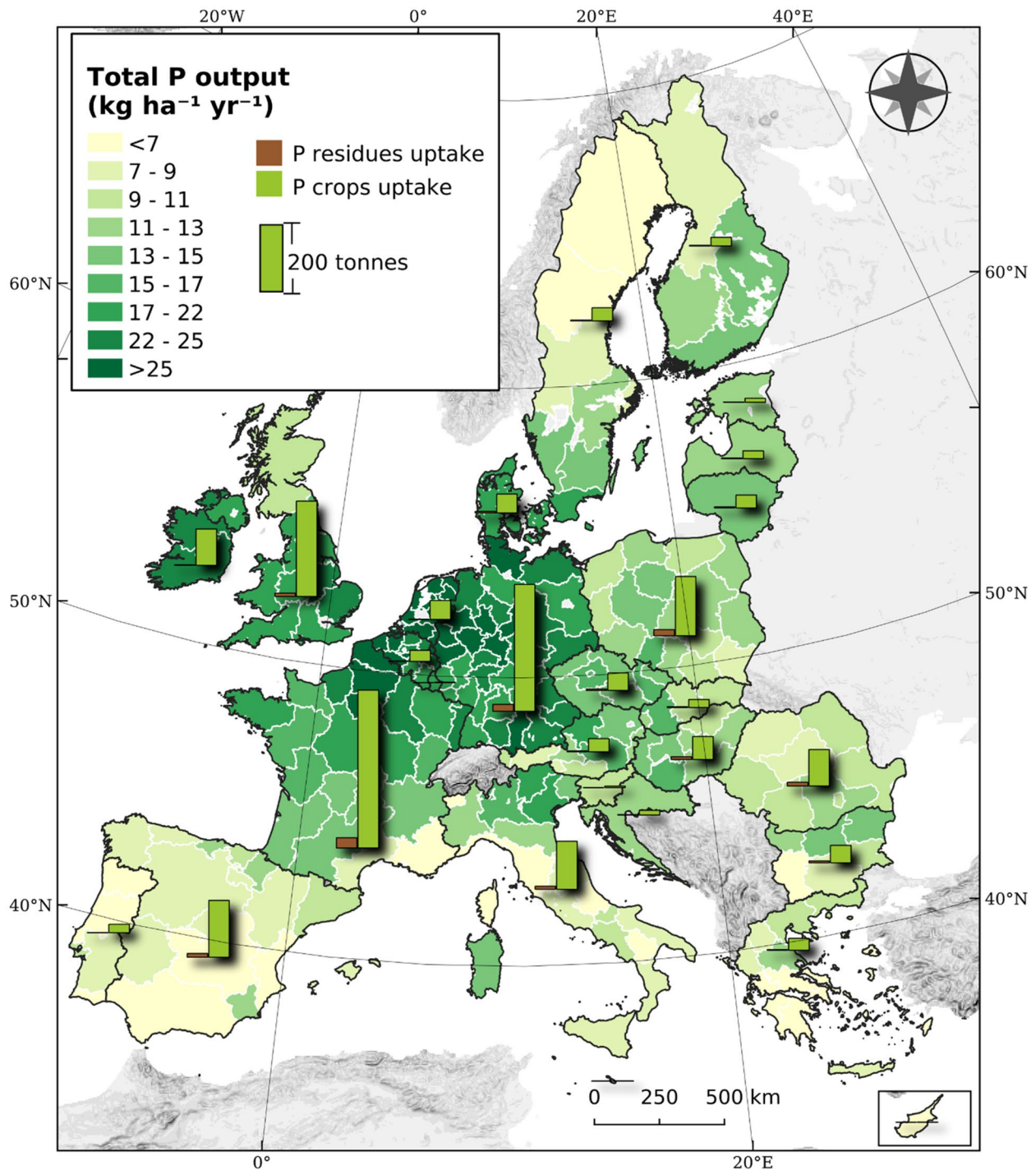


Fig. 7 Total phosphorus removal per country and region. Green bars aggregate P crop removal per country and brown ones are the aggregated P removal with residues (Color figure online)

the medium-term future (2030) under the F2F Strategy. In addition, it is important to further investigate how the ambitious environmental objectives of the F2F Strategy can be reached in a competitive global trade system which projects increase in food and feed requirements.

The data, maps, and the model implementation for P removal will be available in the European Soil Data Centre (ESDAC) (Panagos et al. 2012).

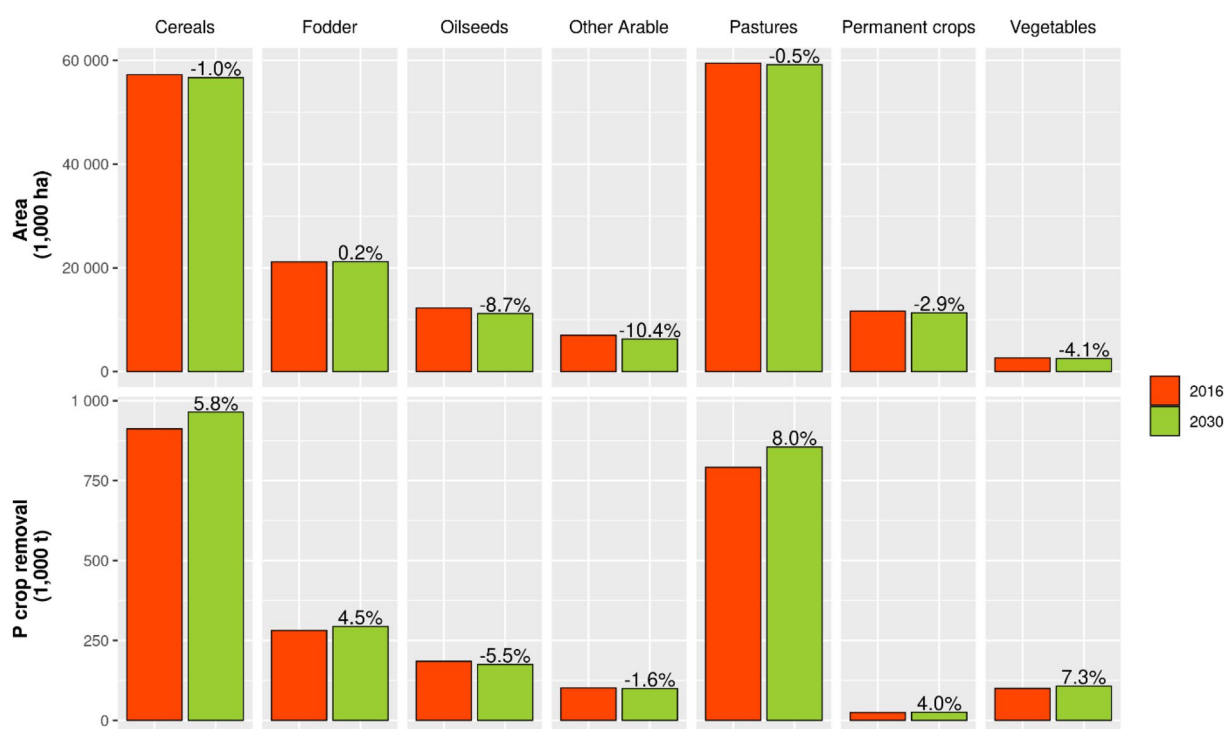


Fig. 8 Projections of crop area changes in 2030 (top) and scenarios for future P removal with crop harvesting (bottom)

5 Conclusions

The P removal from agricultural lands in the EU and UK (ca. 170 Mha) by crop harvesting and residues is about 2.55 Mt with an uncertainty of $\pm 9\%$. Based on the P budget data framework that we built, we estimated P removal per country, region, and each of the 37 crops cultivated.

Mean P removal by crop harvesting is $14 \text{ kg ha}^{-1} \text{ year}^{-1}$, with cereals and vegetables having higher rates, while fruits having much lower ones. In most of the North-western European regions, the rates of P removal are higher than $20 \text{ kg ha}^{-1} \text{ year}^{-1}$, while rates are lower than 10 kg ha^{-1} in Mediterranean regions and South-East EU countries. The crop residues represent a small proportion of the total P output (ca. 6%), while areas cultivating cereals contribute the most.

Due to the high costs of P fertilizers, limited availability and potential risk of diffuse contamination, the knowledge of P removal and its use by crop plants is essential for the best management of this essential nutrient. The outputs of the P budget data framework may contribute to improve the current indicators on P balance at regional and European scale.

Scenarios of agricultural production in 2030 estimate an increase in P removal at 4%. Therefore, the investigation on how the increased agricultural productivity (and hence P demand) projected for 2030 will affect the policy targets of F2F Strategy is necessary.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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