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Distribution pattern of major crops and their cultivation intensity indicated by soil phosphorus concentrations in Europe

Nóra Szigeti[1,2] | Tamás Hermann[1] | Katalin Juhos[3] | Gergely Tóth[1,4]

[1]Institute of Advanced Studies, Kőszeg, Hungary

[2]Hungarian Research Institute of Organic Agriculture (ÖMKi), Budapest, Hungary

[3]Department of Agro-Environmental Studies, Institute of Environmental Sciences, Hungarian University of Agriculture and Life Sciences, Budapest, Hungary

[4]Institute for Soil Sciences, Centre for Agricultural Research, Budapest, Hungary

Correspondence
Nóra Szigeti, Institute of Advanced Studies, 9730 Chernel u. 14. Kőszeg, Hungary.
Email: nora.szigeti@biokutatas.hu

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Abstract

The sowing area and yield of crops are primarily determined by climatic suitability and modified by terrain conditions. This study presents the actual sowing area of 10 major crops in Europe and reveals the spatial pattern of available soil phosphorus (P) concentrations between and within the sowing areas of the crops, based on the Land Use/Land Cover Area Frame Survey (LUCAS) database. A great variance in cropping pattern over Europe was observed, especially for crops with a broad climatic tolerance. Results show significant differences between soil phosphorus concentrations under different agricultural crops, indicating the differences in management intensities of major crops. A strong relationship between high yields and P-fertilizer use was found, as indicated by soil P concentration. In the context of environmental zones, P-concentration values were higher in northern zones, medium in the zones in central Europe, and lower in the Mediterranean zones. The more suitable the climate is for growing crops, the more it pays to apply P fertilizers. Consequently, soil P-concentration is a good indicator of crop cultivation intensity, land productivity, P-fertilizer use, and the total P demand of plants. Among the most commonly cultivated crops, maize seems to be the most dependent crop for the level of P-concentration of soil or the P inputs. For more sustainable P use in Europe, further research is needed to calculate how the P-requirements of yields compare to the P-fertilizer use in the case of different crop types.

1 | INTRODUCTION

The sowing area of the crops is indirectly related to several environmental characteristics, which are taken into account when planning crop production. The key factors that determine land suitability for a crop are climatic and morphological features, the availability and quality of water, and the biophysical characteristics of the soil (Baker & Capel, 2011). Within the sowing area, actual land use and management and demand influence the cultivation of the crop (Baranzelli et al., 2015).

Intensification of crop production increased significantly from the 1960s. This led to the degradation of several soil functions, such as nutrient cycles (Palm et al., 2007). Nowadays, almost half of the terrestrial area of Europe is an agricultural area, affected by the use of millions of tons of fertilizer (Rega et al., 2020). The availability of soil phosphorus (P) content for agricultural crops would be limited without fertilization in most soils. Biological processes strongly influence the global cycle of this element (Schoumans et al., 2015).

Abbreviations: LUCAS, Land Use/Land Cover Area Frame Survey; NPK, nitrogen, phosphorus, and potassium; P, phosphorus.

Phosphate ions easily react with other substances; thus, only a minor part of soil P content is mobile (Hinsinger, 2001). However, while P fertilization increases crop yield significantly, the environmental effects of the excessive application are serious (Cordell & White, 2014) and can also result in the deficiency of micronutrients (Csathó et al., 2019). The vast majority of P loss to water bodies comes from agriculture due to inefficient use of easily soluble P-fertilizers (monoammonium phosphate and diammonium phosphate) (Kanter & Brownlie, 2019; Palmer-Felgate et al., 2009), and erosional processes which translocate soil (Alewell et al., 2020; Berhe et al., 2018). Furthermore, soluble soil P also gets adsorbed on soil colloids (Chen & Arai, 2020; Nziguheba et al., 1998). Thus, a more sustainable use and improved usage efficiency are needed (Richardson et al., 2011). The adaptation of different crops to low P content soils depends on the rooting system, mycorrhizal contacts, and so on (Hetrick, 1991). Those plant species that can accumulate soil phosphate can also release it into the soil after decomposition (Soltangheisi et al., 2020). Researches reflect that P use efficiency can be significantly improved by integrating mineral P fertilizer types with soil–crop systems (Gong et al., 2022). As the availability of P is limited, it is also in economic and environmental interest to use it prudently, which can be rationalized based on an assessment of current practices.

Monitoring the global processes according to the soil quality needs large-scale, harmonized databases of soil properties. The Land Use/Land Cover Area Frame Survey (LUCAS) of Europe was extended to measure basic soil properties such as particle size distribution, pH, organic carbon, carbonates, and nitrogen, phosphorus, and potassium (NPK) concentration of the topsoil in 2009 in EU countries, later extended to new member states and other countries of Europe. Currently more than 20,000 sampling points provide the basis of the open-access, pan-European topsoil database (Tóth et al., 2013). Ballabio et al. (2019) presented the soil chemical properties in the EU, based on all of the topsoil data of the LUCAS database.

Several methods exist for the determination of field management intensity, for example, the amount of nitrogen (van der Zanden et al., 2016) or energy (Rega et al., 2020) input, or production output (Shriar, 2000).

Our study aimed to identify the boundaries of suitable sowing areas of major crops in Europe and to assess the sowing frequency within these boundaries.

Furthermore, we aimed to reveal the intensity of farming within European environmental zones (Metzger et al., 2005; Figure S1) and within the actual sowing areas as indicated by P fertilizer use, crop yields, and available soil P concentration. Our first hypothesis is that the available soil P concentration is a good indicator of crop cultivation intensity, while acknowledging the fact that soil soluble P content is influenced by a number of other factors too (e.g., soil chemical parameters). According to our second hypothesis, different P requirements of yields in the environmental zones are reflected in the differences in the P concentration within their sowing areas. Our goal is to compile crop distribution maps including the intensity of cultivation of each crop within their sowing areas. We believe that such maps could contribute to the understanding of agronomical background of farming including P use in Europe.

Core Ideas

- The cultivation pattern of different crops follows both climatic and soil suitability.
- Great geographical diversity in cropping pattern as well as soil phosphorus concentration under different crops is observed.
- The amount of phosphorus applied is higher in areas where higher yields are expected.

2 | MATERIALS AND METHODS

2.1 | Data sources

Crop distribution maps are based on the LUCAS dataset from years 2006, 2009, 2012, 2015, and 2018 (Eurostat, 2020). Eurostat carries out a land use and land cover monitoring every 3 years in a 2 km × 2 km grid in the EU. The available P concentration data (Olsen et al., 1954) originate from the topsoil dataset of the LUCAS database, sampled in 2015 (Eurostat, 2020). Lucas topsoil datasets aimed to present the spatial variability of soil properties in relation to land use characteristics. Soil samples were collected following a standard sampling procedure (Orgiazzi et al., 2018). The sample collected at each location comprises five topsoil (0–20 cm) subsamples that were mixed to form a single composite sample. Soil sampling was investigated between two growing periods when fertilizing did not affect the P concentration. We hypothesize that the potentially available P concentrations characterize the medium-term fertilization intensity of crop rotations. Yield data were obtained from Eurostat Agricultural production database (https://ec.europa.eu/eurostat/web/agriculture/data/database; Figure S2), years 2013–2020.

Based on the LUCAS 2015 dataset, which contains topsoil characteristics, we have determined the 10 most frequently used crop species, crops found in the highest number of sampling points were included in the analysis (Table S1). The nomenclature also follows the LUCAS database.

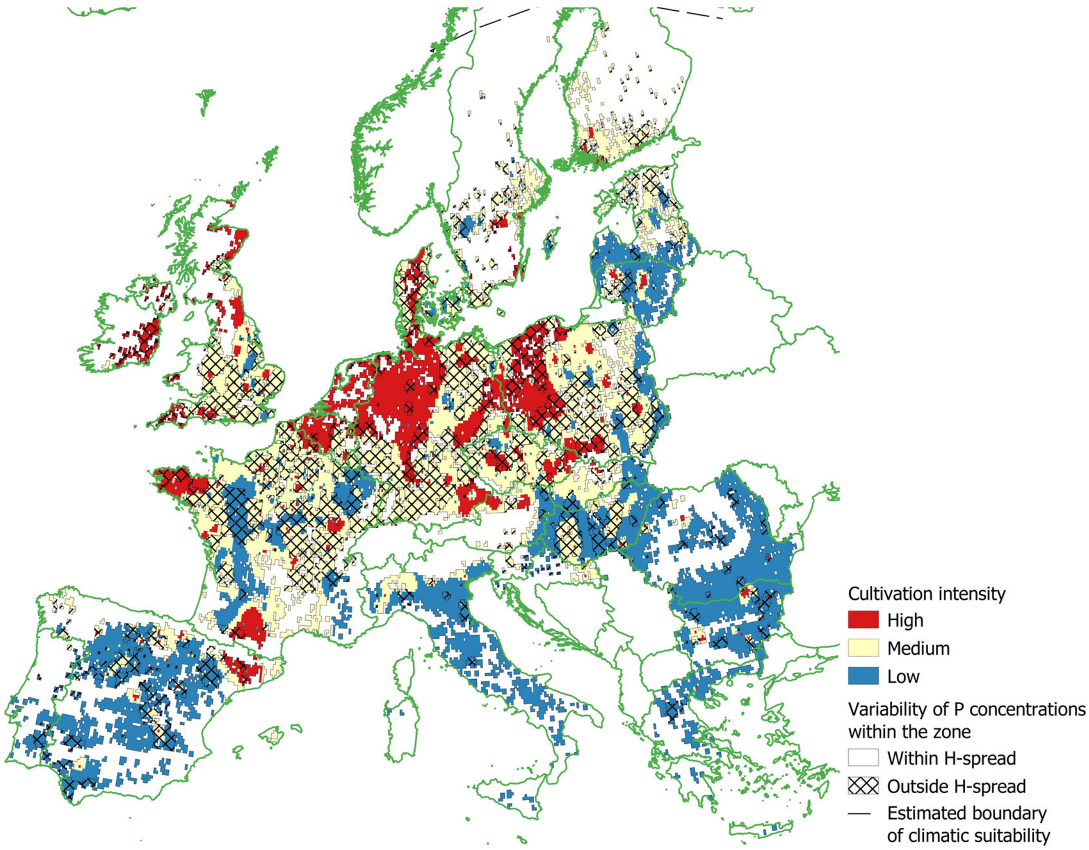

FIGURE 1 Cultivation intensity zones within the sowing area of common wheat in Europe as indicated by available soil phosphorus concentration (mg/kg ± standard deviation [SD]). High: 70 ± 20; medium: 44 ± 6; low: 23 ± 6. H-spread, interquartile range.

2.2 | Analyses

The distribution area of the crops was determined by a 10 km wide buffer zone around the points that were covered with the studied crop in one of the years 2006, 2009, 2012, 2015, and 2018. We set estimated boundaries of climatic suitability as on the northest and southest reach of crops in these years.

The maps of cultivation intensity classes are determined based on an (i) interpolation of point values of the available soil P concentration of soil samples. These are obtained from LUCAS 2015 topsoil dataset and (ii) a spatial clustering of the points to delineate continuous areas belonging to the same classes. Interpolation was performed with QGIS using the nearest neighbor method. In order to set classes of soil P levels for different crops in a spatial context, we employed separate cluster analysis (Pelleg & Moore, 1999) for spatial data layers of each crop. Low, medium, and high P supply categories were set for the distinct sowing areas of the studied crops. Central values and standard deviation (SD) of P concentrations of each category were determined during the classification. We assumed that the categories mark different cultivation intensity zones. The Precision Agriculture Tool plugin of QGIS 3.16 was used for the classification. The tool uses k-means clustering to identify classes from P data by minimizing variability within, and maximizing between the clusters. P intensity classes were further divided into four quartiles, based on the P concentration values, using the "Tukey's hinges" method (Tukey, 1977). Areas within the interquartile range (H-spread) were considered having low P variability around the zone's mean P concentration. This categorization was applied to display the homogeneity of the zones.

For the P-yield analyses, we sorted LUCAS topsoil data by countries and added yield values from Eurostat agricultural production database (Table S2).

We have also studied the soil P concentration according to crop species and environmental zones.

Soil properties and crop cover were obtained from the same LUCAS topsoil 2015 dataset as the P data. The sampling points were sorted by the Environmental Stratification of Europe (Metzger et al., 2005; Figure 1). The environmental zonation takes 20 different environmental variables into account, which determine 13 European environmental zones. We excluded the two Alpine zones from the analysis because

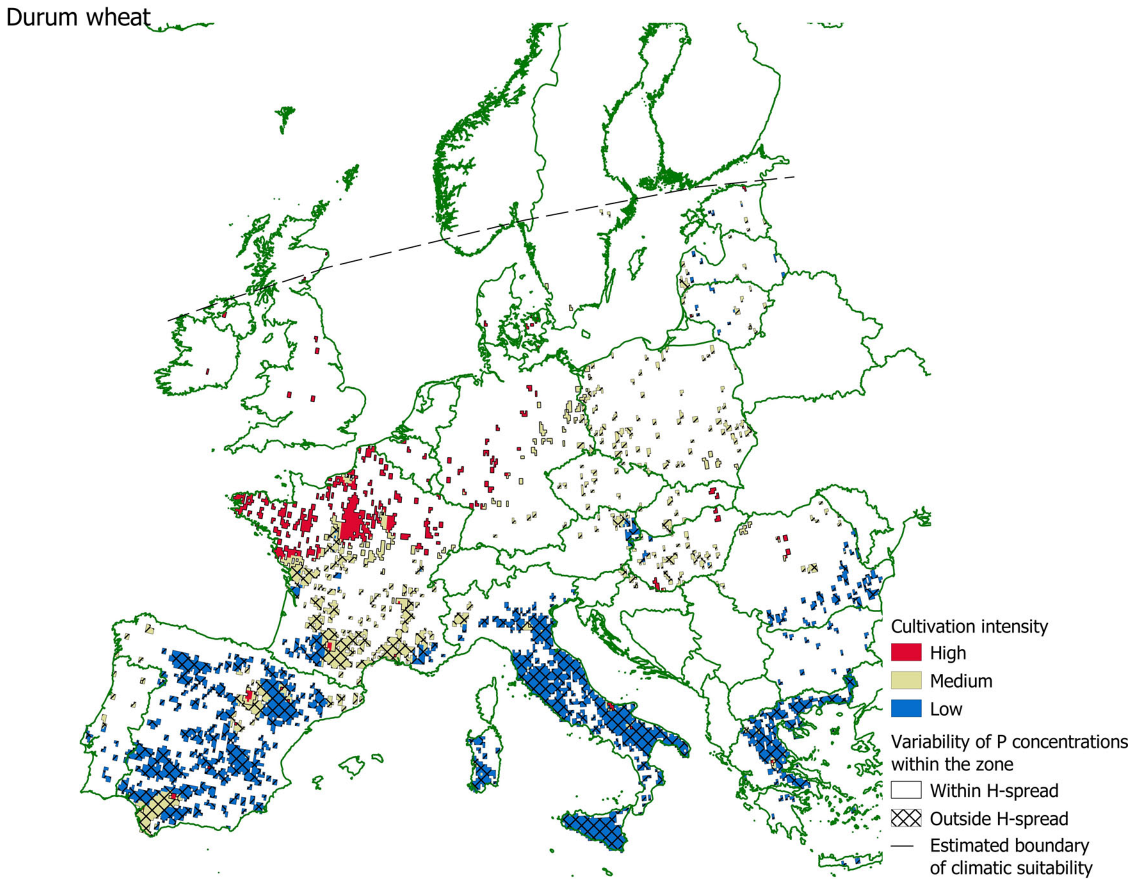

FIGURE 2 Cultivation intensity zones within the sowing area of durum wheat in Europe as indicated by available soil phosphorus concentration (mg/kg ± standard deviation [SD]). High: 48 ± 5; medium: 31 ± 4; low: 18 ± 4. H-spread, interquartile range.

of very few crop-covered points, and Anatolian zone, which does not contain LUCAS points.

Kruskal-Wallis rank-sum tests followed by pairwise comparisons using Wilcoxon rank-sum tests show the separated groups with significantly different means of P concentration. For better results, data above 10 pieces were considered in the statistics. Outlier values above 300 mg/kg were omitted.

Further to the geostatistical analysis and comparative statistical tests, we extended our analysis to visual comparison of the intensity maps that resulted from our study and the Crop Production Maps of the USDA (USDA-FAS, 2021). These visual analyses helped to assess the relationship between crop yields and the soluble P concentrations and also for crops for which the Eurostat regional statistics were incomplete.

3 | RESULTS

3.1 | Distribution and management intensity of crops in Europe

Common wheat is a widely cultivated crop in Europe. The sowing area covers almost the entire continent, leaving only the high mountains and the northernmost regions. Wheat is cropped in contiguous areas in the northern half of Europe, while its appearance in the Mediterranean is somewhat fragmented. The highest available P concentration is about 70 mg/kg. The most intensively managed wheat fields are located in the northern part of Europe and central and western areas to a smaller extent. The SD of P values in these intensive areas is mainly low. The mean soil P concentration in the most extensively managed fields is 23 mg/kg, with a low SD. This area covers the Mediterranean and Northeast Europe. About 44 mg/mg P values and high SD determine the intermediate intensity of field management. These areas can be found in the central and northern European countries (Figure 1).

Durum wheat is a typical crop in the Mediterranean areas, as shown in Figure 2. Although the northern boundary of cultivation reaches Scandinavia, contiguous sowing areas are located in Italy, and relatively high frequency can be observed in Spain and France. However, scattered durum fields appear on the whole continent. The P values determining the management intensity clusters are much lower when compared to common wheat. The SD is high in almost all areas except for the northwestern, most intensively managed fields. The

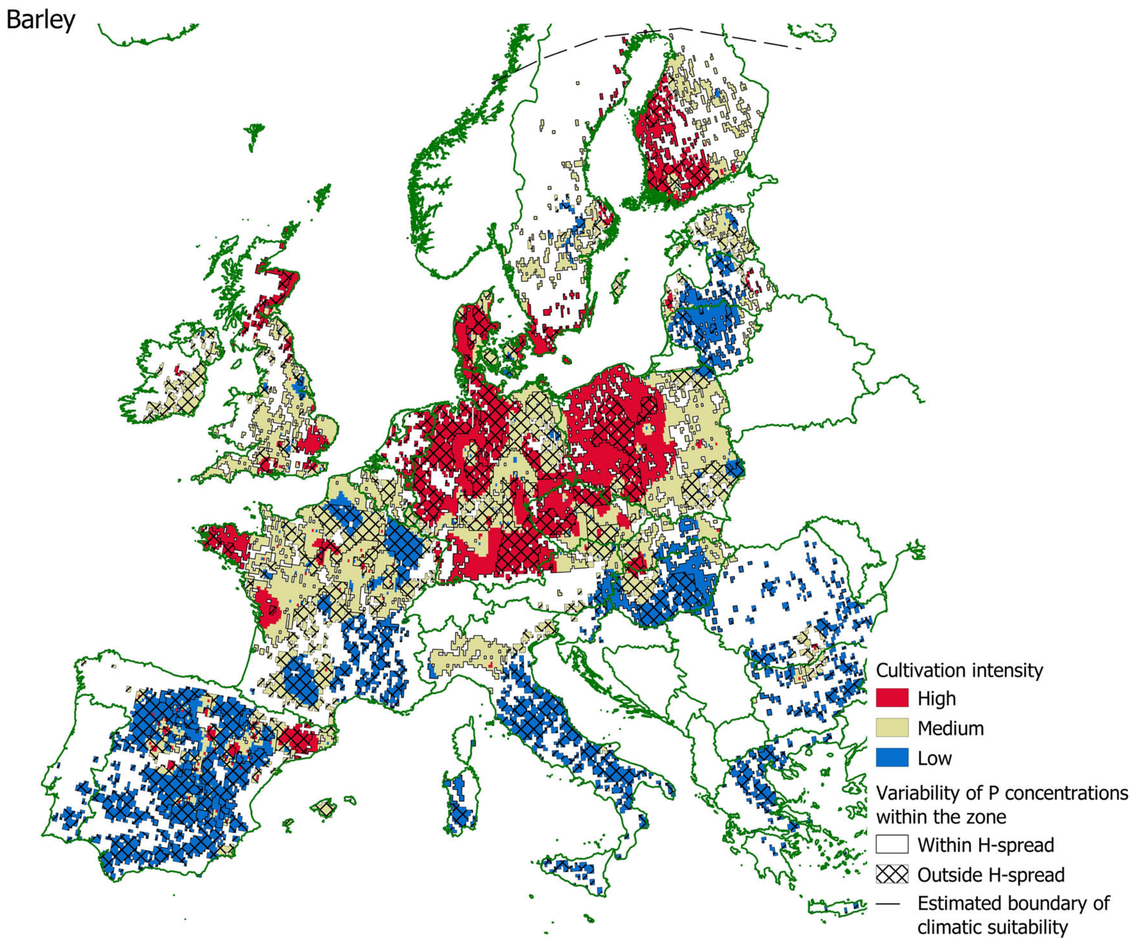

FIGURE 3 Cultivation intensity zones within the sowing area of barley in Europe as indicated by available soil phosphorus concentration (mg/kg ± standard deviation [SD]). High: 61 ± 12; medium: 39 ± 5; low: 22 ± 5. H-spread, interquartile range.

lowest intensity cluster covers the Mediterranean regions, while medium intensity is characteristic of central-west Europe.

Barley is among the most frequently cropped plants in Europe. The sowing area is similar to that of common wheat: contiguous areas are characteristic to Central, and West Europe, while Mediterranean regions are mosaic. The P values of the intensity classes are slightly lower than that of common wheat, but the SD is high in all areas. The location of the intensity classes is also similar to common wheat: central-north and part of western Europe exhibit high P values, Mediterranean countries being the lowest ones. The transition areas lie scattered on the continent (Figure 3).

The pattern of lucerne fields is quite different from the others. The extent of these fields is relatively small and concentrated in a few distinct areas of central and south Europe. Although the northern boundary of the sowing area crosses North Europe, the frequency of cultivation is extremely low in this region. The intensity categories represent lower P levels than main crops like wheat or barley, while the SD is high in all areas. The majority of the cultivation area belongs to the low-intensity cluster. Higher P levels can be observed only in small fragments across the continent (Figure 4).

Maize (corn-cob-mix) is frequently cropped in western and central Europe. The sowing area includes Mediterranean and northern regions, but there the cropping frequency is much lower, except for Denmark, where a significant amount of maize is cultivated. Only scattered spots appear in the Baltics and Sweden. The P levels determining the intensity classes are the highest among all crops. However, the difference between the mean of the highest and lowest categories is also quite large. The most intensive areas are located in northwest Europe, where the SD is generally low. The continent's central and Northeast areas belong to the medium-intensity cluster, while the southern part of the distribution area is linked with lower P levels (Figure 5).

The cropping pattern of oats shows that Northeast Europe and the South Mediterranean regions are the main cultivation areas. The sowing area includes the Mediterranean, Baltics, and Scandinavia as well. Central and West Europe exhibit lower cropping frequencies; however, the sowing area covers

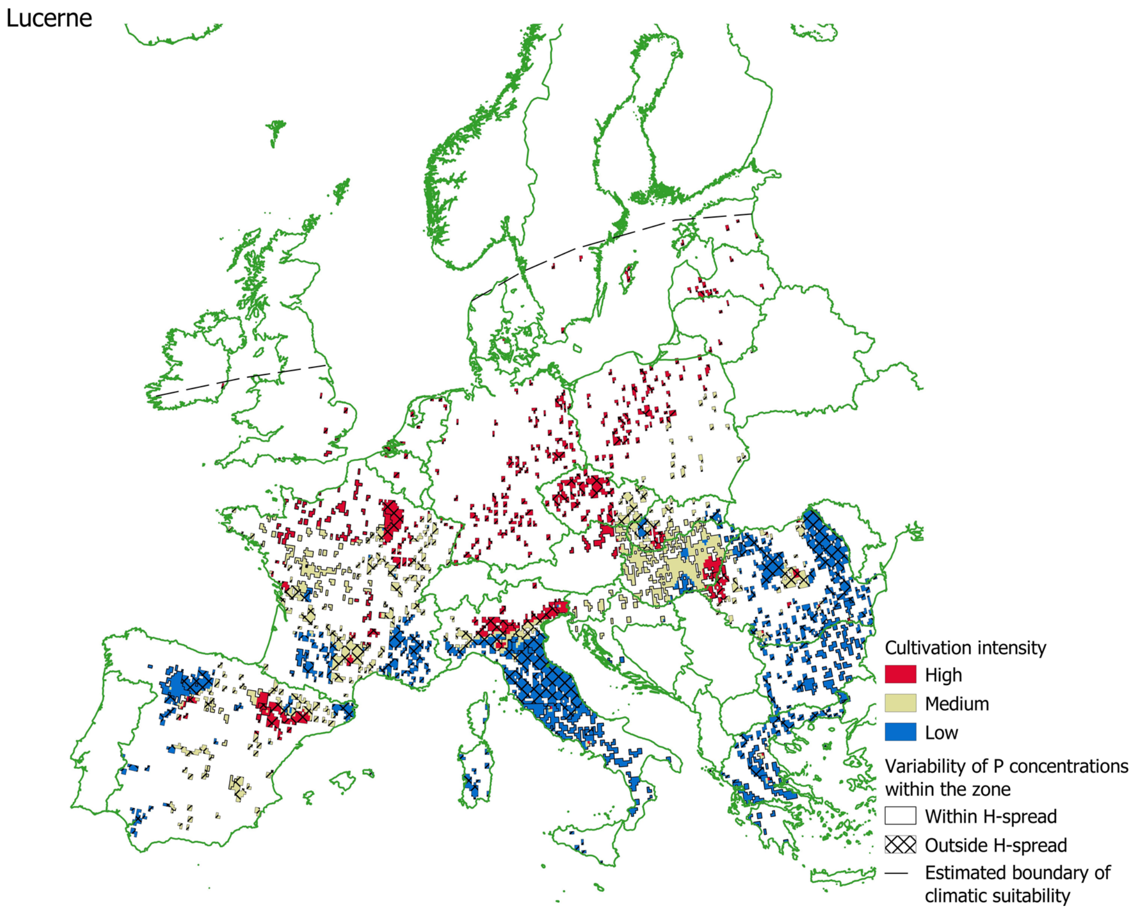

FIGURE 4 Cultivation intensity zones within the sowing area of lucerne in Europe as indicated by available soil phosphorus concentration (mg/kg ± standard deviation [SD]). High: 40 ± 4; medium: 30 ± 3; low: 19 ± 4. H-spread, interquartile range.

all regions of the continent. The intensity clusters are defined with similar P values like durum wheat, significantly below common wheat, barley, or maize, and the SD is high in all areas. The most intensively cultivated oat fields are located in Northeast Europe, while the low-intensity regions are on the opposite, south-eastern side of the continent. Central Europe belongs to the medium-intensity category (Figure 6).

Rape and turnip rape is cultivated in the central northern areas of Europe, and it is almost totally absent from the Mediterranean, and quite rare in East Europe. It has a southern boundary of cultivation in the Mediterranean region. The high cropping frequency is shifted to the northern half of the continent. P levels of the intensity categories are medium-high, similar to that of barley. The SD is mainly high. Most of the rape and turnip rape fields belong to the intensively managed category in the north and central parts of Europe. Medium and low-intensity areas appear across the continent (Figure 7).

Most rye fields are located in North-East Europe; fragmented areas appear in the Mediterranean, North, and central Europe. The sowing area covers all parts of the continent, but in the United Kingdom and Italy very few rye fields appear. Medium P values determine the intensity categories. The high and the medium-intensity regions lie in the Northeast part of the continent and exhibit low SD. The low-intensity cluster covers central and Southwest Europe with a high SD (Figure 8).

Sunflower is a typical crop of the central, western, and southern regions of Europe. The sowing area excludes northern areas. High cropping frequency can be observed in France, Hungary, and East-European countries, followed by Spain and Italy. The P levels are low, and most crop fields belong to the lowest intensity category. However, the SD is high in all areas. The few intensively managed areas are located in the western regions and Central Europe, mosaically along with the medium category. Low intensity is characteristic in the central parts and the Mediterranean (Figure 9).

Triticale fields are located in the North, West, and central parts of Europe to a great extent. Although the sowing area almost covers the continent, the Mediterranean and eastern and northern countries exhibit low cropping frequency. The intensity categories are linked to medium P levels compared to the other crops. The high and medium-intensity categories cover the northern regions, while the central and Southwest

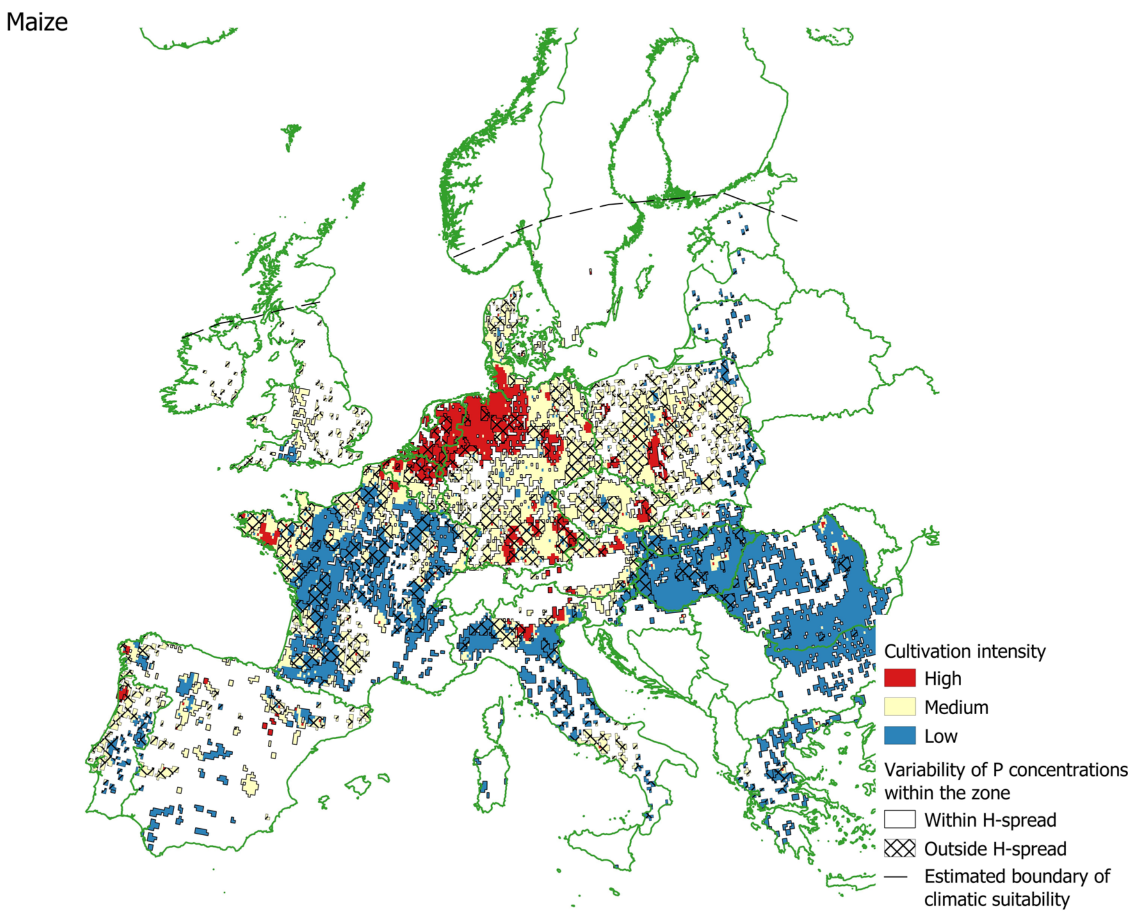

FIGURE 5 Cultivation intensity zones within the sowing area of maize in Europe as indicated by available soil phosphorus concentration (mg/kg ± standard deviation [SD]). High: 91 ± 18; medium: 55 ± 8; low: 29 ± 8. H-spread, interquartile range.

areas generally belong to the low-intensity cluster. The SD is high in the medium category and low in the high and low classes (Figure 10).

According to the environmental zonation (Metzger et al., 2005), in the Mediterranean North zone, more than 30% of the agricultural fields are cropped with barley. Common wheat is also a frequent crop, while maize and sunflower have lower importance in this zone. In the South-Mediterranean areas, barley is still the most important crop, but durum wheat becomes more frequent than common wheat, and sunflower appears on a slightly higher percentage of fields compared to northern Mediterranean areas. Maize is cropped more frequently in the mountains of the Mediterranean. In the Lusitanian and Alpine South regions, maize becomes prevailing, followed by common wheat and barley. Central Atlantic areas prefer common wheat, while in the northern part barley is preferred. Both precede maize production here. Continental, Pannonian, and nemoral zones are mainly cropped with common wheat, followed by maize in the first two, and barley in the case of nemoral areas. In the Pannonian fields, the proportion of sunflower is the highest among the zones. Rye, triticale, and oats are produced mainly in the Atlantic South, Continental, and nemoral zones, with a percentage of 8%–10%. Rape and turnip rape appear with a medium proportion in the Atlantic Central and nemoral zones, while clovers have limited importance in all areas, with the highest frequency in the Alpine South zone.

3.2 | Available soil phosphorus concentration and yield on a country scale

Agricultural efficiency can be estimated by matching the P concentration, as an indicator of P input and yields as a measure of the output of cultivation. In order to assess the efficiency of cropping in Europe, data on these parameters were analyzed. However, yield data were available only on a country level, therefore, we needed to upscale the P concentration data to the country level too, despite the variability of this indicator within countries in Europe.

At the country level, available soil P concentration is generally low in Romania, Greece, Bulgaria, Italy, Spain, and Portugal. Medium-low P concentration values can be found in Latvia, Lithuania, Hungary, Slovakia, Estonia, and Austria,

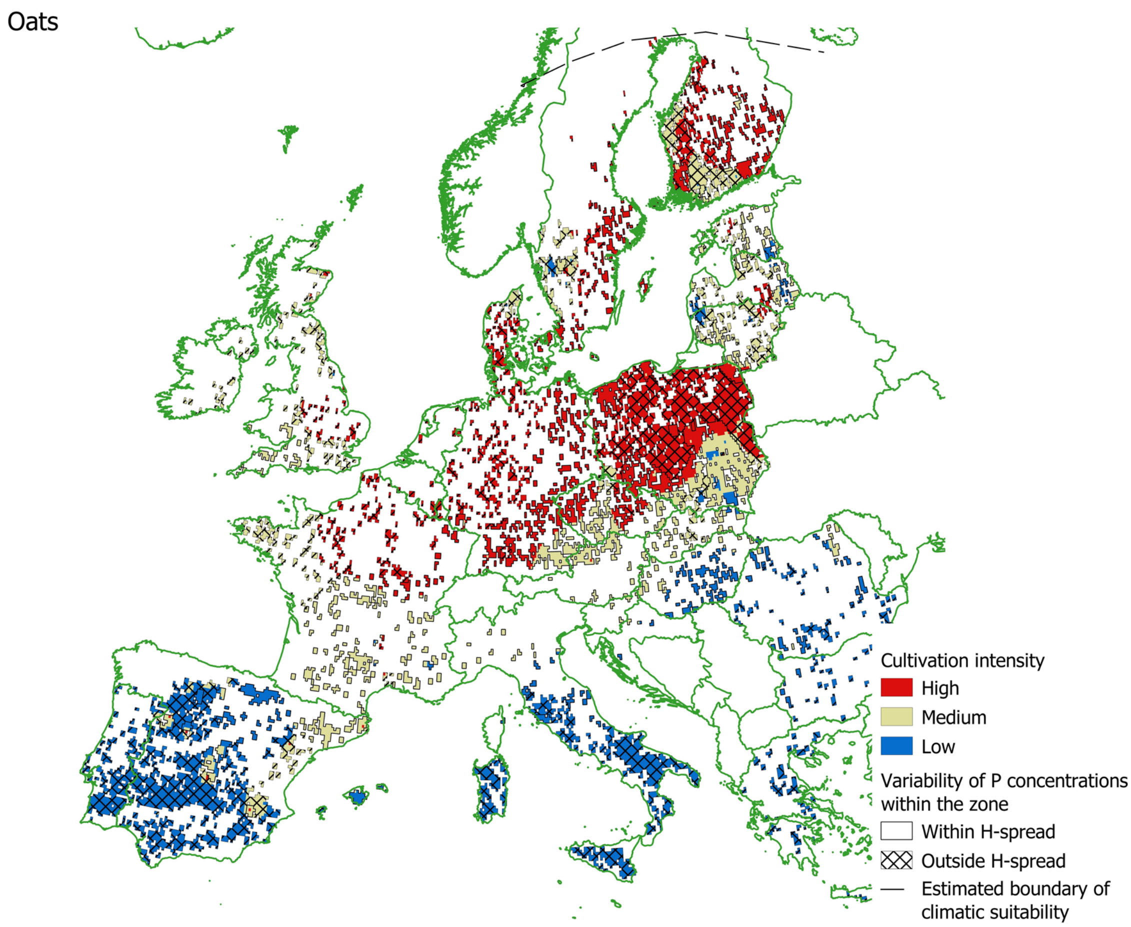

FIGURE 6 Cultivation intensity zones within the sowing area of oats in Europe as indicated by available soil phosphorus concentration (mg/kg ± standard deviation [SD]). High: 48 ± 7; medium: 34 ± 4; low: 17 ± 5. H-spread, interquartile range.

while the highest values are related to France, Sweden, UK, Denmark, Poland, Czechia, Finland, Germany, Belgium, and the Netherlands. P values in maize fields are slightly different; Italy and Spain exhibit higher values than Hungary, Slovakia, and France. Greece belongs to the medium category in this regard. Yield values are relatively well related to P concentration, but in Italy and Spain, the yield of several crops is relatively higher than it could be expected from P values. In the case of sunflower, Hungary exhibits relatively high yield (Table S2). These findings reflect the fact that no straightforward assumption can be made on the relationship between P concentration and yields based on country-level data. Thus, P use efficiency cannot be estimated based on course scale data.

3.3 | Soil phosphorus in the crop fields according to the environmental zonation

According to our findings, cultivation areas of major crops in Europe mark the level of input intensity indicated by soil P concentration. From the viewpoint of soil P concentration, we can state that it determines three groups of crops on a European scale, the highest values (>44.3 mg/kg) belong to maize, rape, rye, and triticale. Medium values (34.7–37.8 mg/kg) are associated with barley, common wheat, and oats. P values lower than 25.5 mg/kg characterize the third group, covered with durum wheat, lucerne, and sunflower (Figure 11).

Available soil P concentrations show several significant differences according to crop types and environmental zonation (Environmental Stratification of Europe, Metzger et al., 2005). Maize is associated with the highest P concentration in every zone, where significant differences appeared. Rye also correlates with higher P values in all zones, while sunflower regularly appears on soils with a lower P concentration. In the Atlantic Central zone, triticale, maize, and oats are linked to high P values; these three crops do not exhibit significant differences according to P levels. Common and durum wheat, lucerne, sunflower, Brassica species, and barley appeared on soils with lower P concentration, but the difference from the three high-level crops is significant only in the case of barley and maize. In the Atlantic North zone, significantly higher P values can be observed in maize than in barley, common

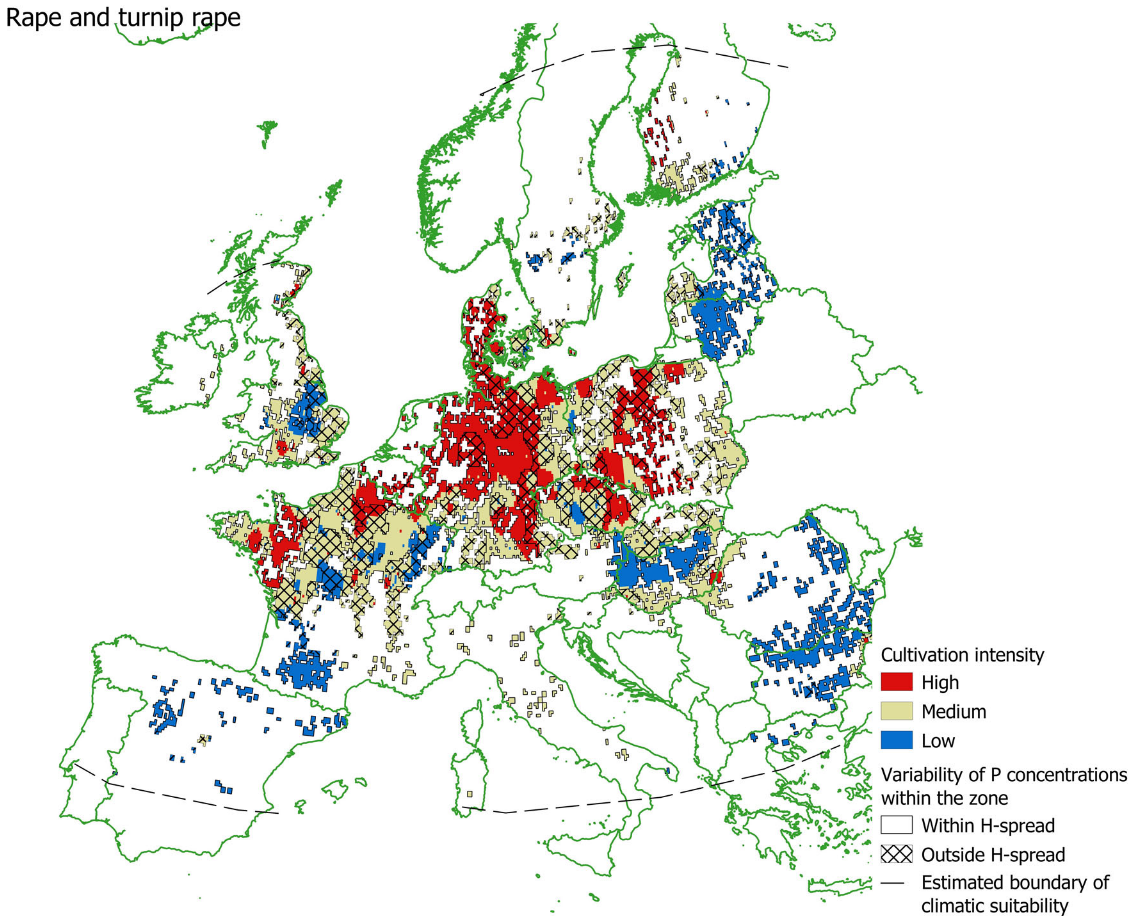

FIGURE 7 Cultivation intensity zones within the sowing area of rape and turnip rape in Europe as indicated by available soil phosphorus concentration (mg/kg ± standard deviation [SD]). High: 64 ± 11; medium: 43 ± 5; low: 27 ± 5. H-spread, interquartile range.

wheat, oats, rye, rape, and turnip rape fields. In the Boreal zone, just four crops were present in at least 10 sampling points in 2015. Oats are linked with significantly lower P values than barley, common wheat, rape, and turnip rape. Under continental climate, almost all crops were present in at least 10 samples, except for durum wheat; lucerne and sunflower exhibit low soil P values. Common wheat, barley, oats, rye, and triticale represent the medium level, while maize, rape, and turnip rape are the highest ones. In the Lusitanian zone, the statistical analysis did not result in significant differences. Barley, common and durum wheat, oats, sunflower, rape, and turnip rape were found in at least 10 samples. The Mediterranean Mountains zone exhibits relatively low soil P values. Maize fields were richer in P than barley, lucerne, or sunflower, while common wheat and rye represent medium values. Durum wheat is linked with the lowest, while maize is linked with the highest P levels in the Mediterranean North areas. Barley, common wheat, lucerne, oats, rye, sunflower, rape, and turnip rape are in medium categories. According to soil P, the only significant difference in the Mediterranean South zone was found between maize and durum wheat. Agricultural soils in the nemoral zone are balanced in terms of P concentration values, similar to those in the Pannonian areas (Table 1).

4 | DISCUSSION

Compared to European crop yields (Eurostat) and average P-fertilizer use in 2014 (Figure S3), in most cases there is a strong correlation between high yields and cropping intensity as indicated by soil P concentration. This is in line with the finding of Tóth et al. (2013) that the amount of P applied is higher in areas where higher yields are expected. However, some exceptions can be observed, presumably related to climatic and soil quality characteristics in the case of common wheat, the outstanding high P concentration in north-western areas of Poland and the outstanding values of the Netherlands are not reflected on the crop map, and in Finland low yield belongs to high P. Spain has vast areas with low-intensity cultivated wheatland, resulting in high gross output, despite the low per unit area yields. Winter wheat is a crop that adapts well to a relatively wide range of ecological conditions. Its yield is mainly determined by the use of N-fertilizer (Mancuso

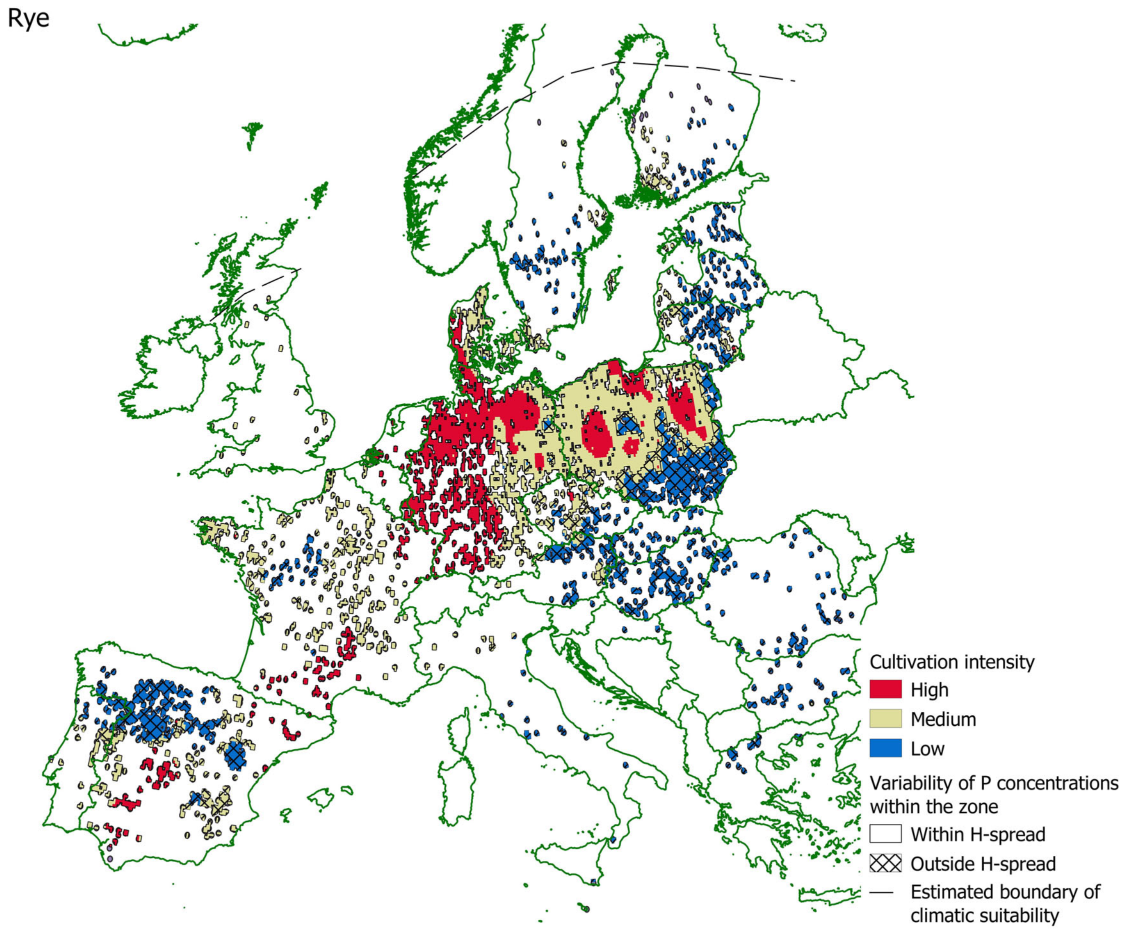

FIGURE 8 Cultivation intensity zones within the sowing area of rye in Europe as indicated by available soil phosphorus concentration (mg/kg ± standard deviation [SD]). High: 65 ± 9; medium: 46 ± 5; low: 30 ± 5. H-spread, interquartile range.

et al., 2019). In the case of barley, the management intensity classes match well with the production and yield; the differences are similar to that of common wheat. In addition, the high P values in Poland do not result in high yields, but the medium intensity in France is linked to high yields. Due to its shorter growing stage and better adaptability, barley can be grown more successfully even under less favorable conditions and with less P-fertilization. The yield and the quality of the crop in this case are significantly determined by the N-fertilization (Papastylianou, 2004; Shrestha & Lindsey, 2019). In the case of maize, the management intensity classes do not harmonize with the production map, except for the Italian Po-valley. The high-intensity areas of the Netherlands and North Germany produce less maize than the low-intensity southern part of France. Also, in terms of yield, this crop shows the largest differences; high-intensity North-European areas exhibit lower yields than Mediterranean areas. Although maize is a nutrient-intensive crop, its yields are significantly determined by the degree-day heat units and solar radiation in the area. In this respect, the southern production zones have an advantage if irrigation is possible (Gabaldón-Leal et al., 2015). While precipitation may be a limiting factor, the uptake of P in soils no longer affects the amount of crop as much as it does with adequate rainfall (Hermann & Tóth, 2011). The crop production maps of oats, rye, rape, and turnip rape fit very well with the management intensity categories. Presumably, they can be grown under the optimal ecological conditions for them.

The regional crop production map of sunflower (USDA-FAS, 2021) shows great total harvest amounts in Southwest France, Spain, and the Romanian-Bulgarian borderland, which runs contrary with our intensity maps. This underlines the limitation of using regional production maps to prove the relationship between P concentration and crop yields, as low regional production outputs may be caused by the small distribution area of a crop, even with high yields of the cropped fields. In terms of per unit area yield the relationship with management intensity is much closer. Nevertheless, low-intensity sunflower cultivation with high yields may be because of their deep roots, which have access to the nutrient reserves of the deeper layers of the soil (Ahmad et al., 2014). In addition, higher P input does not necessarily lead to higher crop yield; using P fertilization above the agronomic optimum does not give significantly better yields (Liebisch et al., 2013).

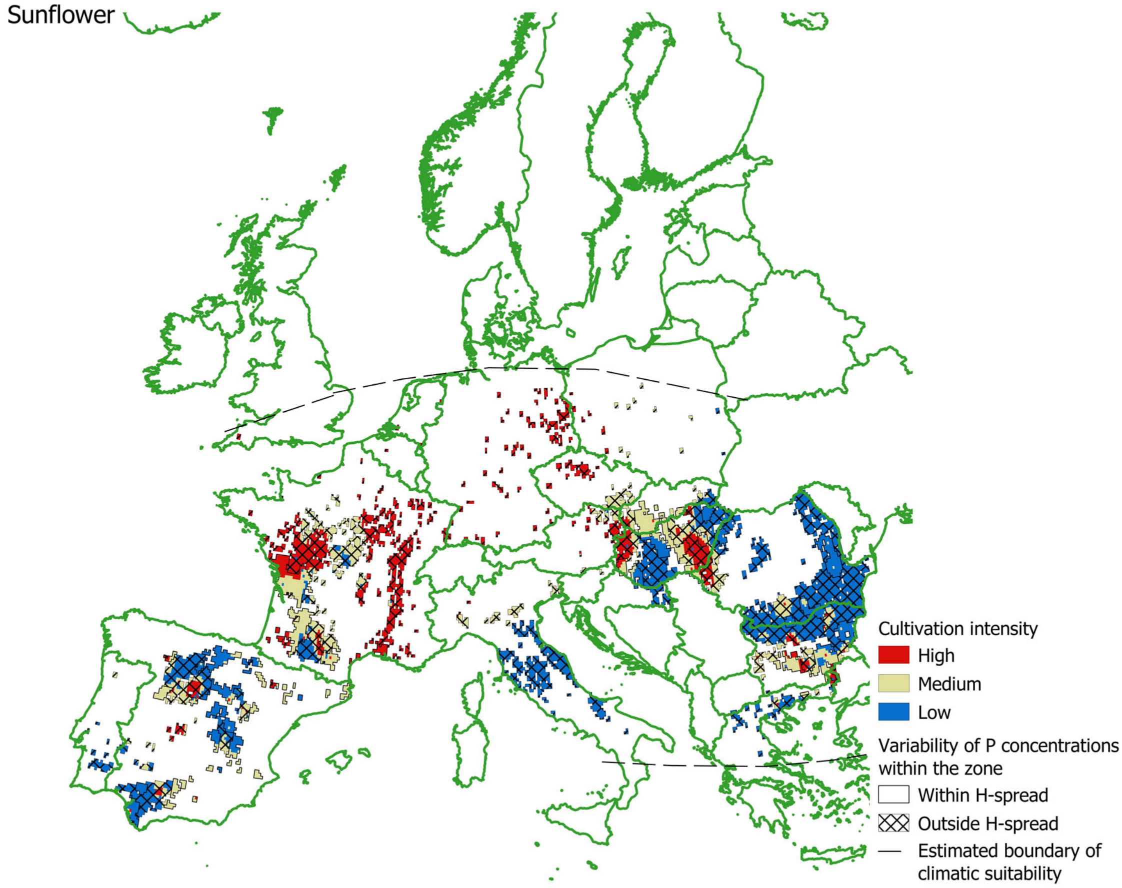

FIGURE 9 Cultivation intensity zones within the sowing area of sunflower in Europe as indicated by available soil phosphorus concentration (mg/kg ± standard deviation [SD]). High: 37 ± 4; medium: 27 ± 3; low: 17 ± 3. H-spread, interquartile range.

The observed soil P concentrations are in accordance with the former general evaluation of LUCAS topsoil data: North Europe exhibits higher, the central parts medium, and the Mediterranean lower values (Ballabio et al., 2019). The higher P-concentration of the soils under better climatic condition can be caused by the application of manure and slurry as well. However, significant differences ($p < 0.05$) were found according to certain crop species at the European level and within the environmental zones. Former studies on the P need or uptake of the agricultural plants do not explain these differences. For example, the P requirement of cereals for 1 ton grain yield is very similar (Antal, 2005). Wheat, barley, oats, and triticale were found to take up similar P amounts (Antal, 2005) but showed significantly different doses of P applications among these crops (Bolland, 1992). Dhillon (2017) measured significantly higher P uptake of wheat and maize than barley, while the lowest values occurred in the case of oats, rye, and triticale. Ketterings et al. (2001) recommend equal P amounts for sunflower, wheat, barley, oats, clovers, and higher amounts for lucerne and rye. In contrast, according to LUCAS topsoil data, maize, triticale, rye, rape, and turnip rape are cultivated on soils with higher P concentration, common wheat, barley and oats are in the medium category, while durum wheat, sunflower, and lucerne were found in areas with lower values. The high values found in soils covered with triticale, rye, rape, and turnip rape at the European level can result from the location of the crop fields covered with this plant; they are more frequent in Northern zones, which have higher P concentration. This is probably due to the combined result of good productivity and good economic potential of farms. The sunflower, durum wheat, and lucerne, which are more frequently cropped in the low P concentration soils of the Mediterranean, can tolerate the drier climate conditions better but their productivity and so their total P-requirements are lower. As an indicator of the intensity of field management (Bomans et al., 2005; Kassai & Tóth, 2020), the P concentration may reflect suitability of climate for crop production, the productivity of arable lands and consequently the total P-demands. The use of P-fertilizer and the P-concentration of soils are relatively well correlated with each other. However, we did not want to analyze the relationship between the yields and P-concentration of soils, because the yields are influenced by a lot of environmental and technological factors. The higher P-concentration of soils are the result of a high-intensity crop-grown system with high productivity and high input usage. Between 2011 and

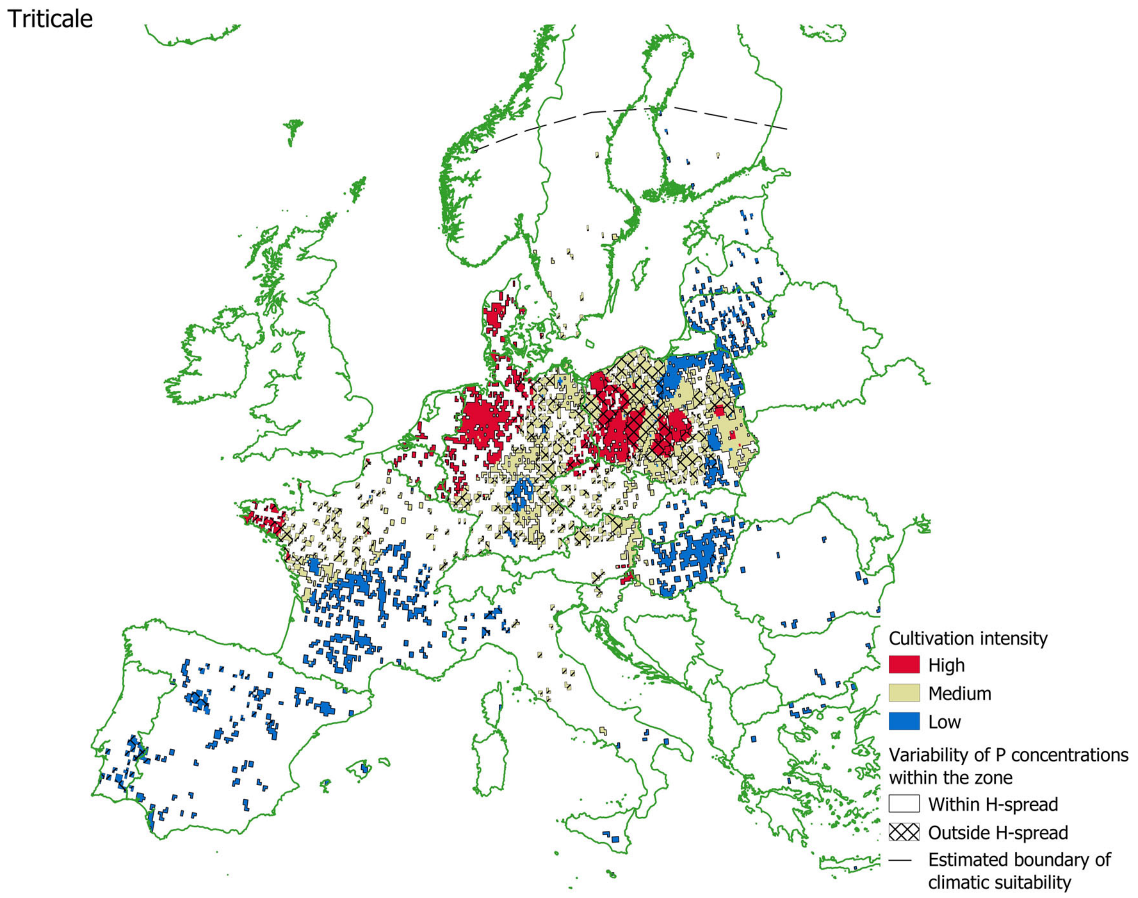

FIGURE 10 Cultivation intensity zones within the sowing area of triticale in Europe as indicated by available soil phosphorus concentration (mg/kg ± standard deviation [SD]). High: 68 ± 11; medium: 44 ± 6; low: 26 ± 5. H-spread, interquartile range.

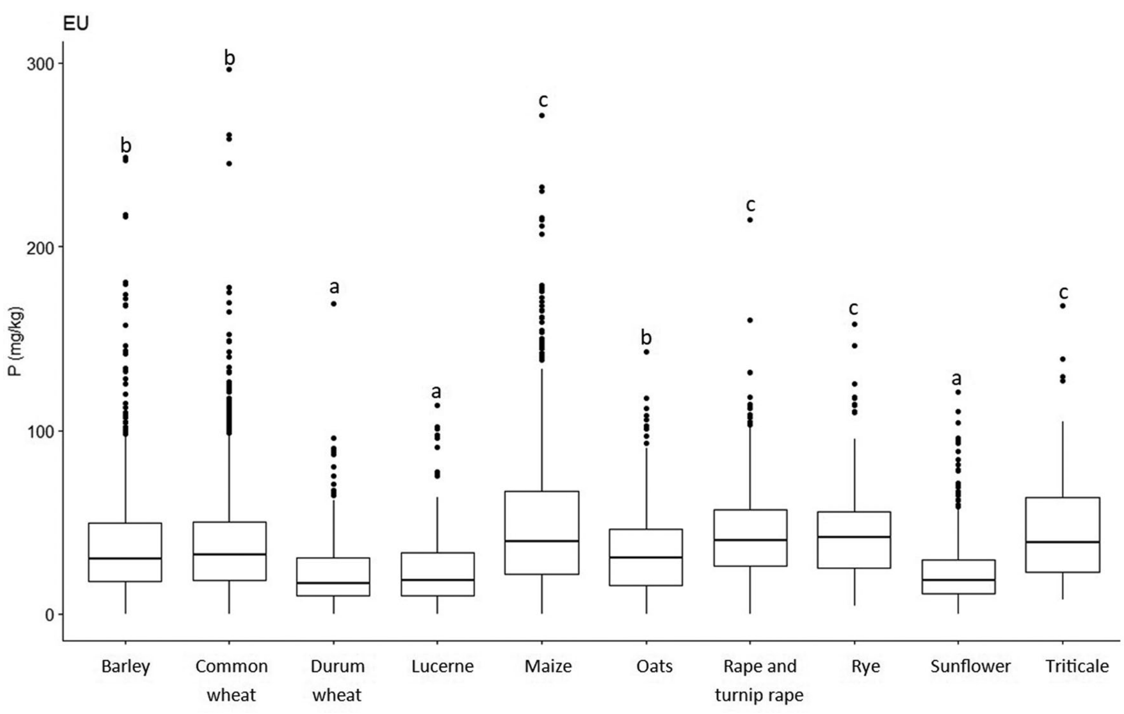

FIGURE 11 Available soil phosphorus of crop fields in Europe. Letters indicate different groups. The same letter indicates no significant difference after the Wilcoxon test ($p > 0.05$).

TABLE 1 Mean values of available phosphorus concentration (P) of the soil in different European environmental zones.

Crop		Atlantic central	Atlantic north	Boreal	Continental	Lusitanian	Mediterranean mountains	Mediterranean north	Mediterranean south	Nemoral	Pannonian
Barley	P (mg/kg)	40.1	61.2	48.7	49.1	47.2	22.6	29	26	30.8	31.2
	Group	a	a	b	bcd	A	a	c	ab	a	a
	CV (%)	47	48	42	58	70	81	103	92	71	92
Common wheat	P (mg/kg)	45.7	59.5	43.3	46.3	38.4	28.8	24.1	25.4	33.5	22.9
	Group	ab	a	b	b	A	ab	b	ab	a	a
	CV (%)	52	52	45	61	67	76	90	94	91	95
Durum wheat	P (mg/kg)	43.7	NA	NA	NA	31.6	NA	16.7	18.8	NA	18.9
	Group	ab				A		a	a		a
	CV (%)	43				44		116	76		66
Lucerne	P (mg/kg)	41.3	NA	NA	20.7	NA	23	22.8	30.8	NA	21.8
	Group	ab			a		a	ab	ab		a
	CV (%)	50			87		79	97	97		97
Maize	P (mg/kg)	56.2	90.2	NA	56.7	45.9	39.7	42	39.6	NA	23.3
	Group	b	b		cd	A	b	d	b		a
	CV (%)	58	43		67	78	94	81	84		87
Oats	P (mg/kg)	56.2	46.9	35.1	44.6	NA	17	18.5	16.2	40.3	NA
	Group	ab	a	a	b		a	ab	ab	a	
	CV (%)	47	60	60	57		68	84	77	60	
Rape and turnip rape	P (mg/kg)	41.6	62.2	37	53.9	50.3	NA	20.1	NA	26.7	25
	Group	ab	a	ab	d	A		abc		a	a
	CV (%)	48	45	71	52	57		77		46	86
Rye	P (mg/kg)	NA	68.9	NA	49.9	NA	31.9	27.1	NA	31.3	NA
	Group		a		bd		ab	bcd		a	
	CV (%)		46		49		88	58		68	
Sunflower	P (mg/kg)	41.2	NA	NA	27.2	32.4	17	21.1	19.8	NA	22.8
	Group	ab			a	A	a	b	ab		a
	CV (%)	61			44	65	80	71	76		93
Triticale	P (mg/kg)	64.2	NA	NA	48	NA	NA	NA	NA	27.4	26.4
	Group	ab			b					a	a
	CV (%)	57			48					87	60

Note: Group letters indicate different groups. The same letter indicates no significant difference after the Wilcoxon test ($p > 0.05$).
Abbreviations: CV, coefficient of variation; NA, not enough data.

2017, P-fertilizer use did not change significantly in Europe (Eurostat).

Nevertheless, regardless of their yield levels, the most profitable cereals in Europe: maize, wheat, and barley (European Commission, Directorate-General for Agriculture and Rural Development, 2019) are sown primarily in areas with the highest soil P concentrations in most environmental zones. Usually, the more suitable the climate for growing a plant, the more secure the crop, so higher doses of P fertilizers are applied.

5 | CONCLUSION

Our study delineated intensity zones within actual sowing areas of 10 major crops of Europe A great geographical diversity in cropping pattern as well as soil P concentration were observed, especially for crops with a broad climatic tolerance. Areas that have high yields, generally show higher soil P concentration. Our study also revealed that the distributions of crops unevenly follow the spatial differences of soil P concentration. Likewise, spatial distribution of soil P levels follow different patterns under different crops.

In the context of environmental zones, northern zones exhibit higher, the zones in central Europe medium, and the Mediterranean zones lower P-concentration values.

The geographical distribution and yield of crops are primarily determined by the climate. The more suitable the climate is for growing crops, the more it pays to apply P fertilizers. Both of our hypotheses were confirmed. Soil P-concentration is a good indicator of crop cultivation intensity, land productivity, P-fertilizer use, and the total P demand of plants. The data suggest that, in order to achieve maximum productivity, barley, common wheat, rape, oats, triticale, and maize can be grown on soils with available P concentrations greater than 40–45 mg/kg primarily in the Atlantic Central, Atlantic North, Boreal, Continental, and Lusitanian region. Among the most commonly cultivated crops, maize seems to be the most dependent crop for the level of phosphorous concentration of soil or the P inputs.

In contrast, the durum wheat, lucerne, rye, and sunflower can be grown economically even with an available P concentration of 15–30 mg/kg in the Continental, Pannonian, Mediterranean North, Mediterranean South, and Mediterranean Mountains regions. However, further studies are needed to validate the connection between intensity of cultivation of field crops and their economic return. We suggest collecting appropriate database at NUTS 2 or NUTS 3 level to calculate how the P-requirements of yields compares to the P-fertilizer use in the case of different crop types. Besides the available soil P concentration, phosphorous fixation capacity should also be considered when planning fertilizer amounts in a region to reach the goals of more sustainable crop management.

AUTHOR CONTRIBUTIONS

Nóra Szigeti: Data curation; formal analysis; visualization; writing—original draft; writing—review and editing. **Tamás Hermann**: Conceptualization; methodology; visualization. **Katalin Juhos**: Conceptualization; supervision; writing—original draft; writing—review and editing. **Gergely Tóth**: Conceptualization; funding acquisition; methodology; supervision; writing—original draft.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Nóra Szigeti https://orcid.org/0000-0003-2483-6761

REFERENCES

Ahmad, R., Waraich, E. A., Ashraf, M. Y., Ahmad, S., & Aziz, T. (2014). Does nitrogen fertilization enhance drought tolerance in sunflower? A review. *Journal of Plant Nutrition*, *37*, 942–963. https://doi.org/10.1080/01904167.2013.868480

Alewell, C., Ringeval, B., Ballabio, C., Robinson, D. A., Panagos, P., & Borrelli, P. (2020). Global phosphorus shortage will be aggravated by soil erosion. *Nature Communications*, *11*, Article 4546. https://doi.org/10.1038/s41467-020-18326-7

Antal, J. (2005). *Növénytermesztéstan* (in Hungarian). Mezőgazda Kiadó.

Baker, N. T., & Capel, P. D. (2011). *Environmental factors that influence the location of crop agriculture in the conterminous United States. U.S. Geological Survey Scientific Investigations Report 2011-5108*. United States Geological Survey https://pubs.usgs.gov/sir/2011/5108/

Ballabio, C., Lugato, E., Fernández-Ugalde, O., Orgiazzi, A., Jones, A., Borrelli, P., Montanarella, L., & Panagos, P. (2019). Mapping LUCAS topsoil chemical properties at European scale using Gaussian process regression. *Geoderma*, *355*, 113912. https://doi.org/10.1016/j.geoderma.2019.113912

Baranzelli, C., Perpiña Castillo, C., Lopes Barbosa, A., Batista E Silva, F., Jacobs, C., & Lavalle, C. (2015). *Land allocation and suitability analysis for the production of food, feed and energy crops in the period 2010–2050. EU Reference Scenario 2013 LUISA platform–Updated Configuration 2014*. JRC Science Hub. https://ec.europa.eu/jrc

Berhe, A. A., Barnes, R. T., Six, J., & Marín-Spiotta, E. (2018). Role of soil erosion in biogeochemical cycling of essential elements: Carbon, nitrogen, and phosphorus. *Annual Review of Earth and Planetary Sciences*, *46*, 521–548. https://doi.org/10.1146/annurev-earth-082517-010018

Bolland, M. D. A. (1992). The phosphorus requirement of different crop species compared with wheat on lateritic soils. *Fertilizer Research*, *32*, 27–36. https://doi.org/10.1007/BF01054391

Bomans, E., Fransen, K., Gobin, A., Mertens, J., Michiels, P., Vandendriessche, H., & Vogels, N. (2005). *Addressing phosphorus related problems in farm practice. Final report to the European Commission*. European Commission, DG Environment. https://ec.europa.eu/environment/natres/pdf/phosphorus/AgriPhosphorusReport%20final.pdf

Chen, A., & Arai, Y. (2020). Current uncertainties in assessing the colloidal phosphorus loss from soil. In D. L. Sparks (Ed.), *Advances in agronomy* (vol. 163, pp. 117–151). Academic Press. https://doi.org/10.1016/bs.agron.2020.05.002

Cordell, D., & White, S. (2014). Life's bottleneck: Sustaining the world's phosphorus for a food secure future. *Annual Review of Environment and Resources*, *39*, 161–188. https://doi.org/10.1146/annurev-environ-010213-113300

Csathó, P., Árendás, T., Szabó, A., Sándor, R., Ragályi, P., Pokovai, K., Tóth, Z., & Kremper, R. (2019). Phosphorus-induced zinc deficiency in maize (*Zea mays* L.) on a calcareous chernozem soil. *Agrokémia és Talajtan*, *68*, 40–52. https://doi.org/10.1556/0088.2018.00016

Dhillon, J., Torres, G., Driver, E., Figueiredo, B., & Raun, W. R. (2017). World phosphorus use efficiency in cereal crops. *Agronomy Journal*, *109*, 1670–1677. https://doi.org/10.2134/agronj2016.08.0483

European Commission, Directorate-General for Agriculture And Rural Development. (2019). *EU cereal farms report based on 2017 FADN data*. https://agriculture.ec.europa.eu/system/files/2020-01/fadn-cereal-report-2017_en_0.pdf

Eurostat. (2020). LUCAS survey. https://ec.europa.eu/eurostat/statistics-explained/index.php/LUCAS_-_Land_use_and_land_cover_survey

Gabaldón-Leal, C., Lorite, I., Mínguez, M., Lizaso, J., Dosio, A., Sanchez, E., & Ruiz-Ramos, M. (2015). Strategies for adapting maize to climate change and extreme temperatures in Andalusia, Spain. *Climate Research*, *65*, 159–173. https://doi.org/10.3354/cr01311

Gong, H., Meng, F., Wang, G., Hartmann, T. E., Feng, G., Wu, J., Jiao, X., & Zhang, F. (2022). Toward the sustainable use of mineral phosphorus fertilizers for crop production in China: From primary resource demand to final agricultural use. *Science of The Total Environment*, *804*, 150183. https://doi.org/10.1016/j.scitotenv.2021.150183

Hermann, T., & Tóth, G. (2011). Evaluating the effect of nutrient levels of major soil types on the productivity of wheatlands in Hungary. *Communications in Soil Science and Plant Analysis*, *42*, 1497–1509. https://doi.org/10.1080/00103624.2011.581728

Hetrick, B. A. D. (1991). Mycorrhizas and root architecture. *Experientia*, *47*, 355–362. https://doi.org/10.1007/BF01972077

Hinsinger, P. (2001). Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: A review. *Plant and Soil*, *237*, 173–195. https://doi.org/10.1023/A:1013351617532

Kanter, D. R., & Brownlie, W. J. (2019). Joint nitrogen and phosphorus management for sustainable development and climate goals. *Environmental Science & Policy*, *92*, 1–8. https://doi.org/10.1016/j.envsci.2018.10.020

Kassai, P., & Tóth, G. (2020). Agricultural soil phosphorus in Hungary: High resolution mapping and assessment of socioeconomic and pedological factors of spatiotemporal variability. *Sustainability*, *12*, 5311. https://doi.org/10.3390/su12135311

Ketterings, Q. M., Czymmek, K. J., & Klausner, S. D. (2001). *Phosphorus recommendations for field crops in New York. Department of crop and soil sciences extension series E01-5*. Cornell University. https://nmsp.cals.cornell.edu/publications/extension/Pdoc.pdf

Liebisch, F., Bünemann, E. K., Huguenin-Elie, O., Jeangros, B., Frossard, E., & Oberson, A. (2013). Plant phosphorus nutrition indicators evaluated in agricultural grasslands managed at different intensities. *European Journal of Agronomy*, *44*, 67–77. https://doi.org/10.1016/j.eja.2012.08.004

Mancuso, T., Verduna, T., Blanc, S., Di Vita, G., & Brun, F. (2019). Environmental sustainability and economic matters of commercial types of common wheat. *Agricultural Economics*, *65*, 194–202. https://doi.org/10.17221/172/2018-AGRICECON

Metzger, M. J., Bunce, R. G. H., Jongman, R. H. G., Mücher, C. A., & Watkins, J. W. (2005). A climatic stratification of the environment of Europe. *Global Ecology and Biogeography*, *14*, 549–563. https://doi.org/10.1111/j.1466-822X.2005.00190.x

Nziguheba, G., Palm, C. A., Buresh, R. J., & Smithson, P. C. (1998). Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. *Plant and Soil*, *198*, 159–168. https://doi.org/10.1023/A:1004389704235

Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular no. 939. US Department of Agriculture.

Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., & Fernández-Ugalde, O. (2018). LUCAS Soil, the largest expandable soil dataset for Europe: A review. *European Journal of Soil Science*, *69*, 140–153. https://doi.org/10.1111/ejss.12499

Palm, C., Sanchez, P., Ahamed, S., & Awiti, A. (2007). Soils: A contemporary perspective. *Annual Review of Environment and Resources*, *32*, 99–129. https://doi.org/10.1146/annurev.energy.31.020105.100307

Palmer-Felgate, E. J., Jarvie, H. P., Withers, P. J. A., Mortimer, R. J. G., & Krom, M. D. (2009). Stream-bed phosphorus in paired catchments with different agricultural land use intensity. *Agriculture, Ecosystems & Environment*, *134*, 53–66. https://doi.org/10.1016/j.agee.2009.05.014

Papastylianou, I. (2004). Effect of rotation system and N fertilizer on barley and vetch grown in various crop combinations and cycle lengths. *The Journal of Agricultural Science*, *142*, 41–48. https://doi.org/10.1017/S0021859604004009

Pelleg, D., & Moore, A. (1999). Accelerating exact k -means algorithms with geometric reasoning. *In Proceedings of the fifth ACM SIGKDD international conference on Knowledge discovery and data mining (KDD '99)* (pp. 277–281). ACM Press. https://doi.org/10.1145/312129.312248

Rega, C., Short, C., Pérez-Soba, M., & Luisa Paracchini, M. (2020). A classification of European agricultural land using an energy-based intensity indicator and detailed crop description. *Landscape and Urban Planning*, *198*, 103793. https://doi.org/10.1016/j.landurbplan.2020.103793

Richardson, A. E., Lynch, J. P., Ryan, P. R., Delhaize, E., Smith, F. A., Smith, S. E., Harvey, P. R., Ryan, M. H., Veneklaas, E. J., Lambers, H., Oberson, A., Culvenor, R. A., & Simpson, R. J. (2011). Plant and microbial strategies to improve the phosphorus efficiency of agriculture. *Plant and Soil*, *349*, 121–156. https://doi.org/10.1007/s11104-011-0950-4

Schoumans, O. F., Bouraoui, F., Kabbe, C., Oenema, O., & van Dijk, K. C. (2015). Phosphorus management in Europe in a changing world. *Ambio*, *44*, 180–192. https://doi.org/10.1007/s13280-014-0613-9

Shrestha, R. K., & Lindsey, L. E. (2019). Agronomic management of malting barley and research needs to meet demand by the craft brew industry. *Agronomy Journal*, *111*, 1570–1580. https://doi.org/10.2134/agronj2018.12.0787

Shriar, A. J. (2000). Agricultural intensity and its measurement in frontier regions. *Agroforestry Systems*, *49*, 301–318. https://doi.org/10.1023/A:1006316131781

Soltangheisi, A., Teles, A. P. B., Sartor, L. R., & Pavinato, P. S. (2020). Cover cropping may alter legacy phosphorus dynamics under long-term fertilizer addition. *Frontiers in Environmental Science*, *8*, Article 13. https://doi.org/10.3389/fenvs.2020.00013

Tóth, G., Jones, A., & Montanarella, L. (2013). The LUCAS topsoil database and derived information on the regional variability of cropland topsoil properties in the European Union. *Environmental Monitoring and Assessment*, *185*, 7409–7425. https://doi.org/10.1007/s10661-013-3109-3

Tukey, J. W. (1977). *Exploratory data analysis*. Addison-Wesley.

USDA Foreign Agricultural Service (USDA-FAS). (2021). Europe–Crop production maps. https://ipad.fas.usda.gov/rssiws/al/europe_cropprod.aspx

van der Zanden, E. H., Levers, C., Verburg, P. H., & Kuemmerle, T. (2016). Representing composition, spatial structure and management intensity of European agricultural landscapes: A new typology. *Landscape and Urban Planning*, *150*, 36–49. https://doi.org/10.1016/j.landurbplan.2016.02.005

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