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ASSESSMENT OF NATURAL RESOURCE POTENTIAL OF THE AGROECOSYSTEMS OF UKRAINE AND THE EU COUNTRIES BY PHOSPHORUS BALANCE

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Aim. To conduct a comparative assessment of the current state and dynamics of phosphorus balance in the agroecosystems of Ukraine and the EU and determine the methods to manage phosphorus flows and restore its funds in the soils. **Methods.** The methods of the Organization for Economic Cooperation and Development (OECD, 2007) to assess the flows and balance of phosphorus and its use efficiency (PUE) in the crop production subsystems were used (Chowdhury et al., 2021). The initial data were taken from the electronic resources of the State Statistics Service of Ukraine (http://www.ukrstat.gov.ua), Eurostat (https://ec.europa.eu), and State Institution of Soil Protection of Ukraine (https://www.iogu.gov) regarding the inspection of agricultural fields by the results of XI round (2016–2020). The index maps were built in the MS Excel 2021. **Results.** The gross balance of phosphorus in the agroecosystems of Ukraine and 30 European countries in 1990–2021 was determined. A decrease in the soil potential for phosphorus content, calculated by the indices of phosphorus flows in modern agricultural production, was determined. It was shown that, on average, the amount of phosphorus removed by the economically valuable part of the crop significantly exceeded its entry into the soil with fertilizers. The state of the use of mineral and organic fertilizers in crop production in Ukraine and EU countries was compared. The unbalanced use of soil phosphorus in Ukraine's agroecosystems in 1995–2021 was revealed: the negative phosphorus balance increased from –5.6 to –11.4 kg P/ha/year and the intensive soil load — PUE 139–256 %, which is primarily due to a decrease in the use of organic fertilizers from 9.6 to 0.8 kg P/ha/year, and phosphorus mineral fertilizers — from 17.9 to 6.9 kg P/ha/year. The minimal gross P balance (0.6 P/ha/year) established in the EU countries was observed only in 2019. Among the EU countries in 2019, the gross P balance ranged from –5.6 to 6.0 kg P/ha/year. The countries with a negative P balance (2019) include Romania (–5.6 kg P/ha/year), Bulgaria (–5.4), Germany (–4.8), Slovakia (–1.9), Sweden (–1.5), Lithuania (–1.3), Hungary (–0.4) and the Czech Republic (–0.03 kg P/ha/year), the indices of which are lower than those for Ukraine. The PUE in the EU countries (2019) was within the range of 62–167 %. In particular, the PUE above 100 % was found in Hungary — 103 %, Lithuania — 111 %, Sweden — 113 %, Germany — 126 %, Slovakia — 118 %, Romania — 152 %, and Bulgaria — 167 %, which is lower than in Ukraine — 186 %. Currently, in Ukraine, the amount of mineral phosphorus applied to the sown area is close to the EU average but 11 times lower than the amount of organic phosphorus applied to the soil. **Conclusions.** To achieve a deficit-free balance of phosphorus, restore its content in soils, minimize negative environmental impacts, and increase economic benefits, it is advisable to compensate for the removal of phosphorus with the main products not only by applying industrial phosphate mineral and organic fertilizers but also by creating agroecosystems with a high level of phosphorus recycling and using current local phosphorite deposits.

Keywords: phosphorus, soil, phosphorus flows, phosphorus use efficiency (PUE), fertilizers, waste of animal breeding and crop production, recycling, phosphorites.

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INTRODUCTION

Rational management of phosphorus flows in agroecosystems has a significant impact on food security due to the low natural content of plant-available forms of phosphorus in soils and limited resources of phosphate rock for the production of appropriate fertilizers. Phosphorus (P) is one of the six chemical elements that make up the basis of organic compounds and the second most important macronutrient required by plants for biomass formation during photosynthesis. P is a component of organelles and cell membranes, proteins, and enzymes of energy metabolism and transmission of hereditary information. Phosphorus, like the other seventeen major biogenic elements necessary for plant growth, plays a key role as a central regulator of plant physiological responses to abiotic stresses due to adverse environmental conditions such as drought, salinity, and extreme temperatures, affects root system architecture, nutrient uptake, photosynthesis and stomatal regulation (Khan et al., 2023).

The main primary source of P is the soil-forming parent rock (Kramarov et al., 2015). Global resources of P are getting exhausted faster, and, according to some estimates, by 2050, the P resources in soil will be limited, which creates a potential threat to the stable development of crop production. Its deficiency limits the yield of more than 40 crops in the world (Balemi et al., 2012). Among biogenic elements, P has the smallest reserves, most of which are concentrated in a few countries (85 in Morocco) (Penuelas et al., 2023).

The formation of the soil phosphate fund is ensured by soil biota, which induces the transformation of primary phosphorus-containing minerals of the parent rock that ensures the formation of secondary inorganic and organic phosphates. In fact, under natural conditions, soil formation is a closed cycle of P, which is determined by the ratio of humification and mineralization of organic matter, so one of the main tasks is to reduce the deficit of P available to plants in the soil by increasing the use of phosphorus fertilizers, including those from local raw materials — organic fertilizers, phosphorites and apatites, sapropels, peat, crop residues, etc. (Nosko, 2018; Torma et al., 2018).

Considering soils with Olsen phosphorus content above and below the threshold (1 $mg \cdot kg^{-1}$), which corresponds to the likely agronomic optimal yield for 28 of the most common and valuable crops in the world, as well as pastures for intensive grazing, it was found that 73 % of the land area is below the optimal production thresholds in terms of available soil phosphorus (McDowell et al., 2024). For soils close to the critical level of P, the efficiency of its use becomes high since the phosphorus applied to the soil with fertilizers and its consumption by crops is almost the same. Maintaining soil near the critical P level should optimize yields and use of global phosphorus resources while minimizing the risk of excessive phosphorus amount being transferred to water sources (Johnston et al., 2019). Moreover, for example in China, despite local successes, the widespread mobilization of smallholder farmers to adopt sustainable management practices of phosphorus remains a challenge, primarily due to the associated high costs and complicated sampling. Therefore, to optimize the determination of the soil phosphorus status and to reduce the use of phosphorus fertilizers by half, a dynamic optimization of soil phosphorus status (DOP) approach is proposed, aimed at managing the long-term soil phosphorus status within a range of agronomic and ecological threshold values (Gong et al., 2025).

Understanding quantitative agronomic and ecological thresholds for soil phosphorus at a global scale is necessary to improve phosphorus use efficiency and crop productivity while preventing phosphorus losses in the environment (Wang et al., 2023). Limited resources of phosphate raw materials are among the most pressing problems not only in Ukraine but also globally (Romanova et al., 2023). The optimization of phosphate nutrition of crops should be based on information about their yield, nutrient content in plants and soil properties of a particular field. The phosphorus balance is significantly affected by the doses of phosphorus supplied with mineral and organic fertilizers. The balanced content of phosphorus in soil is achieved in the fields with low doses of phosphorus, applied with mineral fertilizers and manure, and the absence of phosphorus fertilizers has a negative effect on phosphorus balance and may result in a decrease in crop yield. This information is required for efficient soil management, environment protection, and a decrease in industrial expenses for phosphate fertilizers (Matějková et al., 2021).

The level of nitrogen and phosphate fertilizers used per unit of sown area in the world has increased 8 times and 3 times, respectively, since 1961, when IFA (International Fertilizer Association) and FAO (Food and Agricultural Organization) conducted the following country-level studies. In the early 21st century, the hotspots of fertilizer use in the 1960s shifted from the United States and Western Europe to East Asia with the current hotspot in Brazil (Lu et al., 2017). Globally, the major trends include the general increase in nutrient inputs and outputs of N, P and K during the period from 1961 to 2020, reflecting the increased scale and intensity of food production in most countries over the same period. The relative larger increase in the growth of inputs vs. outputs has concurrently resulted in greater nutrient surpluses for N and P, whereas K surpluses have decreased. This indicates that more emphasis has been placed globally on inputs of N and P compared with K, relative to removed nutrients (Ludemann, et al., 2024).

Since the main source of phosphorus, phosphate rock, is a vital non-renewable natural resource that permeates different sectors, governance levels, materials and social relations, phosphorus governance can be described as a wicked non-renewable resource problematic that has been translated into a complex system of knowledge sub-systems not sharing the information (siloed knowledge). This siloed thinking is reflected in the vast number of EU regulations and policies that are at the same time narrowly limited to discrete aspects and sectoral uses of phosphorus, which are dominated by the sectors of agriculture and resource recovery (Kalpakchiev et al., 2023).

Today, P has become a critical and often unbalanced element in European agriculture. At the same time, in May 2020, the European Commission published the From Farm to Fork (F2F) strategy, one of the main goals of which was to reduce fertilizer use by at least 20%. It is important to look for the optimal use of P to reduce environmental phosphate pollution and, at the same time, ensure food security (Panagos et al., 2022). In addition, the Directive on Nitrates (91/676/EEC) sets guidelines for agricultural practices to reduce nitrate (NO_3) leaching, which are implemented in each Member State through the National Action Program (NAP), which is legislated as Good Agricultural Practice (GAP) rules. The GAP rules set out farming practices to reduce NO3 leaching but also limit the use of P on farms and establish soil P indices (Mihailescu et al., 2015).

Despite European regulations, the elevated P levels persist in many water bodies across the continent. Phosphorus excess in soils promotes eutrophication and deterioration of water quality in surface waters. In particular, the total excess of phosphorus in the EU–27 increased three times in 170 years, from 1.19 (±0.28) $kg \cdot ha^{-1} \cdot year^{-1}$ in 1850 to about 2.48 (±0.97) $kg \cdot ha^{-1} \cdot year^{-1}$ in recent years. The long-term perennial data about the phosphorus excess in soil are relevant for understanding of these levels and determining future management strategies (Batool et al., 2024).

The informative index of the substance flow analysis (SFA) in the agricultural production system nationwide is phosphorus use efficiency (PUE). The PUE in the overall agricultural production system averages 46% (30 countries), which is lower than in the crop and pasture subsystem (average 72%), but higher than in the livestock breeding subsystem (average 18%). Shifting from animal feed/pasture production for animal products to crop production for food can improve the PUE in the agricultural production system (Chowdhury et al., 2021). Although manure is a source of P excess in areas with high livestock density, P deficiency is often common in areas where crops are grown for livestock fodder (MacDonald et al., 2011).

Among all the resources needed to increase agricultural productivity, nutrients are considered the most important (Timsina, 2018). The management of phosphorus, nitrogen, and potassium fertilizers is at the center of the main dichotomy between food security and environmental issues such as climate change and eutrophication. Such a key role requires the adoption of the well-known common sense principle of the 4Rs (right nutrient source at the right rate, at the right time, and in the right place), which would help ensure proper use of nutrient resources and optimize productivity (Penuelas et al., 2023). In addition, a phosphorus management strategy requires a better understanding of soil-plant-animal P dynamics, effective soil P restoration, and innovative technologies to improve plant uptake of P fertilizers (Withers et al., 2014).

The purpose of this study is to assess the current state and dynamics of phosphorus balance in agroecosystems of Ukraine and EU countries and to identify the ways to restore phosphorus reserves in soils.

MATERIALS AND METHODS

The calculation of the gross phosphorus balance in crop production in Ukraine (the total phosphorus balance of all crops on the total harvested area in Ukraine per year) was based on the methodology of the Organization for Economic Cooperation and Development (OECD, 2007). The gross surplus/deficit of phosphorus (P_{surplus}), which may remain in soil, get leached into soil waters, or flow into surface waters, was calculated using equation 1 (OECD, 2007):

$$P_{\text{surplus}} = P_{\text{soil surface balance}} \div A_{\text{UAA}} \times 100, \qquad (1)$$

where: P_{surplus} — gross surplus/deficit of phosphorus in the soil while cultivating crops, kg of P/ha/year; $P_{\text{soil surface balance}}$ — gross balance of phosphorus in the soil while cultivating crops, t P/year; A_{UAA} — harvested area of crop yield, ha.

The soil surface balance of phosphorus was calculated as the difference between the total amount of phosphorus, annually entering soil, and the amount of phosphorus, leaving soil, using equation 2 (OECD, 2007):

$$P_{\text{soil surface balance}} = \sum P_{\text{inputs}} - \sum P_{\text{outputs}}, \qquad (2)$$

where: P_{inputs} — incoming flows of phosphorus in crop production (mineral fertilizers, organic fertilizers, seeds, and atmospheric precipitation), t P/year; P_{outputs} — outgoing flows of phosphorus with the crop products (food and fodder crops, by-products), t P/year.

After-harvest crop residues are additionally included in the incoming and outgoing phosphorus flows. In Ukraine, in addition to livestock waste, after-harvest crop residues (straw, tops, stubble, leaves) from corn for grain, soybeans, potatoes, vegetables, sunflower, and food and fodder crops are used as organic fertilizers. The straw and tops of other crops are used as fodder or bedding for animals. P is added to the soil through mineralization of crop residues and removal of P with crop by-products. ($P_{(\text{cr})}$) was calculated based on the method of F.I. Levin, using equation 3 (MEPR, 2023):

$$P_{(\text{cr})} = \sum \text{i}\{[(a_i \times P_i + b_i) + (c_i \times P_i + d_i) \times f_{ai}\}S_i, \qquad (3)$$

where: i — index of the crop species; P_i — yield of the i-th crop, kg/ha; S_i — harvested area under the i-th crop, ha; a_i and b_i — regression coefficients for the straw of the i-th crop; c_i and d_i — regression coefficients for the stubble of the i-th crop (MEPR, 2023); f_{ai} — content of phosphorus in the straw and stubble of the i-th crop, % (**Table 2**);

The phosphorus use efficiency (PUE) in crop production was calculated using the proposed general methodological approaches to assessing the crop production subsystem (Cc), which includes the production of cereals and non-cereals, fruits and vegetables, processes and material flows according to equation 4 (Chowdhury et al., 2021):

$$\text{CcPUE} = (\text{CcTPO} \div \text{CcTi}) \times 100, \qquad (4)$$

where: PUE — phosphorus use efficiency in the crop production subsystem (Cc), %; CcTPO — total incoming phosphorus inflows in the crop production subsystem (Cc) (mineral fertilizers, organic fertilizers, seeds, atmospheric precipitation, and mineralization of after-harvest (ploughed under) plant residues), t P/year; CiTi — total flows of phosphorus, outgoing with plant products (food and fodder crops, by-products) in the crop production subsystem (Cc), t P/year.

The coefficients of phosphorus content in organic fertilizers and atmospheric precipitation of phosphorus are presented in **Table 1**.

The coefficients for the calculation of P input into soil and P removal with grain and plant residues of crops are presented in **Tables 2, 3**.

The initial data to calculate P balance and phosphorus use efficiency (PUE) in Ukraine — inputs of mineral and organic fertilizers into the soil, sown and harvested crop area, yield and volume of production of crops were taken from the database of electronic resource of the State Statistics Service of Ukraine (http://www.ukrstat.gov.ua) for 1990–2021. The initial data for calculations P balance and PUE in EU countries — total P inputs/outputs, harvested crop area & P inputs from mineral & organic fertilizers were

Table 1. The coefficients of phosphorus content in organic fertilizers and atmospheric precipitation of phosphorus

Source of phosphorus	P content, %	References
Manure of farm animals, average	0.12	As per the data of the laboratory of organic fertilizers and humus, the NSC "Institute for Soil Science and Agrochemistry, named after O.N. Sokolovsky"
Poultry manure, average	0.88	Voitenko L. et al., 2009
Sludge and sapropel, average	0.28	
Peat and its substrates, average	0.08	
Other kinds of organic fertilizers, average	0.11	
Atmospheric precipitation, average, kg/ha	0.05	Korsun S.H. et al., 2018

Table 2. The coefficients of phosphorus content in the grain of crops

Source of phosphorus	P content, %	References
Cereals, interval	0.22–0.45	FAO, 2022
Grain legumes (except soybeans), interval	0.40–0.87	Sharasia et al., 2017; FAO, 2022
Soybeans	0.81	FAO, 2022
Oil crops, interval	0.17–0.59	FAO, 2022; Vovchenko, 2008; Bhat et al., 2014
Root crops, interval	0.05–0.10	FAO, 2022
Vegetables, interval	0.02–0.34	FAO, 2022; Hospodarenko, 2018
Cucurbits, average	0.03	FAO, 2022; Hospodarenko, 2018
Fodder root crops, interval	0.03–0.05	FAO, 2022; Hospodarenko, 2018

Table 3. The coefficients of phosphorus content in the after-harvest residues of the crops

Source of phosphorus	P content, %	References
Cereals, interval	0.08–0.23	Hospodarenko, 2018; Senchuk, 2017; Servi-Tech Laboratories (https://cropfile.servitech.com/index#h.qzirp2rqvds0)
Grain legumes (except soybeans), interval	0.10–0.22	Sharasia et al., 2017
Soybeans	0.09	Gelderman, 2009
Oil crops, interval	0.08–0.48	Hospodarenko, 2018; Vovchenko, 2008; Bhat et al., 2013; Servi-Tech Laboratories (https://cropfile.servitech.com/index#h.qzirp2rqvds0)
Root crops, interval	0.04–0.14	Hospodarenko, 2018
Vegetables, interval	0.03–0.19	Hospodarenko, 2018; FAO, 2017
Cucurbits, average	0.04	Hospodarenko, 2018
Fodder corn	0.08	FAO, 2022
Fodder root crops, interval	0.03–0.04	Hospodarenko, 2018
Grasses for green fodder, interval	0.05–0.11	Ibatullin, 2003; 2015.
Grasses for hay, interval	0.20–0.25	Ibatullin et al., 2003; 2015; Hospodarenko, 2018

taken from the Eurostat database (https://ec.europa.eu) for 1990–2019.

To determine the average weighted P2O5 content in the soil, we used the materials of scientific research of State Institution of Soil Protection of Ukraine, on the survey of agricultural land based on the results of the XI round (2016–2020) (https://www.iogu.gov.ua/).

The balance calculations and index maps were done in the MS Excel 2021.

RESULTS

The main sources of phosphorus input into the soil in Ukraine (2021) are mineral fertilizers — 48.1 %, after-harvest crop residues — 42.6 %, organic fertilizers — 5.6 %, seeds — 3.4 % and atmospheric precipitation — 0.3 % (**Table 4**).

About two-thirds of the incoming phosphorus flows in the "soil-plant" system are deposited in grain (fruit) and one-third — in the by-products of plant production (stubble, straw, and leaves), remaining in the field after harvesting the main crop products. On average, in Ukraine 97.2 % of phosphorus is used for the production of food crops, and only 2.8 % — for fodder production (**Table 5**).

Some part of the after-harvest residues of crops (straw and leaves) is used for bedding and feeding of farm animals, and the rest is returned to the soil. The after-harvest crop residues with high green biomass — corn, sunflower, soybeans, and vegetables, are intentionally ploughed into the soil. It is believed that the organic matter of the after-harvest residues is mineralized in soil for two years (MEPR, 2023).

On average, in Ukraine in 2021, the input into soil was 14.2 kg P/ha, and the output with the crop harvesting — 25.0 kg P/ha.

Results obtained in 2021, showed that the average P balance in Ukraine was 10.8 kg/ha. The negative P balance was determined for all the administrative regions of Ukraine, with the highest values in the Khmelnytskyi (–17.2 kg p/ha/year), Vinnytsia (–16.8), Ternopil (–15.7) and Cherkasy regions (–15.5 kg P/ha/year). The minimal value (–2.4 kg P/ha/year) was registered in the Luhansk region. (**Fig. 1**).

The average PUE value in Ukraine (2021) was 176.0 % and in the administrative regions of Ukraine in 2021, it fluctuated from 115 % (Luhansk region) to 251 % (Chernivtsi region) (**Fig. 2**).

Table 4. Phosphorus input flows from mineral and organic fertilizers, seeds, atmospheric precipitation and mineralization of after-harvest residues in Ukraine, 2021

Input P flows in the "soil-plant" system											
P of mineral fertilizers		P of organic fertilizers		P of seeds		P of atmospheric precipitation		P of after-harvest residues		Total	
thousand tons/year	kg P/ha	thousand tons/year	kg P/ha	thousand tons/year	kg P/ha	thousand tons/year	kg P/ha	thousand tons/year	kg P/ha	thousand tons/year	kg P/ha
198.4	6.9	23.0	0.8	14.07	0.5	1.54	0.05	175.9	6.2	412.8	14.2

Table 5. Phosphorus output flows for the production of the main and by-products of crop production in Ukraine, 2021

Output P flows in the "soil-plant" system								
Grain (fruit)		Fodder		By-products		Total		The ratio between the main and by-products
thousand tons/year	kg P/ha	thousand tons/year	kg P/ha	thousand tons/year	kg P/ha	thousand tons/year	kg P/ha	
463.0	17.2	20.0	9.4	243.4	8.4	726.5	25.0	2.0

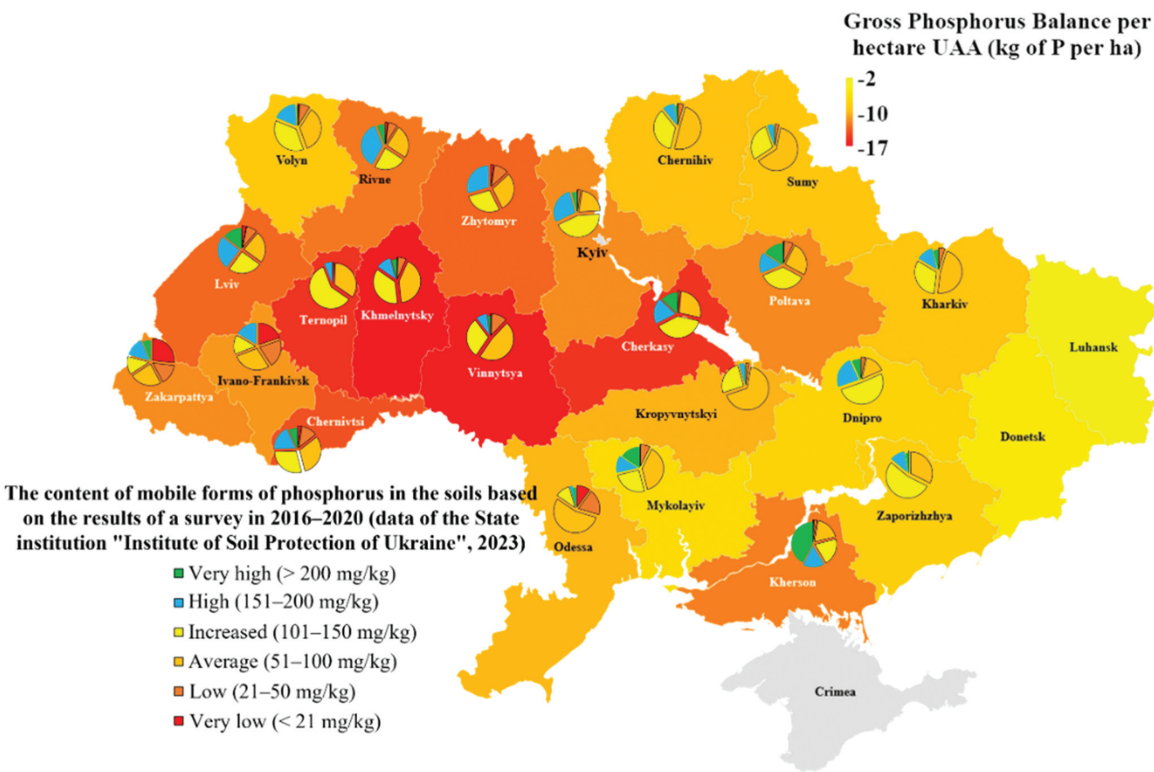

Fig. 1. The gross balance of P for the harvested area of crops of all the farm categories at the level of administrative regions* of Ukraine, 2021 (present study)

* Data for the Crimea was not available.

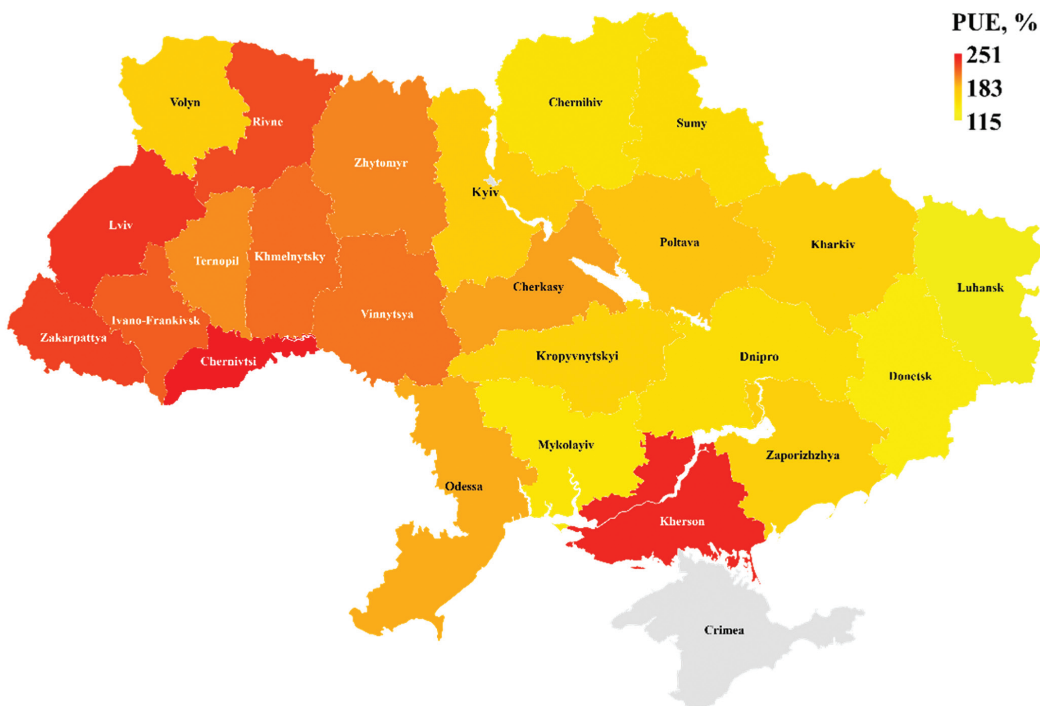

Fig. 2. The PUE in the crop production of all the farm categories at the level of administrative regions* of Ukraine, 2021 (present study)

* Data for the Crimea was not available.

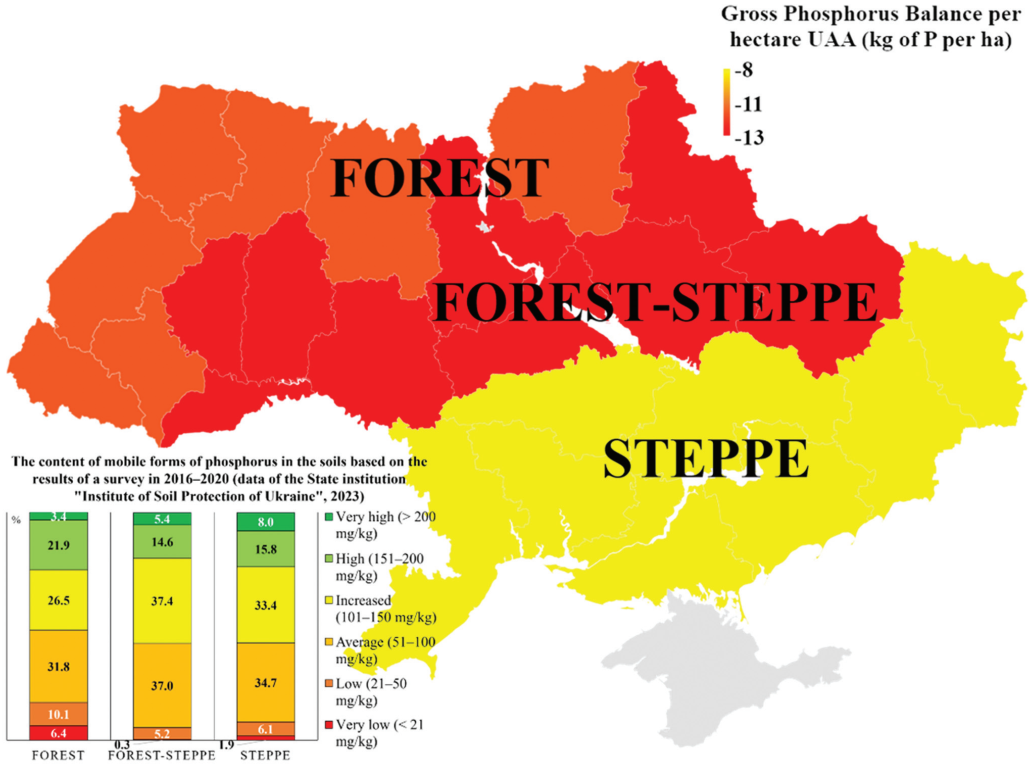

Fig. 3. The gross balance of P regarding the harvested area of crops in terms of the natural agricultural zones* of Ukraine, 2021 (present study)

* Data for the Crimea was not available.

Fig. 4. The PUE in the crop production of all the farm categories in terms of the natural agricultural zones* of Ukraine, 2021 (present study)

* Data for the Crimea was not available.

The negative values of the gross balance and the PUE were found in the Forest-Steppe zone (–13.2 kg P/ha and 185 %, respectively), in Polissia (–11.5 kg P/ha and 184 %) and Steppe (–8.2 kg P/ha and 162 %) (**Fig. 3, 4**).

Fig. 5 and **6** demonstrate the gross balance and the PUE of Ukraine as compared to 20 countries, which were permanent and associate member states of the EU in 2019.

Among the EU countries, the gross P balance ranged from –5.6 to 6.0 kg P/ha/year. The countries with the negative P balance include Romania (–5.6 kg P/ha/year), Bulgaria (–5.4), Germany (–4.8), Slovakia (–1.9), Sweden (–1.5), Lithuania (–1.3), Hungary (–0.4) and Czech Republic (-0.03 kg P/ha/year), the indices of which are lower as compared to Ukraine (–10.7 kg P/ha/year). The PUE in the EU countries is within the range of 62–167 %. In particular, the PUE above 100 % was found in Hungary — 103 %,

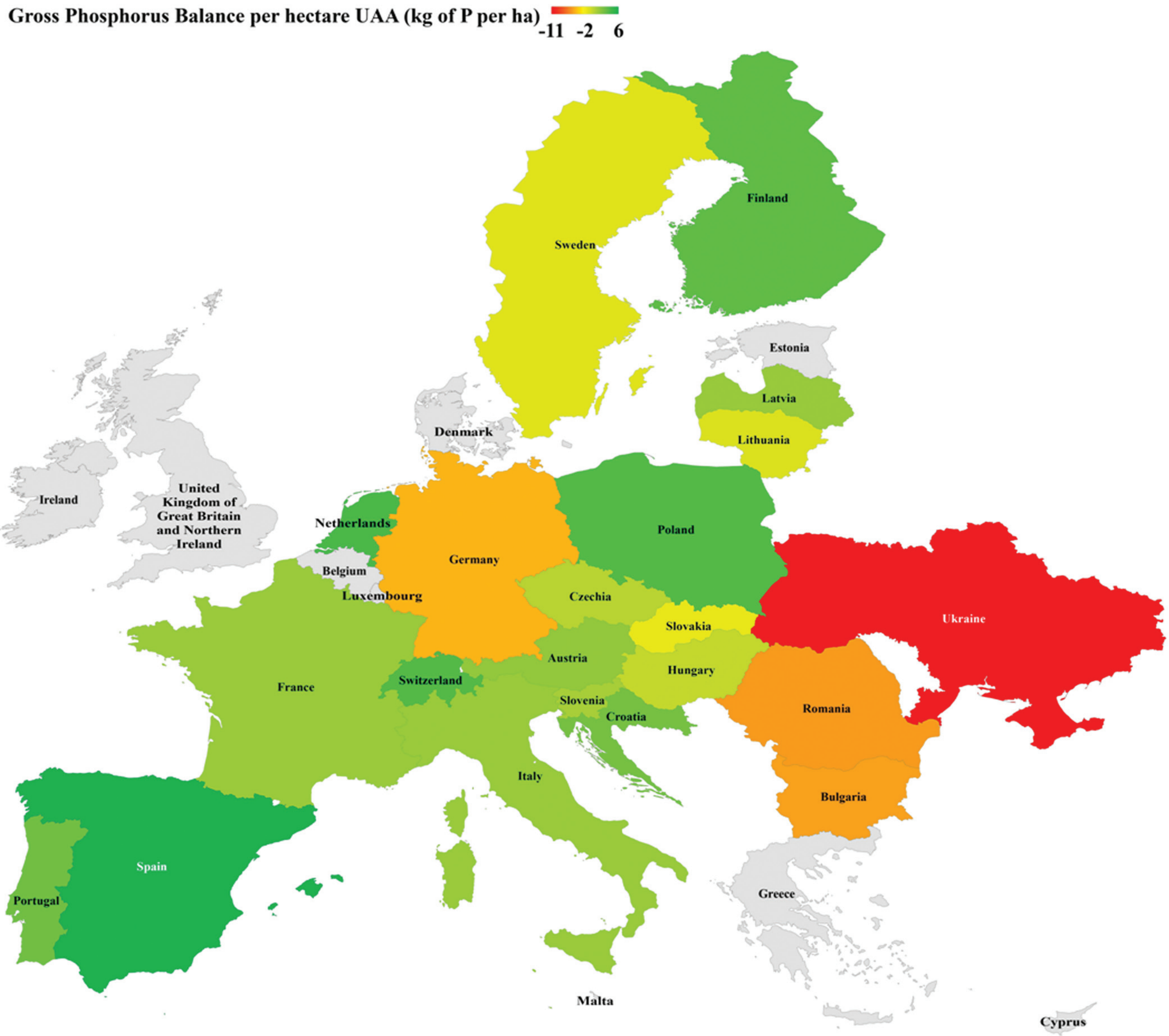

Fig. 5. The gross balance of P for the area of agricultural fields of Ukraine (present study) and 20 countries which are permanent and associate member states of the EU*, 2019 (the index was calculated by the data of Eurostat from 20 countries, 2019)

* Data for the Belgium, Cyprus, Denmark, Estonia, Greece, Ireland, Luxembourg, Malta & United Kingdom of Great Britain and Northern Ireland were not available.

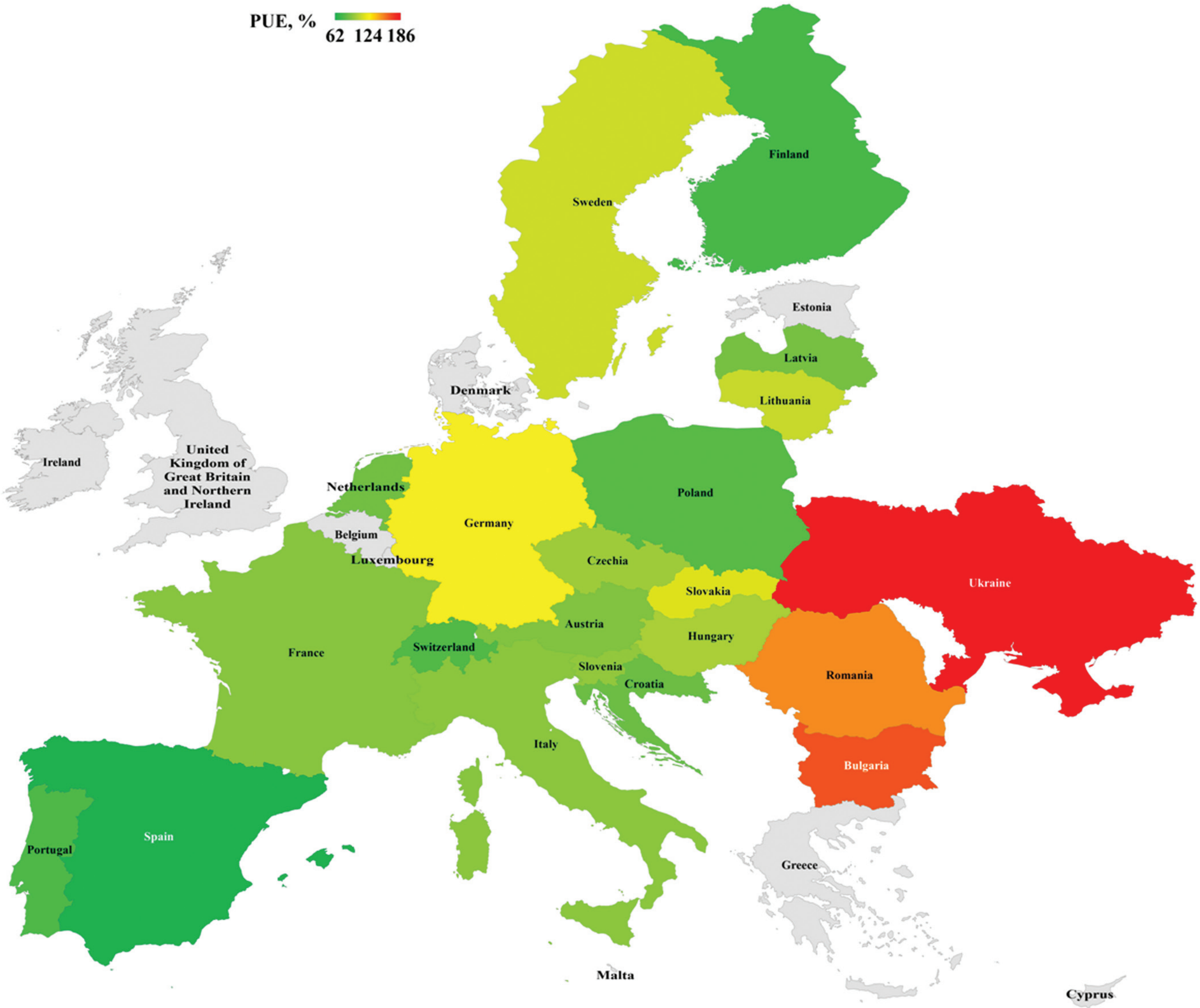

Fig. 6. The phosphorus use efficiency (PUE) in the agricultural fields of Ukraine (present study) and 20 countries that are permanent and associate member states of the EU*, 2019 (the index was calculated by the data of Eurostat from 20 countries, 2019)

* Data for the Belgium, Cyprus, Denmark, Estonia, Greece, Ireland, Luxembourg, Malta & United Kingdom of Great Britain and Northern Ireland was not available.

Lithuania — 111 %, Sweden — 113 %, Germany — 126 %, Slovakia — 118 %, Romania — 152 %, and Bulgaria — 167 %, which is lower than in Ukraine — 186 %.

Considering the negative gross P balance in 2021 at the level of all the regions of Ukraine and the presence of ploughed areas with low and very low content of P2O5, we studied the dynamics of P balance in 1990–2021 in Ukraine and in comparison with the EU indices (**Fig. 7**).

Since 1995, on average in Ukraine, the amount of the removed nutrients as compared to their input into the soil increased up to –10.8 kg P/ha/year. In the EU, the minimal balance of P (0.6 P/ha/year) was observed in 2019 (according to the data of 20 investigated countries, permanent and associate EU member-states).

The optimal PUE indices (31 %) were observed in Ukraine only in 1990 and, on average, in the EU in 1990–2005 (52–75 %). Instead, intense soil burdening has been observed in Ukraine in the recent

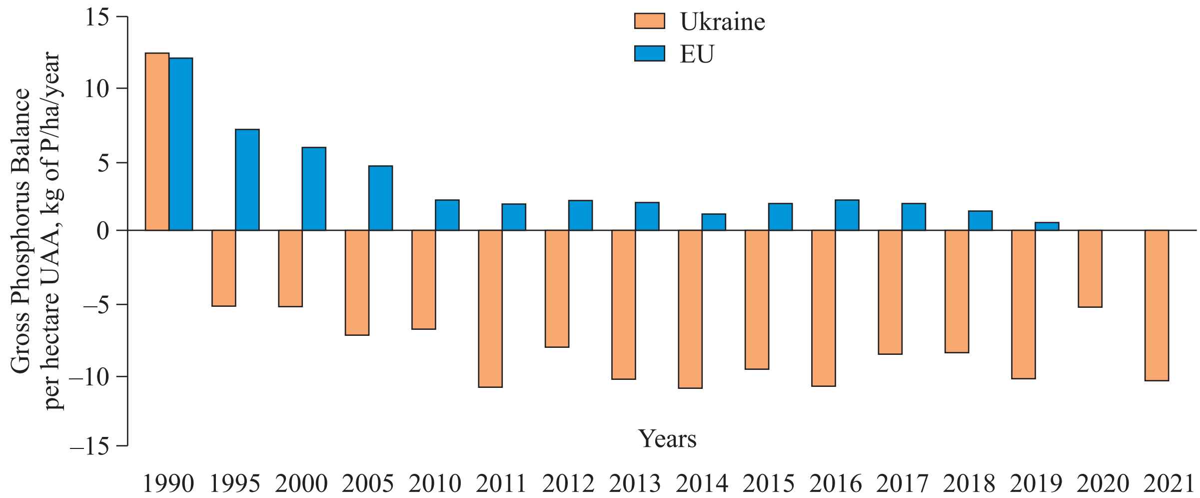

Fig. 7. The dynamics of the gross balance of P for the harvested area of crops in Ukraine (present study) and the EU (the index was calculated by the data of Eurostat from 30 countries, 1990–2019), 1990–2021

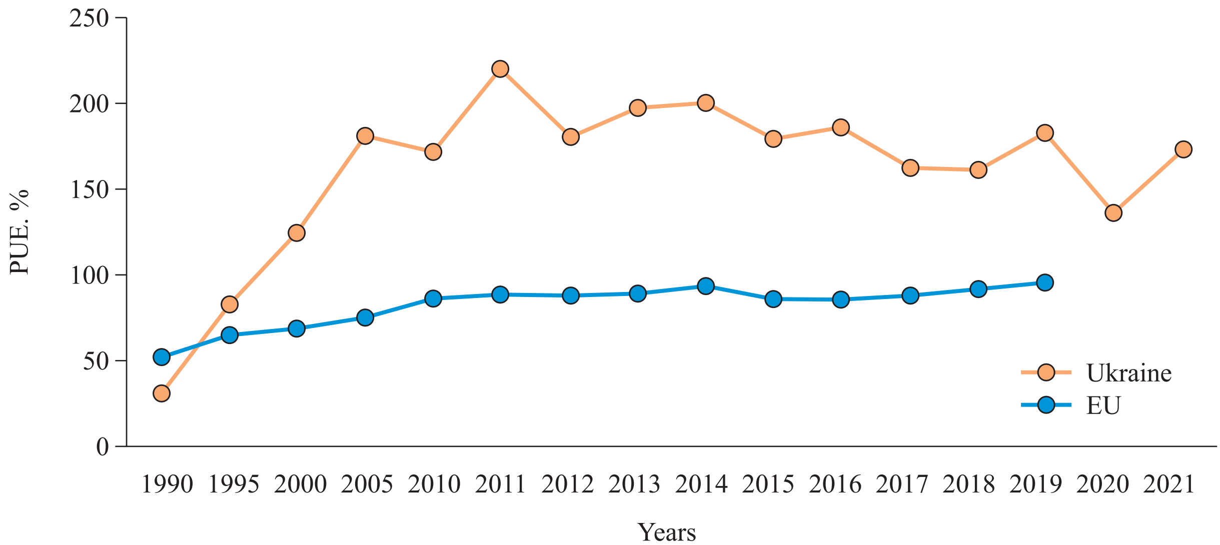

Fig. 8. The PUE dynamics in the crop production of Ukraine (present study) and the EU (the index was calculated by the data of Eurostat from 30 countries, 1990–2019), 1990–2021

26 years — PUE up to 256 %. The highest PUE index, 97 %, was registered in the EU in 2019, i.e. under the worst scenario, the amount of P, removed with the crop harvest, is approximately the same as the amount of the input P (**Fig. 8**).

In 1990–2021, there was a decrease in the application of P into soil with fertilizers regarding the sown areas in Ukraine, namely, with mineral fertilizers — from 17.9 to 6.9 kg P/ha/year; with organic fertilizers — from 9.6 to 0.8 kg P/ha/year. The ratio between the mineral P and organic P, applied to the soil, also changed — the mineral P started prevailing: in 1990, it was 1.9:1, and in 2021 — 8.6:1 (**Fig. 9**).

In general, only in 1990, more P was applied in Ukraine with organic and mineral fertilizers than the EU average index. Today, the amount of mineral P applied to the sown area in Ukraine is close to the EU average, but 11 times lower than the amount of organic P applied to the soil.

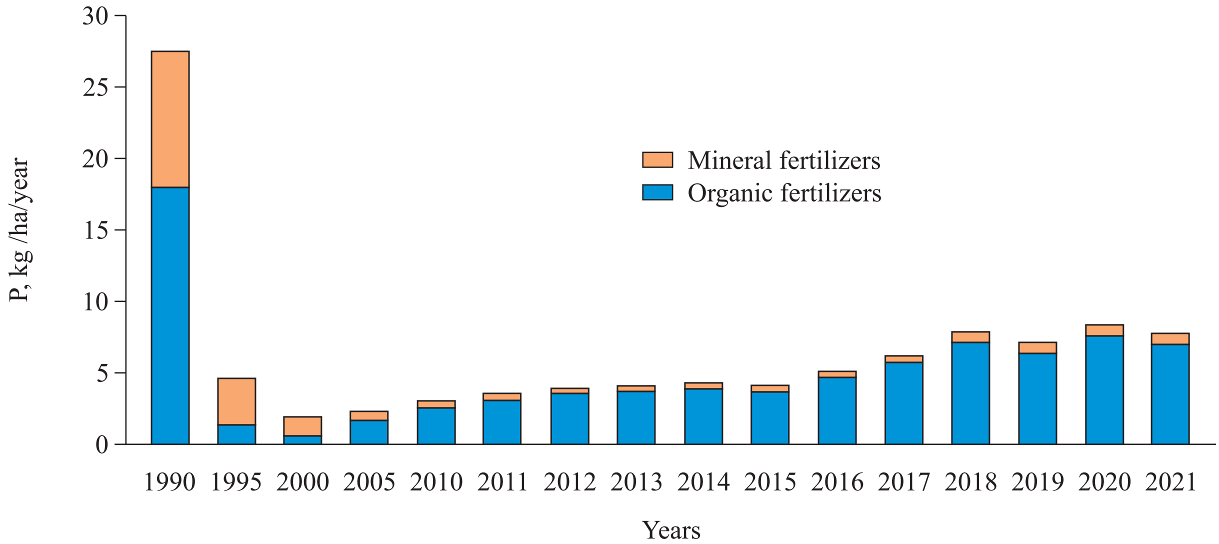

Fig. 9. The input of P of mineral and organic fertilizers for the harvest of crops in terms of the sown areas of Ukraine, 1990–2021 (present study)

DISCUSSION

The phosphorus balance can be used as a critical indicator for phosphorus management in agriculture, providing a reliable benchmark for limiting excess phosphorus and developing a more productive, efficient, and environmentally sound phosphorus fertilizer management strategy (Xiao et al., 2022; Xu et al., 2023). A positive nutrient balance means that phosphorus, in particular, can cause a potential environmental problem and potential yield loss (Gaj et al., 2012). A negative phosphorus balance was found, which (Figs. 1, 2) leads to a decrease in its content in the soil. To achieve optimal yields with minimal risk to the environment, the recommended range of critical P balance is 2.15–4.45 kg P ha^{-1}. The critical range of phosphorus application, estimated on the basis of the phosphorus balance, is 95.7–101 kg P2O5 ha-1, which improves relative yield (>90 %) and PUE (90.0–94.9 %) (Xu et al., 2023). The Institute of Soil Protection of Ukraine, advices in order to improve the soil nutrient regime, that P return should be in the range of 150–200 % (Romanova et al., 2023), as the use rate of P from mineral fertilizers is only 10–20 %, while that of N is up to 50 % and K is up to 70 % (Kramariov et al., 2015).

According to the PUE indicator, on average, in Ukraine, 1.7 times more phosphorus is removed from the soil than is supplied with fertilizers. Given the low use rate of P from mineral fertilizers, which are the main source of phosphorus input to the soil (**Table 4**), this level of removal is critical and leads to the depletion of soil fertility. The gross phosphorus balance at the regional and national levels has significant differences, conditioned by both organizational and production management, which together affect the efficiency of phosphorus use in agriculture (Kopiński et al., 2016). The periodic report of the SI, the Institute of Soil Protection of Ukraine, on the state of soils in agricultural land based on the results of the X round (2016–2020) of agrochemical land survey, showed that only 8 % of the arable land has low or very low P2O5 content in the soil and 24 % has high and very high levels, respectively. The phosphorus balance has been negative in recent decades, for example, in 2016–2020, it was –17 kg P_2O_5/ha, and the statement about the good phosphorus supply of Ukrainian soils is erroneous and associated with incorrect generalization of data without the consideration of changes in the survey area. Thus, while in 1966–1970, the area of arable land surveyed was 30.9 million hectares, in 2016–2020, it was only 8.58 million hectares. First of all, the least fertile soils, including heavily eroded soils and soils with light particle size distribution, were removed from circulation and survey. Ignoring this fact in the generalization of the data obtained led to an artificial overestimation of statistical indicators, in particular, the phosphorus content in the soil.

The gross P balance relative to the area of agricultural land of the 20 EU permanent and associate member states studied (**Fig. 5**) has a wide variation — from –5.6 to 6.0 kg P/ha/year. The efficiency of phosphorus use can vary significantly across EU countries (**Fig. 6**), but in most countries, phosphorus inputs to soils exceeded phosphorus removal with crops. The Land Use/Cover Area frame Survey (LUCAS) of 22,000 topsoil (0–20 cm) samples yielded values for both total and available phosphorus in agricultural soils of the EU and UK. Total P stocks (mean: 1412 kg·ha^{-1}) and available P stocks (mean: 83 kg·ha^{-1}). The P available to total P ratio is 1:17 for the whole study area, with distinct spatial patterns from North to South Europe. An average surplus of 0.8 kg P·ha^{-1}·yr^{-1}. Total P losses to river basins and sea outlets were estimated to be around 100,000 t P yr^{-1} (Panagos et al., 2022).

Thus, unlike Ukraine, the problem of optimizing phosphorus flow management in EU agroecosystems is associated with both a lack and excess of phosphorus in the soil and its losses in the environment, which is confirmed by other researchers. In particular, insight into the role of phosphorus (P) in soil fertility and crop nutrition at Rothamsted, UK, and its involvement in associated environmental issues, has come from long-term (175 years) field experiments on different soils. Results confirmed that residues of P applied in fertilizers and manures build up reserves of P in soil and there is a strong relationship between crop yield and Olsen P from which the critical level of Olsen P at which a soil should be maintained to optimize crop yield and P-use efficiency can be determined. PUE, calculated by the balance method, can exceed 90% when the amount of P applied is nearly equal to that removed in harvested crops. Maintaining sufficient plant-available P in soil to ensure food security by adding P in fertilizers and manures must not lead to the transfer of P to the aquatic environment where it can disturb the biological balance (Johnston et al., 2019 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% (Panagos et al., 2022)). Identification of P-responsive sites in EU-28 (including the UK) is possible using a simple model for the estimation of Olsen P threshold values involving soil properties routinely determined in soil analysis (clay and pH). This will allow for a better allocation of P resources and more accurate estimates of P fertilizer rates as a basis for sustainable fertilization schemes. This will lead to a decrease in P fertilizer needs in the future by increasing P levels in P-responsive sites while decreasing excessive enrichment in non-P-responsive sites and the associated environmental impact. The estimated demand for P in Europe based on this information indicated that it is possible to cover most of this demand (86%) by optimizing the recycling of P from food processing, manure, wastewater, and municipal solid waste as the circular economy approach (Recena et al., 2022). In general, agricultural production and maintenance of the phosphorus stock in European countries depends on imports of phosphate fertilizers.Moreover, there is an environmental problem of phosphorus pollution of surface waters, which is also partly due to climate change (Schoumans et al., 2015).

The tendency of negative phosphorus balance identified in Ukraine over the past 26 years (**Figs. 7, 8**) due to the expansion of intensive crops such as corn, sunflower, and rapeseed, leads to accelerated depletion of natural P reserves in the soil. The growing global demand for bioenergy crops has had implications for future phosphorus use, particularly when grown on additional marginal lands with low phosphorus fertility status. The area under these crops was expected to increase in Argentina, Brazil, Indonesia, Malaysia, Russia and Ukraine (Smit et al., 2009).

The changes in the phosphorus balance and PUE indicators in the time dimension are obviously related to changes in economic conditions in Ukraine. For example, after 1990, the economy declined. Agricultural enterprises sometimes did not have the finances to buy planting material, fuel and lubricants, and fertilizers were mostly used in a limited way or not at all (Moshenskyi, 2024). Since 2000, there has been a sharp decline in the average level of phosphorus application to the soil with phosphorus mineral and organic fertilizers to 1.9 kg P/ha/year (Romanova et al., 2023). Currently, the amount of mineral P applied to the soil is close to the EU average but 11 times lower for organic P (**Fig. 9**).

It was found that the application of P from mineral and organic fertilizers relative to the sown area in the EU has also changed. According to the data of Eurostat of P inputs from mineral & organic fertilizers from 30 countries from 1990 to 2019, the ratio of mineral to organic P has shifted towards the predominance of organic P. In particular, in 1990, on average in the EU 14.3 kg P/ha/year was the input to the soil with mineral fertilizers and 10.8 kg P/ha/year with organic fertilizers. In 2019 it decreased to 6.5 and 9.1 P/ha/year, respectively. Based on these data and average EU gross phosphorus balance over 1990–2019 (**Fig. 7**), it can be assumed that this is due to the fact that, unlike Ukraine, the soils of the EU countries have accumulated a significant amount of residual fertilizer phosphates, and in this case, it is not economically and environmentally feasible to apply high doses of mineral phosphate fertilizers). Only in the late 1980s, the European Union started implementing policies that linked to environmental objectives. As a result, the EU P surplus has decreased over the last three decades about 80 % on a per-hectare basis (Ludemann, et al., 2024). The continuation of environmental policy was the adoption of the European Farm to Fork (F2F) strategy in 2020, which aims to reduce the use of mineral fertilizers by at least 20 %, increase the share of agricultural land used by organic farming with 25 %, and a reduction of agricultural nutrient pollution by 50 % by 2030, and a significant increase in prices for phosphate rock and phosphate fertilizers in the EU since 2008. Although organic farming restricts off-farm nutrient inputs, on average, 2.1 kg P ha^{-1} of mineral fertilizer P is used in crop production in each NUTS2 region of EU (Wesseler, 2022; Kalpakchiev et al., 2023; Magaya et al., 2025).

According to the results phosphorus flows and balances studies for EU-27 and its Member States in the sectors crop production, animal production, food processing, non-food production and consumption the following conclusions were made: although wide-ranging variation between countries, generally phosphorus use in EU-27 was characterized by relatively (1) large dependency on (primary) imports, (2) long-term accumulation in agricultural soils, especially in west European countries, (3) leaky losses throughout entire society, especially emissions to the environment and sequestered waste, (4) little recycling with the exception of manure, and (5) low use efficiencies, because of aforementioned issues, providing ample opportunities for improvement (van Dijk et al., 2025).

However, given the current socio-economic conditions and the consequences of military operations in Ukraine, it is still relevant to use economically affordable ways to restore the phosphorus potential of soils and reproduce their fertility at the expense of internal reserves. First of all, this applies to existing phosphorite deposits, which, according to the Ukrainian State Institute of Mineral Resources, have reserves of about 360 million tons. However, due to their low phosphorus concentration, they are not currently processed into superphosphate and other water-soluble phosphate fertilizers. However, their use after primary processing, mainly grinding, can be an important factor in reducing phosphorus deficiency and improving its balance in agroecosystems with acidic and slightly acidic soils in the Polissia and Forest-Steppe regions. The total required annual amount of phosphate rock flour for the Polissia zone is at least 90 thousand tons of P_2O_5 per year, and for the Forest-Steppe zone — 110 thousand tons of P_2O_5 per year. However, the use of existing phosphorite deposits requires further study and scientific substantiation (Khrystenko et al., 2016).

The issue of improving the balance of phosphorus and its content in soils is relevant to enhancing its recycling in agroecosystems. Currently, models of agricultural production are being developed around the world to put into practice the latest scientific advances and identify strategies for farmers to increase the efficiency of using the nutrients of fertilizers in order to reduce costs and environmental risks. These are such models: The EPIC model was developed primarily to investigate the effects of soil erosion by wind and water on crop production and crop growth in the USA; The DSSAT model includes a sub model to simulate P dynamics and crop uptake in a range of P deficient soils including highly weathered and calcareous soils in Colombia, Syria and Tanzania, Kenya and Ghana; The APSIM model is based on simulate the effects of N and P in low input maize systems in Kenya where the nutrient sources are often not commercial fertilizers but rather manures and biomass etc. (Das et al., 2019). From this point of view, the formation of mixed specialization agroecosystems with maximum recycling of biogenic elements, including phosphorus, seems to be quite effective. The most efficient way is to use this strategy in mixed specialization agroecosystems where non-commodity biomass from crop production can be used as organic fertilizers, and livestock waste after methane fermentation and energy production can be used as highly effective organic fertilizers (Tarariko, 2012). As a result, a high level of phosphorus recycling is achieved, which creates conditions for reducing the use of industrial phosphate fertilizers. The selection and rotation of crops in crop rotations with green manure and cover legumes is also important in this regard, especially with no-till, which also creates conditions for reducing the need for external sources of phosphorus (Lukowiak et al., 2016; Steiner et al, 2012; Williams et al, 2017).

Long-term field studies of phosphorus changes in the soil during the "Static Fertilization Experiment" in 1902–2012 on black soil in Germany, demonstrated that the application of organic and mineral phosphorus fertilizers at rates of 22 to 55 t ha^{-1} $year^{-1}$ led to a significant increase in the content of available phosphorus in the soil. The accumulation of total phosphorus amounted to 1.3–3.1 t ha^{-1} depending on the fertilization system. P reserves increased up to the depth of 60 cm of soil (Medinski et al., 2018)

Process-based biogeochemical models are valuable tools to monitor the phosphorus cycle and predicting the impact of agricultural management policies. For example, agricultural management scenarios have identified a range of potential changes in the phosphorus budget to 2030 and 2050, influenced by the interaction of phosphorus with the biogeochemical cycles of carbon and nitrogen in European agricultural soils. Areas of phosphorus surplus or deficit identify where agricultural management changes will be most urgent to achieve policy objectives on pollution, food security and the efficiency of critical raw material use (Muntwyler et al., 2024).

Phosphorus availability and pricing are crucial for the entire food system. Transformative phosphorus management is needed to reduce the vulnerability of the European Union to fertilizers, which also depends on Ukraine. Commodity prices have increased with the war in Ukraine. Seen from Kingdon's conceptual interpretation, the Ukraine crisis has acted as a trigger for the moving of the fertiliser issue towards a globally recognizable problem. Proposed are five alternatives that apply powerful spillover framings to implement phosphorus governance that is synchronous with the European Commission's sectoral priorities. An extension of the EU's current environmental policy along these pathways can potentially contribute to phosphorus sustainability: Recover Nutrients and Energy, Regulatory pilots, Market Support and Risk Approvals, Address resource leakage & Omnibus targets (Kalpakchiev et al., 2025).

CONCLUSIONS

Based on the balance studies over the past 26 years, unbalanced use of soil P — up to –11.4 kg P/ha/year and intensive soil load — PUE up to 256 % — have been identified in Ukrainian crop production, which is associated with a significant decrease in the use of organic fertilizers — from 9.6 to 0.8 kg P/ha/year and phosphate mineral fertilizers — from 17.9 to 6.9 kg P/ha/year. This negative trend was found in all administrative regions and natural and agricultural zones of Ukraine, which led to a critical level of phosphorus decline in soil and a drop in soil fertility.

The EU agroecosystems have a minimal positive gross P balance (0.6 P/ha/year), but this was only in 2019, according to the data of Eurostat of P inputs/outputs from 20 countries. A negative P balance was found in 8 of the 20 countries — from –0.03 to –5.6 kg P/ha/year and an intensive load on the soil — PUE=103...167 %, which is significantly lower compared to Ukraine. Unlike Ukraine, according to the data of Eurostat of P inputs from mineral & organic fertilizers from 30 countries, the EU agricultural policy in recent years has seen a gradual decline in the use of phosphate mineral fertilizers and prioritized the use of organic phosphorus.

To achieve a deficit-free balance of phosphorus, restore its content in Ukrainian soils, minimize negative environmental impacts, and increase economic benefits, it is necessary to compensate for the removal of phosphorus with the main products not only by applying industrial phosphate mineral and organic fertilizers, but also by creating agroecosystems with a high level of phosphorus recycling and using current local phosphorite deposits.

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ОЦІНКА ПРИРОДНО-РЕСУРСНОГО ПОТЕНЦІАЛУ АГРОЕКОСИСТЕМ УКРАЇНИ І КРАЇН ЄС ЗА БАЛАНСОМ ФОСФОРУ

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Мета. Порівняльне оцінювання сучасного стану і динаміки балансу фосфору в агроекосистемах України та ЄС й встановлення способів управління потоками фосфору та відновлення його фонду в ґрунтах. **Методи.** Використано методологію Організації економічного співробітництва та розвитку (OECD, 2007) з оцінки потоків і балансу фосфору та ефективність його використання (PUE) у підсистемах рослинництва (Chowdhury et al., 2021). Вихідні дані використано із електронних ресурсів Державної служби статистики України (http://www.ukrstat.gov.ua), Eurostat (https://ec.europa.eu) та ДУ "Інститут охорони ґрунтів України" (https://www.

iogu.gov.) із обстеження сільськогосподарських угідь за результатами XI туру (2016–2020). Побудова картограм виконувалась у середовищі пакету програми MS Excel 2021. **Результати.** Встановлено валовий баланс фосфору у агроекосистемах України та 30 країн Європи впродовж 1990–2021 рр. Виявлено зниження потенціалу ґрунтів за вмістом фосфору, розрахованого за показниками потоків фосфору, які мають місце у сучасному сільськогосподарському виробництві. Показано, що у середньому кількість фосфору, винесеного господарсько-цінною частиною врожаю значно перевищує його надходження у ґрунт із добривами. Порівняно стан використання мінеральних і органічних добрив у рослинництві України та країнах ЄС. Виявлено незбалансоване використання P ґрунту у агроекосистемах України впродовж 1995–2021 рр. — від'ємний баланс фосфору відповідно збільшувався від –5,6 до –11,4 кг P/га/рік та інтенсивне навантаження на ґрунт — PUE 139–256 %, що насамперед пов'язано як зі зниженням використання органічних добрив — від 9,6 до 0,8 кг P/га/рік, так і фосфорних мінеральних добрив — від 17,9 до 6,9 кг P/га/рік. Установлений в країнах ЄС мінімальний валовий баланс P (0.6 P/га/рік) спостерігався лише в 2019 р. Серед країн ЄС у 2019 р. валовий баланс P становив від –5.6 до 6.0 кг P/га/рік. До країн із негативним балансом P (2019 р.) відносяться Румунія (–5,6 кг P/га/рік), Болгарія (–5,4), Німеччина (–4,8), Словаччина (–1,9), Швеція (–1,5), Литва (–1,3), Угорщина (–0,4) і Чехія (–0,03 кг P/га/рік), показники яких нижчі порівняно з Україною. Показник PUE в країнах ЄС (2019 р.) становив 62–167 %. Зокрема PUE вище 100 % виявлено в Угорщині — 103 %, Литві — 111 %, Швеції — 113, Німеччині — 126, Словаччині — 118, Румунії — 152 і Болгарії — 167 %, що нижче ніж в Україні — 186 %. Нині в Україні кількість внесення мінерального фосфору відносно посівної площі наближаються до середнього значення ЄС, але в 11 раз нижча щодо внесеного у ґрунт органічного фосфору. **Висновки.** Для досягнення бездефіцитного балансу фосфору, відновлення його вмісту у ґрунтах, мінімізації негативних екологічних наслідків, а також підвищення економічного ефекту доцільно компенсувати винос фосфору з основною продукцією не лише за рахунок унесення промислових фосфорних мінеральних та органічних добрив, а й формування агроекосистем із високим рівнем рециркуляції фосфору та використання наявних місцевих родовищ фосфоритів.

Ключові слова: фосфор, ґрунт, потоки фосфору, ефективність використання фосфору (PUE), добрива, відходи тваринництва і рослинництва, рециркуляція, фосфорити.