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Global trends of cropland phosphorus use and sustainability challenges

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T. Zou[1], X. Zhang[1]✉ & E. A. Davidson[1]

To meet the growing food demand while addressing the multiple challenges of exacerbating phosphorus (P) pollution and depleting P rock reserves[1–15], P use efficiency (PUE, the ratio of productive P output to P input in a defined system) in crop production needs to be improved. Although many efforts have been devoted to improving nutrient management practices on farms, few studies have examined the historical trajectories of PUE and their socioeconomic and agronomic drivers on a national scale[1,2,6,7,11,16,17]. Here we present a database of the P budget (the input and output of the crop production system) and PUE by country and by crop type for 1961–2019, and examine the substantial contribution of several drivers for PUE, such as economic development stages and crop portfolios. To address the P management challenges, we found that global PUE in crop production must increase to 68–81%, and recent trends indicate some meaningful progress towards this goal. However, P management challenges and opportunities in croplands vary widely among countries.

Phosphorus (P) is a critical nutrient for growing crops and feeding the growing global population[1–3]. Consequently, the need for more food production and higher crop yields is likely to drive up the demand for P inputs to cropland. The total global application of P fertilizer on croplands had increased from around 5 TgP yr^{-1} in 1961 to 18 TgP yr^{-1} by 2013[4], already exceeding an estimated planetary boundary (6 TgP yr^{-1} to 12 TgP yr^{-1})[5], and it is projected to increase to 22–27 TgP yr^{-1} by 2050[6].

Overuse and improper use of P in crop production result in excessive P leaching to adjacent water bodies, causing nutrient pollution and threatening the health of aquatic organisms and humans[7–11]. Agriculture, especially the production of cereals, fruits, vegetables and oil crops, contributed 38% of the global anthropogenic P load to freshwater systems during 2002–2010[9]. Inorganic fertilizer use was identified as the primary source (about 47% during 2005–2010) of P going to the world's largest 100 lakes[8]. Even after the reduction or cessation of fertilizer inputs, the large surplus of P accumulated in soil (known as legacy P, or residual P) can continue to pollute surface waters, offsetting or delaying the benefits brought by nutrient-abatement measures[7,12].

At the same time, many countries have concerns about the scarcity of phosphate rock (PR) reserves. Global PR production can probably meet fertilizer-P demand for decades to centuries[1,2,13,14]. However, PR is non-renewable and unevenly distributed throughout the world[2,15]. Most PR reserves are concentrated in a few countries, including Morocco and China[2]. Countries with low reserves and high demand for P need to rely on the import of PR or P fertilizer, and farmers in many low-income countries do not have access to affordable P fertilizer to improve crop yields[1,2].

To address the P pollution and scarcity challenges, it is critical to use P more efficiently in agriculture. Therefore, research efforts have been devoted to examining the historical P budget, P use efficiency (PUE), current P management challenges, and potential solutions for a range of spatial and temporal scales[1,2,6,7,11,16,17]. However, few studies have quantified the P budget and PUE by crop type or examined the potential impacts of both socioeconomic and agronomic drivers on national PUE collectively. In addition, even fewer studies have assessed how improvement in PUE can reduce P pollution and scarcity at national scales.

To fill these research gaps and to inform policymaking for tackling P challenges, we first developed a database of the P budget (Fig. 1) for croplands from 1961 to 2019 for over 200 countries or regions and 169 crop types (Supplementary Information). We then evaluated the historical and spatial patterns of the P budget and PUE, and developed statistical models to investigate the key socioeconomic and agronomic drivers for national PUE. Finally, we discuss global and national P management challenges and evaluate the impacts of PUE improvement on addressing P pollution and scarcity challenges by 2050.

Historical trends of phosphorus use

The database of the P budget we developed, as with previous studies of the nitrogen (N) budget[18–20], includes fertilizer and manure inputs, outputs removed in crop yield, and losses to the environment; but unlike the N budget, it also considers the substantial accumulation of P in the soil.

Corresponding to the increased agricultural productivity on the global scale, the global sum of P in harvested crop products (P yield) has more than doubled, from around 5 kgP ha^{-1} yr^{-1} in 1961 to 11 kgP ha^{-1} yr^{-1} in 2019 (Fig. 2a). Meanwhile, global PUE first decreased from 55% in 1961 to a low of 44% in the 1980s, then began to increase to around 66% in 2019 (Fig. 2a). As a result, the global P surplus (the difference between P inputs and P yield, and a measure of potential P pollution) increased from around 4 kgP ha^{-1} yr^{-1} in 1961 to a peak of 9 kgP ha^{-1} yr^{-1} in the 1980s and then declined to 6 kgP ha^{-1} yr^{-1} in 2019. The mean global P residual in soil has accumulated to 212 kgP ha^{-1} in 2019 since 1961 (Fig. 2b), which can serve as a potential P source for future crop production or could be lost to the environment.

[1]Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD, USA. ✉e-mail: xin.zhang@umces.edu

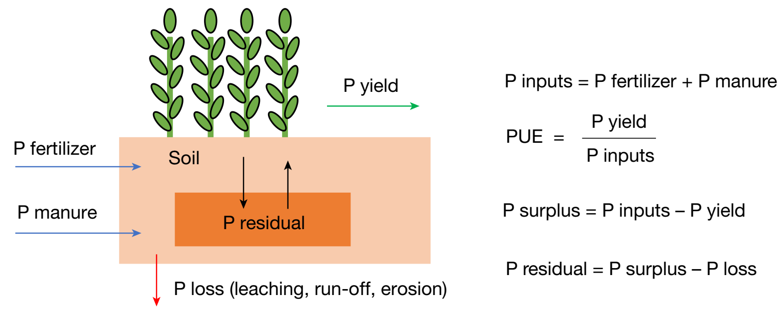

Fig. 1 | Illustration of the main cropland P budget terms used in this study. Blue arrows, major P inputs; green arrow, P yield (that is, P removed from the field in harvested crop production); red arrow, P loss; black arrows, internal soil cycling. This figure was created in Microsoft PowerPoint software.

The historical trends of the regional P budget and PUE vary by country and income level (Fig. 2 and Supplementary Fig. 2). Malawi, as a low-income country[21], has had minimal success in increasing its P yield in the past 50 years, and has relied mainly on mining native soil P with a PUE level above 100% and minimal P inputs. Middle-income economies, such as Brazil, China and India, have experienced a U-shaped development of PUE. Their crop yield increased at the expense of declining or low PUE and increasing P surplus and accumulated P residual during the first few decades, and then with improved PUE in the twenty-first century. For example, PUE in China and India had declined to around 40% in 2010, and then improved to somewhere close to 50% by 2019. Many high-income economies, such as the United States and France, also have relatively high PUE, similar to those in low-income countries, but for very different reasons. The United States and France have passed the early development stage (enhancing yield by increasing nutrient inputs) of the 1960s and 1970s, and have since transitioned to a stage characterized as sustainable intensification[22] (yield enhancement with better nutrient management that utilizes the vast P residual that built up in agricultural soils). As a result, PUE had steadily increased to 102% and 142% and yield had increased to around 19 kgP ha^{-1} yr^{-1} and 23 kgP ha^{-1} yr^{-1} in 2010 in the United States and France, respectively. The historical trends of these countries are very similar to the aggregated trajectories of the income groups they belong to (Fig. 3 and Supplementary Fig. 2).

A typical pattern of PUE

Despite differences among countries, global and national trajectories collectively suggest a typical pattern of PUE changes as P yields and economies develop (Fig. 3). P surplus increases and PUE declines during an early development stage, when economic growth is usually achieved at the expense of more pollution. During a later development stage with improved management practices and nutrient accumulated in soil, P surplus starts to level off and even decrease, accompanied by a levelling off and increase in PUE. These mechanisms and observed typical pattern are consistent with and provide support for the predicted relationship between PUE and gross domestic product (GDP) per capita, called the environmental Kuznets curve (EKC) (Fig. 3)[18,23], which predicts a

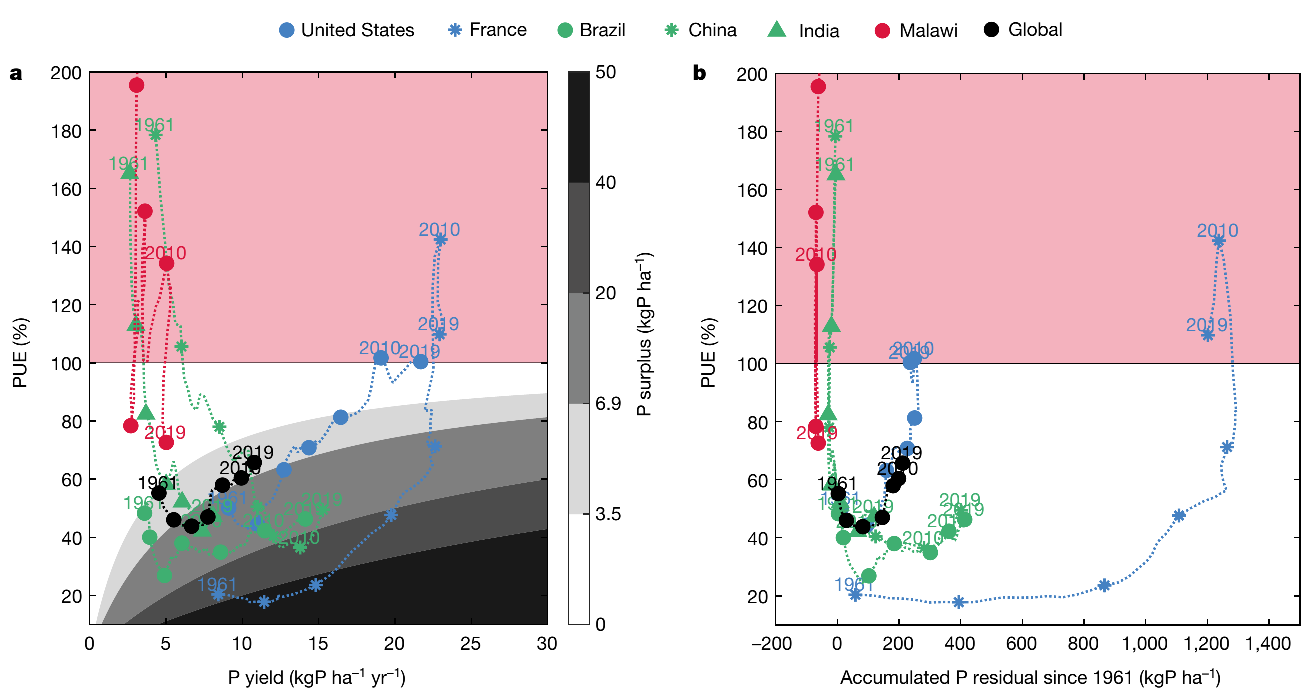

Fig. 2 | Historical P budget and PUE trends from 1961 to 2019. a, PUE versus P yield for selected country examples. **b**, PUE versus accumulated P residual by country. The trends of the P budget in other regions and countries can be found in Supplementary Figs. 2 and 13. The greyscale in **a** indicates the P surplus. The data for high-, middle- and low-income economies are in blue, green and red, respectively. PUE data larger than 200% are not shown. The pink area indicates soil mining (negative P surplus). We used five-year moving average data here to limit the year-to-year variation influenced by factors such as weather conditions[18]. The seven points on each line represent the moving average as of 1961, 1970, 1980, 1990, 2000, 2010 and 2019.

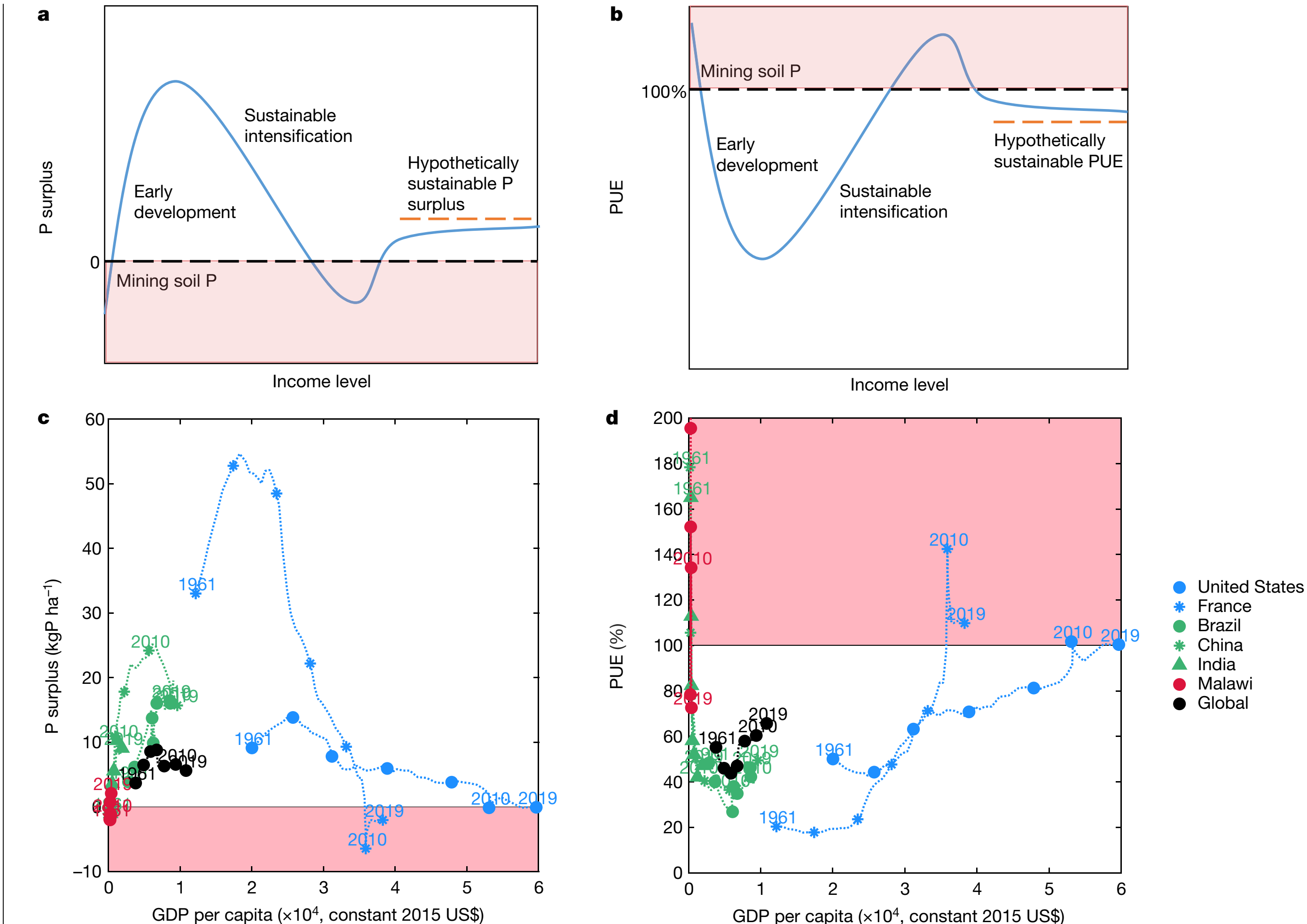

Fig. 3 | The relationships between income level and P surplus and between income level and PUE. a–d, Hypothesized relationships (**a**,**b**) and historical records of several countries and the world (**c**,**d**) for P surplus (**a**,**c**) and PUE (**b**,**d**). The trends of PUE and GDP per capita of more countries can be found in Supplementary Fig. 13. The data for high-, middle- and low-income economies are in blue, green and red, respectively. PUE data larger than 200% are not shown. The pink area indicates soil mining (negative P surplus). We used five-year moving average data here to limit the influence of yield variation due to year-to-year fluctuation in weather conditions[18]. The seven points on each line represent the data in 1961, 1970, 1980, 1990, 2000, 2010 and 2019.

bell-shaped relationship between pollution and income. As the statistical tests for the EKC hypothesis are challenging and equivocal[24–26], we apply a variety of state-of-the-art tests, described in Methods and Supplementary Information. Our main purpose here is not necessarily to prove or disprove unequivocally the EKC hypothesis, but rather to note the commonalities (the shapes of the temporal curves) and the differences (stages and inflection points) that may reflect current and historical responses to national economic and agricultural policies.

We examined the relationship between PUE and GDP per capita (in 2015 constant US$) with historical records for 113 major crop-producing countries. The period studied here for driver analysis is 1961–2014, when data were most available for potential drivers. The results of most fixed-effects models for the panel data and cross-sectional analysis for the data at one time point both indicate a general U-shaped relationship between PUE and GDP per capita, with a positive coefficient for the quadratic GDP per capita term ($P < 0.01$; Supplementary Fig. 7, and Supplementary Tables 19 and 21–23). The typical pattern of PUE and GDP per capita observed in many individual countries from historical records resembles all or part of an EKC (Supplementary Fig. 13). Simple regression results show a U-shaped relationship between PUE and GDP per capita for 61 out of 113 countries (Supplementary Table 11). For example, after China's PUE approached an asymptote between 30% and 40% in 2010 (Fig. 2a), it began to increase in recent years, which is consistent with an EKC. The results of extended methods and the autoregressive distributed lag method also partly support the EKC hypothesis (Supplementary Table 10).

However, not all countries necessarily follow the same pathway. Whether and how quickly a country's declining or low PUE reaches an inflection point depends on development and adoption of technologies and proper policies. The panel data fixed-effects models indicate an inflection point for GDP per capita between US$2,300 and US$3,100 (Supplementary Table 19). For the 61 countries showing a U-shaped trend of GDP per capita, the mean inflection point across countries was about US$2,800, but with a large variation (mean US$2,812, median US$2,574, minimum US$311 and maximum US$25,395; Supplementary Fig. 13). Hence, although the inflection points are commonly between US$2,000 and US$3,000, large variation among countries indicates that the inflection points can also be affected by country-specific circumstances.

Other drivers for PUE

In addition to economic growth, a range of socioeconomic and agronomic factors may affect PUE on a national scale (Supplementary Table 9). We applied statistical methods to examine their potential relationships with PUE by country (for example, using Pearson's correlation tests) and across all 113 countries (for example, using fixed-effects models; Supplementary information). The following factors show a significant and consistent relationship with PUE in our tests.

Nitrogen use efficiency

Nitrogen use efficiency (NUE), defined as the ratio of N output to N input in the crop production system, is significantly positively correlated with PUE on a national scale (Supplementary Tables 20–23). Regarding the tests for individual countries, 99% of the countries with significant results (101 countries) show a positive relationship between PUE and NUE. In the fixed-effects models tested across 113 countries, the coefficients of NUE are all positive and statistically significant. These results align with the expectation on a farm scale that improvement in nutrient management practices usually benefits both PUE and NUE.

Fertilizer-to-crop-price ratio

The fertilizer-to-crop-price ratio, determined by farm-gate prices of P fertilizers and crops, shows a positive relationship with PUE in most countries and in the fixed-effects models (Supplementary Tables 20–23). Among the 113 countries, only 49 countries have sufficient farm-gate fertilizer-to-crop-price ratio data to be analysed. Of these, 22 countries have a significant ($P < 0.05$) positive relationship between the fertilizer-to-crop-price ratio and PUE. The 22 countries with a significant positive relationship include important crop-producing countries (for example, the United States and China), and they accounted for 33% of the global harvested area and 45% of fertilizer P input in 2017 (averaged between 2015 and 2019). In the fixed-effects models tested in this study, the coefficients of the fertilizer-to-crop-price ratio are always positive. These results are similar to the finding between NUE and the fertilizer-to-crop-price ratio for N on a national scale[18]. It also aligns with the economic analysis on a farm scale that higher fertilizer price or lower crop price is likely to encourage farmers to use fertilizer more efficiently[27].

Farm size

Farm size has a positive relationship with PUE in the cross-country fixed-effects models (Supplementary Tables 21–23). From the total of 39 significant country-scale correlations of PUE and farm size, 23 of them (that is, 59%) are positive (Supplementary Table 20). These results imply that the relationship between PUE and farm size is dominated by a positive relationship on a global scale, but may vary among countries and evaluation methods, partly explaining the controversial conclusions in previous studies. For example, some studies have found that smaller farms tend to use more fertilizer to ensure productivity and consequently have lower nutrient use efficiency in China and on a global scale[28,29]. Other studies have suggested that farmers with smaller farms may have limited access to nutrient fertilizer or need to manage their limited resources more effectively, both resulting in higher nutrient use efficiency[30,31]. These results do not necessarily mean that large farms are ‘better’ than small farms, as there may be other socioeconomic reasons behind the relationship as well as other socioeconomic and environmental impacts of varying farm size[32,33].

Crop mix

As PUE varies among crop types (Fig. 4), the difference in crop mix (the portfolio of crop production for a country) can explain part of the difference in national PUE among countries. For example, if China improved its PUE of each crop type to the US level, China’s national PUE would be noticeably improved, but still only about halfway to the United States’s national PUE (Supplementary Fig. 1). The remaining difference is caused by the difference in crop mix, primarily attributed to the high percentage of harvested area and fertilizer devoted to fruit and vegetable production in China (about 21% and 40% in 2017, respectively). The global average PUE of fruits and vegetables was around 22% in 2017 (2015–2019 average), much lower than that of other crop groups, and the value for China is even lower (Fig. 4). Our statistical tests for individual countries and across all countries indicated a negative relationship between national PUE and the percentage of harvested area for fruits and vegetables ($frac_{fv}$) (Supplementary Tables 20–23), which is similar to the results of a previous study on NUE[18].

Agricultural machinery

Agricultural machinery, measured by tractors per square kilometre of arable land, has a negative relationship with PUE in the panel data analysis and in 49 tested countries (Supplementary Tables 20–23). The 49 countries include major crop-producing and agriculture-dominant countries such as China, India, the United States and Kenya. However, this pattern is strongest during the early stages of agricultural development, when the number of tractors is low (Supplementary Fig. 9). As countries such as the United States and China became more mechanized in recent decades, the correlation with PUE weakened or disappeared. It is likely that the trends related to agricultural machinery are reflecting complex relationships and covariation with other factors, such as increased P fertilizer use in the early stages of development and improved nutrient management in later stages of development. To address the negative impacts of mechanization on PUE, sustainable mechanization is needed to increase not only P yield but also the use efficiency of P and other resources[34,35].

Phosphorus pollution challenge by 2050

The recent level of P fertilizer inputs to croplands (Supplementary Tables 5 and 32) has exceeded a proposed planetary boundary estimated as 6–12 TgP yr^{-1} for fertilizer inputs[5]. This P input planetary boundary is equivalent to a P surplus planetary boundary of 4.5–9 TgP yr^{-1} for croplands (Supplementary Fig. 11). Focusing on the potential P lost from cropland instead of P fertilizer input enables scenario analyses that consider improvements in PUE. We projected the P surplus in 2050 using three PUE scenarios, business as usual (BAU), moderate policy ambition (MPA) and high policy ambition (HPA), and compared it with the calculated boundary for P surplus to assess the P pollution challenge. The scenario design considers different levels of PUE improvement (Extended Data Table 2 and Supplementary Section 4).

According to the projections from 2012 to 2050 by the Food and Agriculture Organization (FAO) of the United Nations[36], the amount of P in harvested crops will increase from 13 TgP yr^{-1} in 2010 to 19.3 TgP yr^{-1} in 2050 (Extended Data Table 1). If PUE by country and crop type stays at the 2010 level worldwide while the crop mix changes as projected (under the BAU scenario in this study), the 48% increase in harvested P by 2050 will result in the global P surplus increasing from 8.6 TgP yr^{-1} to 14.1 TgP yr^{-1}, far exceeding the planetary boundary for P surplus. To meet the food demand in 2050 while bringing the P surplus level below the planetary boundary, global PUE needs to improve to 68–81%. The lower boundary of 68% is not much higher than 65%, the averaged PUE for the most recent five years (Supplementary Table 32), and could potentially be achieved under the MPA or HPA scenario. The upper threshold of 81% is also possible under the HPA scenario.

However, the P pollution challenge varies widely among world regions (Figs. 5 and 6). In 2010, the average P surplus levels in China and India were 24 kgP ha^{-1} yr^{-1} and 10 kgP ha^{-1} yr^{-1}, respectively. In contrast, 69 countries had a negative P surplus, indicating P mining from the soil, including developed countries such as the United States and France and 20 low-income countries. If all global cropland shared a similar burden in maintaining P surplus within the planetary boundary, then the average per-hectare planetary boundary of the P surplus rate would be 3.5–6.9 kgP ha^{-1} yr^{-1} (ref. [37]). Using this initial estimate of the P boundary as a reference point, 82 countries in 2010 and 90 countries in 2050 under the BAU scenario are projected to have a P surplus rate higher than 6.9 kgP ha^{-1} yr^{-1} (the upper planetary boundary), including countries such as China and India. Under the MPA and HPA scenarios,

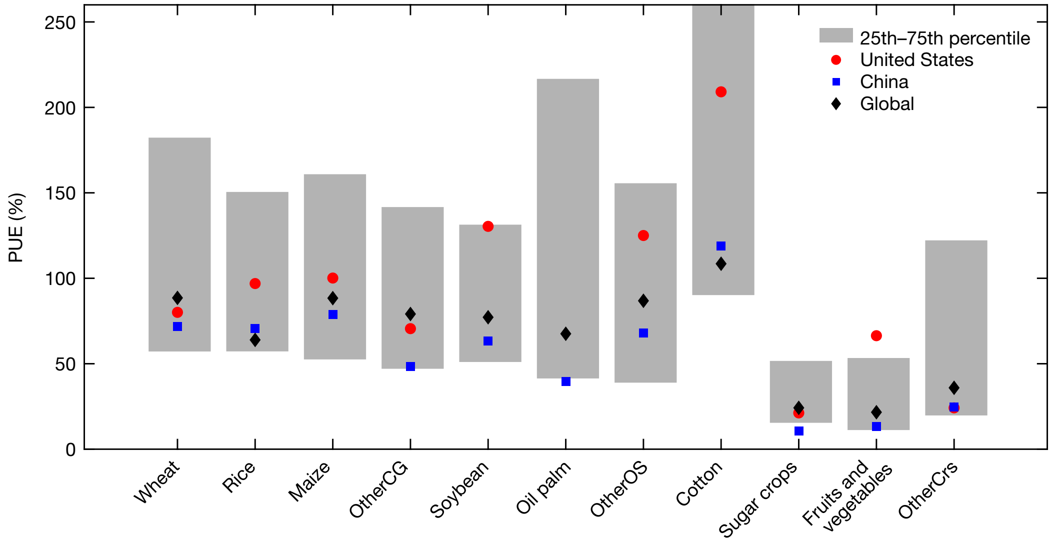

Fig. 4 | PUE by crop group. The PUE distribution (25th–75th percentile) of all countries for 11 crop groups (Supplementary Table 29) in 2017 (averaged between 2015 and 2019) and the 2015–2019 average PUE of the United States (red dots), China (blue squares) and the world (black diamonds). OtherCG, other cereal crops; OtherOS, other oil seeds; OtherCrs, other crop types. The US oil-palm data are not available.

the number of countries above the P boundary in 2050 reduces to 53 and 16, respectively. By 2019, some improvement had already been taking place, as the P surplus levels in China dropped to around 16 kgP ha^{-1} yr^{-1} (Fig. 3c) and the number of countries with a P surplus rate above the upper planetary boundary decreased to 73.

Phosphorus scarcity challenge by 2050

To assess the P scarcity challenge considering the recent P use patterns and future production needs[36], we defined a P scarcity indicator (noted as $P_{scarcity}$), which is the ratio of accumulated P fertilizer demand for

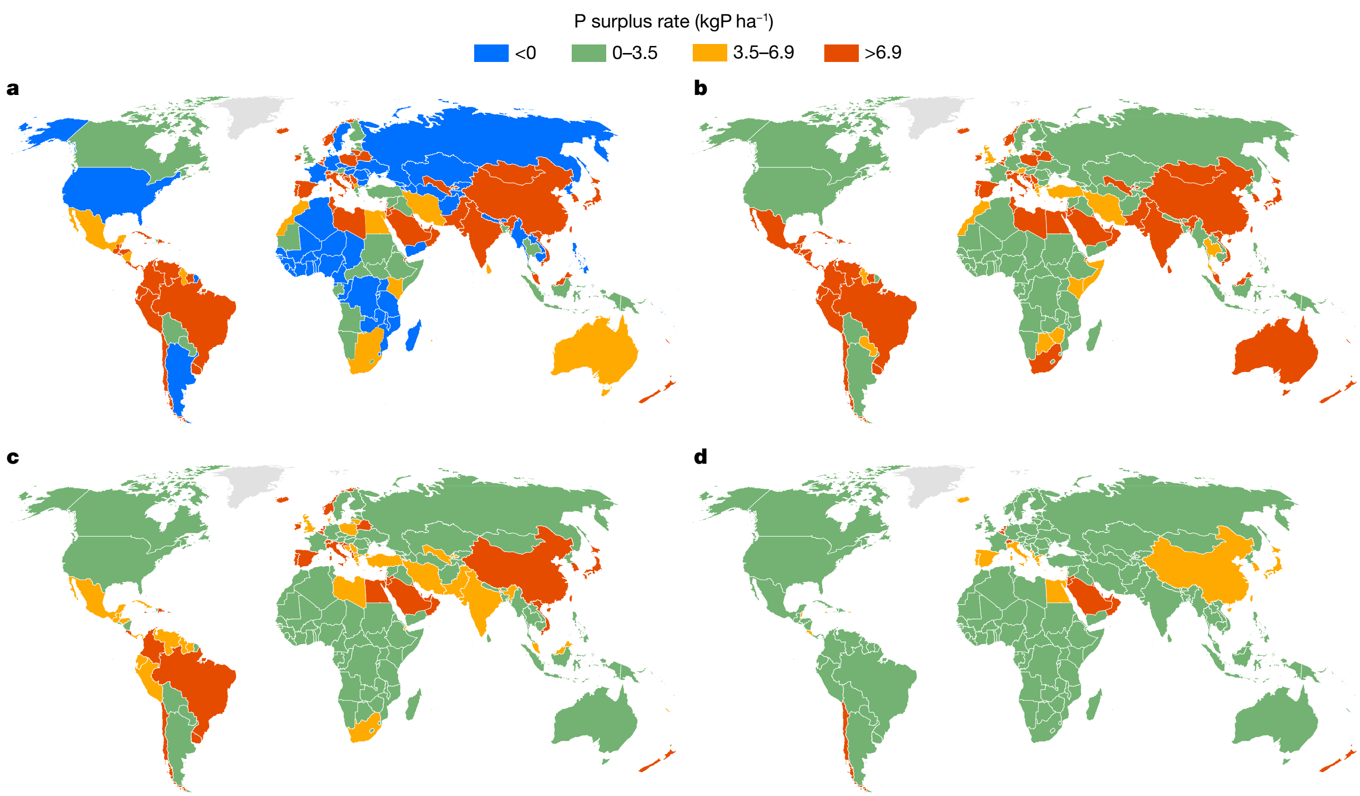

Fig. 5 | P surplus rate by country. a, The 2008–2012 running-average P surplus rate. **b**, The P surplus rate in 2050 under the BAU scenario. **c**, The P surplus rate in 2050 under the MPA scenario. **d**, The P surplus rate in 2050 under the HPA scenario. Grey areas, no data; blue areas, negative P surplus rate; green areas, P surplus rate between 0 kgP ha^{-1} and 3.5 kgP ha^{-1}, not higher than the lower planetary boundary; orange areas, P surplus rate between 3.5 kgP ha^{-1} and 6.9 kgP ha^{-1}, not higher than the upper planetary boundary; red areas, P surplus rate over 6.9 kgP ha^{-1}, higher than the upper planetary boundary. Maps were generated in ArcGIS 10.8.1 (https://www.esri.com/) using generalized country boundaries originally sourced by Esri, Garmin and the National Geographic Society and made available through ArcGIS Online.

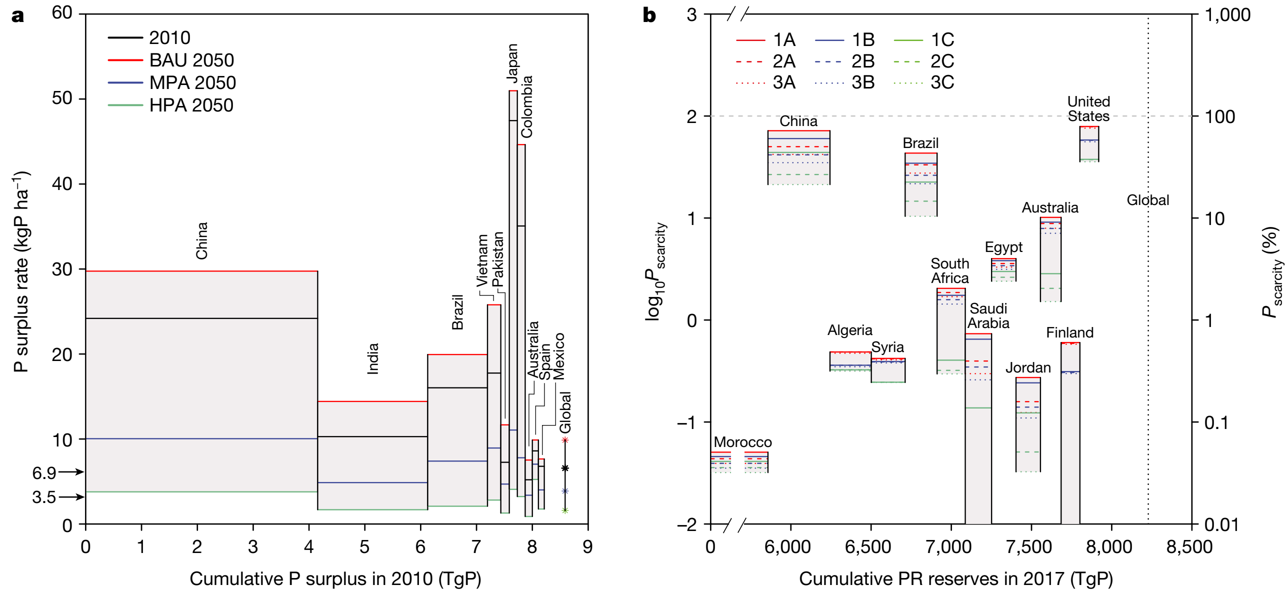

Fig. 6 | P surplus and P scarcity in 2010 and in 2050 under various scenarios. **a**,**b**, Each grey box represents one country or region. The width of each box is determined by the country's total P surplus in 2010 (averaged between 2008 and 2012; **a**) or PR reserves in 2017 (**b**). In **a**, countries from left to right are sorted in descending order based on their 2010 total P surplus, and the position of the four stars on the right side is determined by global P surplus in 2010. Within each box, the *y* value of each horizontal solid line (or each star on the right side) is determined by the P surplus rate for the country (or for the globe) in 2010 or in 2050 under one of the three scenarios. Lower and upper P surplus planetary boundaries at 3.5 kgP ha^{-1} and 6.9 kgP ha^{-1}, respectively, are shown on the *y* axis. In **b**, countries from left to right are sorted in descending order based on their P reserves. Within each box, the *y* value of each horizontal line is the $P_{scarcity}$ projected under each scenario. We use the common logarithm of $P_{scarcity}$ here; thus 2 on the left *y* axis is equivalent to $P_{scarcity}$ at 100% on the right *y* axis. The vertical line noted 'Global' indicates the total global P reserves for fertilizer production estimated in 2017. Each scenario represents a certain level of PUE improvement (BAU, MPA or HPA), or a certain level of PUE improvement combined with certain sources of P inputs (from 1A to 3C; Extended Data Table 2).

2017–2050 to the national PR reserves for fertilizer production estimated in 2017[38] (Fig. 6b and Supplementary Table 26). A $P_{scarcity}$ close to or higher than 100% indicates the need to use more P from alternative sources or to import more P fertilizer to support future food production. For all scenarios tested in this study, the global $P_{scarcity}$ is around or lower than 10%, meaning that crop production would consume about 10% or less of global PR reserves by 2050. Nevertheless, some countries with high reserves would still experience potential concerns of $P_{scarcity}$ between 10% and 100%, such as China (21–72%), the United States (36–79%) and Brazil (10–43%).

The challenge of P scarcity is more concerning for many countries that have very limited PR reserves (Supplementary Table 26). Assuming that PUE and the ratio of P fertilizer input to total inputs remain at 2010 levels (that is, scenario 1B in Extended Data Table 2), India, Mexico and Vietnam will deplete their P reserves and have the highest $P_{scarcity}$ if they solely rely on domestic reserves. Even with the ideal scenario (scenario 3C), India, Vietnam and many other countries would still have $P_{scarcity}$ higher than 100%. To alleviate the pressure of P scarcity, these countries can increase import of PR or P fertilizer, improve PUE and supply P inputs with other sources (for example, from accumulated soil P, recovered manure and human excreta). Some countries (such as India and Brazil) currently relying on P fertilizer import have rich P sources from manure and human excreta near croplands[39]. All countries that rely on imported P fertilizers need to consider their vulnerability to geopolitical events that could affect trade and identify alternative sources.

Global and regional challenges

By examining the historical trajectories of the P budget for crop production by country and by crop type over the past five decades, this work demonstrates a common trajectory of PUE as countries develop their economies and intensify crop production. It also identifies socioeconomic and agronomic factors (that is, NUE, fertilizer-to-crop-price ratio, farm size, crop mix and agricultural machinery) that have important relationships with PUE.

The dominant global challenge is to enhance crop yield while bringing human disturbance of P cycles back to the planetary boundary (Extended Data Table 1 and Supplementary Table 32). To address this pollution challenge, cropland PUE needs to increase from 65% in 2017 to 68–81%, and P yield needs to increase from 15.1 TgP yr^{-1} in 2017 to 19.3 TgP yr^{-1} in 2050. This could be achieved by developing and implementing more efficient nutrient management practices and allocating production and/or input resources to regions with higher PUE levels[40,41]. Meanwhile, the global P scarcity challenge appears to be less critical as less than 10% of the PR reserves will be depleted by 2050 based on recent estimation, even without strong measures in improving PUE or utilizing non-fertilizer P sources (Supplementary Table 26).

Regionally, the dominant challenges appear to be different (Fig. 6 and Supplementary Fig. 12), varying among countries based on their socioeconomic and agronomic conditions. For example, the P surplus in Brazil is driven by the expansion of soybean plantings on P fixing soil[42]. In contrast, China had been increasing yield with declining PUE and increasing P surplus until about 2010 (early development stage; Fig. 2), owing to a combination of relatively low fertilizer price[18,43], relatively small farm size[28,29] and expanding production of low-PUE crops (for example, fruits and vegetables; Fig. 4). Although improvements have been made in some countries (for example, China and India in Fig. 2), many regions still need to reduce P surplus, increase P yield and find solutions to their P scarcity challenge (Supplementary Fig. 12).

For countries with low PUE and facing P pollution and/or scarcity challenges, on-farm strategies include: (1) adjusting the crop mix to meet production, economic and pollution-reduction needs; (2) improving the efficiency of low-PUE crops; (3) maximizing benefits and minimizing pollution risks by optimizing farm size and mechanization; (4) applying the '4Rs' approach (applying the right nutrient source at the right rate, right time and right place) and adjusting for local situations[44,45]; (5) promoting precision agriculture and nutrient budgeting[46]; (6) increasing the usage of legacy P in soil (Supplementary Table 31); and (7) increasing recycling of P from manure and waste[39]. For countries facing severe P scarcity challenges (for example, India, Mexico and Vietnam), they will also need appropriate strategies to import fertilizer and perhaps stronger efforts to increase recycling of P from manure, food waste and human waste. We provide a toolbox in the Supplementary Information, which list examples of technologies and policies that can be used to improve PUE (Supplementary Table 31).

Addressing P pollution and scarcity challenges also relies on better quantification of the nutrient budget in the whole agriculture-food system and identification of management gaps beyond the farm gate. Potential strategies to improve management of P across systems and spatial scales include: (1) identifying and building stronger connections between places with P needs and P surplus[17,39,47] (for example, improving the integration of crop and animal production systems to close the nutrient cycle at the farm or district scale); (2) reallocating nutrient application and production among regions based on regional demands and nutrient use efficiencies[5,48]; and (3) encouraging food waste recycling and diets with low nutrient footprints[5,48]. Economic and policy assistance is also necessary to encourage these practices, to support farmers and to ensure food security. Continued tracking of the P indicators developed in this study (for example, P yield, P surplus, PUE and P scarcity) will help countries and regions to evaluate their performances in addressing P pollution and scarcity challenges, and guide actions towards a more sustainable future.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-022-05220-z.

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Methods

The phosphorus budget database

We developed a database for the P budget of the crop production system for 1961–2019 by synthesizing data from existing data sources and literature (see data sources in Supplementary Table 2 and more details in Supplementary Section 1). Most budget data are available during the time period 1961–2019 and 1961 is the earliest year that the FAO database has a record[49]. Key P budget terms include P fertilizer input, P manure input, P yield (P in harvested crops), P loss (P loss to the environment through leaching, erosion and run-off) and P residual (P accumulating in the soil) (Fig. 1).

P yield is calculated as the product of crop yield[49] and P content by crop type. The P content of each harvested crop type is collected from previous studies[7,16,50–53] and we take the average when there are multiple values for one crop. The P content used in this study and the P content range in previous studies by crop type can be found in Supplementary Data 1.

There is uncertainty in the P content data by crop type used to estimate the P yield. Nutrient content data in previous work are limited, and they vary by study[19,20]. Besides, published studies usually assume that nutrient content by crop type does not change over time and that the nutrient contents are constant in all spatial units, as data by country and year are not available[7,16,19,20]. We made the same assumptions in this study, but we conducted a sensitivity analysis of the potential impact of varying P contents on PUE estimates through Monte Carlo simulations (3,000 iterations) for major countries and crop types (Supplementary Section 1.6 and Supplementary Data 2). We found that this uncertainty did not have a big impact on the trajectories of PUE. However, further studies on whether and how each crop's P content varies by region, time, climate, species and moisture content would be valuable.

For each country, the total amount of P in applied fertilizer by country and year was obtained from the FAO database[49]. To estimate P fertilizer applied by country and crop type, we first calculated the P fertilization rates for 11–14 crop groups and 24–29 country groups based on the International Fertilizer Association reports on fertilizer use by crop in 2006, 2007, 2010 and 2014–2015[54,55], and then derived the fertilizer application rate between 1961 and 2019 by country and by crop type according to the methods developed by ref. [18] (see more details in Supplementary Section 1.2).

The total P in manure applied to cropland was estimated by multiplying the amount of N in manure applied to soils[49] with the fraction of manure to cropland (opposed to pasture)[18] and the P-to-N ratio in manure by animal type[16]. We then estimated the manure application rate by dividing the total amount of applied manure in each country by the total harvested area, assuming that manure application rates are the same for all crop types for a given country and year. There are also uncertainties in the P-to-N ratios in manure. Following previous work[16], we assume that the P-to-N ratios do not change by region, time or treatment methods. We expect improvement in these estimates in the future when more detailed data and parameters are available for P.

We consider only fertilizer and manure as P inputs because (1) information about the inputs from other sources are scarce by country and by crop type; (2) other sources accounted for only a small amount of total P inputs on a larger spatial scale; for example, between 2002 and 2010, P deposition, crop residues, seed and sludge were around 2%, 13%, 1% and 5% of total P inputs to global cropland, respectively[16]; and (3) P input from crop residues is usually considered as an internal recycled components within the crop production system and is thus not accounted for in the budget[19].

To validate our database, we compared our P inputs and yield data with those estimates in the previous studies. On the global scale, our P inputs and yield are close to other estimates (Supplementary Table 6).

On the basis of the major inputs and the major productive output (that is, P yield), we calculated P surplus and PUE with the following equations:

$$\text{P surplus} = \text{P inputs} - \text{P yield} \tag{1}$$

$$\text{PUE} = \frac{\text{P yield}}{\text{P inputs}} \tag{2}$$

$$\text{P residual} = \text{P surplus} - \text{P loss} \tag{3}$$

PUE indicates the efficiency of P use in the cropping system. PUE larger than 100% suggests that the crop production is mining P from the soil, whereas PUE smaller than 100% indicates extra P remained in the soil or was lost to the environment.

P residual is calculated as the difference between P surplus and P loss, indicating the amount of P available in the soil for future plant growth or loss.

Partitioning P surplus into residual P retained in the soil and P leaving the soil is also challenging on national and global scales. Sophisticated biogeochemistry models to estimate P residual are necessary but still have large uncertainties associated with their application on national scales. There are at least two ways to estimate P loss: (1) develop a dynamic soil model to evaluate annual change considering varying soil characteristics and P budget[56], and (2) assume P loss as a fixed fraction of P in inputs or surplus. For example, P loss has previously been assumed to be 10% of the sum of fertilizer and manure inputs[57], 12.5% of total P inputs[16] or 20% of P added to the soil[5]. To estimate P loss during 1961–2014, we used P loss data by country and by year from the IMAGE-Global Nutrient Model and the spatially explicit Dynamic Phosphorus Pool Simulator (DPPS) model[56]. We assume that the P loss rate is the same for all crop types within the same country and in the same year. To estimate P loss by 2050 when the data are not available, we assume that 12.5% of P inputs will be lost, which was adopted in a previous study[16] and also close to the P loss ratio estimated using our budget data and the DPPS model results for the 2008–2012 period (Supplementary Table 4). It should be noted that the uncertainty in P loss estimation does not affect the calculation of P surplus and PUE, but they do affect the calculation of P residual. The estimation of P residual will be improved when more soil data before 1961 are available and better soil P models are developed.

Studies using data downloaded in different years from the same database can also cause differences in results[20]. We compared FAOSTAT datasets downloaded in different years (Supplementary Fig. 14) and did not find large differences.

In addition, one limitation of estimating the annual crop-level P budget is that it does not reflect the PUE of rotation systems. However, the PUE ranges of some common rotation systems are close to the PUE ranges of the crops within each system; more details and discussions can be found in Supplementary Section 4.5.

It is important to note that this study focuses on cropland only, which accounts for the major anthropogenic P inputs and a major source of P loss to the waterways. However, to achieve sustainable P management, it is also important to improve P management in other agricultural systems (for example, pasture) and beyond the farm, and to better understand the relationship of nutrient management across different systems[19].

Phosphorus planetary boundary

Reference [58] estimated the global planetary boundary range for fertilizer P applied to cropland as 6.2–11.2 TgP yr^{-1}, whereas ref. [5] suggested the planetary boundary range for global P fertilizer input at 6–12 TgP yr^{-1} or 8–16 TgP yr^{-1}, depending on the recycling rate of P. Here we use the range 6–12 TgP yr^{-1} under the 'no waste recycling' scenario, which assumes that no P in human waste is recycled back to croplands[5,37]. This scenario was chosen for this study because (1) our P budget database only considers major P inputs including fertilizer and manure inputs; (2) there are varying waste recycling ratios around the world; and (3) the 'no waste recycling' scenario is the worst case of waste recycling thus it can help us set a planetary boundary with some buffer space[37]. We use P surplus rather than P fertilizer input to evaluate P pollution (Supplementary Section 4.3) because (1) P surplus measures the amount of applied P that is subject to being accumulated in soil or lost to the environment; (2) it is more relevant to environmental stress[59] than P fertilizer input; (3) it allows for the effects of varying PUE in scenario analyses; and (4) a similar indicator, N surplus, has been proposed for tracking progress towards reductions in nutrient pollution caused by food production on farm to regional scales[18,60]. The planetary boundary of the P surplus rate was estimated at 3.5–6.9 kgP ha^{-1} yr^{-1}, calculated by dividing the global P surplus planetary boundary by global total harvested area at the average of 2008–2012[37].

It is noted that the P surplus does not necessarily reflect the actual environmental impacts, such as eutrophication of lakes and estuaries. Thus, the estimated boundary should only be used as a reference point to provide a general direction for P management improvement. More research is needed to translate global planetary boundary targets and country-level P surplus to local and regional environmental impacts.

Statistical analyses

GDP per capita data and country classifications by income level (low, lower-middle, upper-middle and high-income countries) are from the World Bank[21]. Data sources and definitions of other potential drivers can be found in Supplementary Table 9.

Given the evolving field of statistical analysis of non-stationary data[24–26], statistical tests for the EKC hypothesis are challenging and the test results are equivocal. Accordingly, we apply a variety of state-of-the-art tests, but our main purpose here is not necessarily to prove or disprove unequivocally the EKC hypothesis, but rather to note the commonalities (the shapes of the temporal curves) and the differences (stages and inflection points) that may reflect current and historical responses to national economic and agricultural policies.

For each country, we used three approaches to examine the relationship between PUE and GDP per capita, which are simple regression, extended methods and autoregressive distributed lag methods (Supplementary Section 2.1). Specifically, the extended methods include the second generation of unit root test[61], extended cointegration test[25,26], extended non-cointegration test[25,26] and extended fully modified ordinary least squares estimator adapted for the cointegrating polynomial regression[24–26,62].

We then analysed panel data of 113 major crop-producing countries (see Supplementary Section 3.1 for the full list of countries) during 1961–2014 using a fixed-effects model with PUE as the dependent variable and GDP per capita (including both linear and quadratic terms) as the independent variable (Supplementary Section 2.2.1). We tested different model types, including constant intercept model, fixed-effects model and random-effects model (Supplementary Table 19), and regression models with or without a linear or a quadratic term of the time-effect variable (Supplementary Tables 21–23). We did not consider other more complex forms of the time-effect variable, because we consider that PUE change is not directly driven by time but other factors, and the focus of the study is to test the predicted relationship between PUE and GDP per capita. In addition, more complex forms of a time-effect variable may lead to multicollinearity issues that are challenging to identify. Therefore, considering a more complex time effect is beyond the scope of this study.

Besides using time series data for statistical analysis for individual countries and across countries, we also conducted a cross-sectional analysis with GDP per capita and PUE data for all countries at one time point to check the pattern without the time effect (Supplementary Fig. 7).

In addition to GDP per capita, we identified nine potential socio-economic and agronomic drivers for PUE (Supplementary Table 9) based on reviewing existing literature on drivers of nutrient use[18,23,27–29] as well as consultation with experts, and investigated their relationships with the historical trends of PUE with multiple statistical approaches, including Pearson's correlation and fixed-effects regression (Supplementary Sections 2.3 and 2.4). Farm size is quantified as the adjusted average farm size, which is a parameter developed by ref. [29] to discount the influence of arable land per capita on average farm size. We acknowledge that there could be other drivers affecting the P budget, such as changes in irrigation and land use. However, given the current lack of relevant data with sufficient spatial and temporal coverage, examination of additional drivers must await future studies.

Projection of future phosphorus budget

We first estimated P in harvested crops based on the projection by the FAO for food demand under their assumed baseline scenario by 2050[36]. We then projected the P surplus and the P input by country, by crop type and by year under different scenarios (Extended Data Table 2).

By design, both the MPA and HPA scenarios focus on improving PUE in those countries with relatively low PUE and high P surplus in 2010. For countries with relatively higher PUE and negative P surplus rate in 2010 (for example, France and some African countries), their negative surplus rate would increase to around zero, as we assume that PUE higher than 100% would decrease to around 100% by 2050 (Fig. 3b).

Data availability

All data are available in the article and its Supplementary information. Other raw data supporting the findings of this study are available at https://doi.org/10.5061/dryad.573n5tb74. Source data are provided with this paper.

Code availability

The code used to perform analyses in this study was generated in MATLAB R2020b. Figures were created in Microsoft PowerPoint software, R 4.2.0, MATLAB R2020b, Adobe Acrobat Pro 2022.001.20169 and ArcGIS 10.8.1 (https://www.esri.com/). Maps in Supplementary Information were generated in Tableau 2020.2 using free map data from OpenStreetMap (https://www.openstreetmap.org/copyright). The MATLAB code needed to generate the results presented in the paper is available at https://doi.org/10.5061/dryad.573n5tb74. Additional code is available from the corresponding author upon reasonable request.

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Author contributions X.Z. and T.Z. conceptualized the study. T.Z. coded the numerical analyses and analysed the data based on X.Z.'s previous work and suggestions from X.Z. and E.A.D. T.Z. wrote the paper. T.Z., X.Z. and E.A.D. edited the paper.

Competing interests The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to X. Zhang.

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Extended Data Table 1 | P budget and PUE aggregated to 12 regions/countries and 11 crop groups in 2010 (averaged between 2008–2012) and projected for 2050 under three scenarios

	2010 (Averaged between 2008-2012)			2050 Business-As-Usual			2050 Moderate-Policy Ambition		2050 High-Policy-Ambition	
Region /country	Harvest	PUE	Surplus	Harvest	PUE	Surplus	PUE	Surplus	PUE	Surplus
Africa	0.9	109	-0.1	1.2	78	0.3	86	0.2	92	0.1
Brazil	0.8	42	1.1	1.3	45	1.6	69	0.6	89	0.2
Canada	0.3	98	0.0	0.5	89	0.1	89	0.1	92	0.0
China	2.4	36	4.2	3.3	38	5.3	64	1.8	83	0.7
Europe	1.7	84	0.3	2.3	74	0.8	81	0.5	88	0.3
Former Soviet Union	1.0	115	-0.1	1.5	84	0.3	91	0.1	94	0.1
India	1.4	42	2.0	2.2	43	3.0	69	1.0	86	0.3
Middle East	0.2	57	0.1	0.2	59	0.2	69	0.1	81	0.1
Other OECD	0.3	40	0.4	0.4	44	0.5	72	0.1	89	0.0
Other Asia	1.4	76	0.4	2.2	70	1.0	82	0.5	91	0.2
Other Latin America	0.8	70	0.4	1.5	62	0.9	83	0.3	92	0.1
USA	1.9	101	0.0	2.8	92	0.2	93	0.2	98	0.1
Total	13.0	60	8.6	19.3	58	14.1	78	5.5	89	2.3
Crop type	Harvest	PUE	Surplus	Harvest	PUE	Surplus	PUE	Surplus	PUE	Surplus
Wheat	2.9	80	0.7	4.2	71	1.7	90	0.5	100	0.0
Rice	1.8	63	1.0	2.5	58	1.8	79	0.7	96	0.1
Maize	2.4	74	0.8	4.2	71	1.7	92	0.4	100	0.0
Other cereal	0.9	70	0.4	1.3	67	0.6	82	0.3	92	0.1
Soybean	1.4	76	0.4	2.0	66	1.0	84	0.4	100	0.0
Oil palm	0.1	71	0.1	0.3	73	0.1	74	0.1	90	0.0
Other oil seeds	0.9	69	0.4	1.4	63	0.8	83	0.3	91	0.1
Cotton	0.8	102	0.0	1.1	90	0.1	100	0.0	100	0.0
Sugar crops	0.2	23	0.6	0.3	23	1.0	31	0.6	35	0.5
Fruits and vegetables	0.7	19	2.9	1.0	20	3.9	35	1.8	44	1.2
Other crops	0.8	42	1.1	1.1	46	1.3	69	0.5	86	0.2
Total	13.0	60	8.6	19.3	58	14.1	78	5.5	89	2.3

The business-as-usual scenario assumes that the PUE for each country and crop type stays the same as the 2008–2012 level (the approximate baseline date of the FAO study). The moderate-policy-ambition scenario and high-policy-ambition scenario assume that the PUE will increase to the global 50th and 75th percentile level respectively (see Supplementary Data 3 and Supplementary Section 4.1 for more details). Units: TgP yr^{-1} for Harvest and Surplus and % for PUE. A value of 0.0 indicates that the value is smaller than 0.05.

Extended Data Table 2 | Scenarios developed for projecting P surplus and P input in 2050

PUE scenarios by 2050	P input scenarios		
	A) 100% P inputs from fertilizer	B) P inputs from fertilizer and manure	C) P inputs from fertilizer, manure, and accumulated P residual
1) Business-As-Usual (BAU): PUE in 2050 staying at 2010 level	1A	1B	1C
2) Moderate-Policy-Ambition (MPA): PUE in 2050 not lower than 50th percentile of regional PUE values in 2010	2A	2B	2C
3) High-Policy-Ambition (HPA): PUE in 2050 not lower than 75th percentile of regional PUE values in 2010	3A	3B	3C

These scenarios were designed based on assumptions regarding ambitions of PUE improvements (rows) and P inputs (columns) by 2050. The 50th and 75th percentiles of regional PUE values by crop type can be found in Supplementary Data 3. See Supplementary Section 4.1 for more details about the scenario design.