Improving Phosphorus Use Efficiency in Cropland to Address Phosphorus Challenges by 2050

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Abstract

Applying Phosphorus (P) to global cropland supports crop growth and helps to address the increasing global food demand. However, poor management of P application leads to nutrient loss and environmental pollution in many countries, while some countries (e.g., India and Vietnam) are also facing the depletion of national phosphate rock reserves. One critical strategy to address these challenges is to improve phosphorus use efficiency (PUE) in crop production. The success of this strategy depends on improving regional PUE with advanced technologies and effective management strategies, and an understanding of relevant socio-economic and agronomic drivers influencing regional and global PUE. However, low-efficiency regions and the key drivers remain unclear, and no studies have quantified the impacts of PUE improvement on addressing P challenges. This study developed a unique database of P budget and PUE by country and crop type over 50 years, and examines the temporal and spatial patterns, and makes projection of future P budget under three scenarios with different PUE improvement levels. By studying the historical data, we found that PUE has been significantly affected by a country's development stage, crop portfolios, nitrogen use efficiency (NUE), fertilizer to crop price ratio, and average farm size. By improving the global PUE in crop production from the current 60% to around 69-82% by 2050, we could decrease the global P surplus from 8.8 in 2010 to about 4.5-9 Tg P yr-1 by 2050. Improvement of some countries (e.g., China and India) and some crop types (e.g., fruit and vegetable) should be prioritized, as they currently have relatively lower PUE.

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Key Points:

- Two phosphorus challenges have arisen as the world is trying to meet increasing food demand: phosphorus depletion and phosphorus pollution
- To address these challenges, phosphorus use efficiency would need to increase from the current 60% to 69-82% globally, but with different regional implications.
- Phosphorus use efficiency has been significantly affected by socio-economic and agronomic factors, including economic development and fertilizer to crop price ratio

Abstract

Applying Phosphorus (P) to global cropland supports crop growth and helps to address the increasing global food demand. However, poor management of P application leads to nutrient loss and environmental pollution in many countries, while some countries (e.g., India and Vietnam) are also facing the depletion of national phosphate rock reserves. One critical strategy to address these challenges is to improve phosphorus use efficiency (PUE) in crop production. The success of this strategy depends on improving regional PUE with advanced technologies and effective management strategies, and an understanding of relevant socio-economic

and agronomic drivers influencing regional and global PUE. However, low-efficiency regions and the key drivers remain unclear, and no studies have quantified the impacts of PUE improvement on addressing P challenges. This study developed a unique database of P budget and PUE by country and crop type over 50 years, and examines the temporal and spatial patterns, and makes projection of future P budget under three scenarios with different PUE improvement levels. By studying the historical data, we found that PUE has been significantly affected by a country's development stage, crop portfolios, nitrogen use efficiency (NUE), fertilizer to crop price ratio, and average farm size. By improving the global PUE in crop production from the current 60% to around 69-82% by 2050, we could decrease the global P surplus from 8.8 in 2010 to about 4.5-9 Tg P yr^{-1} by 2050. Improvement of some countries (e.g., China and India) and some crop types (e.g., fruit and vegetable) should be prioritized, as they currently have relatively lower PUE.

Plain Language Summary

Phosphorus (P) is one of the essential nutrients that crops need to grow. As the global population increases, we need to use P fertilize at cropland continually. However, inappropriate use of P in agriculture will cause trouble for both the environment and society. First, the available amount of phosphate rock, which is the raw material for P fertilizer, is limited on earth and in short in many countries. Second, too much P lost to the environment can lead to bad water quality, causing the death of fish in waters and impairing human health. To address these challenges, we need to understand factors influencing the use efficiency of P, and how improvement in P use efficiency can alleviate P shortage and nutrient pollution problems. This study answers the two questions by examining historical P use data and projecting future P budget at cropland in different scenarios. Based on the study results, we suggest national and global P efficiency improvement goals to achieve by 2050 to produce enough food and reduce P pollution to an acceptable level.

1 Introduction

Phosphorus (P) is one of the nutrients critical for growing crops, which are fundamental for feeding the growing population (Tilman et al. 2002, Cordell et al. 2009, Cordell and White 2014). Consequently, the urge for more food production and higher yield is likely to drive up the demand for P inputs to cropland. By estimate, the total global consumption of P fertilizer at cropland has increased by almost four times from 1961 to 2013 (Lu and Tian 2017), and the demand may increase to 22-27 Tg P yr^{-1} by 2050, even assuming a sustainable future (Mogollón et al. 2018).

However, over and improper use of P results in excessive P leaching to adjacent water bodies, causing nutrient pollution (Foley et al. 2011, Bouwman et al. 2017, Fink et al. 2018, Mekonnen and Hoekstra 2018). Inorganic fertilizer use was the primary source (47%) of P going to the world's largest 100 lakes between 2005-2010 and 1990-1994, and developing countries had a higher chance of P-stimulated eutrophication (Fink et al. 2018). Even after the reduction or cessation of fertilizer input, the large surplus of P accumulated in soil (known as legacy P) will continue to pollute surface waters, offsetting the benefits brought by nutrient abatement measures (Sharpley et al. 2013, Powers et al. 2016, Bouwman et al. 2017, McCrackin et al. 2018).

At the same time, many countries have concerns about P depletion. The reported phosphate rock reserves on a global scale may be adequate for the current food production need (Cordell and White 2014). However, there are debates on the abundancy (Edixhoven et al. 2014), and stocks of phosphate rock on a local scale in many countries are insufficient for agricultural production. Besides the uneven distribution of phosphate rock throughout the world, its non-renewable nature and inefficient management increase the P depletion concern (Cordell et al. 2009, Cooper et al. 2011).

One key solution to these two P challenges is to improve P use efficiency (PUE) at cropland (Cordell and White 2014, Bouwman et al. 2017, Heuer et al. 2017, Lun et al. 2018). The goal of improving efficiency goes beyond increasing production through intensification or extensification. It also emphasizes better managing inputs to reduce the negative impacts of agriculture on the environment and society. Improving efficiency is the critical pathway towards synergies between agriculture productivity, sustainability, and resilience (Coomes et al. 2019).

Improvement in PUE relies on not only an understanding of P use patterns but also its key drivers. Previous studies have examined cropland P budget (P inputs and output at cropland) and use efficiency on different temporal and spatial scales (Cordell et al. 2009, MacDonald et al. 2011, Cordell and White 2014, Chen and Graedel 2016, Bouwman et al. 2017, Lu and Tian 2017, Lun et al. 2018, Mogollón et al. 2018). However, no studies have evaluated enough socio-economic and agronomic drivers influencing PUE, or quantifying the impacts of PUE improvement on addressing the two P challenges. Besides, global and regional priorities of P management are still unclear, which are critical information for decision-makers to develop effective strategies. To fill the research and political gaps, we (1) evaluated the historical patterns of P budget and PUE at cropland by country and crop type between 1961-2014; (2) identified key socio-economic and agronomic drivers influencing global and national PUE; and (3) suggested global and regional priorities for addressing P challenges by 2050.

2 Data and Methods

2.1 The Phosphorus Budget Model

Focusing on the crop production system, we identified four major P budget terms to quantify (Fig. 1; Text S1). Methods for database development and P budget analysis were developed based on a previous study on cropland nitrogen use (Zhang et al. 2015a).

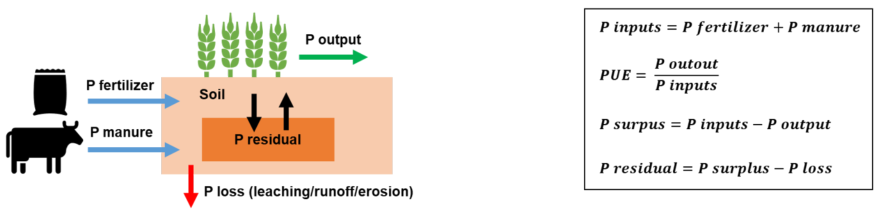


Figure 1. Illustration of P flows and P budget terms used in this study. P inputs: blue arrows. P output (P yield): green arrow. P loss: red arrow.

Major P inputs to cropland include P fertilizer and P manure:

$$P\ inputs = P\ fertilizer + P\ manure$$

To determine the amount of fertilizer applied to 150+ crop types and 200+ countries, we started with IFA fertilization data of 10+ crop type groups and 20+ country groups reported in 2006 2007, 2010, and 2014 and 2015 (IFA 2018) and the national fertilizer use data published by the Food and Agriculture Organization of the United Nations (FAO) (FAOSTAT 2020). Then, we projected fertilization rate by country and crop type from 1961 to 2014, assuming that the fraction of fertilizer applied to each crop type in each year is the same as that reported by IFA (1961-2006, same fraction as reported in IFA 2006 report; 2007, same fraction as reported in IFA 2007 report; 2008-2010, same fraction as reported in IFA 2010 report; 2011-2014, same fraction as reported in IFA 2014 report). For countries belonging to the same country group and crop types belong to the same crop type group, we assumed the same fertilization rate. For missing data between years, we did linear interpolation. The projected results were then further adjusted to increase accuracy, with other fertilizer use details mentioned by FAO (FAO 2002, FAOSTAT 2018) and in published studies (Smil 1999, Schroder et al. 2010, Lassaletta et al. 2014). In the previous work, P in fertilizer is expressed as the weight of P_2O_5, and we changed the unit to kg P. The content of P in animal excretion is also available in previous studies (Sheldrick et al. 2003, Andersen 2013, Chen and Graedel 2016, Chowdhury 2016, Liu et al. 2016, Bouwman et al. 2017). With that, we can estimate the total P in applied fertilizer and manure. More details of these calculations can be found in SI. On the global scale, our P inputs and output are similar with that found in the previous studies (Table S5 and S6).

With P fertilizer input data, we calculated P fertilizer demand to supply ratio and used it as the indicator of the P depletion challenge. P fertilizer demand is the total P demanded from fertilizer, and P supply is the total P provided by local phosphate rock reserves. This indicator suggests whether a country's phosphate rock reserves along are sufficient for its food production. A ratio close to or higher than one (threshold: one) indicates the need to use more P from alternative sources or import more P to support future food production. Phosphate rock reserves data were collected from the United States Geological Survey (USGS) (2018).

The two pathways of P leaving the cropland system are (1) P in harvested crops (known as P output, or P yield to describe the P in harvested crops per unit land), including any part of the plants removed from the field, and (2) P loss through leaching, erosion, and runoff. Each crop's P content was decided by taking the average of P content reported by FAO (2006), the United States Department of Agriculture (USDA 2013), AUSNUT (2013), Gourley et al. (2010), and Bouwman et al. (2017). The impacts of varying P content by crop type on P yield and PUE were examined with sensitivity tests (Text S6).

P surplus is also called P imbalance (MacDonald et al. 2011, Lun et al. 2018) or P budget (Bouwman et al. 2017). P surplus is the difference between P inputs and P output, and the sum of P loss and P residual:

$$P\ surplus = P\ inputs - P\ output$$

$$P\ surplus = P\ loss + P\ residual$$

Here we used P surplus to measure P pollution and compared it with estimated planetary boundary, which in many studies marks the safe operating space for humanity (Rockström et al. 2009, Carpenter and Bennett 2011, Steffen et al. 2015). Based on Springmann et al.'s global P flow model (Springmann et al. 2018), we estimated the planetary boundary for global cropland P surplus is 4.5-9 Tg P yr^{-1} (i.e., 3.5-6.9 kg P $ha^{-1}yr^{-1}$, see Section TextS14 for the assumptions and methods used for deriving this planetary boundary).

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

$$P\ residual = P\ surplus - P\ loss$$

PUE, sometimes also called the recovery ratio, is defined as the ratio of P output (i.e., P in harvested crops or P yield) to P inputs:

$$PUE = \frac{\text{P output}}{\text{P inputs}}$$

A PUE larger than one means the crop production is mining nutrients from the soil, while PUE smaller than one indicates extra P remained in the soil and/or lost. Our estimated PUE on the global scale is similar to the estimations in the earlier studies (Tables Sx).

2.2 Key Drivers for P Use Efficiency (PUE)

Based on consultation with experts and the previous work studying drivers of nutrient use (Dinda 2004, Zhang et al. 2015a, Zhang et al. 2015b, Ju et al. 2016, Wu et al. 2018), we considered and examined the relationships between PUE and multiple potential drivers, including eight socio-economic drivers and seven agronomic drivers (Table 1, Table S11).

Table 1 Selected PUE drivers, data sources, and methodology.

Driver	Data source	Methodology
Socio-economic drivers	*Socio-economic drivers*	*Socio-economic*
Economic development	World Bank (2018)	GDP per capita
Consumption per capita for certain crop types	FAOSTAT (2018), Zhang et al. (2015a)	Production + i
Fertilizer to crop price ratio	FAOSTAT (2018)	Fertilizer price
Per hectare spending on agricultural machinery	FAOSTAT (2018)	Agricultural ma
Patent application per capita	World Bank (2018)	Resident patent
Education expenditure as a percentage of government spending	World Bank (2018)	Government ex
Agriculture, value added	World Bank (2018)	The net output
Ratio of net import of certain crop types	FAOSTAT (2018), Zhang et al. (2015a)	Net import / lo
Agronomic drivers	*Agronomic drivers*	*Agronomic driv*
Crop mix	FAOSTAT (2018), Zhang et al. (2015a)	Percentage of t
NUE	Zhang et al. (2015a)	N output (N in
Adjusted average farm size	Graeub et al. (2016)	Residual of the
Conservation area ratio	FAO AQUASTAT database	Conservation a
P yield	FAOSTAT (2018), Zhang et al. (2015a)	P in harvested
Accumulated P surplus	Calculation	P inputs (fertil
Accumulated P residual	Calculation	P surplus - P lo

Besides P budget and PUE by crop type, we also tried to collect data of all drivers for over 200 countries by crop type from 1961 to 2014. However, as the available data of most drivers are limited to a smaller set of countries (Table S13), we studied the drivers and their relationships with PUE in 113 major crop-producing and nutrient use countries (Text S8). These countries accounted for around 85% of the global total harvest area, 86% of total P in crop production, and 94% of total P fertilizer input in 2010 (average of 2005-2014).

We analyzed the relationships between PUE and all potential factors in and across these 113 major countries, using three methods:

1) fitting regression models with PUE as the dependent variable and the linear and quadratic terms of economic development as the independent variables, to test the Environmental Kuznets Curve (EKC) hypothesis (Dinda 2004, Zhang et al. 2015a) for individual country and across all 113 countries (Text S7);

2) studying the association between PUE and each drive for individual countries, by calculating Pearson's correlation coefficient (Pradhan et al. 2017) (Text S10);

3) fitting constant intercept and fixed effects models with PUE as the dependent variable and other driver(s) as the independent variable(s) across all 113 countries (Text S11).

We examined the relationships both for individual countries and across countries to avoid the effects of the Simpsons Paradox (Scholz and Hirth 2015).

2.3 Projection of Future PUE and Phosphorus Budget

We projected future PUE and P budget for crop production in three PUE improvement scenarios (Table 2): 1) the Business-As-Usual (BAU) scenario, 2) the Moderate-Policy-Ambition (MPA) scenario, and 3) the High-Policy-Ambition (HPA) scenario. From scenario BAU to HPA, we assume that PUE by country and crop type would have no improvement, median improvement, and significant improvement, respectively. To decide the improvement level, we first calculated the PUE by crop type of 12 regions (Table S17) in 2010 (the average of 2005-2014). Then for each crop type, we set the median and 75^{th} percentile value of the 12 regions' PUE as the minimum PUE level to achieve in MPA and HPA scenarios, respectively.

Table 2 The settings of three PUE improvement scenarios and three cases of P fertilizer to total inputs ratio from 2014 to 2050.

PUE scenarios	P fertilizer to total inputs ratio
	A) Least sustainable
1) Business-As-Usual (BAU)	1A 2050 PUE at current level; P fertilizer to total inputs (fertilizer + manure)
2) Moderate-Policy-Ambition (MPA)	2A 2050 PUE linearly improved to median level; P fertilizer to total inputs (fe
3) High-Policy-Ambition (HPA)	3A 2050 PUE linearly improved to 75th percentile level; P fertilizer to total in

In the BAU scenario, we assumed that PUE by country and crop type by 2050 would remain at the current level (the average of 2005-2014). In the MPA scenario, for each crop type, PUE by country lower than the MPA minimum level (median level of the 12 regions) would be improved to that level by 2050 and other PUE values would be kept the same. Similarly, in the HPA scenario, PUE by country and crop type lower than the HPA minimum level (75th percentile level of the 12 regions) would be improved to that level and other PUE values would be kept the same. Besides, we assumed that PUE by country and crop type by 2050 would not exceed one, considering that soil mining is unsustainable in the long run, and the PUE change between 2015 and 2050 would be linear. With these assumptions and designed scenarios, we projected PUE by country and crop type from 2015 to 2050.

We estimated future P yield based on FAO's projection (FAO 2018). FAO projected crop production and harvested area change by region and crop type in 2030, 2035, and 2040 and 2050 in three scenarios (2018). We adopted the projection in FAO's Business as Use scenario to project P in harvested crops. We assumed that the data's change within those reported years would be linear, and P content by crop type will not change over time or by country.

With P yield and PUE by country and cop type by 2050, we then estimated P inputs (P demanded for crop production):

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

To calculate P fertilizer input by 2050, we need to know P fertilizer to total inputs ratio (total inputs include P in fertilizer and manure). As this ratio by country and crop type may change in the future, we designed three extreme cases to consider its uncertainties (Table 2): A) the least sustainable case, in which P fertilizer to total inputs (including fertilizer and manure) ratio would equal to 100% from 2014 to 2050 (meaning all P inputs would be from fertilizer) and total inputs would equal to the projected P inputs; B) the normal case, in which P fertilizer to total inputs (including fertilizer and manure) ratio would remain at the current level (the average of 2005-2014) from 2014 to 2050 and total inputs would equal to the projected P inputs; C) the most sustainable case, in which to P fertilizer to total inputs ratio would remain at the current level, but the total inputs would equal to the projected P inputs minus the total P residual accumulated in the soil since 1961, assuming that P residual would be used for crop production.

In total, we designed three scenarios (BAU, MPA, and HPA) to project PUE, P yield, P inputs, and P surplus by 2050, and nine scenarios (from 1A to 3C, Table 2) to project future P fertilizer and manure inputs. We designed these nine scenarios to study how much we can reduce P pollution and the demand for phosphate rock with different P management ambitions measured by PUE improvement and fertilizer to total inputs ratio.

3 Results

3.1 Historical Phosphorus Budget and PUE

On the global scale, P yield has increased by around two times from 1961 (5 kg P ha^{-1} yr^{-1}) to 2014 (11 kg P ha^{-1} yr^{-1}) (Fig. 2a), indicating increased agricultural productivity. At the same time, global PUE decreased since 1961 (54%), then began to grow in the 1980s (40%), and stabilized after entering the 21st century (Fig. 2a). Though the improved PUE indicates a smaller fraction of P inputs lost to soil and environment, P residual has accumulated from 1961 to 2014 (2 to 195 ha^{-1} yr^{-1}, Fig. 2b), as a potential P source for future crop production.

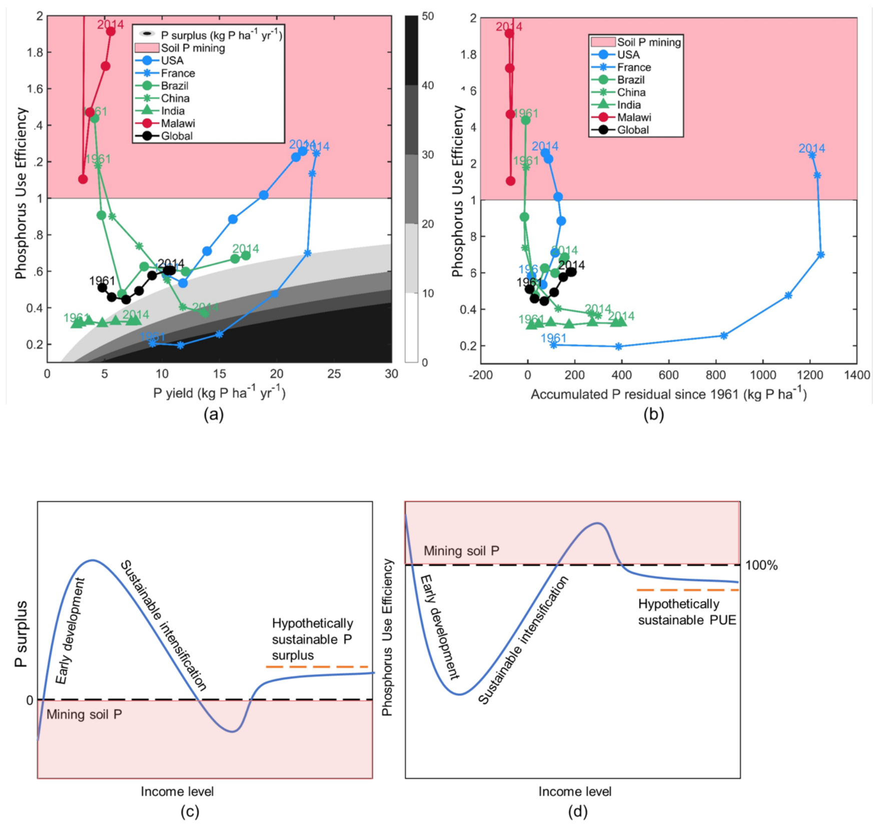


Figure 2. Historical and hypothesized P budget and PUE trends. (a) PUE versus P yield from 1961 to 2014. PUE larger than 2 (200%) is not shown. The greyscale indicates P surplus (kg P ha^{-1}). (b) PUE versus accumulated P residual from 1961 to 2014. PUE larger than 2 (200%) is not shown. High- and middle-income economies' (The World Bank 2017) data are in blue and green, respectively. Malawi's data are in red. The pink area indicates soil mining (negative P surplus). Data have been smoothed by ten years to limit the data variation influenced by weather conditions. Seven data points represent the data in 1961, 1970, 1980, 1990, 2000, 2010, and 2014. (c) The hypothesized relationship between P surplus and GDP per capita. (d) The hypothesized relationship between PUE and GDP per capita.

Different from the global trends, the historical patterns of regional P budget and PUE vary by country, and their historical trajectories suggest a typical pattern of PUE as countries increase their P yield, accumulated P residual, and income levels. Malawi, as a low-income country, has had minimal success in increasing its yield in the past 50 years, and it relied mainly on mining native soil P (Fig. 2a). Middle-income economies like Brazil, China, and India, have had increased crop yield at the expense of nutrient use efficiency and managing P surplus (Fig. 2a). However, their accumulated P residual was still lower than that of France since 1961 (Fig. 2b). The relatively high P residual accumulated in France, lower accumulation in the U.S., and the increasing accumulation in China and India due to large P surplus in recent years were also found in a previous study estimating P residual since 1900 (Zhang et al. 2017). Our estimation differs from theirs on the starting point of estimation and assumptions for initial values. As middle-income economies continuously improve their soil fertility and yield, they may still have low PUE and high P surplus in the next few years or even decades. High-income economies such as the U.S. and France, have experienced yield enhancement in the 1960s, relying on increased fertilizer input. They transited to the second phase of yield enhancement and surplus reduction in the 1970s and 1980s, which benefited from improved PUE (Fig. 2a).

Based on those observations (Fig. 2a and 2b), we hypothesized that the relationship between GDP per capita and PUE follows the Environmental Kuznets Curve (EKC) (Dinda 2004, Zhang et al. 2015a). EKC suggests that P pollution first increases with GDP per capita at the early development stage. It starts to level off and decreases at a later stage due to technological development and increased environmental awareness. Accordingly, as the economy develops, the P surplus first increases and PUE first decreases, leading to more P accumulated in the soil or lost to the environment (Fig. 2c and 2d). P surplus then decreases, and PUE improves, as more P inputs are converted to crop products (Fig. 2c and 2d). We consider that the PUE of a county (e.g., the U.S. and France) may exceed 100% during the sustainable intensification, as the crop production may mine some accumulated residual P before reaching a relatively steady state (Fig. 2d). For each country, the whole EKC process may take a longer time than current databases have recorded, and many other factors (such as social and climate change, and global collaboration) can affect its development and change rate. Thus, the suggested U-shape curve is clearly seen on a global scale but is not obvious in individual countries (Fig. 2a and 2b).

The historical data of P budget and PUE also indicate low-efficiency countries and crops policymakers need to prioritize when improving P management. Comparing the PUE of 12 regions in 2010, China and India had relatively low PUE (<40%) and high P inputs, contributing over half of the P surplus to the global environment (Table 3). On the global scale, rice, fruit, and vegetable had relatively low PUE (<40%) and high P inputs, leading to a global P surplus at 9 Tg P yr^{-1} in 2010 (Table 3).

Table 3. P budget and PUE in crop production by region and crop group in 2010 (average of 2005-2014) and in 2050 in the three scenarios (BAU, MPA, and HPA). The unit of each budget term except for PUE is Tg P yr^{-1}. The unit of PUE is %. The definitions of the 12 regions are in Table S17. The definitions of the 11 crop groups are in Table S12. Value 0.0 means it is smaller than 0.05.

	Current (2010)	**Current (2010)**	**Current (2010)**	**Current (2010)**	**BAU**
By region	**Harvest**	**Input**	**PUE**	**Surplus**	**Harv**
Africa	1.0	0.8	127	-0.2	1.3
Brazil	1.1	1.7	66	0.6	1.8
Canada	0.3	0.4	89	0.0	0.6
China	2.3	6.1	38	3.8	3.3
Europe	1.7	2.1	80	0.4	2.3
FSU	1.0	0.6	169	-0.4	1.6
India	1.4	4.3	32	2.9	2.2
Middle East	0.2	0.3	60	0.1	0.2
Other OECD countries	0.3	0.7	37	0.4	0.4
Other Asian countries	1.2	2.7	44	1.5	1.9
Other Latin America countries	1.0	0.9	111	-0.1	1.7
United States	2.2	1.8	121	-0.4	3.1
Total	13.6	22.5	61	8.8	20.5
By crop type	**Harvest**	**Input**	**PUE**	**Surplus**	**Harv**
Wheat	2.9	3.9	74	1.0	4.1
Rice	1.0	3.5	30	2.5	1.5
Maize	2.4	3.1	78	0.7	4.2
Other cereal crops	0.9	1.4	66	0.5	1.3
Soybean	2.0	1.8	108	-0.1	2.7
Oil palm	0.1	0.3	57	0.1	0.3
Other oilseed	0.9	1.4	65	0.5	1.4
Cotton	1.0	0.9	117	-0.1	1.4
Sugar crops	0.8	0.8	93	0.1	1.2

	Current (2010)	Current (2010)	Current (2010)	Current (2010)	BAU
Fruit and vegetable	0.8	3.6	21	2.8	1.1
Other crops	0.8	1.8	46	1.0	1.2
Total	13.6	22.5	61	8.8	20.5

High PUE does not necessarily correspond to better P management, and it could be associated with a very low input rate and yield. African countries, FSU, and the U.S. all had relatively high PUE in 2010 (Table 3), but for very different reasons and with different implications. High PUE in the U.S. was accompanied by higher P inputs (1.8 Tg P yr^{-1}, Table 3) and higher P in harvested crops (2.2 Tg P yr^{-1}, Table 3), which benefited from the improvement in fertilizer management practices. In contrast, high PUE in African countries and FSU was the result of low P in harvested crops (1.0 Tg P yr^{-1} for both, Table 3) and lower P inputs (0.8 and 0.6 Tg P yr^{-1}, respectively, Table 3). Meeting the goals of increasing food demand and managing pollution from agriculture requires increasing production and PUE, and limiting P surplus.

3.2 Key Drivers for PUE

We tested the EKC hypothesis to study the relationship between economic development and PUE. For other drivers, we used Pearson's correlation coefficient to examine the relationship in each country and regression models across 113 countries. Our analysis results suggest drivers with a significant and consistent relationship with PUE in the global and regional models are economic development, fertilizer to crop price ratio, crop mix, NUE, farm size, and P yield (Table 4). All models mentioned in Table 4 consider time and country effects and have PUE as the dependent variable. Compared to the results of constant intercept models and fixed effects models not considering the time and country effects, the fixed effects models considering these effects behave better with higher adjusted R^2 and lower AIC (Table S10). The fixed effects model in Table 4 is the final chosen model with a high adjusted R^2 (96%) and the lowest AIC, using stepwise regression. More details of calculation, model setting, and comparison can be found in SI.

Table 4 Regression results of three methods studying the relationship between PUE and drivers from 1961 to 2014 in individual countries and across 113 countries. The grey box indicates the driver is not included in the model. *** suggests $p < 0.001$, **suggests $p < 0.01$, and * suggests $p < 0.05$.

Driver	**Individual countries**
	EKC test
	Number of countries with a U-shape relationship
GDP per capita (linear term)	47 (42%)
GDP per capita (quadratic term)	
Consumption per capita for certain crop types	
Fertilizer to crop price ratio	
Per hectare spending on agricultural machinery	
Patent application per capita	
Education expenditure as a percentage of government spending	
Agriculture, value added	
Ratio of net import of certain crop types	
Crop mix	
NUE	
Adjusted average farm size	
Conservation area ratio	
P yield	
Accumulated P surplus	
Accumulated P residual	

3.2.1 Economic Development

On the regional scale, the PUE of 70 out of 113 countries had a significant linear or quadratic relationship with GDP per capita. Among these countries, 47 of them suggest the expected U shape relationship between PUE and GDP per capita (Table 4), though the turning points and slopes vary. These 47 countries accounted for over half of the global harvested area and total P in crop production, and over 80% of P fertilizer consumption at cropland in 2010 (61%, 70%, and 84%, respectively). They include major crop-producing and fertilizer-consuming countries such as the U.S., Brazil, China, and India.

EKC hypothesis was not rejected across the 113 countries when the independent variables only include the linear and quadratic terms of GDP per capita (Table S10). After considering country and time effects and adding more variables to the regression model, only the linear term has a significantly positive relationship with PUE (Table 4, Table S10, and Table S14). These results indicate synergy between global economic development and PUE (the second half of the EKC curve) between 1961-2014 in these 113 countries.

Note that the EKC hypothesis does not tell the future of a country or define the pathway that all countries should follow. Instead, EKC suggests potential reasons behind PUE patterns and informs political strategies to improve PUE. China has been experiencing an increasing GDP per capita and decreasing PUE (Fig. S3). According to the EKC hypothesis, this tradeoff may no longer continue, as China's PUE is approaching a lower asymptote between 30% and 40% (Table 3). However, China's PUE would not inevitably reach a turning point and then increase without any technological innovation or political interventions. Improved technologies and proper policies can help a country like China turn the corner on the EKC and reach a sustainable PUE in an even shorter time.

3.2.2 Crop Mix

The production of cereal crops, fruit, and vegetable influence national PUE, as these crops had relatively lower PUE than that of other crops (Table 3, Fig. 3). Rice's PUE from 1961 to 2014 varied between 20% and 40%, while the PUE of fruit and vegetable varied between 10% and 30% (Fig. 3a). Regression analysis for individual countries and across 113 countries suggests a generally negative relationship between PUE and the percentage of harvest areas for cereal crops or fruit and vegetable (Table 4). These results imply the importance of improving the PUE of low-efficiency crops to improve national PUE.

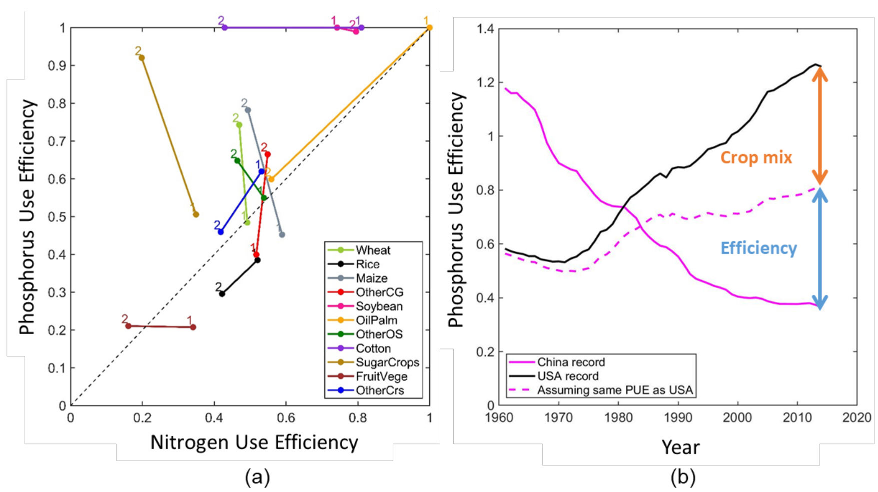


Figure 3. Crop mix as an important driver for PUE. a) Global NUE and PUE of 11 crop groups (Table S12) between 1961-2014. Point 1 represents the average of 1961-1970. Point 2 represents the average of 2005-2014. PUE values of other single years are not shown. PUE values higher than one are plotted at one. 'OtherCG' means other cereal crops. "OtherOS" means other oil seeds. 'OtherCrs' means other crop types.

b) China and U.S. PUE across crops between 1961-2014. The purple line shows China's PUE. The black line shows U.S. PUE. The dashed purple line represents the resulted PUE in China if China improved its PUE to U.S. level for each crop type. The gap between the black line and the dashed purple line shows the difference in PUE determined by the difference in crop mix.

Improving the PUE of low-efficiency crops and crop mix can both improve national PUE. China has increased harvested area and P fertilizer input for fruit and vegetable, due to increased demand and high profits. Those crops' harvested area and P fertilizer input have increased from around 5% and 12% in 1961 to 21% and 36% in 2010 (average of 2005-2014). This shift of low PUE crops reduced China's PUE. If China improved the PUE of each crop type to the U.S. level (Fig. 3a), China's PUE would be significantly improved (Fig. 3b). The remaining difference in PUE (61% lower in 2014) is caused by the difference in crop mix (Fig. 3b).

3.2.3 Nitrogen Use Efficiency (NUE)

Historical data and regression results both indicate a positive relationship between NUE and PUE (Table 4). On the global scale, crops with a relatively higher NUE (e.g., cotton and soybean) tend to have a higher PUE, while crops with relatively lower NUE (e.g., rice, fruit, and vegetable) tend to have smaller PUE (Fig. 3b). On a national scale, 99% of the countries (82 countries) with significant results (positive or negative) (Table 4) show a positive relationship.

Improvement in nutrient management leads to NUE and PUE increase. Accumulated residual soil P allows farmers in many developed countries to reduce current P inputs and increase PUE. At the same time, factors such as the adoption of 4R practices lead to NUE improvement (Zhang et al. 2015a). Future studies need to identify and understand factors that can influence the linkage between PUE and NUE, as well as other nutrients.

3.2.4 Fertilizer to Crop Price Ratio

Higher fertilizer to crop price ratio can encourage farmers to use fertilizer more efficiently, thus increasing nutrient use efficiency in the cropland (Zhang et al. 2015a, Zhang et al. 2015b). Thus, we expected a positive relationship between PUE and fertilizer to crop price ratio.

Fertilizer to crop price ratio was positively related to PUE in over 84% of the countries (21 countries) with a significant relationship (Table 4). These 21 countries accounted for 47% of the global harvested area, 53% of P in harvested crops, and 65% of fertilizer P input in 2010. In the regression analysis on the global scale, the hypothesis of a positive relationship was also not rejected (Table 4). These results indicate a synergy between fertilizer to crop price ratio and PUE on the global and national scales.

3.2.5 Farm Size

Farm size is relevant to the efficiency of resource use in crop production, but with controversial conclusions. Many studies suggested that smaller farms are more sustainable in their uses of some resources (D'Souza and Ikerd 1996, Altieri 2009). However, some studies found that smaller farms tend to use more fertilizer and have lower nutrient use efficiency (Ju et al. 2016, Wu et al. 2018).

Analysis both on the national and global scales suggests a generally positive relationship between adjusted average farm size and PUE (Table 4). Twenty-three countries show a significant positive relationship with PUE, more than those with a significant negative relationship (16 countries). These 23 countries accounted for 14% of the global harvested area, 14% of P in harvested crops, and 13% of P fertilizer input in 2010. Note that these results do not necessarily mean that large farms are "better" than small farms, as there are other socio-economic reasons behind the relationship. Besides, increasing farm size may bring into other problems, such as decreased food diversity (Herrero et al. 2017).

3.3 Projected Phosphorus Budget and Challenges in 2050

3.3.1 Phosphorus Pollution in 2050

Based on FAO's projection for food demand by 2050 (FAO 2018) and our calculation, the amount of P in harvested crops would increase from 13.6 Tg P yr^{-1} in 2010 to 20.5 Tg P yr^{-1}in 2050 (Table 3). Increased P in harvested crops indicates that P inputs would increase, and more P would be lost unless PUE is improved.

The global P surplus was projected to increase from 8.8 in 2010 to 15.3 Tg P yr^{-1} in 2050, without PUE improvement (Table 3). By improving PUE, the global P surplus would decrease to 5.6 (MPA), and even 2.2 Tg P yr^{-1} (HPA) in 2050 (Table 3), and the global P surplus rate would decrease from 7 in 2010 to 4 (MPA) and 2 (HPA) kg P ha^{-1} yr^{-1} in 2050. This reduction in P surplus would be more significant in countries with a relatively larger P surplus rate in 2010, such as China, India, and Brazil (Fig. 4). For countries with relatively higher PUE and negative P surplus rate in 2010 (e.g., the U.S. and African countries), their negative surplus rate would increase to around zero, as we assumed that PUE higher than one would decrease to around one in 2050 (Fig. 4).

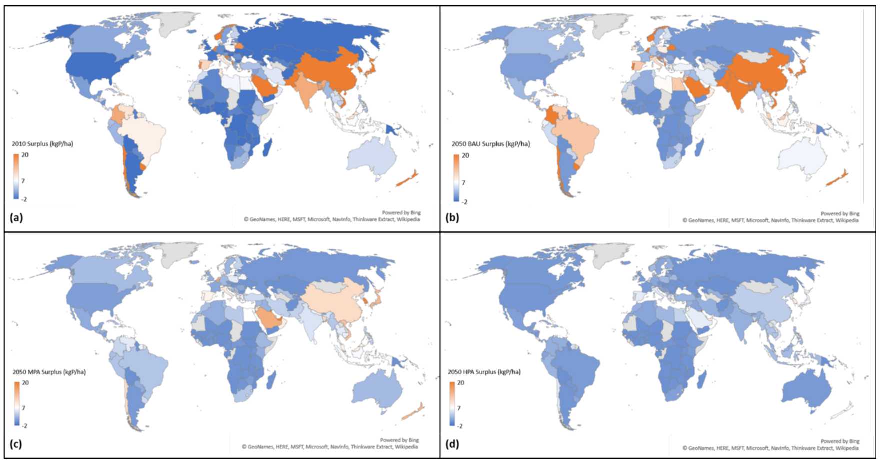


Figure 4. P surplus rate (kg P ha^{-1}yr^{-1}) by region. (a) P surplus rate (kg P ha^{-1} yr^{-1}) estimated in 2010 (average of 2005-2014). (b) P surplus rate (kg P ha^{-1}yr^{-1}) projected in the 2050 BAU scenario. (c) P surplus rate (kg P ha^{-1} yr^{-1}) projected in the 2050 MPA scenario. (d) P surplus rate (kg P ha^{-1} yr^{-1}) projected in the 2050 HPA scenario. Grey area: missing data. Orange area: P surplus rate higher than the upper planetary boundary (6.9 kg P ha^{-1}yr^{-1}, rounded to 7 kg P ha^{-1}yr^{-1}). Blue and white areas: P surplus rate lower than the upper planetary boundary. Rates larger than 20 kg P ha^{-1} yr^{-1} are shown in red. Rates lower than -2 kg P ha^{-1} yr^{-1} are shown in blue.

Based on our estimation, the global planetary boundary of P surplus is at 4.5-9 Tg P yr^{-1}. To keep the global P surplus under the boundary in 2050, we need to improve the global PUE from the current 60% to somewhere between 69% and 82%. Dividing the global P surplus planetary boundary (4.5-9 Tg P yr^{-1}) by global total harvest area in 2010 (average of 2005-2014, 1.3×10^9 ha), we estimated the regional planetary boundary of P surplus rate at 3.5-6.9 kg P ha^{-1} yr^{-1}. With this threshold, only in the HPA scenario or even more ambitious scenarios could the P surplus in major countries fall into this "safe" range (Fig. 4). In the BAU and MPA scenarios, 62 and 30 countries would still transgress the upper planetary boundary of the regional surplus rate (6.9 kg P ha^{-1} yr^{-1}) in 2050. These countries occupied 46% and 19% of the harvested area in 2010 (average of 2005-2014), respectively.

3.3.2 Phosphorus depletion in 2050

The demand for P fertilizer is likely to increase with P inputs if we assumed that all countries would maintain their current P fertilizer to total P inputs ratio (average of 2005-2014) after 2014 (scenarios 1B-3B, Table 2). With this assumption, we projected that global P fertilizer input would increase from 16.4 Tg P yr^{-1} in 2010 to 25.4 Tg P yr^{-1} in 2050 in the 1B scenario (Table S3). With PUE improvement, P fertilizer input would decrease to 18.5 (2B scenario) and 16.1 Tg P yr^{-1} (3B scenario) in 2050 (Table S3). Similarly, P manure input would increase from 6.0 Tg P yr^{-1} in 2010 to 10.4 Tg P yr^{-1} in 2050 in the 1B scenario. Improvement in PUE would reduce this input to 7.6 (2B) and 6.6 Tg P yr^{-1} (3B) in 2050 (Table S3).

The global phosphate rock reserves would be sufficient for crop production from 2017 to 2050. In all nine scenarios, the fertilizer demand to supply ratio would be at around 0.1% (Table S16), meaning that crop production would consume only about 10% of the global phosphate rock reserves. On the regional scale, the ratio of P demand to supply ratio would decrease as PUE improves (Fig. 5). However, non-major P producing countries would still face the P depletion challenge by 2050 or even earlier (Fig. 5, Table S16). Even in the most ambitious scenario and most ideal case (Fig. 5i), India (demand to supply ratio 3.7), Mexico (demand to supply ratio 1.7), and non-major P producing countries would still need to rely on phosphate rock or P fertilizer import (Fig. 5, Table S16) to support their food production. This ratio in the U.S. and China would be between 0.2-0.8 (Table S16), as they had relatively high P storage (Table S18). However, to secure food production, these two countries have adopted increasingly tight policies on phosphate rock export (Sattari et al. 2014, van de Wiel et al. 2015). P depletion challenge is severe on a regional scale.

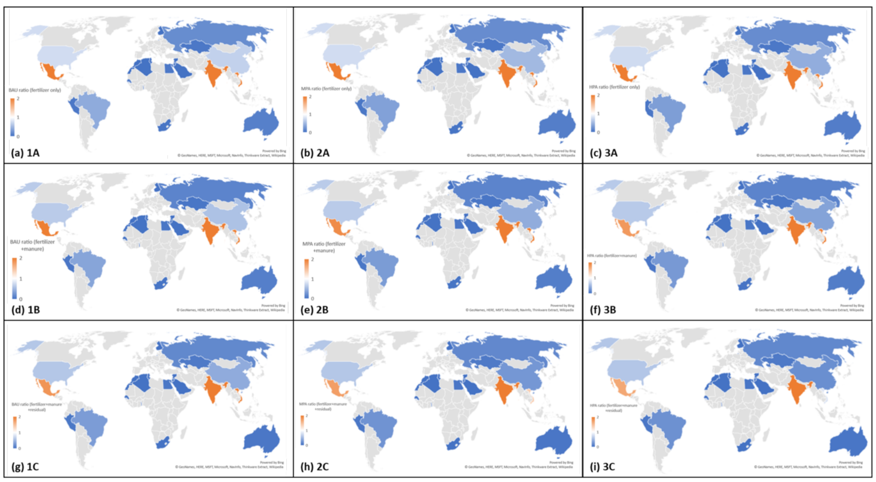


Figure 5. P depletion challenge (represented by P fertilizer demand to supply ratio) in major phosphate rock producing countries in nine scenarios (Table 2). (a) 1A scenario. (b) 2A scenario. (c) 3A scenario. (d) 1B scenario. (e) 2B scenario. (f) 3B scenario. (g) 1C scenario. (h) 2C scenario. (i) 3C scenario. Orange area: fertilizer demand to supply ratio larger than one, indicating P depletion by 2050. Blue area: fertilizer demand to supply ratio smaller than one, indicating P sufficiency by 2050. Grey area: non-major P producing countries with no phosphate rock production data.

4 Discussion

4.1 Improving PUE to Address Phosphorus Challenges

Addressing P pollution and depletion depends on the improvement of PUE, especially the PUE of low-efficiency countries and crops. These low PUE countries include India and China, and low PUE crops include rice, fruit, and vegetable.

Our study also identified key drivers for PUE improvement. We found a positive relationship between PUE and NUE, fertilizer to crop price ratio, and average farm size; and a negative relationship between PUE and the percentage of the harvested area of cereals, fruit, and vegetable. The relationship between PUE and economic development was close to an EKC curve on a regional scale, and it is synergy on a global scale.

P-efficient technologies and management practices are critical for PUE improvement. Some of these technologies and practices are available and have become more affordable. However, farmers' decision making is affected by many other socio-economic drivers, such as access to information and financial capacity

(Baumgart-Getz et al. 2012, Davidson et al. 2015, Liu et al. 2018). To promote these technologies and strategies, we need more inter- and transdisciplinary research on farmers' decision making and further collaboration of academic researchers, government, farmers, private crop advisors, fertilizer producers, and consumers (Davidson et al. 2015).

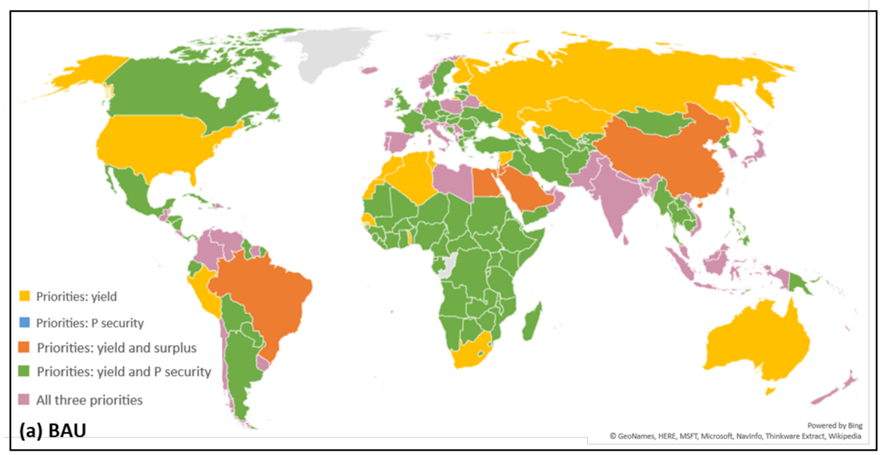
4.2 Global Targets and Regional Priorities

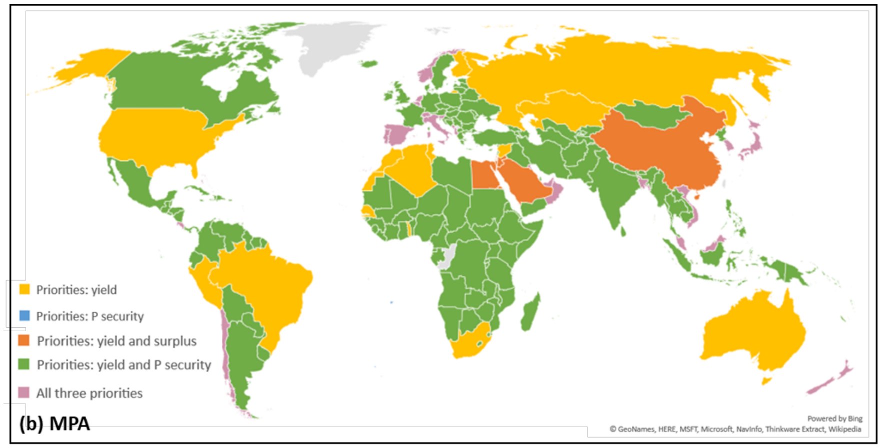
The priorities on the global and national scales are different. On a global scale, food security and P pollution challenges are the most urgent. The global P fertilizer demand to supply ratio was approximately 10%, meaning sufficient P supply for global crop production.

To meet the moderate food security goal (FAO 2018), we would need to increase the global harvested P from the current 13.6 Tg P yr^{-1} to 20.5 Tg P yr^{-1} by 2050 (Table 3). To reduce the global P surplus from the current level (9.1 Tg P yr^{-1}) to the planetary boundary (4.5-9 Tg P yr^{-1}), we would need to improve the current cropland PUE from 60% to 69%-82% by 2050.

Given their different socio-economic and agronomic conditions, different regions have unique challenges in P use to address (Fig. 6). In the BAU scenario, India, Pakistan, and a few other countries have all three priorities: increasing yield, reducing P surplus, and enhancing P sufficiency. While in countries such as China and Brazil, the priorities are to increase yield and reduce P surplus. The U.S., Russia, and Morocco would only need to focus on increasing yield. In most other countries, especially African countries, the priorities are to increase yield and enhance P sufficiency (Fig. 6a).

As PUE improves, most countries would face fewer challenges. In the MPA scenario, reducing the P surplus would not be the priority in most countries, except for China, Japan, and a few other countries (Fig. 6b). In the most ambitious HPA scenario, the challenges in most countries would be to increase yield from 2010 levels and enhance P sufficiency (Fig. 6c).





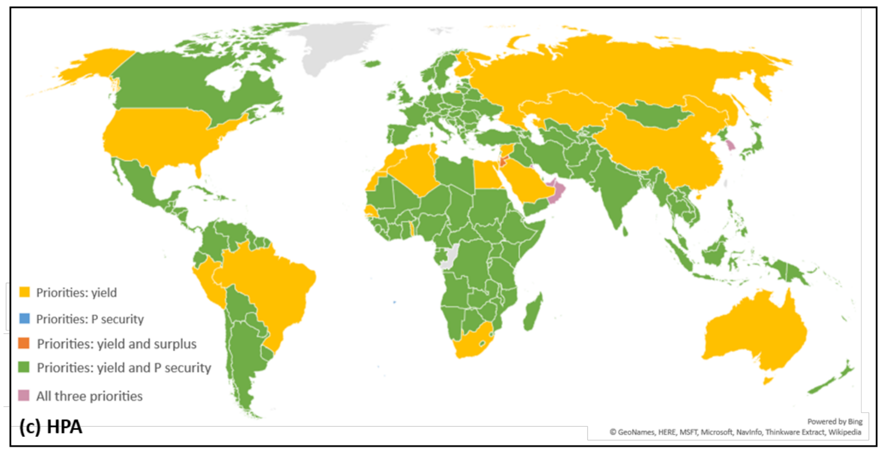


Figure 6. Regional priorities in the three scenarios. (a) Regional priorities in the BAU scenario. (b) Regional priorities in the MPA scenario. (c) Regional priorities in the HPA scenario. Yellow area: regions with the priority to increase P yield (i.e., estimated 2010 average P yield is lower than the projected 2050 P yield). Blue area: regions with the priority to enhance P sufficiency (i.e., P fertilizer demand to supply ratio is greater than one if assuming P fertilizer to total input ratio remains at the 2010 level). Orange area: regions with the priorities to increase P yield and reduce P surplus (i.e., P surplus rate in 2050 is larger than the upper planetary boundary, 6.9 kg P ha^{-1} yr^{-1}). Green area: regions with the priorities to increase P yield and enhance P sufficiency. Pink area: regions with all three priorities.

For countries facing the pressing risk of depleted reserves (e.g., India and Mexico, Fig. 6a-c), their priorities should also include investing in technologies and infrastructures that can recover and recycle P from sources such as manure and waste. Establishing stable trade relationships with countries with rich reserves could be another strategy to address this challenge.

Policymakers should also recognize the heterogeneity of P pollution within a country. Some regions have environmental problems more acute than those in other regions. In the U.S., even though the P surplus was negative as a country (Table 3), many regions in the U.S. (e.g., the Great Lakes region and the Gulf of Mexico) are still suffering from eutrophication caused by high N and P loads to the water (Van Meter et al. 2018, Le Moal et al. 2019).

4.3 Potential Sources of Uncertainties

4.3.1 Phosphorus Inputs

In this study, we only consider fertilizer and manure as P inputs. Other inputs' data by country and crop type are not available, and they only accounted for a small amount of total P input in the previous studies. Between 2002-2010, P deposition, crop residues, seed, and sludge were around 2%, 13%, 1%, and 5% of total P inputs to global cropland, respectively (Lun et al. 2018).

4.3.2 Phosphorus Content

Another source of uncertainty in P budget work is the P content of each crop. Previous studies usually used nutrient content data from published work with different estimates (Zhang et al. 2020). Besides, these studies assumed that P content by crop type would not change over time and that the P contents were consistent in all spatial units (Bouwman et al. 2017, Lun et al. 2018). We made the same assumption in this study. Our results are comparable to previous studies on P budget analysis on the global scale (Table S5 and S6).

By assuming the same P content in all countries and years, the impact of this uncertainty on the analysis of P budget historical trends becomes smaller (Bouwman et al. 2017). To quantify this impact, we conducted a Monte Carlo simulation (1,000 iterations) for major countries and crop types, testing both normal and uniform distributions (SI Section Text S6). We found that this uncertainty did not affect PUE significantly. However, further studies on whether and how each crop's P content varies by country and time are of great value.

4.3.3 Phosphorus Planetary Boundary

Estimates of P planetary boundary and methodologies for calculation remain uncertain. Steffen et al. (2015) estimated the regional planetary boundary range for fertilizer P going to erodible soil as 6.2-11.2 Tg P yr^{-1}, while Springmann et al. (2018) suggest the planetary boundary range for global P fertilizer input at 6-12, or 8-17 Tg P yr^{-1}, depending on the recycling rate of P. Here we use P surplus rather than P fertilizer input to evaluate P pollution 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 has more direct environmental impacts than P fertilizer input; 3) a similar indicator, N surplus, have been proposed for tracking progress towards reductions in nutrient pollution caused by food production on farm to regional scales (Eagle et al. 2018).

Note that the P surplus does not reflect the actual environmental impacts. Thus, the estimated boundary should only be used as a reference point to provide a general direction for P management improvement. It warrants more research to understand: 1) whether the concept of a planetary boundary for P is useful for informing policy; 2) which indicators, such as global and regional P surplus, could be used for setting such a planetary boundary target; and 3) how to interpret the implication of the global target on a local to regional scale.

4.3.4 Phosphorus Residual

Partitioning P surplus into residual P retained in the soil and P loss is also challenging to assess on national to global scales. Sophisticated biogeochemistry modeling is necessary, but not yet well developed on the scale we were working on. There are at least two ways to estimate P loss. One way is to develop a dynamic soil model to evaluate annual change considering varying soil characteristics and P budget (Zhang et al. 2017). Another simpler way is to assume a constant fraction of P in inputs or surplus, leaving the cropland system. Sattari et al. (2012) assumed that P loss accounts for around 10% of the sum of fertilizer and manure inputs. Bouwman et al. (2013) and Lun et al. (2018), on the other hand, assumed that P loss is about 12.5% of total P inputs. Even more conservatively, Springmann et al. (2018) assumed 20% of P stored in the sediment was lost.

In this study, P loss data during the historical period (i.e., 1961-2014) are from the IMAGE-Global Nutrient Model (Bouwman et al. 2017). To project P loss after 2014, we assumed that 12.5% of P inputs would leave the cropland system (Bouwman et al. 2013, Lun et al. 2018) as P loss, to ensure that P loss had non-negative values. Note that the uncertainties in P loss estimation do 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 more mature soil models are developed.

4.3.5 Projection of Phosphorus Budget

The projection of future P budget was based on certain assumptions and can introduce uncertainties. We adopted the projection data of the middle pathway scenario developed by FAO (FAO 2018). This scenario assumed that moderate food security improvement would be achieved by 2050 (FAO 2018). This assumption means that the 2050 harvested P may have been underestimated if a more ambitious food security goal will be achieved. Also, given that most African countries are still at the early stage of agricultural intensification, the PUE in these countries in the three scenarios could have been overestimated, and their P inputs could have been underestimated. However, if PUE on the national scale will be significantly improved (such as in the HPA scenario) and more alternative P sources will be available, P pollution and depletion problems will still be properly addressed.

To project future P fertilizer input, we assumed that each country would maintain its current fertilizer to manure use ratio (average of 2005-2014) from 2015 to 2050. To estimate the uncertainties of this assumption, we have developed two other extreme cases to discuss how P input sources will affect P depletion (see Section 3.3.2). The results show that these uncertainties do not change our conclusions.

5. Conclusion

The world faces P depletion and pollution challenges, which can be measured by P fertilizer demand to supply ratio and P surplus. Improving PUE in crop production is one key pathway to address these two challenges and achieve synergies between agricultural productivity, sustainability, and resilience. To keep the global P surplus within safe limits, we would need to improve the global PUE in crop production from the current 60% to 69%-82%. On a regional scale, priorities and PUE improvement levels vary by local conditions. To achieve PUE improvement goals, we need strategies targeting key socio-economic and agronomic drivers for PUE. These drivers include economic development, crop mix, NUE, fertilizer to crop price ratio, and average farm size.

In this resource-limited and developed world, addressing P challenges also requires efforts beyond improving cropland PUE. In regions with limited phosphate rock reserves, addressing P depletion also depends on P import and alternative sources. While in regions where agriculture is not the only source of P pollution, managing non-agricultural P loads should be part of the solution. If we can effectively reduce P loads from non-agricultural sources (e.g., industrial and domestic wastes (Chen and Graedel 2016, Mekonnen and Hoekstra 2018)), the boundary for P surplus from cropland could be relieved. Methods to reduce non-agricultural P loss include, for example, reducing P loss along its supply chain (Nedelciu et al. 2020) and recovering P from wastewater treatment plants (Chrispim et al. 2019).

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Improving Phosphorus Use Efficiency in Cropland to Address Phosphorus Challenges by 2050

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Key Points:

- Two phosphorus challenges have arisen as the world is trying to meet increasing food demand: phosphorus depletion and phosphorus pollution
- To address these challenges, phosphorus use efficiency would need to increase from the current 60% to 69-82% globally, but with different regional implications.
- Phosphorus use efficiency has been significantly affected by socio-economic and agronomic factors, including economic development and fertilizer to crop price ratio

Abstract

Applying Phosphorus (P) to global cropland supports crop growth and helps to address the increasing global food demand. However, poor management of P application leads to nutrient loss and environmental pollution in many countries, while some countries (e.g., India and Vietnam) are also facing the depletion of national phosphate rock reserves. One critical strategy to address these challenges is to improve phosphorus use efficiency (PUE) in crop production. The success of this strategy depends on improving regional PUE with advanced technologies and effective management strategies, and an understanding of relevant socio-economic and agronomic drivers influencing regional and global PUE. However, low-efficiency regions and the key drivers remain unclear, and no studies have quantified the impacts of PUE improvement on addressing P challenges. This study developed a unique database of P budget and PUE by country and crop type over 50 years, and examines the temporal and spatial patterns, and makes projection of future P budget under three scenarios with different PUE improvement levels. By studying the historical data, we found that PUE has been significantly affected by a country's development stage, crop portfolios, nitrogen use efficiency (NUE), fertilizer to crop price ratio, and average farm size. By improving the global PUE in crop production from the current 60% to around 69-82% by 2050, we could decrease the global P surplus from 8.8 in 2010 to about 4.5-9 Tg P yr^{-1} by 2050. Improvement of some countries (e.g., China and India) and some crop types (e.g., fruit and vegetable) should be prioritized, as they currently have relatively lower PUE.

Plain Language Summary

Phosphorus (P) is one of the essential nutrients that crops need to grow. As the global population increases, we need to use P fertilize at cropland continually. However, inappropriate use of P in agriculture will cause trouble for both the environment and society. First, the available amount of phosphate rock, which is the raw material for P fertilizer, is limited on earth and in short in many countries. Second, too much P lost to the environment can lead to bad water quality, causing the death of fish in waters and impairing human health. To address these challenges, we need to understand factors influencing the use efficiency of P, and how improvement in P use efficiency can alleviate P shortage and nutrient pollution problems. This study answers the two questions by examining historical P use data and projecting future P budget at cropland in different scenarios. Based on the study results, we suggest national and global P efficiency improvement goals to achieve by 2050 to produce enough food and reduce P pollution to an acceptable level.

1 Introduction

Phosphorus (P) is one of the nutrients critical for growing crops, which are fundamental for feeding the growing population (Tilman et al. 2002, Cordell et al. 2009, Cordell and White 2014). Consequently, the urge for more food production and higher yield is likely to drive up the demand for P inputs to cropland. By estimate, the total global consumption of P fertilizer at cropland has increased by almost four times from 1961 to 2013 (Lu and Tian 2017), and the demand may increase to 22-27 Tg P yr^{-1} by 2050, even assuming a sustainable future (Mogollón et al. 2018).

However, over and improper use of P results in excessive P leaching to adjacent water bodies, causing nutrient pollution (Foley et al. 2011, Bouwman et al. 2017, Fink et al. 2018, Mekonnen and Hoekstra 2018). Inorganic fertilizer use was the primary source (47%) of P going to the world's largest 100 lakes between 2005-2010 and 1990-1994, and developing countries had a higher chance of P-stimulated eutrophication (Fink et al. 2018). Even after the reduction or cessation of fertilizer input, the large surplus of P accumulated in soil (known as legacy P) will continue to pollute surface waters, offsetting the benefits brought by nutrient abatement measures (Sharpley et al. 2013, Powers et al. 2016, Bouwman et al. 2017, McCrackin et al. 2018).

At the same time, many countries have concerns about P depletion. The reported phosphate rock reserves on a global scale may be adequate for the current food production need (Cordell and White 2014). However, there are debates on the abundancy (Edixhoven et al. 2014), and stocks of phosphate rock on a local scale in many countries are insufficient for agricultural production. Besides the uneven distribution of phosphate rock throughout the world, its non-renewable nature and inefficient management increase the P depletion concern (Cordell et al. 2009, Cooper et al. 2011).

One key solution to these two P challenges is to improve P use efficiency (PUE) at cropland (Cordell and White 2014, Bouwman et al. 2017, Heuer et al. 2017, Lun et al. 2018). The goal of improving efficiency goes beyond increasing production through intensification or extensification. It also emphasizes better managing inputs to reduce the negative impacts of agriculture on the environment and society. Improving efficiency is the critical pathway towards synergies between agriculture productivity, sustainability, and resilience (Coomes et al. 2019).

Improvement in PUE relies on not only an understanding of P use patterns but also its key drivers. Previous studies have examined cropland P budget (P inputs and output at cropland) and use efficiency on different temporal and spatial scales (Cordell et al. 2009, MacDonald et al. 2011, Cordell and White 2014, Chen and Graedel 2016, Bouwman et al. 2017, Lu and Tian 2017, Lun et al. 2018, Mogollón et al. 2018). However, no studies have evaluated enough socio-economic and agronomic drivers influencing PUE, or quantifying the impacts of PUE improvement on addressing the two P challenges. Besides, global and regional priorities of P management are still unclear, which are critical information for decision-makers to develop effective strategies. To fill the research and political gaps, we (1) evaluated the historical patterns of P budget and PUE at cropland by country and crop type between 1961-2014; (2) identified key socio-economic and agronomic drivers influencing global and national PUE; and (3) suggested global and regional priorities for addressing P challenges by 2050.

2 Data and Methods

2.1 The Phosphorus Budget Model

Focusing on the crop production system, we identified four major P budget terms to quantify (Fig. 1; Text S1). Methods for database development and P budget analysis were developed based on a previous study on cropland nitrogen use (Zhang et al. 2015a).

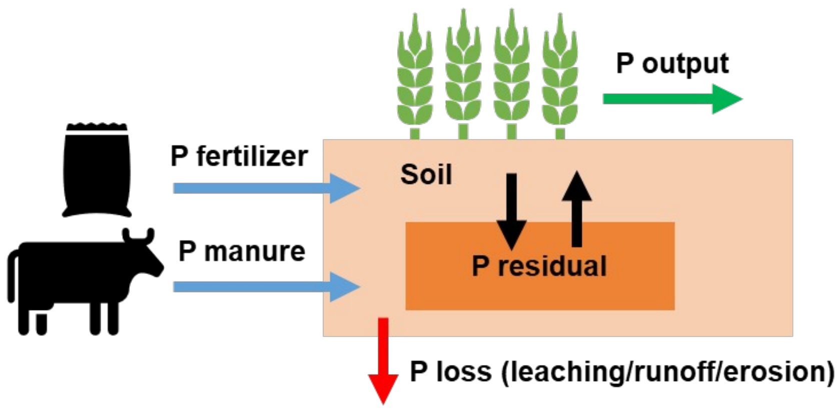


Figure 1. Illustration of P flows and P budget terms used in this study. P inputs: blue arrows. P output (P yield): green arrow. P loss: red arrow.

Major P inputs to cropland include P fertilizer and P manure:

$$P\,inputs = P\,fertilizer + P\,manure$$

To determine the amount of fertilizer applied to 150+ crop types and 200+ countries, we started with IFA fertilization data of 10+ crop type groups and 20+ country groups reported in 2006 2007, 2010, and 2014 and 2015 (IFA 2018) and the national fertilizer use data published by the Food and Agriculture Organization of the United Nations (FAO) (FAOSTAT 2020). Then, we projected fertilization rate by country and crop type from 1961 to 2014, assuming that the fraction of fertilizer applied to each crop type in each year is the same as that reported by IFA (1961-2006, same fraction as reported in IFA 2006 report; 2007, same fraction as reported in IFA 2007 report; 2008-2010, same fraction as reported in IFA 2010 report; 2011-2014, same fraction as reported in IFA 2014 report). For countries belonging to the same country group and crop types belong to the same crop type group, we assumed the same fertilization rate. For missing data between years, we did linear interpolation. The projected results were then further adjusted to increase accuracy, with other fertilizer use details mentioned by FAO (FAO 2002, FAOSTAT 2018) and in published studies (Smil 1999, Schroder et al. 2010, Lassaletta et al. 2014). In the previous work, P in fertilizer is expressed as the weight of P_2O_5, and we changed the unit to kg P. The content of P in animal excretion is also available in previous studies (Sheldrick et al. 2003, Andersen 2013, Chen and Graedel 2016, Chowdhury 2016, Liu et al. 2016, Bouwman et al. 2017). With that, we can estimate the total P in applied fertilizer and manure. More details of these calculations can be found in SI. On the global scale, our P inputs and output are similar with that found in the previous studies (Table S5 and S6).

With P fertilizer input data, we calculated P fertilizer demand to supply ratio and used it as the indicator of the P depletion challenge. P fertilizer demand is the total P demanded from fertilizer, and P supply is the total P provided by local phosphate rock reserves. This indicator suggests whether a country's phosphate rock reserves along are sufficient for its food production. A ratio close to or higher than one (threshold: one) indicates the need to use more P from alternative sources or import more P to support future food production. Phosphate rock reserves data were collected from the United States Geological Survey (USGS) (2018).

The two pathways of P leaving the cropland system are (1) P in harvested crops (known as P output, or P yield to describe the P in harvested crops per unit land), including any part of the plants removed from the field, and (2) P loss through leaching, erosion, and runoff. Each crop's P content was decided by taking the average of P content reported by FAO (2006), the United States Department of Agriculture (USDA 2013), AUSNUT (2013), Gourley et al. (2010), and Bouwman et al. (2017). The impacts of varying P content by crop type on P yield and PUE were examined with sensitivity tests (Text S6).

P surplus is also called P imbalance (MacDonald et al. 2011, Lun et al. 2018) or P budget (Bouwman et al. 2017). P surplus is the difference between P inputs and P output, and the sum of P loss and P residual:

$$P\,surplus = P\,inputs - P\,output$$

$$P\,surplus = P\,loss + P\,residual$$

Here we used P surplus to measure P pollution and compared it with estimated planetary boundary, which in many studies marks the safe operating space for humanity (Rockström et al. 2009, Carpenter and Bennett 2011, Steffen et al. 2015). Based on Springmann et al.'s global P flow model (Springmann et al. 2018), we estimated the planetary boundary for global cropland P surplus is 4.5-9 Tg P yr^{-1} (i.e., 3.5-6.9 kg P ha^{-1} yr^{-1}, see Section TextS14 for the assumptions and methods used for deriving this planetary boundary).

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

$$P\,residual = P\,surplus - P\,loss$$

PUE, sometimes also called the recovery ratio, is defined as the ratio of P output (i.e., P in harvested crops or P yield) to P inputs:

$$PUE = \frac{P\,output}{P\,inputs}$$

A PUE larger than one means the crop production is mining nutrients from the soil, while PUE smaller than one indicates extra P remained in the soil and/or lost. Our estimated PUE on the global scale is similar to the estimations in the earlier studies (Tables Sx).

2.2 Key Drivers for P Use Efficiency (PUE)

Based on consultation with experts and the previous work studying drivers of nutrient use (Dinda 2004, Zhang et al. 2015a, Zhang et al. 2015b, Ju et al. 2016, Wu et al. 2018), we considered and examined the relationships between PUE and multiple potential drivers, including eight socio-economic drivers and seven agronomic drivers (Table 1, Table S11).

Table 1 Selected PUE drivers, data sources, and methodology.

Driver	Data source	Methodology
	Socio-economic drivers	
Economic development	World Bank (2018)	GDP per capita, gross domestic product / midyear population
Consumption per capita for certain crop types	FAOSTAT (2018), Zhang et al. (2015a)	Production + import - export
Fertilizer to crop price ratio	FAOSTAT (2018)	Fertilizer price (Single Superphosphate) / crop price (maize)
Per hectare spending on agricultural machinery	FAOSTAT (2018)	Agricultural machinery, tractors per 100 sq. km of arable land
Patent application per capita	World Bank (2018)	Resident patent applications per capita
Education expenditure as a percentage of government spending	World Bank (2018)	Government expenditure on education
Agriculture, value added	World Bank (2018)	The net output of a sector after adding up all outputs and subtracting intermediate inputs
Ratio of net import of certain crop types	FAOSTAT (2018), Zhang et al. (2015a)	Net import / local production
	Agronomic drivers	
Crop mix	FAOSTAT (2018), Zhang et al. (2015a)	Percentage of the harvested area of a certain crop type, i.e., harvested area of a specific crop type / total harvested area
NUE	Zhang et al. (2015a)	N output (N in harvested crops) / N inputs
Adjusted average farm size	Graeub et al. (2016)	Residual of the regression of average farm size on arable land per capita, see Text S9 and Wu et al. (2018)
Conservation area ratio	FAO AQUASTAT database	Conservation agriculture area as % of arable land area = 100*Conservation agriculture area / Arable land area
P yield	FAOSTAT (2018), Zhang et al. (2015a)	P in harvested crops / harvested area
Accumulated P surplus	Calculation	P inputs (fertilizer and manure) - P output (P in harvested crops), accumulated since 1961
Accumulated P residual	Calculation	P surplus - P loss, accumulated since 1961

Besides P budget and PUE by crop type, we also tried to collect data of all drivers for over 200 countries by crop type from 1961 to 2014. However, as the available data of most drivers are limited to a smaller set of countries (Table S13), we studied the drivers and their relationships with PUE in 113 major crop-producing and nutrient use countries (Text S8). These countries accounted for around 85% of the global total harvest area, 86% of total P in crop production, and 94% of total P fertilizer input in 2010 (average of 2005-2014).

We analyzed the relationships between PUE and all potential factors in and across these 113 major countries, using three methods:

1) fitting regression models with PUE as the dependent variable and the linear and quadratic terms of economic development as the independent variables, to test the Environmental Kuznets Curve (EKC) hypothesis (Dinda 2004, Zhang et al. 2015a) for individual country and across all 113 countries (Text S7);

2) studying the association between PUE and each drive for individual countries, by calculating Pearson's correlation coefficient (Pradhan et al. 2017) (Text S10);

3) fitting constant intercept and fixed effects models with PUE as the dependent variable and other driver(s) as the independent variable(s) across all 113 countries (Text S11).

We examined the relationships both for individual countries and across countries to avoid the effects of the Simpsons Paradox (Scholz and Hirth 2015).

2.3 Projection of Future PUE and Phosphorus Budget

We projected future PUE and P budget for crop production in three PUE improvement scenarios (Table 2): 1) the Business-As-Usual (BAU) scenario, 2) the Moderate-Policy-Ambition (MPA) scenario, and 3) the High-Policy-Ambition (HPA) scenario. From scenario BAU to HPA, we assume that PUE by country and crop type would have no improvement, median improvement, and significant improvement, respectively. To decide the improvement level, we first calculated the PUE by crop type of 12 regions (Table S17) in 2010 (the average of 2005-2014). Then for each crop type, we set the median and 75th percentile value of the 12 regions' PUE as the minimum PUE level to achieve in MPA and HPA scenarios, respectively.

Table 2 The settings of three PUE improvement scenarios and three cases of P fertilizer to total inputs ratio from 2014 to 2050.

PUE scenarios	**P fertilizer to total inputs ratio** **A) Least sustainable**	**B) Normal**	**C) Most sustainable**
1) Business-As-Usual (BAU)	1A 2050 PUE at current level; P fertilizer to total inputs (fertilizer + manure) ratio = 100%, and total inputs = projected P inputs	1B 2050 PUE at current level; P fertilizer to total inputs (fertilizer + manure) ratio = current level, and total inputs = projected P inputs	1C 2050 PUE at current level; P fertilizer to total inputs (fertilizer + manure) ratio = current level, and total inputs = projected P inputs - P residual accumulated since 1961
2) Moderate-Policy-Ambition (MPA)	2A 2050 PUE linearly improved to median level; P fertilizer to total inputs (fertilizer + manure) ratio = 100%, and total inputs = projected P inputs	2B 2050 PUE linearly improved to median level; P fertilizer to total inputs (fertilizer + manure) ratio = current level, and total inputs = projected P inputs	2C 2050 PUE linearly improved to median level; P fertilizer to total inputs (fertilizer + manure) ratio = current level, and total inputs = projected P inputs - P residual accumulated since 1961
3) High-Policy-Ambition (HPA)	3A 2050 PUE linearly improved to 75th percentile level; P fertilizer to total inputs (fertilizer + manure) ratio = 100%, and total inputs = projected P inputs	3B 2050 PUE linearly improved to 75th percentile level; P fertilizer to total inputs (fertilizer + manure) ratio = current level, and total inputs = projected P inputs	3C 2050 PUE linearly improved to 75th percentile level; P fertilizer to total inputs (fertilizer + manure) ratio = current level, and total inputs = projected P inputs - P residual accumulated since 1961

In the BAU scenario, we assumed that PUE by country and crop type by 2050 would remain at the current level (the average of 2005-2014). In the MPA scenario, for each crop type, PUE by country lower than the MPA minimum level (median level of the 12 regions) would be improved to that level by 2050 and other PUE values would be kept the same. Similarly, in the HPA scenario, PUE by country and crop type lower than the HPA minimum level (75th percentile level of the 12 regions) would be improved to that level and other PUE values would be kept the same. Besides, we assumed that PUE by country and crop type by 2050 would not exceed one, considering that soil mining is unsustainable in the long run, and the PUE change between 2015 and 2050 would be linear. With these assumptions and designed scenarios, we projected PUE by country and crop type from 2015 to 2050.

We estimated future P yield based on FAO's projection (FAO 2018). FAO projected crop production and harvested area change by region and crop type in 2030, 2035, and 2040 and 2050 in three scenarios (2018). We adopted the projection in FAO's Business as Use scenario to project P in harvested crops. We assumed that the data's change within those reported years would be linear, and P content by crop type will not change over time or by country.

With P yield and PUE by country and cop type by 2050, we then estimated P inputs (P demanded for crop production):

$$P\ inputs = \frac{P\ yield}{PUE}$$

To calculate P fertilizer input by 2050, we need to know P fertilizer to total inputs ratio (total inputs include P in fertilizer and manure). As this ratio by country and crop type may change in the future, we designed three extreme cases to consider its uncertainties (Table 2): A) the least sustainable case, in which P fertilizer to total inputs (including fertilizer and manure) ratio would equal to 100% from 2014 to 2050 (meaning all P inputs would be from fertilizer) and total inputs would equal to the projected P inputs; B) the normal case, in which P fertilizer to total inputs (including fertilizer and manure) ratio would remain at the current level (the average of 2005-2014) from 2014 to 2050 and total inputs would equal to the projected P inputs; C) the most sustainable case, in which to P fertilizer to total inputs ratio would remain at the current level, but the total inputs would equal to the projected P inputs minus the total P residual accumulated in the soil since 1961, assuming that P residual would be used for crop production.

In total, we designed three scenarios (BAU, MPA, and HPA) to project PUE, P yield, P inputs, and P surplus by 2050, and nine scenarios (from 1A to 3C, Table 2) to project future P fertilizer and manure inputs. We designed these nine scenarios to study how much we can reduce P pollution and the demand for phosphate rock with different P management ambitions measured by PUE improvement and fertilizer to total inputs ratio.

3 Results

3.1 Historical Phosphorus Budget and PUE

On the global scale, P yield has increased by around two times from 1961 (5 kg P ha^{-1} yr^{-1}) to 2014 (11 kg P ha^{-1} yr^{-1}) (Fig. 2a), indicating increased agricultural productivity. At the same time, global PUE decreased since 1961 (54%), then began to grow in the 1980s (40%), and stabilized after entering the 21st century (Fig. 2a). Though the improved PUE indicates a smaller fraction of P inputs lost to soil and environment, P residual has accumulated from 1961 to 2014 (2 to 195 ha^{-1} yr^{-1}, Fig. 2b), as a potential P source for future crop production.

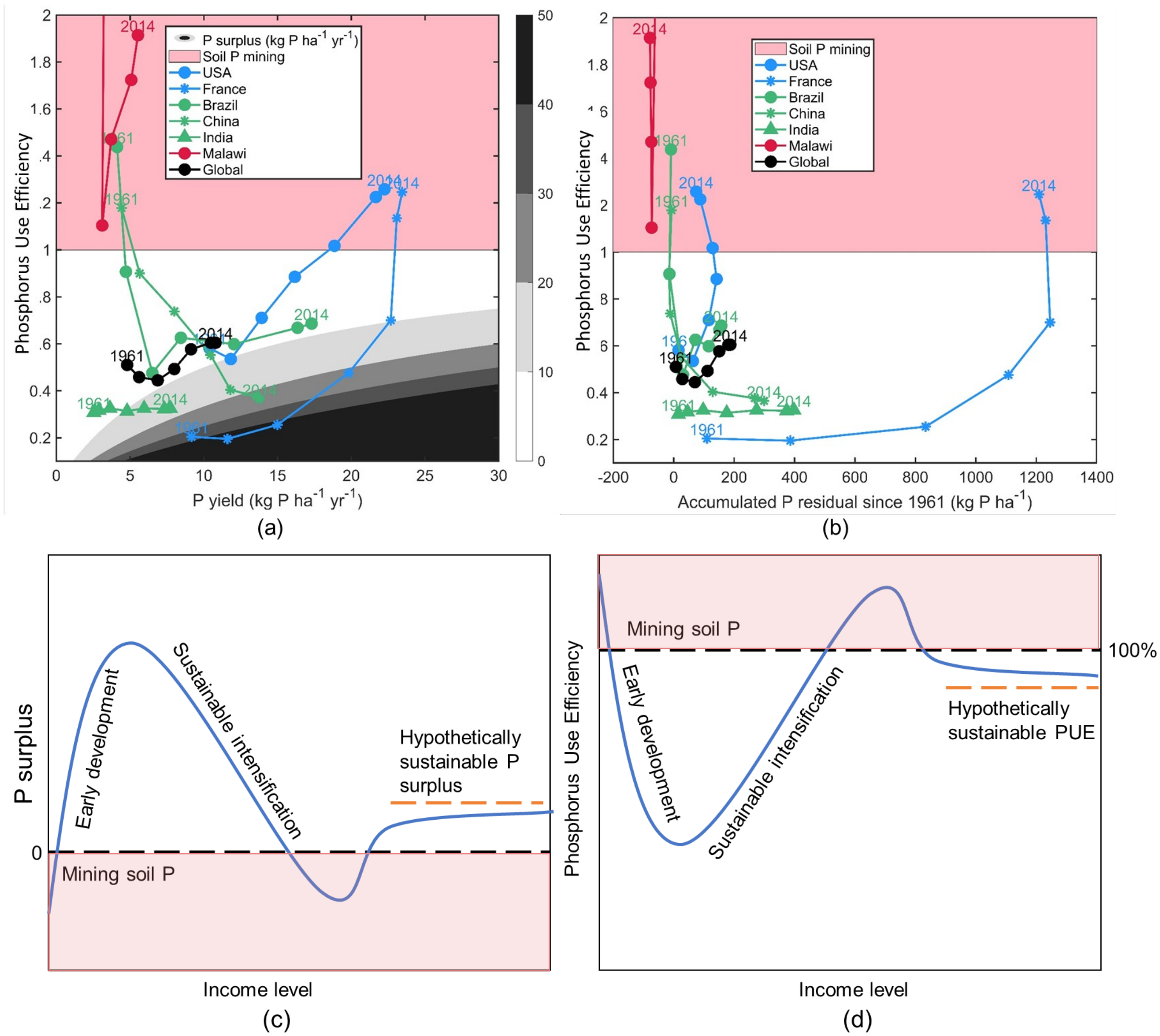


Figure 2. Historical and hypothesized P budget and PUE trends. (a) PUE versus P yield from 1961 to 2014. PUE larger than 2 (200%) is not shown. The greyscale indicates P surplus (kg P ha^{-1}). (b) PUE versus accumulated P residual from 1961 to 2014. PUE larger than 2 (200%) is not shown. High- and middle-income economies' (The World Bank 2017) data are in blue and green, respectively. Malawi's data are in red. The pink area indicates soil mining (negative P surplus). Data have been smoothed by ten years to limit the data variation influenced by weather conditions. Seven data points represent the data in 1961, 1970, 1980, 1990, 2000, 2010, and 2014. (c) The hypothesized relationship between P surplus and GDP per capita. (d) The hypothesized relationship between PUE and GDP per capita.

Different from the global trends, the historical patterns of regional P budget and PUE vary by country, and their historical trajectories suggest a typical pattern of PUE as countries increase their P yield, accumulated P residual, and income levels. Malawi, as a low-income country, has had minimal success in increasing its yield in the past 50 years, and it relied mainly on mining native soil P (Fig. 2a). Middle-income economies like Brazil, China, and India, have had increased crop yield at the expense of nutrient use efficiency and managing P surplus (Fig. 2a). However, their accumulated P residual was still lower than that of France since 1961 (Fig. 2b). The relatively high P residual accumulated in France, lower accumulation in the U.S., and the increasing accumulation in China and India due to large P surplus in recent years were also found in a previous study estimating P residual since 1900 (Zhang et al. 2017). Our estimation differs from theirs on the starting point of estimation and assumptions for initial values. As middle-income economies continuously improve their soil fertility and yield, they may still have low PUE and high

P surplus in the next few years or even decades. High-income economies such as the U.S. and France, have experienced yield enhancement in the 1960s, relying on increased fertilizer input. They transited to the second phase of yield enhancement and surplus reduction in the 1970s and 1980s, which benefited from improved PUE (Fig. 2a).

Based on those observations (Fig. 2a and 2b), we hypothesized that the relationship between GDP per capita and PUE follows the Environmental Kuznets Curve (EKC) (Dinda 2004, Zhang et al. 2015a). EKC suggests that P pollution first increases with GDP per capita at the early development stage. It starts to level off and decreases at a later stage due to technological development and increased environmental awareness. Accordingly, as the economy develops, the P surplus first increases and PUE first decreases, leading to more P accumulated in the soil or lost to the environment (Fig. 2c and 2d). P surplus then decreases, and PUE improves, as more P inputs are converted to crop products (Fig. 2c and 2d). We consider that the PUE of a county (e.g., the U.S. and France) may exceed 100% during the sustainable intensification, as the crop production may mine some accumulated residual P before reaching a relatively steady state (Fig. 2d). For each country, the whole EKC process may take a longer time than current databases have recorded, and many other factors (such as social and climate change, and global collaboration) can affect its development and change rate. Thus, the suggested U-shape curve is clearly seen on a global scale but is not obvious in individual countries (Fig. 2a and 2b).

The historical data of P budget and PUE also indicate low-efficiency countries and crops policymakers need to prioritize when improving P management. Comparing the PUE of 12 regions in 2010, China and India had relatively low PUE (<40%) and high P inputs, contributing over half of the P surplus to the global environment (Table 3). On the global scale, rice, fruit, and vegetable had relatively low PUE (<40%) and high P inputs, leading to a global P surplus at 9 Tg P yr^{-1} in 2010 (Table 3).

Table 3. P budget and PUE in crop production by region and crop group in 2010 (average of 2005-2014) and in 2050 in the three scenarios (BAU, MPA, and HPA). The unit of each budget term except for PUE is Tg P yr^{-1}. The unit of PUE is %. The definitions of the 12 regions are in Table S17. The definitions of the 11 crop groups are in Table S12. Value 0.0 means it is smaller than 0.05.

	Current (2010)				BAU (2050)				MPA (2050)			HPA (2050)		
By region	**Harvest**	**Input**	**PUE**	**Surplus**	**Harvest**	**Input**	**PUE**	**Surplus**	**Input**	**PUE**	**Surplus**	**Input**	**PUE**	**Surplus**
Africa	1.0	0.8	127	-0.2	1.3	1.5	86	0.2	1.3	1.4	91	0.1	1.3	1.4
Brazil	1.1	1.7	66	0.6	1.8	2.8	64	1.0	1.8	2.1	87	0.3	1.8	1.9
Canada	0.3	0.4	89	0.0	0.6	0.7	88	0.1	0.6	0.7	88	0.1	0.6	0.6
China	2.3	6.1	38	3.8	3.3	8.1	40	4.9	3.3	5.2	63	1.9	3.3	4.0
Europe	1.7	2.1	80	0.4	2.3	3.1	74	0.8	2.3	2.9	82	0.5	2.3	2.6
FSU	1.0	0.6	169	-0.4	1.6	1.7	92	0.1	1.6	1.6	97	0.1	1.6	1.6
India	1.4	4.3	32	2.9	2.2	6.7	33	4.5	2.2	3.3	67	1.1	2.2	2.6
Middle East	0.2	0.3	60	0.1	0.2	0.4	62	0.1	0.2	0.3	72	0.1	0.2	0.3
Other OECD countries	0.3	0.7	37	0.4	0.4	1.0	41	0.6	0.4	0.5	73	0.1	0.4	0.4
Other Asian countries	1.2	2.7	44	1.5	1.9	4.3	45	2.4	1.9	3.0	64	1.1	1.9	2.4
Other Latin America countries	1.0	0.9	111	-0.1	1.7	2.2	79	0.4	1.7	1.9	91	0.2	1.7	1.8
United States	2.2	1.8	121	-0.4	3.1	3.3	97	0.1	3.1	3.3	97	0.1	3.1	3.2
Total	13.6	22.5	61	8.8	20.5	35.7	57	15.3	20.5	26.1	78	5.6	20.5	22.7
By crop type	**Harvest**	**Input**	**PUE**	**Surplus**	**Harvest**	**Input**	**PUE**	**Surplus**	**Input**	**PUE**	**Surplus**	**Input**	**PUE**	**Surplus**
Wheat	2.9	3.9	74	1.0	4.1	6.3	66	2.2	4.1	4.6	90	0.4	4.1	4.1
Rice	1.0	3.5	30	2.5	1.5	5.1	29	3.6	1.5	3.3	46	1.8	1.5	2.4
Maize	2.4	3.1	78	0.7	4.2	5.6	76	1.4	4.2	4.7	91	0.4	4.2	4.2
Other cereal crops	0.9	1.4	66	0.5	1.3	2.0	63	0.8	1.3	1.6	81	0.3	1.3	1.4
Soybean	2.0	1.8	108	-0.1	2.7	3.5	79	0.7	2.7	2.8	98	0.1	2.7	2.7
Oil palm	0.1	0.3	57	0.1	0.3	0.4	59	0.2	0.3	0.4	61	0.2	0.3	0.3
Other oilseed	0.9	1.4	65	0.5	1.4	2.3	62	0.9	1.4	1.6	85	0.2	1.4	1.4
Cotton	1.0	0.9	117	-0.1	1.4	1.6	90	0.2	1.4	1.4	101	0.0	1.4	1.4
Sugar crops	0.8	0.8	93	0.1	1.2	1.6	76	0.4	1.2	1.3	95	0.1	1.2	1.2
Fruit and vegetable	0.8	3.6	21	2.8	1.1	5.0	22	3.9	1.1	2.9	38	1.8	1.1	2.1
Other crops	0.8	1.8	46	1.0	1.2	2.3	50	1.2	1.2	1.5	81	0.3	1.2	1.3
Total	13.6	22.5	61	8.8	20.5	35.7	57	15.3	20.5	26.1	78	5.6	20.5	22.7

High PUE does not necessarily correspond to better P management, and it could be associated with a very low input rate and yield. African countries, FSU, and the U.S. all had relatively high PUE in 2010 (Table 3), but for very different reasons and with different implications. High PUE in the U.S. was accompanied by higher P inputs (1.8 Tg P yr^{-1}, Table 3) and higher P in harvested crops (2.2 Tg P yr^{-1}, Table 3), which benefited from the improvement in fertilizer management practices. In contrast, high PUE in African countries and FSU was the result of low P in harvested crops (1.0 Tg P yr^{-1} for both, Table 3) and lower P inputs (0.8 and 0.6 Tg P yr^{-1}, respectively, Table 3). Meeting the goals of increasing food demand and managing pollution from agriculture requires increasing production and PUE, and limiting P surplus.

3.2 Key Drivers for PUE

We tested the EKC hypothesis to study the relationship between economic development and PUE. For other drivers, we used Pearson's correlation coefficient to examine the relationship in each country and regression models across 113 countries. Our analysis results suggest drivers with a significant and consistent relationship with PUE in the global and regional models are economic development, fertilizer to crop price ratio, crop mix, NUE, farm size, and P yield (Table 4). All models mentioned in Table 4 consider time and country effects and have PUE as the dependent variable. Compared to the results of constant intercept models and fixed effects models not considering the time and country effects, the fixed effects models considering these effects behave better with higher adjusted R^2 and lower AIC (Table S10). The fixed effects model in Table 4 is the final chosen model with a high adjusted R^2 (96%) and the lowest AIC, using stepwise regression. More details of calculation, model setting, and comparison can be found in SI.

Table 4 Regression results of three methods studying the relationship between PUE and drivers from 1961 to 2014 in individual countries and across 113 countries. The grey box indicates the driver is not included in the model. *** suggests $p < 0.001$, **suggests $p < 0.01$, and * suggests $p < 0.05$.

Driver	Individual countries			Across 113 countries	
	EKC test	Pearson's correlation coefficient		EKC test	Fixed effects model
	Number of countries with a U-shape relationship (% of 113 countries)	Number of countries with a significant positive relationship (% of the countries with either significantly positive or negative correlation)	Number of countries with a significant negative relationship (% of the countries with either significantly positive or negative correlation)	Coefficient	Coefficient
GDP per capita (linear term)	47 (42%)			3.3925e-05***	1.2979e-05***
GDP per capita (quadratic term)				5.8554e-11	
Consumption per capita for certain crop types		75% for cereal crops, 57% for fruit and vegetable	25% for cereal crops, 43% for fruit and vegetable		
Fertilizer to crop price ratio		84%	16%		0.59956***
Per hectare spending on agricultural machinery		37%	63%		

Patent application per capita		45%	55%	
Education expenditure as a percentage of government spending		45%	55%	
Agriculture, value added		47%	53%	
Ratio of net import of certain crop types		35% for cereal crops, 50% for fruit and vegetable	65% for cereal crops, 50% for fruit and vegetable	
Crop mix		48% for cereal crops, 39% for fruit and vegetable	52% for cereal crops, 61% for fruit and vegetable	-0.65446 *** for cereal crops
NUE		99%	1%	1.4113***
Adjusted average farm size		59%	41%	0.058155***
Conservation area ratio		73%	27%	
P yield		56%	44%	0.00077645***
Accumulated P surplus		62%	38%	
Accumulated P residual		81%	19%	

3.2.1 Economic Development

On the regional scale, the PUE of 70 out of 113 countries had a significant linear or quadratic relationship with GDP per capita. Among these countries, 47 of them suggest the expected U shape relationship between PUE and GDP per capita (Table 4), though the turning points and slopes vary. These 47 countries accounted for over half of the global harvested area and total P in crop production, and over 80% of P fertilizer consumption at cropland in 2010 (61%, 70%, and 84%, respectively). They include major crop-producing and fertilizer-consuming countries such as the U.S., Brazil, China, and India.

EKC hypothesis was not rejected across the 113 countries when the independent variables only include the linear and quadratic terms of GDP per capita (Table S10). After considering country and time effects and adding more variables to the regression model, only the linear term has a significantly positive relationship with PUE (Table 4, Table S10, and Table S14). These results indicate synergy between global economic development and PUE (the second half of the EKC curve) between 1961-2014 in these 113 countries.

Note that the EKC hypothesis does not tell the future of a country or define the pathway that all countries should follow. Instead, EKC suggests potential reasons behind PUE patterns and informs political strategies to improve PUE. China has been experiencing an increasing GDP per capita and decreasing PUE (Fig. S3). According to the EKC hypothesis, this tradeoff may no longer continue, as China's PUE is approaching a lower asymptote between 30% and 40% (Table 3). However, China's PUE would not inevitably reach a turning point and then increase without any technological innovation or political interventions. Improved technologies and proper policies can help a country like China turn the corner on the EKC and reach a sustainable PUE in an even shorter time.

3.2.2 Crop Mix

The production of cereal crops, fruit, and vegetable influence national PUE, as these crops had relatively lower PUE than that of other crops (Table 3, Fig. 3). Rice's PUE from 1961 to 2014 varied between 20% and 40%, while the PUE of fruit and vegetable varied between 10% and 30% (Fig. 3a). Regression analysis for individual countries and across 113 countries suggests a generally negative relationship between PUE and the percentage of harvest areas for cereal crops or fruit and vegetable (Table 4). These results imply the importance of improving the PUE of low-efficiency crops to improve national PUE.

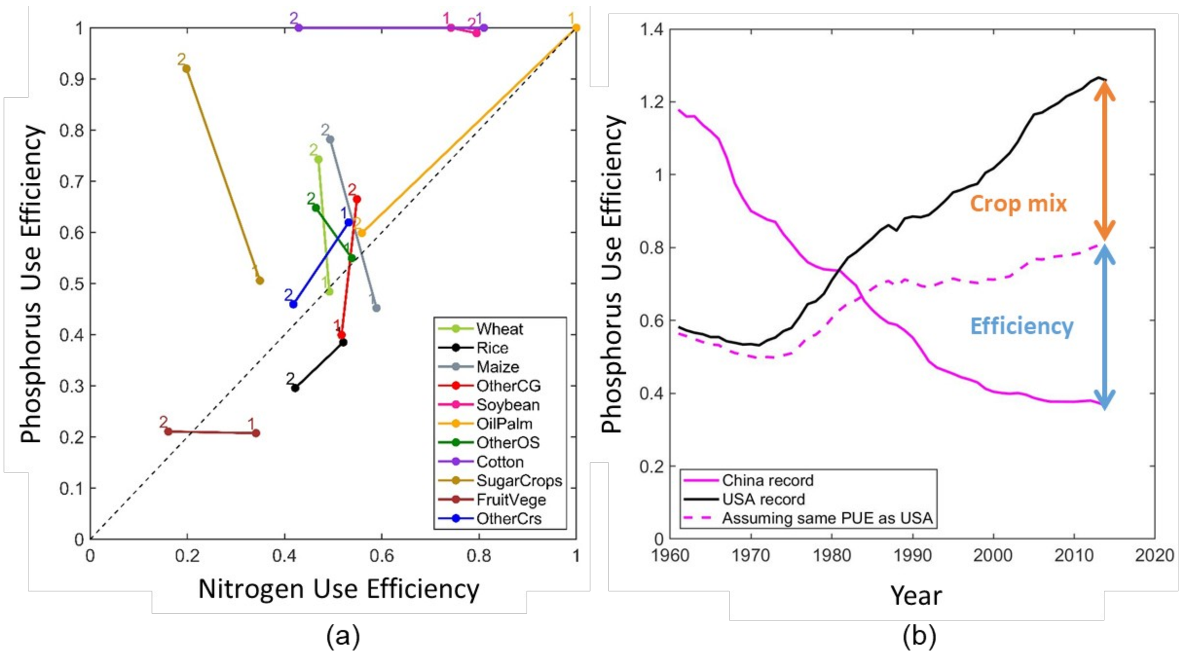


Figure 3. Crop mix as an important driver for PUE. a) Global NUE and PUE of 11 crop groups (Table S12) between 1961-2014. Point 1 represents the average of 1961-1970. Point 2 represents the average of 2005-2014. PUE values of other single years are not shown. PUE values higher than one are plotted at one. 'OtherCG' means other cereal crops. "OtherOS" means other oil seeds. 'OtherCrs' means other crop types. b) China and U.S. PUE across crops between 1961-2014. The purple line shows China's PUE. The black line shows U.S. PUE. The dashed purple line represents the resulted PUE in China if China improved its PUE to U.S. level for each crop type. The gap between the black line and the dashed purple line shows the difference in PUE determined by the difference in crop mix.

Improving the PUE of low-efficiency crops and crop mix can both improve national PUE. China has increased harvested area and P fertilizer input for fruit and vegetable, due to increased demand and high profits. Those crops' harvested area and P fertilizer input have increased from around 5% and 12% in 1961 to 21% and 36% in 2010 (average of 2005-2014). This shift of low PUE crops reduced China's PUE. If China improved the PUE of each crop type to the U.S. level (Fig. 3a), China's PUE would be significantly improved (Fig. 3b). The remaining difference in PUE (61% lower in 2014) is caused by the difference in crop mix (Fig. 3b).

3.2.3 Nitrogen Use Efficiency (NUE)

Historical data and regression results both indicate a positive relationship between NUE and PUE (Table 4). On the global scale, crops with a relatively higher NUE (e.g., cotton and soybean) tend to have a higher PUE, while crops with relatively lower NUE (e.g., rice, fruit, and vegetable) tend to have smaller PUE (Fig. 3b). On a national scale, 99% of the countries (82 countries) with significant results (positive or negative) (Table 4) show a positive relationship.

Improvement in nutrient management leads to NUE and PUE increase. Accumulated residual soil P allows farmers in many developed countries to reduce current P inputs and increase PUE. At the same time, factors such as the adoption of 4R practices lead to NUE improvement (Zhang et al. 2015a). Future studies need to identify and understand factors that can influence the linkage between PUE and NUE, as well as other nutrients.

3.2.4 Fertilizer to Crop Price Ratio

Higher fertilizer to crop price ratio can encourage farmers to use fertilizer more efficiently, thus increasing nutrient use efficiency in the cropland (Zhang et al. 2015a, Zhang et al. 2015b). Thus, we expected a positive relationship between PUE and fertilizer to crop price ratio.

Fertilizer to crop price ratio was positively related to PUE in over 84% of the countries (21 countries) with a significant relationship (Table 4). These 21 countries accounted for 47% of the global harvested area, 53% of P in harvested crops, and 65% of fertilizer P input in 2010. In the regression analysis on the global scale, the hypothesis of a positive relationship was also not rejected (Table 4). These results indicate a synergy between fertilizer to crop price ratio and PUE on the global and national scales.

3.2.5 Farm Size

Farm size is relevant to the efficiency of resource use in crop production, but with controversial conclusions. Many studies suggested that smaller farms are more sustainable in their uses of some resources (D'Souza and Ikerd 1996, Altieri 2009). However, some studies found that smaller farms tend to use more fertilizer and have lower nutrient use efficiency (Ju et al. 2016, Wu et al. 2018).

Analysis both on the national and global scales suggests a generally positive relationship between adjusted average farm size and PUE (Table 4). Twenty-three countries show a significant positive relationship with PUE, more than those with a significant negative relationship (16 countries). These 23 countries accounted for 14% of the global harvested area, 14% of P in harvested crops, and 13% of P fertilizer input in 2010. Note that these results do not necessarily mean that large farms are "better" than small farms, as there are other socio-economic reasons behind the relationship. Besides, increasing farm size may bring into other problems, such as decreased food diversity (Herrero et al. 2017).

3.3 Projected Phosphorus Budget and Challenges in 2050

3.3.1 Phosphorus Pollution in 2050

Based on FAO's projection for food demand by 2050 (FAO 2018) and our calculation, the amount of P in harvested crops would increase from 13.6 Tg P yr^{-1} in 2010 to 20.5 Tg P yr^{-1} in 2050 (Table 3). Increased P in harvested crops indicates that P inputs would increase, and more P would be lost unless PUE is improved.

The global P surplus was projected to increase from 8.8 in 2010 to 15.3 Tg P yr^{-1} in 2050, without PUE improvement (Table 3). By improving PUE, the global P surplus would decrease to 5.6 (MPA), and even 2.2 Tg P yr^{-1} (HPA) in 2050 (Table 3), and the global P surplus rate would decrease from 7 in 2010 to 4 (MPA) and 2 (HPA) kg P ha^{-1} yr^{-1} in 2050. This reduction in P surplus would be more significant in countries with a relatively larger P surplus rate in 2010, such as China, India, and Brazil (Fig. 4). For countries with relatively higher PUE and negative P surplus rate in 2010 (e.g., the U.S. and African countries), their negative surplus rate would increase to around zero, as we assumed that PUE higher than one would decrease to around one in 2050 (Fig. 4).

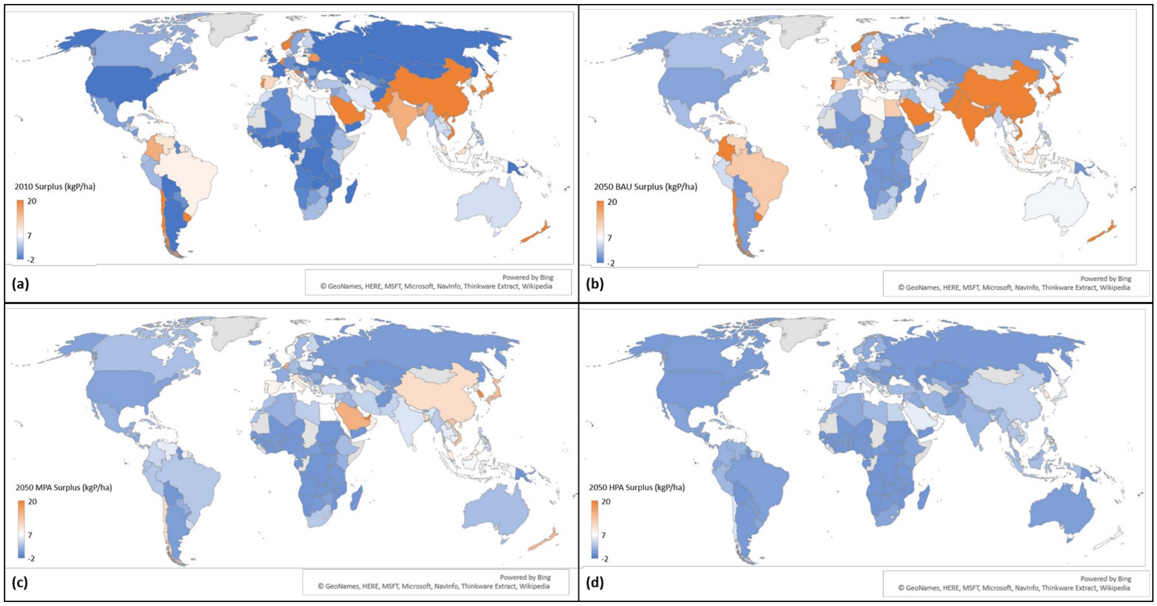


Figure 4. P surplus rate (kg P ha^{-1} yr^{-1}) by region. (a) P surplus rate (kg P ha^{-1} yr^{-1}) estimated in 2010 (average of 2005-2014). (b) P surplus rate (kg P ha^{-1} yr^{-1}) projected in the 2050 BAU scenario. (c) P surplus rate (kg P ha^{-1} yr^{-1}) projected in the 2050 MPA scenario. (d) P surplus rate (kg P ha^{-1} yr^{-1}) projected in the 2050 HPA scenario. Grey area: missing data. Orange area: P surplus rate higher than the upper planetary boundary (6.9 kg P ha^{-1} yr^{-1}, rounded to 7 kg P ha^{-1} yr^{-1}). Blue and white areas: P surplus rate lower than the upper planetary boundary. Rates larger than 20 kg P ha^{-1} yr^{-1} are shown in red. Rates lower than -2 kg P ha^{-1} yr^{-1} are shown in blue.

Based on our estimation, the global planetary boundary of P surplus is at 4.5-9 Tg P yr^{-1}. To keep the global P surplus under the boundary in 2050, we need to improve the global PUE from the current 60% to somewhere between 69% and 82%. Dividing the global P surplus planetary boundary (4.5-9 Tg P yr^{-1}) by global total harvest area in 2010 (average of 2005-2014, 1.3×10^9 ha), we estimated the regional planetary boundary of P surplus rate at 3.5-6.9 kg P ha^{-1} yr^{-1}. With this threshold, only in the HPA scenario or even more ambitious scenarios could the P surplus in major countries fall into this "safe" range (Fig. 4). In the BAU and MPA scenarios, 62 and 30 countries would still transgress the upper planetary boundary of the regional surplus rate (6.9 kg P ha^{-1} yr^{-1}) in 2050. These countries occupied 46% and 19% of the harvested area in 2010 (average of 2005-2014), respectively.

3.3.2 Phosphorus depletion in 2050

The demand for P fertilizer is likely to increase with P inputs if we assumed that all countries would maintain their current P fertilizer to total P inputs ratio (average of 2005-2014) after 2014 (scenarios 1B-3B, Table 2). With this assumption, we projected that global P fertilizer input would increase from 16.4 Tg P yr^{-1} in 2010 to 25.4 Tg P yr^{-1} in 2050 in the 1B scenario (Table S3). With PUE improvement, P fertilizer input would decrease to 18.5 (2B scenario) and 16.1 Tg P yr^{-1} (3B scenario) in 2050 (Table S3). Similarly, P manure input would increase from 6.0 Tg P yr^{-1} in 2010 to 10.4 Tg P yr^{-1} in 2050 in the 1B scenario. Improvement in PUE would reduce this input to 7.6 (2B) and 6.6 Tg P yr^{-1} (3B) in 2050 (Table S3).

The global phosphate rock reserves would be sufficient for crop production from 2017 to 2050. In all nine scenarios, the fertilizer demand to supply ratio would be at around 0.1% (Table S16), meaning that crop production would consume only about 10% of the global phosphate rock reserves. On the regional scale, the ratio of P demand to supply ratio would decrease as PUE improves (Fig. 5). However, non-major P producing countries would still face the P depletion challenge by 2050 or even earlier (Fig. 5, Table S16). Even in the most ambitious scenario and most ideal case (Fig. 5i), India (demand to supply ratio 3.7), Mexico (demand to supply ratio 1.7), and non-major P producing countries would still need to rely on phosphate rock or P fertilizer import (Fig. 5, Table S16) to support their food production. This ratio in the U.S. and China would be between 0.2-0.8 (Table S16), as they had relatively high P storage (Table S18). However, to secure food production, these two countries have adopted increasingly tight policies on phosphate rock export (Sattari et al. 2014, van de Wiel et al. 2015). P depletion challenge is severe on a regional scale.

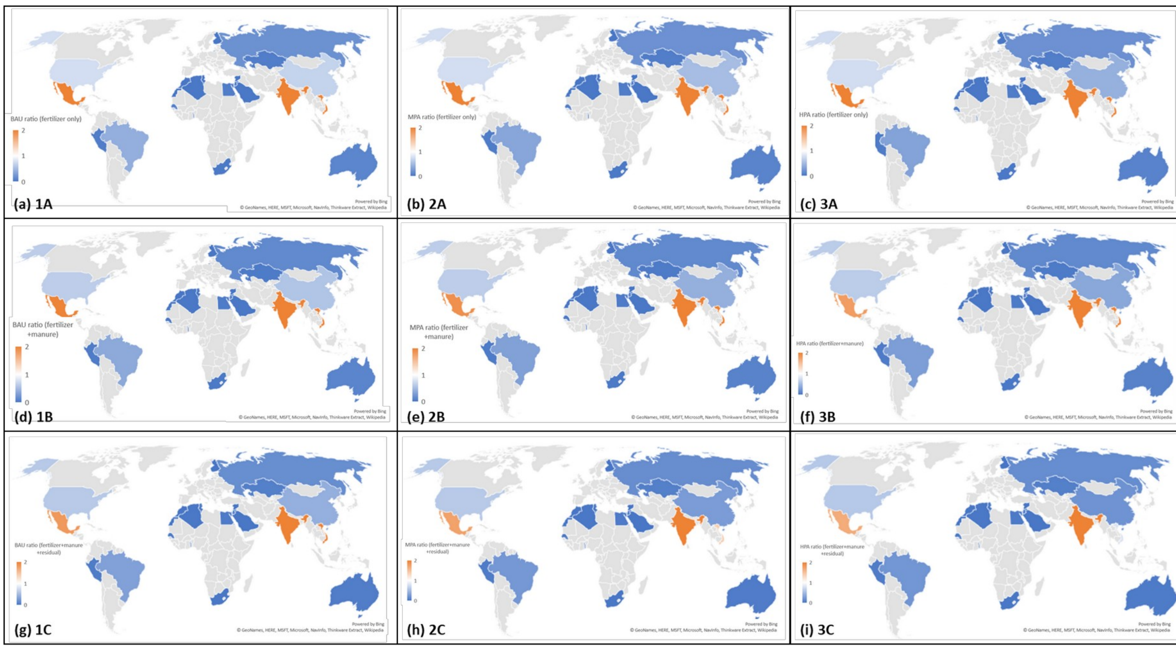


Figure 5. P depletion challenge (represented by P fertilizer demand to supply ratio) in major phosphate rock producing countries in nine scenarios (Table 2). (a) 1A scenario. (b) 2A scenario. (c) 3A scenario. (d) 1B scenario. (e) 2B scenario. (f) 3B scenario. (g) 1C scenario. (h) 2C scenario. (i) 3C scenario. Orange area: fertilizer demand to supply ratio larger than one, indicating P depletion by 2050. Blue area: fertilizer demand to supply ratio smaller than one, indicating P sufficiency by 2050. Grey area: non-major P producing countries with no phosphate rock production data.

4 Discussion

4.1 Improving PUE to Address Phosphorus Challenges

Addressing P pollution and depletion depends on the improvement of PUE, especially the PUE of low-efficiency countries and crops. These low PUE countries include India and China, and low PUE crops include rice, fruit, and vegetable.

Our study also identified key drivers for PUE improvement. We found a positive relationship between PUE and NUE, fertilizer to crop price ratio, and average farm size; and a negative relationship between PUE and the percentage of the harvested area of cereals, fruit, and vegetable. The relationship between PUE and economic development was close to an EKC curve on a regional scale, and it is synergy on a global scale.

P-efficient technologies and management practices are critical for PUE improvement. Some of these technologies and practices are available and have become more affordable. However, farmers' decision making is affected by many other socio-economic drivers, such as access to information and financial capacity (Baumgart-Getz et al. 2012, Davidson et al. 2015, Liu et al. 2018). To promote these technologies and strategies, we need more inter- and transdisciplinary research on farmers' decision making and further collaboration of academic researchers, government, farmers, private crop advisors, fertilizer producers, and consumers (Davidson et al. 2015).

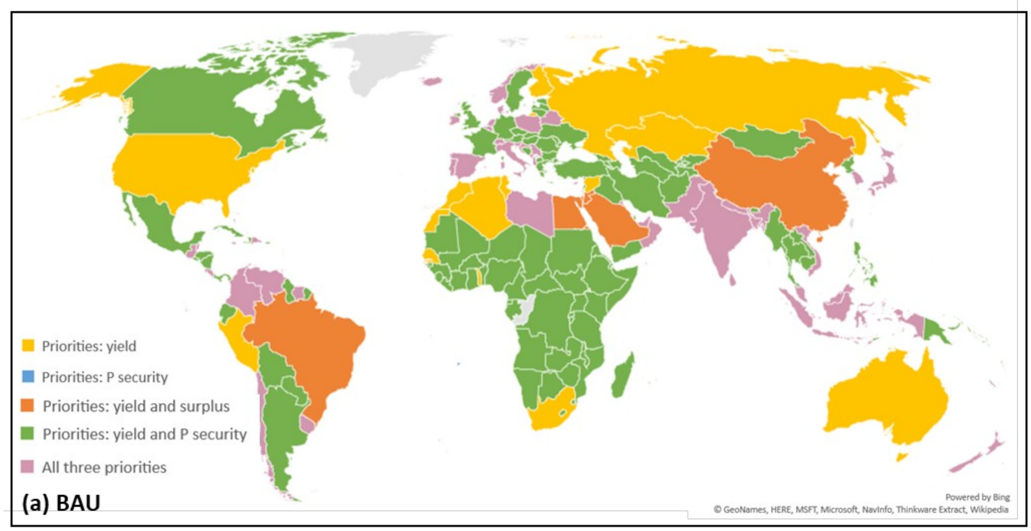
4.2 Global Targets and Regional Priorities

The priorities on the global and national scales are different. On a global scale, food security and P pollution challenges are the most urgent. The global P fertilizer demand to supply ratio was approximately 10%, meaning sufficient P supply for global crop production.

To meet the moderate food security goal (FAO 2018), we would need to increase the global harvested P from the current 13.6 Tg P yr^{-1} to 20.5 Tg P yr^{-1} by 2050 (Table 3). To reduce the global P surplus from the current level (9.1 Tg P yr^{-1}) to the planetary boundary (4.5-9 Tg P yr^{-1}), we would need to improve the current cropland PUE from 60% to 69%-82% by 2050.

Given their different socio-economic and agronomic conditions, different regions have unique challenges in P use to address (Fig. 6). In the BAU scenario, India, Pakistan, and a few other countries have all three priorities: increasing yield, reducing P surplus, and enhancing P sufficiency. While in countries such as China and Brazil, the priorities are to increase yield and reduce P surplus. The U.S., Russia, and Morocco would only need to focus on increasing yield. In most other countries, especially African countries, the priorities are to increase yield and enhance P sufficiency (Fig. 6a).

As PUE improves, most countries would face fewer challenges. In the MPA scenario, reducing the P surplus would not be the priority in most countries, except for China, Japan, and a few other countries (Fig. 6b). In the most ambitious HPA scenario, the challenges in most countries would be to increase yield from 2010 levels and enhance P sufficiency (Fig. 6c).



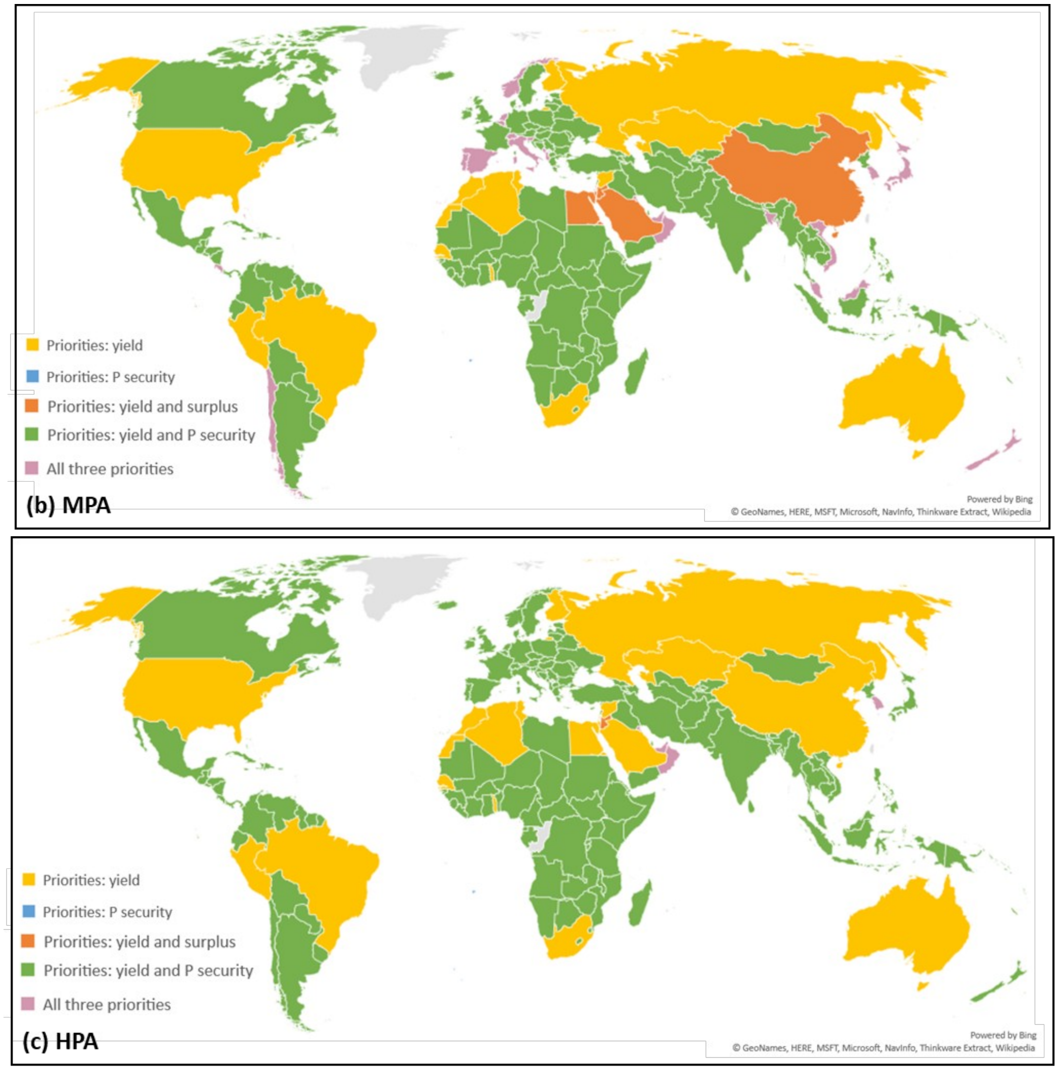


Figure 6. Regional priorities in the three scenarios. (a) Regional priorities in the BAU scenario. (b) Regional priorities in the MPA scenario. (c) Regional priorities in the HPA scenario. Yellow area: regions with the priority to increase P yield (i.e., estimated 2010 average P yield is lower than the projected 2050 P yield). Blue area: regions with the priority to enhance P sufficiency (i.e., P fertilizer demand to supply ratio is greater than one if assuming P fertilizer to total input ratio remains at the 2010 level). Orange area: regions with the priorities to increase P yield and reduce P surplus (i.e., P surplus rate in 2050 is larger than the upper planetary boundary, 6.9 kg P ha^{-1} yr^{-1}). Green area: regions with the priorities to increase P yield and enhance P sufficiency. Pink area: regions with all three priorities.

For countries facing the pressing risk of depleted reserves (e.g., India and Mexico, Fig. 6a-c), their priorities should also include investing in technologies and infrastructures that can recover and recycle P from sources such as manure and waste. Establishing stable trade relationships with countries with rich reserves could be another strategy to address this challenge.

Policymakers should also recognize the heterogeneity of P pollution within a country. Some regions have environmental problems more acute than those in other regions. In the U.S., even though the P surplus was negative as a country (Table 3), many regions in the U.S. (e.g., the

Great Lakes region and the Gulf of Mexico) are still suffering from eutrophication caused by high N and P loads to the water (Van Meter et al. 2018, Le Moal et al. 2019).

4.3 Potential Sources of Uncertainties

4.3.1 Phosphorus Inputs

In this study, we only consider fertilizer and manure as P inputs. Other inputs' data by country and crop type are not available, and they only accounted for a small amount of total P input in the previous studies. Between 2002-2010, P deposition, crop residues, seed, and sludge were around 2%, 13%, 1%, and 5% of total P inputs to global cropland, respectively (Lun et al. 2018).

4.3.2 Phosphorus Content

Another source of uncertainty in P budget work is the P content of each crop. Previous studies usually used nutrient content data from published work with different estimates (Zhang et al. 2020). Besides, these studies assumed that P content by crop type would not change over time and that the P contents were consistent in all spatial units (Bouwman et al. 2017, Lun et al. 2018). We made the same assumption in this study. Our results are comparable to previous studies on P budget analysis on the global scale (Table S5 and S6).

By assuming the same P content in all countries and years, the impact of this uncertainty on the analysis of P budget historical trends becomes smaller (Bouwman et al. 2017). To quantify this impact, we conducted a Monte Carlo simulation (1,000 iterations) for major countries and crop types, testing both normal and uniform distributions (SI Section Text S6). We found that this uncertainty did not affect PUE significantly. However, further studies on whether and how each crop's P content varies by country and time are of great value.

4.3.3 Phosphorus Planetary Boundary

Estimates of P planetary boundary and methodologies for calculation remain uncertain. Steffen et al. (2015) estimated the regional planetary boundary range for fertilizer P going to erodible soil as 6.2-11.2 Tg P yr^{-1}, while Springmann et al. (2018) suggest the planetary boundary range for global P fertilizer input at 6-12, or 8-17 Tg P yr^{-1}, depending on the recycling rate of P. Here we use P surplus rather than P fertilizer input to evaluate P pollution 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 has more direct environmental impacts than P fertilizer input; 3) a similar indicator, N surplus, have been proposed for tracking progress towards reductions in nutrient pollution caused by food production on farm to regional scales (Eagle et al. 2018).

Note that the P surplus does not reflect the actual environmental impacts. Thus, the estimated boundary should only be used as a reference point to provide a general direction for P management improvement. It warrants more research to understand: 1) whether the concept of a planetary boundary for P is useful for informing policy; 2) which indicators, such as global and regional P surplus, could be used for setting such a planetary boundary target; and 3) how to interpret the implication of the global target on a local to regional scale.

4.3.4 Phosphorus Residual

Partitioning P surplus into residual P retained in the soil and P loss is also challenging to assess on national to global scales. Sophisticated biogeochemistry modeling is necessary, but not yet well developed on the scale we were working on. There are at least two ways to estimate P loss. One way is to develop a dynamic soil model to evaluate annual change considering varying soil characteristics and P budget (Zhang et al. 2017). Another simpler way is to assume a constant fraction of P in inputs or surplus, leaving the cropland system. Sattari et al. (2012) assumed that P loss accounts for around 10% of the sum of fertilizer and manure inputs. Bouwman et al. (2013) and Lun et al. (2018), on the other hand, assumed that P loss is about 12.5% of total P inputs. Even more conservatively, Springmann et al. (2018) assumed 20% of P stored in the sediment was lost.

In this study, P loss data during the historical period (i.e., 1961-2014) are from the IMAGE-Global Nutrient Model (Bouwman et al. 2017). To project P loss after 2014, we assumed that 12.5% of P inputs would leave the cropland system (Bouwman et al. 2013, Lun et al. 2018) as P loss, to ensure that P loss had non-negative values. Note that the uncertainties in P loss estimation do 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 more mature soil models are developed.

4.3.5 Projection of Phosphorus Budget

The projection of future P budget was based on certain assumptions and can introduce uncertainties. We adopted the projection data of the middle pathway scenario developed by FAO (FAO 2018). This scenario assumed that moderate food security improvement would be achieved by 2050 (FAO 2018). This assumption means that the 2050 harvested P may have been underestimated if a more ambitious food security goal will be achieved. Also, given that most African countries are still at the early stage of agricultural intensification, the PUE in these countries in the three scenarios could have been overestimated, and their P inputs could have been underestimated. However, if PUE on the national scale will be significantly improved (such as in the HPA scenario) and more alternative P sources will be available, P pollution and depletion problems will still be properly addressed.

To project future P fertilizer input, we assumed that each country would maintain its current fertilizer to manure use ratio (average of 2005-2014) from 2015 to 2050. To estimate the uncertainties of this assumption, we have developed two other extreme cases to discuss how P input sources will affect P depletion (see Section 3.3.2). The results show that these uncertainties do not change our conclusions.

5. Conclusion

The world faces P depletion and pollution challenges, which can be measured by P fertilizer demand to supply ratio and P surplus. Improving PUE in crop production is one key pathway to address these two challenges and achieve synergies between agricultural productivity, sustainability, and resilience. To keep the global P surplus within safe limits, we would need to improve the global PUE in crop production from the current 60% to 69%-82%. On a regional scale, priorities and PUE improvement levels vary by local conditions. To achieve PUE improvement goals, we need strategies targeting key socio-economic and agronomic drivers for PUE. These drivers include economic development, crop mix, NUE, fertilizer to crop price ratio, and average farm size.

In this resource-limited and developed world, addressing P challenges also requires efforts beyond improving cropland PUE. In regions with limited phosphate rock reserves, addressing P depletion also depends on P import and alternative sources. While in regions where agriculture is not the only source of P pollution, managing non-agricultural P loads should be part of the solution. If we can effectively reduce P loads from non-agricultural sources (e.g., industrial and domestic wastes (Chen and Graedel 2016, Mekonnen and Hoekstra 2018)), the boundary for P surplus from cropland could be relieved. Methods to reduce non-agricultural P loss include, for example, reducing P loss along its supply chain (Nedelciu et al. 2020) and recovering P from wastewater treatment plants (Chrispim et al. 2019).

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