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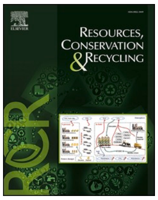

Full length article

Optimizing phosphorus fertilizer use to enhance water quality, food security and social equality

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ABSTRACT

There are large regional differences regarding the use of phosphorus (P) fertilizer in global crop production. Likewise, people's accesses to crop calories and exposure to water pollution differ largely among world regions. The use of P fertilizer is needed to meet agricultural requirement and solve these inequalities. We developed a multi-objective framework for optimizing P fertilizer use that considered water quality, food security and social equality. Different optimal objectives yield contrasting results for the geographical distribution of P fertilizer use, crop calorie production and social equality. Optimized P fertilizer use without recycling P management may pose a threat to global food security. Approximately 3 %–43 % of the current global crop calorie production may be decreased, and inequality in access to crop calories may also increase. Overall, although a multi-objective framework to optimize the use of P fertilizer reduces crop calorie yield, it can help intergenerational equality of P fertilizer use and improve water quality.

1. Introduction

Phosphorus (P) is a finite resource that may be depleted in a few centuries (Némery et al., 2016). Input of P into cropland has greatly contributed to the rapid increases in food production to meet the increasing demand from a rapidly growing population (Cordell et al., 2014). However, phosphate resources and demand are spread unevenly (Reijnders et al., 2014). It is predicted that world phosphate rock production will become increasingly dominated by Morocco, including the Western Sahara. The current phosphate demand of the European Union is covered by imports at a rate of more than 90 %. The uneven P distribution and demand across the globe leads to large regional differences in access to food calories (Bell et al., 2021; Kahiluoto et al., 2021; Gong et al., 2023). The current global P cycles had excessed the planetary boundary and concentrated in regions of higher population density (Rockström et al., 2023). Spatial hotspot transgressions implied the P pollution was uneven and unequal. This raised questions about regional difference of aquatic eutrophication and intergeneration justice.

International trade is a measure that can address the uneven P resource distribution for food security. However, trade ignores the water quality and results in eutrophication problems in developed and large emerging countries (Yang et al., 2019; Bai et al., 2023). Global financial transfer is a straightforward financial deal that can alleviate P pollution in origin countries, but the countries involved in financial transfer do not easily to hold up their end of the bargain. Taking climate as an example, most climate finance is directed toward middle-income countries, and not the poorest, most vulnerable countries (Timperley et al., 2021). In addition, the volatility of phosphate rock price means that farmers have unequal access to affordable P fertilizers (Brownlie et al., 2022; Alexander et al., 2023; Snapp et al., 2023). These factors have negative

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impacts on farmers' sufficient access to affordable P fertilizers. Therefore, it is essential to optimize P fertilizer use while simultaneously considering pollution control, food security, and social equality.

Currently, there is no clear multi-objective (pollution control, food security and social equality) framework for the optimization of P fertilizer use. Previous studies regarding P pollution control have mainly focused on waste recovery technology, field management and optimized trade patterns (Tonini et al., 2019; Bai et al., 2023; Liu et al., 2023). Langhans et al. (2022) reported that an increase in P application by almost 40 % in smallholder farms in sub-Saharan Africa would double productivity between 2015 and 2030 and thus improve global food security. Regarding social equality, recent studies have focused on nationally determined contributions (NDCs) to achieve the 1.5-degree climate control goal (Robiou et al., 2016; Fyson et al., 2020; Pozo et al., 2020). A similar concept could be applied form the basis of P fertilizer use to alleviate pollution and resource distribution. Hence, a multi-objective framework with the objective of optimizing P fertilizer use is greatly needed.

Recently, the increasing trade of agricultural products has highlighted the issues associated with P fertilizer use. Globally, approximately 25 % of P fertilizer is used for exported agricultural commodities (Barbieri et al., 2021). Among global trade agricultural commodities, approximately 44 % of P flows to animal feed (Nesme et al., 2018). In addition, the amount of cereal production used for feeding animas increased from 30 % in 2006 to 64 % in 2019 (Guyomard et al., 2013; FAO, 2022). Increased use of cereals for livestock feed indirectly exacerbates the use of P fertilizer in crops (Appleby et al., 2015). Therefore, there are complex P resource interdependencies, making P recycling difficult (Nesme et al., 2018; Lun et al., 2021; Wang et al., 2022). The P flows and stocks in livestock production add to the large differences in fertilizer P use among countries (Rothwell et al., 2020). Trade and livestock production levels have a large impact on the resilience of countries to low P inputs (Rothwell et al., 2020). However, there are no comprehensive studies regarding the potential impact of multi-objective optimal framework for P fertilizer on crop calorie production in countries with varying levels of P trade and livestock production.

Here, we aim to i) develop a multi-objective optimal framework of P fertilizer use, ii) assess how this framework affects crop calorie production and inequality in the availability of crop calories for people, and iii) explore potential options to increase resilience to low and likely insufficient P inputs.

2. Material and methods

2.1. Overview of multi-objective framework design, its impacts on crop production and food inequality

We developed a multi-objective framework to optimize P fertilizer use that considers aquatic eutrophication control, food security and social equality. First, we given two thresholds for global P fertilizer use based on the planetary boundary (PB). The two thresholds were a lower limit (6.2 Tg P) (the limit of P flow from fertilizers to avert widespread eutrophication of freshwater systems) and an upper value (11.2 Tg P) (the limit of P flow from freshwater systems into the ocean) (Carpenter et al., 2011; Steffen et al., 2015). Second, within the proposed framework, global P fertilizer use should be optimized to achieve objectives including responsibility, capability, equality and food security (Table 1). Third, use Lorenz curves and Gini coefficients to assess multi-objective optimal P fertilizer use on inequality for people available to food (Bell et al., 2021). Fourth, explore potential options to increase resilience to low and likely insufficient P inputs.

Table 1
Description of the optimal phosphorus fertilizer use under multiple-objectives and categorization of countries into four different groups.

	Multi-objectives or country groups	Descriptions of principles and main rationales
Multi-objective	Responsibility	Each country shares the P fertilizer reduction target based on their contributions to cumulative soil P surplus from 1961 to 2018; the premise is that higher P surplus countries have a greater responsibility to reduce P fertilizer use. In addition, higher soil P surplus countries also have greater resilience to no or little P fertilizer input, since crops can utilize P from the soil.
	Capability	Each country shares the P fertilizer reduction target based on their contributions to total GDP value of crop production during 2016 and 2018, since higher GDP value countries have greater capability to invest in technologies and facilities to recycle P from the food system and to implement new technologies for high yield modern crop production. However, the GDP value of different country groups has been corrected with different accounts, based on their level of economic development.
	Equality	Each population in each country will share the same amount of P fertilizer per capita from 1961 to 2050, instead of based on current population.
	Food security	P fertilizer use will redistribute to each country according to their share of total crop calorie production during the period 2016–2018.
Country groups *(The judgment is based on the average of three years' data between 2016 and 2018.)*	Exporting and large livestock production (ExL) or small livestock (ExS) production countries	The net agriculture-exporting countries, and with the average livestock protein production per capita larger or smaller than the global average.
	Importing and large livestock production (ImL) or import and small livestock (ImS) production countries	The net agriculture-importing countries, and with the average livestock protein production per capita larger or smaller than the global average.

2.2. Calculation for optimizing P fertilizer use under multi-objective

2.2.1. Responsibility objective: low P fertilizer use for countries with high soil P surplus

The responsibility objective considers the historical responsibilities from 1961 to 2018, of which the cumulative soil apparent P surplus per country has been considered the key indicator for P fertilizer use. Soil P surplus is also the potential source to aggravating aquatic environmental pollution (Toor and Sims 2016; Rockström et al., 2023). The apparent soil P surplus was defined as follows:

$$P_i^{surplus} = P_i^{total\ input} - P_i^{crop\ harvest} \tag{1}$$

where $P_i^{surplus}$ is the apparent soil P surplus of cropland in country *i* from 1961 to 2018, in Tg; $P_i^{total\ input}$ is the total P input into croplands, including P fertilizer, manure, and straw, in Tg. $P_i^{crop\ harvet}$ is the amount of crop product P harvest in country *i* from 1961 to 2018, in Tg. $P_i^{crop\ harvet}$ was calculated based on the total yield of 178 crops and their P content (Nesme et al., 2018). The amount of manure P, straw P applied to soil was calculated from fractions of N to P for crop straw, and livestock manure (Table S3).

If $P_i^{surplus} > 0$, the share of each county to the global total apparent soil P surplus was used to determine the reduced amount of P fertilizer. This means that countries with higher soil P surplus will need to reduce more P fertilizer use, which is logical since crops can benefit from residual P in the soil (Sattari et al., 2012). If $P_i^{surplus} < 0$, the P fertilizer use was maintained at the current value. The equation of optimal fertilizer use is shown as follows:

$$P_i^{res} = \begin{cases} P_i^{surplus} > 0, & P_i^{2016-2018} - \left(P_{global}^{2016-2018} - P_{global}^{PB}\right) \times \left(\dfrac{P_i^{surplus}}{P_{global}^{surplus}}\right) \\ P_i^{surplus} < 0, & P_i^{2016-2018} \end{cases} \tag{2}$$

where P_i^{res} is the amount of P fertilizer use based on the responsibility objective, in Tg. $P_i^{surplus}$ is the P surplus of crop production in country *i* from 1961 to 2018, in kg; $P_i^{2016-2018}$ is the average amount of P fertilizer use in country *i* during 2016–2018, in Tg. $P_{global}^{2016-2018}$ is the average amount of global P fertilizer use during 2016–2018, in Tg. P_{global}^{PB} is the global boundary of P fertilizer use (6.2 or 11.2 Tg). The amounts of $P_i^{2016-2018}$ and $P_{global}^{2016-2018}$ were obtained from FAO (2022).

2.2.2. *Capability objective: low P fertilizer use for countries with high GDP per capita*

Capability builds on the current ability to invest in advanced technologies to ensure food production at lower levels of P input by using gross production value as the main indicator. Crop GDP is helpful in explaining economic trends and why they take place (FAO, 2022). Additionally, rich countries have more capacity to invest in high-tech solutions that rely on less P fertilizer (Altamira-Algarra et al., 2022). However, we consider common, but differentiated, responsibilities between countries with different levels of income (Pauw et al., 2014; Althor et al., 2016). For example, the crop GDP values of low-income countries, lower-middle-income countries, high-income countries, and the rest of the countries were corrected by 75 %, 50 %, 0 % and 25 % discount factors, respectively (Urs, 2022). The detailed list of different countries and the groups they belong to is shown in Table S1. The reduction target differs among countries based on their corrected share of the global crop GDP value when needed. The overall equation is shown as:

$$P_i^{cap} = P_i^{2016-2018} - \left[\left(P_{global}^{2016-2018} - P_{global}^{PB}\right) \times \left(\frac{GDP_i}{GDP_{global}}\right)\right] \tag{3}$$

where P_i^{cap} is the amount of P fertilizer use based on the capability objective, in Tg. $P_i^{2016-2018}$ is the average amount of P fertilizer use in country *i* during 2016–2018, in Tg. $P_{global}^{2016-2018}$ is the average amount of global P fertilizer use during 2016–2018, in Tg. P_{global}^{PB} is the global boundary of P fertilizer use (6.2 or 11.2 Tg). $\left(\frac{GDP_i}{GDP_{global}}\right)$ is the share of GDP for country *i* to global GDP. The crop GDP value of each country was also derived from FAOSTAT (Table S2).

2.2.3. *Equality objective-low P fertilizer use for countries with high historical use*

Equality considers intergenerational equality, which aims to achieve an equal P fertilizer use rate per capita for the entire world from 1961 to 2050 - an equal P fertilizer use for the next generation toward (trans-generation equality). First, we predicted annual global P fertilizer use between 2018 and 2050 by assuming a linear regression of PB implementation toward 2050. In this regression, the year was used as the x-axis, and the amount of global fertilizer P use was used as the y-axis. The global fertilizer P use in the start year (2018) and fertilizer P use in the end year (2050) were the target values (6.2 and 11.2 Tg P). Second, the amount of P fertilizer use between 1961 and 2050 was calculated. It was the sum of the prediction (2018–2050) and historical use (1961–2018). Third, we calculated the global average fertilizer P use per capita between 1961 and 2050, it is calculated as global cumulative P fertilizer use and the cumulative population between 1961 and 2050. Fourth, we calculated the P fertilizer use for each county in the future. The detailed formula of annual P use per country is shown as follows:

$$P_i^{equ} = \frac{\left(P_{per}^{1961-2050} \times Pop_i^{1961-2050}\right) - P_i^{1961-2018}}{n} \tag{4}$$

$$P_{per}^{1961-2050} = \frac{P_{global}^{1961-2018} + P_{global}^{2018-2050}}{Pop_{global}^{1961-2050}} \tag{5}$$

where P_i^{equ} is the amount of P fertilizer use for country *i* per year based on the equality objective, in Tg; $P_{per}^{1961-2050}$ is the amount of P fertilizer use per capita, in kg cap^{-1}; $Pop_i^{1961-2050}$ and $Pop_{global}^{1961-2050}$ are the total population for country *i* and the global population during the period 1961–2050, head; $P_i^{1961-2018}$ is the total historical use of P fertilizer for country *i* during the period 1961–2018, in Tg; and n is the number of years between 2018 and 2050, 32. $P_{global}^{1961-2018}$ and $P_{global}^{2018-2050}$ are the amounts of global fertilizer P use for history (1961–2018) and the future (2018–2050), in Tg. $P_i^{1961-2018}$, $P_{global}^{1961-2018}$, $Pop_i^{1961-2050}$ and $Pop_{global}^{1961-2050}$ were collected from FAOSTAT (Table S2).

2.2.4. *Food security objective: high fertilizer P use for countries with high crop production*

The food security objective is intended to ensure that human have sufficient food, which considers P optimal use based on current global crop calorie production capability per country. The target upper or lower limit PB is directly distributed to each country according to their share of total global crop calorie production. The production of 178 crops was collected for each country, and the total crop calorie production was calculated based on the production quantity and calorie content of each crop (Renard et al., 2019).

$$P_i^{food} = P_{global}^{PB} \times \left(\frac{crop_i}{crop_{global}}\right) \tag{6}$$

where, P_i^{food} is the amount of P fertilizer use based on the food security objective, in Tg. $\frac{crop_i}{crop_{global}}$ is the share of crop calorie production of country *i* to global production. P_{global}^{PB} is the global boundary of P fertilizer use (6.2 or 11.2 Tg). The crop production of each country was also derived from FAOSTAT (Table S2).

2.3. *Accurate P fertilizer use*

To ensure both the water quality and food security, there are several future optimal measures for P fertilizer use under different objectives. i) The ideal reduction targets, in some cases, exceed the current P fertilizer application rates (since the P fertilizer application rate is unable to be below zero). In such cases, we transferred the reduction targets of these countries to other countries under designated principles. The difference between actual and ideal P application rates has been identified, and the transfer of reduction targets has also been quantified. ii) The P fertilizer application amount had little effect on water quality, even when the rate of P fertilizer use was close to or lower than the strict limit of P. To control P concentration of each watershed below the threshold value, the P fertilizer application method followed the best management practices (BMPs) at the watershed scale. For example, the use of slow-release fertilizer (Sharpley et al., 2015), soil conservation practices (Smith et al., 2018), and apply P in 4R strategy (the right source, right time, right place and right rate) (Bruulsema et al., 2019). The effect of BMPs on the amount of P reduction was shown in Liu et al. (2017).

2.4. *Country groups*

Under a multi-objective optimal framework, the use of P fertilizer will be impacted by countries with varying degrees of agricultural product P trade and livestock output. Thus, all the countries were categorized into four groups. They were: i) agricultural P products (this refers to crop and livestock products) net import and small livestock production countries (ImS); ii) agricultural P products net import and large livestock production countries (ImL); iii) agricultural P products net export and small livestock production countries (ExS); and iv) agricultural P products net export and large livestock production countries (ExL) (Table 1).

2.5. *Impacts of multi-objective on inequality of food availability*

The effect of multi-objective optimal P fertilizer use on inequality of food availability was measured by Lorenz curves and Gini coefficients (Bell et al., 2021). In the Lorenz curves, we used the population accumulated ratio as the x-axis and the accumulated P fertilizer use under the optimal objective as the y-axis. The Gini coefficient can be derived from the Lorenz curve by taking the ratio of the area between the line of equality and the Lorenz curve as the numerator and the area of the triangle (everything under the line of equality) as the denominator. The Gini coefficient can range from 0 to 1 with higher numbers indicating greater inequality.

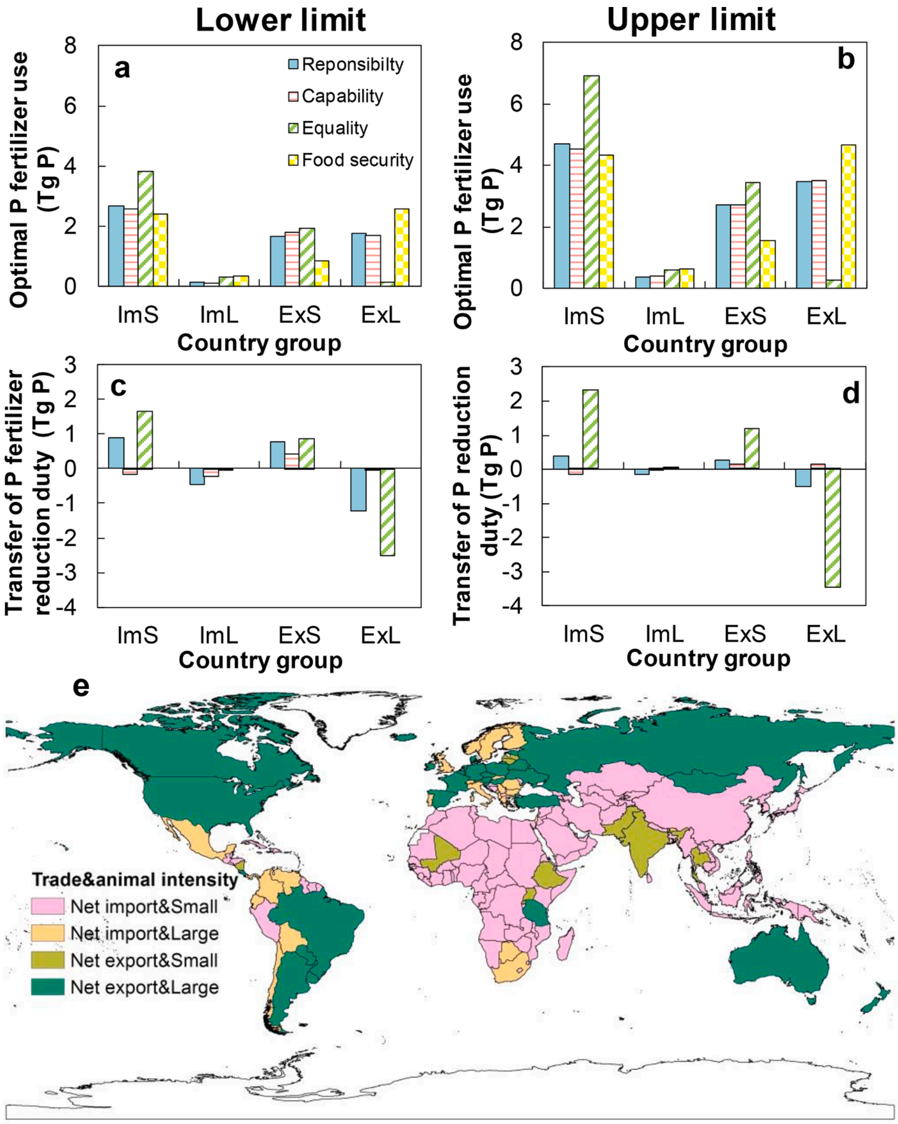

Fig. 1. Optimal phosphorus (P) fertilizer use (a, b) and transfer of P fertilizer reduction duty (c, d) under four objectives with different planetary boundaries for P (lower limit, left panel; upper limit, right panel). Fig. 1e showed spatial distribution of countries groups and detailed definition of these country groups were showed in Table S1.

Note: Importing and large or small livestock production (ImL or ImS) and exporting and large or small livestock production (ExL or ExS).

2.6. Factors impacting crop productivity and P use efficiency

We explored the changes in crop calorie productivity of different country groups and the five main representative countries in the three most recent decades (1990–2018) and quantified possible factors that impact average productivity. In total, six main indicators were selected: synthetic nitrogen (N), P and potassium (K) fertilizer application rate (kg ha^{-1} cropland), pesticide use (kg ha^{-1} cropland), machinery input (number ha^{-1} cropland) and agricultural energy use (TJ ha^{-1} cropland). The data were derived from FAOSTAT; for detailed sources, see Table S2. The Pearson correlation coefficient method was used to analyze the relationship between crop productivity and agricultural resource input. Similarly, the Pearson method was also used to analyze the effect of crop productivity, crop sown area, and manure P input on phosphorus use efficiency. The crop sown areas were calculated as the share of cereal, bean, vegetable, and fruit in the total crop sown area (Table S2).

3. Results

3.1. Optimizing P fertilizer use under multi-objective

3.1.1. Responsibility

To achieve the responsibility objective, the amount of P fertilizer use was varied significantly among countries due to the different cumulative soil P surpluses from 1961 to 2018 (Fig. S1). Under the lower-limit PB, the optimal amounts of P fertilizer use for ImS, ImL, ExS and ExL countries were 2.7, 0.1, 1.6 and 1.7 Tg P, respectively (Fig. 1a). These countries obtained different benefits to achieve their responsibility objective. i) ImL countries benefit less from the responsibility objective. For example, the amount of optimal P fertilizer use is 87 % lower than their current use (Fig. 2). However, these ImL countries have relatively higher resilience to P fertilizer deficits or lower P inputs. This is because ImL countries have extra P embedded in net imported agricultural products and a large amount of P in livestock manure (Lun et al., 2021). ii) ImS countries benefit from the responsibility objective, which helps these countries be more resilient to future low P inputs since they have net imports of P and small farms that easily recycle livestock manure P (Ricciardi et al., 2021).

However, the amount of P fertilizer use under the upper limit is not proportionally increased in different countries compared to the lower

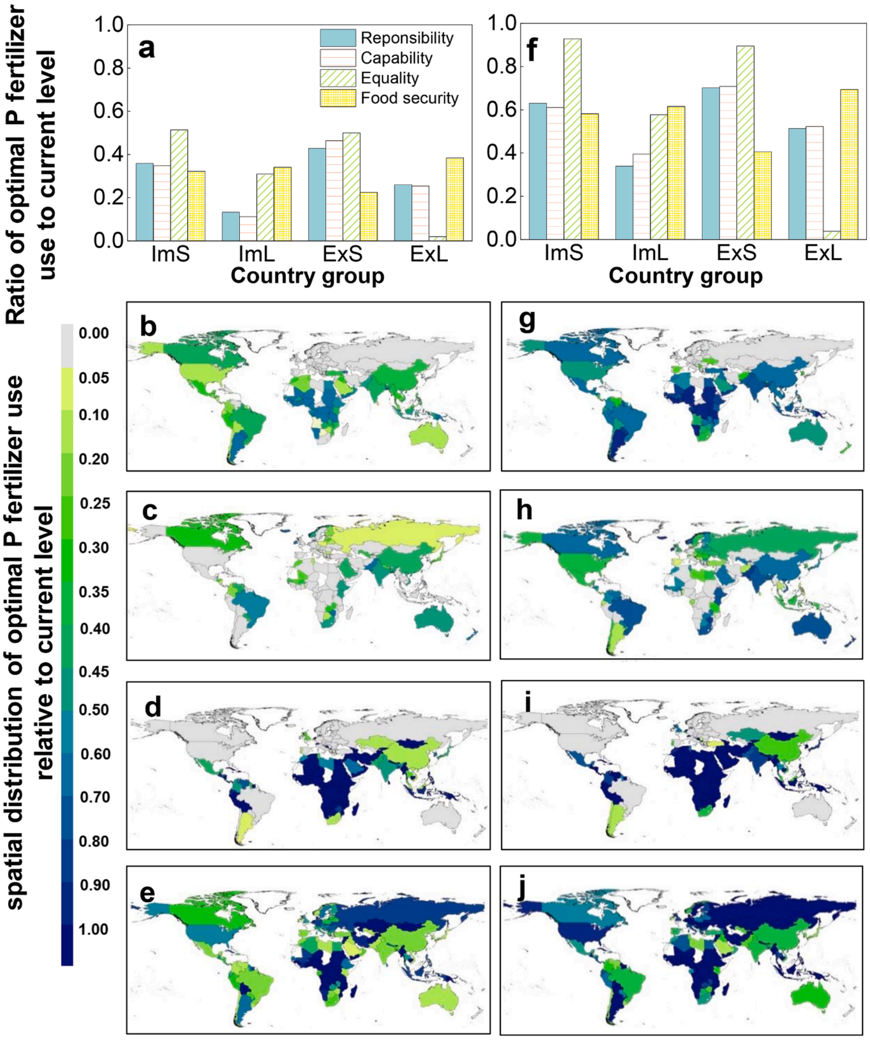

Fig. 2. Ratio of optimal P fertilizer use to current level for different country groups under lower (a) and upper limit planetary boundaries (f). Spatial distribution of the ratio of optimal P fertilizer use to current use under four optimal objectives: responsibility (b, g); capability (c, h), equality (d, i) and food security (e, j) under the lower limit (left panels) and upper limit (right panels).

Note: Importing and large or small livestock production (ImL or ImS) and exporting and large or small livestock production (ExL or ExS).

limit. ImS, ImL, ExS and ExL countries under the upper limit had 76 %, 155 %, 64 % and 98 % higher P fertilizer use than the lower-limit, respectively (Fig. 1a, b); this is mainly because countries under the lower limit must transfer more P fertilizer reduction targets than those the upper limit (Fig. 1c, d). For instance, the ImS and ExS countries together, mainly from Europe, transfer 2.0 Tg P reduction targets to ImL and ExL countries, mainly to Latin America, China and India (Fig. 1c; Fig. S2); this implied that European countries had more P fertilizer use and higher resultant P pollution under the responsibility objective, but other countries, such as China and Brazil, lack P fertilizer.

3.1.2. *Capability*

The geographical distribution of actual P fertilizer use under the capability objective is similar to that for the responsibility objective (Fig. 1a, b; Fig. S3). It is likely that the income levels of different country groups overlap with the levels of soil P surplus. Countries intending to reach the capability objective, however, yield less P fertilizer target transfer than those that reach the responsibility objective (Fig. 1c and d). As shown in Fig. S2, African countries transferred more P fertilizer reduction duty than other countries, which will have more P fertilizer use and benefit crop production. However, China received a larger P fertilizer reduction duty than other countries, which is consistent with China's zero growth goal regarding P fertilizer use.

3.1.3. *Equality*

The reduction amount of P fertilizer use under the equality objective was largely different from that under the other objectives. For example, the reduction amount of P fertilizer for ExL countries (0.13 Tg P fertilizer) under the equality objective was approximately 1/20 to 1/13 of those under the other objectives (Fig. 1; Fig. S3). Small livestock production countries (ImS and ExS) must only halve their P fertilizer use, while P fertilizer use must be reduced by 70 % and 98 % in ImL and ExL countries under the lower limit, respectively (Fig. 2a). This reduction is reasonable since large livestock production is more resilient to low P input due to the large availability of P from livestock manure.

Under the equality objective, the variations in the optimal amount of P fertilizer use between the lower and upper limits are considerable. While countries with large livestock production share the majority of the reduction target under the upper-limit, countries with small livestock production (ImS and ExS) only need to reduce their P fertilizer use by a small amount (Fig. 2b). This disparity is a result of both differences in historic P fertilizer use per capita and prospective population increases between countries. There were much larger transfers of P fertilizer reduction targets under the equality objective than under the other objectives (Fig. 1c, d). However, P fertilizer use per capita was excessively high in a few countries between 1961 and 2018. Hence, many countries must reduce their P fertilizer application to zero, such as, most European Union countries (Fig. S2c, f). This reduction implies that developed countries (such as USA and Australia) need to use soil residual P or recycle waste P.

3.1.4. *Food security*

When the amount of P fertilizer is reduce, its use under food security objective largely follows the current crop production geographical distribution (Fig. 2). Interestingly, most African countries receive similar amounts of P fertilizer compared to the current situation even under the lower-limit (Fig. S3d); this is because these countries currently produce crop calories with low inputs of P fertilizer or even deplete soil P to support crop production. Countries with poor crop calorie productivity, such as Brazil, China, India and Australia, should use less P fertilizer than the current amount (Fig. 2e, j). This factor is caused in part by the distinctive crop production structure, where the production of protein is prioritized over the production of calories, as in Brazil, and in part by overfertilization, as in China (FAO, 2022). There was no transfer of P fertilizer reduction targets under the food security objective, which is different from other objectives (Fig. 1c,d).

3.2. *Impacts on crop calorie production and inequality of human access to crop*

3.2.1. *Impacts on crop calorie production*

Global crop calorie production could potentially decrease by 0.43–4.0 × 10^{15} kcal under the four objectives at the upper limit. This decrease is due to the assumption that P use efficiencies of crop production will remain at the current level, reflecting no improvement of P management in the food production-consumption system. The potential yield reduction was larger (4.1–6.4 × 10^{15} kcal) at the lower limit than at the upper limit (Fig. 3a), 3 %–43 % of the current global crop calorie production may be jeopardized. Crop yield decline may be less severe at the upper limit than at the lower limit (Fig. 3). The equality objective showed the smallest yield reduction at the upper limit when compared to the other objective (Fig. 3a). This net increase in yields was a result of the additional input of P fertilizers to the ImS countries (Fig. 1,2). In comparison to other countries, ImS countries had significantly higher P use efficiency for crop production.

Countries may respond to the different optimal objectives under lower or upper limits in various ways (Fig. 3,4). ExL countries show the greatest reductions in crop calories for most objectives (Fig. 3). This is mainly because these countries share a large extra part of the P reduction targets. However, many of the ImS and ExS countries will benefit from the food security objective, with crop calorie production doubling or tripling compared with their current situation (Fig. 4). These findings are consistent with recent research showing that increasing P inputs to smallholder farmers in Africa could double agricultural productivity, reducing the global requirement of land-use change to support an 11 billion population in the future (Langhans et al., 2022; Mogollón et al., 2021).

3.2.2. *Impacts on inequality in human access to crop calories*

The current production of crop calories is unevenly distributed throughout the world, especially in regard to countries with serious malnutrition (FAO, 2022). The responsibility and capability objectives reduce the inequalities in per capita crop calorie production but at the cost of total crop calorie production (Fig. 3). Reduced crop calorie production losses appear to be in a strong tradeoff relationship with increased crop calorie availability per capita. This negative effect can be alleviated through more intense agricultural product trade from high

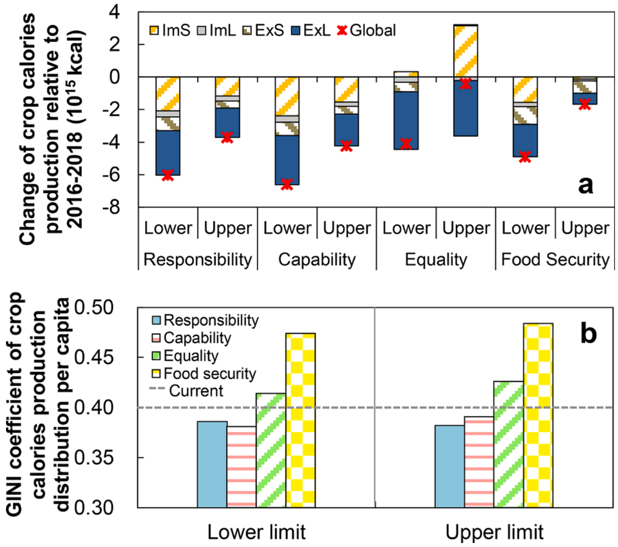

Fig. 3. Potential impacts of the optimal P fertilizer use under the four objectives on crop calorie production (a) and inequality for people access to crop calories (b). *Crop calorie production was relative to 2016–2018; GINI coefficients were used to represent the inequality for people access to crop calories.*

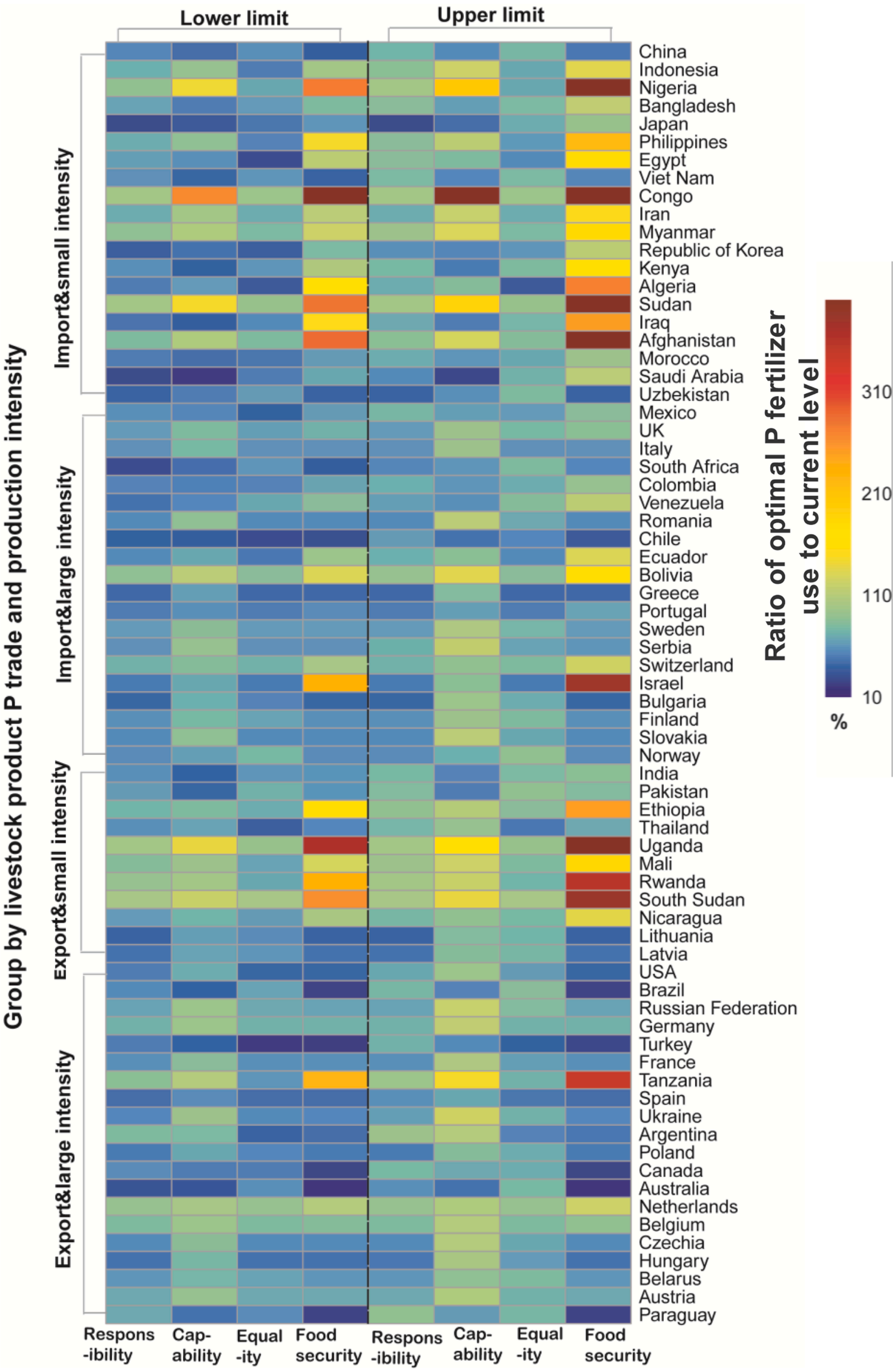

Fig. 4. Potential impacts of optimal P fertilizer use under four objectives on crop calorie production in various countries relative to 2016–2018. The four objectives were responsibility, capability, equality and food security. The scale bar represents the ratio of optimal P fertilizer use to the current level, in%.
Note: Red color represents increasing crop yields relative to 2016–2018, while green and blue color indicates reducing crop yields.

productivity countries (Oldekop et al., 2020; Bai et al., 2023).

3.2.3. *Reasons of crop production and fairness decrease under multi-objective framework*

i) P fertilizer use was based on value of planetary boundary, which was mainly designed to avert eutrophication of freshwater systems (Steffen et al., 2015; Rockström et al., 2023); ii) lack of P to meet crop require, especially in the major crop production countries (such as, China, Indonesia, USA), was caused by a drastic fall in P fertilizer but little improvement in manure recycling; iii) the optimal P fertilizer was based on historical use and made low productivity country (such as African countries) obtained more fertilizer. But such countries were characterized by low P use efficiency and high crop yield gaps (Mueller et al., 2012).

3.3. *Options to increase resilience to lower P fertilizer inputs*

The negative effects of using multi-objective to optimize P fertilizer application on the production of crop calories and fair human availability need to be alleviated. One option is to increase agricultural product trade from high productivity countries (Bai et al., 2023). The adoption of this option is necessary from the perspective of the food security objective of the upper limit, since the GINI coefficient under this objective is higher than for other objectives (Fig. 3). Recent studies also show that rational agricultural trade patterns and recycling of P embedded in agricultural trade products in net importing countries would increase global resilience to the deficit of P (Barbieri et al., 2021).

Pearson correlation analysis indicates that agricultural inputs such as fertilizer, pesticides and energy have a strong positive correlation with crop calorie productivity in the major countries ($P < 0.01$). This correlation relationship means that maintaining or even sustainably increasing these inputs would help increase crop calorie productivity and increase resilience to lower P inputs (Fig. 5a). This is consistent with Mueller et al. (2012), who found increase fertilizers and irrigation application in Sub-Saharan Africa can close the yield gaps to 75 %. In addition, most countries showed a significant positive correlation between crop calorie productivity and crop production structure ($P < 0.01$, Fig. 5b). This implies that improving the crop production structure may favour an increase in crop calorie productivity and reduce P input in a few countries.

Increased recycling of P would also generate additional benefits for increasing crop calorie productivity and reducing P input for crop production (Fig. 5b). This is consistent with Kanter et al. (2020) and Schulte-Uebbing (2021), who suggested that the recycling of P from existing food production systems, such as the recycling of livestock manure, human excreta and food waste, should be increased. An additional 27 Tg P could be recycled if all countries reached the livestock manure recycling rates of the top 5 % of the world's countries and recycled human or food waste to the field (Fig. 5d). This amount is 2.0 or 3.4 times the amount of P fertilizer that needs to be reduced under the lower and upper limits, respectively (Fig. S4, S5).

4. Discussion

4.1. *Possibility of optimizing the P fertilizer use based on multi-objective*

Our findings indicated great potential for optimizing P fertilizer use by using a multi-objective framework. i) Fertilizer use under a multi-objective framework through a combination of PB and the best management of P will keep the P concentration below the threshold values for all watersheds. ii) This framework will ensure the transgenerational equality by saving more limited P rock resources for the next generation. For example, the duration of P rock resources will extend from less than 200 years under the current situation. However, approximately 450 years under loose PB or 800 years under strict PB, as calculated based on P rock reserves and the P rock consumption rate in 2018 (Vaccari et al., 2011; USGS, 2019; FAO, 2022). iii) Equality and food security objectives showed a smaller reduction of crop calories, although inequality in the availability in crop calories per person may slightly increase. This indicates that intergenerational equal P fertilizer use, water quality control and crop calorie availability are possible when adapting the multi-objective framework. Overall, the above advantages of optimized P fertilizer use are the possible with the establishment of the

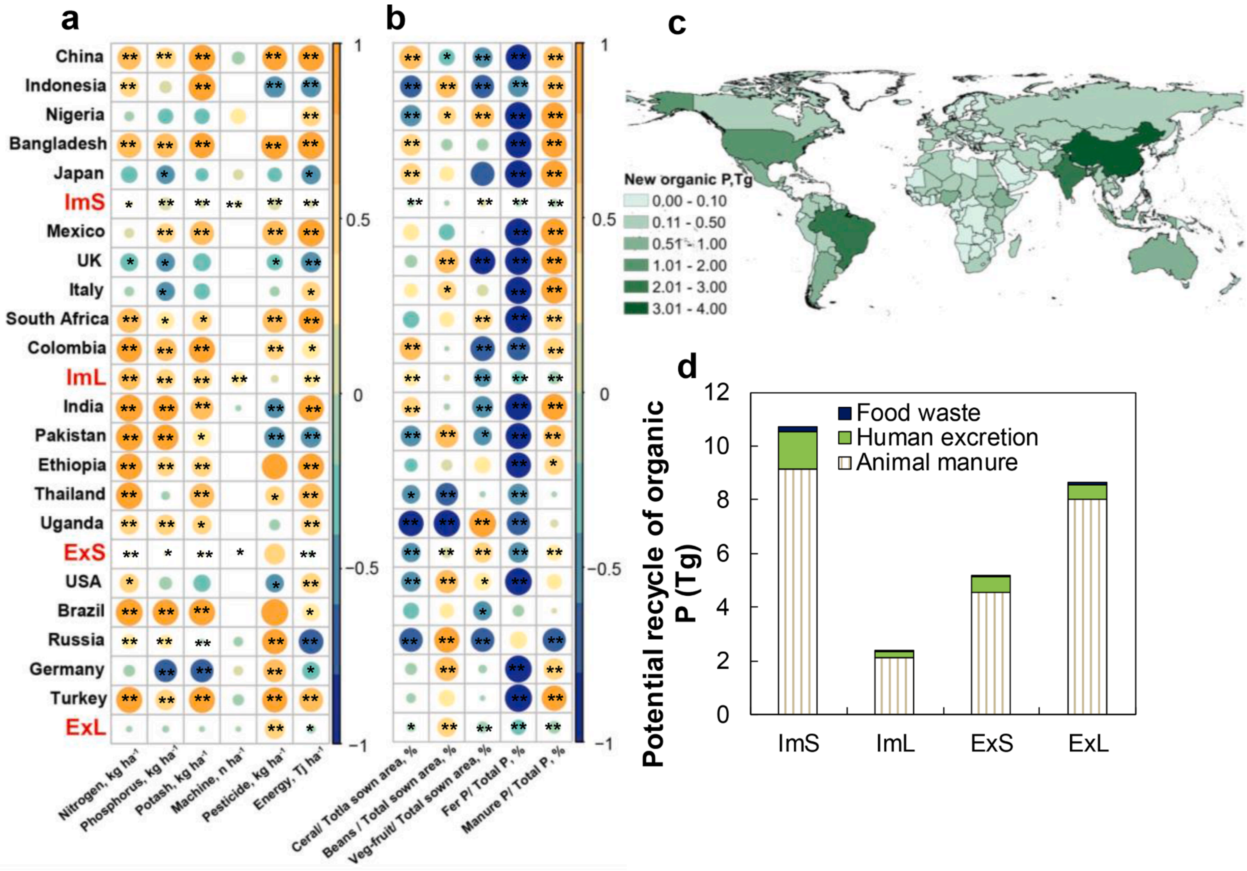

Fig. 5. Pearson analysis of the main factors that impact crop calorie productivity (a) and P use efficiency of crop production (b) for different country groups. The potential amount of recycling P from organic wastes for different countries (c) and country groups (d).

*Note: Orange and blue color represent positive and negative effects, respectively. The darker the color is, the stronger the effects. The blank grid in Fig 5a, indicates that data were not available. The asterisk in Fig. 5a indicates the significance of the correlation. * $P < 0.01$, ** $P < 0.01$.*

multi-objective framework.

The key indicators of the multi-objective framework are soil surplus P, crop GDP, history of P fertilizer use and food production. These indicators were also the key in 'Our phosphorus Future', as its contents included reduced national reliance on the limited regions with P resources through recycling waste and reusing soil residual P, ensuring sufficient access to affordable phosphorus fertilizers for all farmers (Brownlie et al., 2022). These actions will provide opportunities to promote optimal fertilizer P use based on multi-objective.

The existing carbon emission equity framework offers an example to optimize P fertilizer use based on multi-objective. Pozo et al. (2020) drew on existing equity frameworks, and allocated carbon dioxide removal (CDR) quotas globally according to responsibility, capability and equality principles. Similarly, phosphorus is a non-newable resource as well as an element that binds global food security. Therefore, we can use a carbon emission equity framework to manage P fertilizer. In addition, Metson et al. (2022) suggested net-zero P cities should devise strategies to better integrate P management within climate change adaptation and mitigation plans. This concept was based on existing net-zero carbon initiatives. The momentum gained from net-zero carbon initiatives may offer an opportunity to deliver a fertilizer P framework put into practice.

4.2. A multi-objective framework supports P fertilizer use to maintain water quality, food security and social equality

To prevent water eutrophication, the amount of fertilizer P used under the multiple-objective framework was within the PB. China had the greatest amount of fertilizer P application to support food security objectives, followed by India and Brazil. Although these countries have more opportunities to support crop production and maintain food security, a reduction in crop production occurs compared to the current crop quantity. Therefore, it is necessary to adopt recycling practices to fully use fertilizer P under the current policy. As illustrated in Fig. 5, actions aimed higher resilience of lower P input and increasing recycling of P resources have been identified. In addition, an increase in farm size, especially in smallholder regions, such as China and India, would significantly increase crop productivity and nitrogen and P use efficiency of crop production, increasing the resilience to lower P input (Manjunatha et al., 2013; Wu et al., 2018). However, not all of this potential for recycling P from the food system could be achieved. It is because high social economic and environmental costs reduce the availability of cost-effective technologies (Jupp et al., 2021). The uneven geographic distribution of crop and livestock systems also limits the recycling of waste (Jin et al., 2020).

On the other hand, African countries have less fertilizer P under the food security objective. It means we should consider crop production calorie reduction under food security objectives in Africa. It suggested the fertilizer P should be fully used and that actions should be taken for soil P deficits in these African countries. As Withers et al. (2018) reported, added lime to the soil affected the pH and increased the availability of P. However, African countries transferred the fertilizer P reduction duty to other countries under responsibility and capability objectives. It means responsibility and capability objectives increased the availability of crop calories for Africans.

4.3. Policy recommendations

Despite their relevance to most UN Sustainable Development Goals, fair P use, ensuring food security, and water quality protection still lack coordinated global governance as well as clear targets and action plans at the country level, which need to be developed in the future. A global system may need to allow the use of global P fertilizer based on multi-objective. First, such a system would allow trade of the reduction targets among countries, since countries have varying capabilities and motivations to achieve PB, this may allow a better achievement of PB at the global level. Second, this system provided the geospatially differentiated fertilization strategies. For example, the responsibility objective prioritizes high-P fertilizer supply to low-yield and P deficient regions.

In addition, more rational use of P should be strengthened after the country's optimal use target has been determined. In dealing with global nitrogen pollution, Gu et al. (2021) developed a unique credit system that provides new insights for optimizing P use more concretely to reduce water pollution without lowering food security. Such a nitrogen credit system builds on five pillars: i) implement best management practices at farms; ii) mitigate nitrogen pollution beyond the farm level; iii) monitor the performance of farms; iv) transfer abatement costs by the food industry and retailers between farmers and consumers; and v) supervise fair sharing of costs and benefits between stakeholders by the government. A similar system for P use and management could favor the success of fair P use, food security and clean water for all humans.

4.4. Uuncertainties in optimizing the P fertilizer use based on multi-objective

Optimal P fertilizer use rates or reduction targets for different countries may change over time. For example, China's reduction target under the responsibility objective may be lower if the soil P surplus were calculated for the period 2015–2018 due to its Zero fertilizer Increase Action (MOA, 2015) and Promoting Recycle of Manure Action in 2015 (MARA, 2017). Likewise, the results of the equality objective may vary with the selection of the start and end years because of the fast changes in P fertilizer use and population during the past few decades (Fig. S1). P fertilizer use under the food security objective may also vary when considering the role of food in terms of providing protein or other essential nutrients, and changes in crop caloric production affected by changes in P input in the future.

5. Conclusions

It is critical to optimize P fertilizer use based on multi-objective due to uneven P rock distribution, fluctuating P fertilizer prices and agricultural trade ignoring P pollution of the terminal. In this study, a multi-objective framework for optimizing P fertilizer use was developed considering soil P surplus, economics, history of P fertilizer use and crop production. Our results show that there are important trade-offs between smaller crop calorie yield reduction and fair availability of crop calories to humans, especially under a strict P planetary boundary. However, the majority of these negative effects can be alleviated by advocating agricultural product trade from high productivity countries, increasing agricultural inputs (pesticides, energy), adjusting crop structure, and increasing recycling of P within the food production-consumption system.

CRediT authorship contribution statement

Zhaohai Bai: Conceptualization, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing. **Ling Liu:** Data curation, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Carolien Kroeze:** Writing – original draft, Writing – review & editing, Methodology. **Maryna Strokal:** Writing – original draft, Writing – review & editing, Methodology. **Xinping Chen:** Writing – review & editing. **Zengwei Yuan:** Writing – review & editing. **Lin Ma:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107400.

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