Effects of phosphorus fertiliser use redistribution on crop calorie production and equal availability

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Abstract

There are large regional differences in the use of phosphorus (P) in global food production. Likewise, the access of people to food calories and exposure to water pollution differ largely among world regions. Redistribution of P use is needed to meet the planetary boundary (PB) and to improve P-related inequalities. We present a global redistribution of P according to four principles: responsibility, capability, equality and food security, and under strict and loose PB targets. These principles yield contrasting results for the geographical distribution of P fertiliser use, crop calorie production and equal availability. Redistributing P fertiliser use under PB without improvement of P management may pose a threat to global food security: 3–43% of the current global crop calorie production may be threatened. The impact is smaller under the loose PB targets and equality redistribution principle. There is a tradeoff between low crop calorie losses and equal availability for people to crop calories. Overall, the negative impacts on food security could remain limited but would likely be achieved at the cost of increased inequality in per capita food calorie distributions, which implies an increasing need for free international trading of agricultural products.

Main Text

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 increasing population (Cordell et al., 2014). Improving P application is essential to offset global cropland expansion and related climate change risks without comprising food security for 11 billion people in the future (Mogollón et al., 2021; Langhans et al., 2022). Unfortunately, excessive use of P has caused water pollution in recent decades, with an impact on ecosystems worldwide (Steffen et al., 2015; Powers et al., 2016). In addition, the use of P is unevenly distributed across the globe, leading to large regional differences in the access of people to food calories and exposure to water pollution (Bell et al., 2021; Kahiluoto et al., 2021).

A redistribution of P resources is needed to alleviate P-related social inequalities (Kahiluoto et al., 2021). However, there are no clear redistribution principles. Recent examples of studies on social equality in environmental sciences focus on nationally determined contributions (NDCs) to achieve the 1.5-degree climate control goal (Robiou du Pont et al., 2016; Fyson et al., 2020; Pozo et al., 2020). A similar concept could form a basis to determine P redistribution principles. However, the redistribution of P needs to be applied beyond social equity since P is an indispensable element for crop production. For example, an increase in P application by almost 40% in smallholder farms in sub-Saharan Africa would double the productivity between 2015 and 2030 and, thus, help improve global hunger and poverty (Langhans et al., 2022). Hence, there is a great need to develop P redistribution principles, which consider not only social equality but also historical soil accumulations and crop yield responses.

Future use of P should stay within the so-called planetary boundary (PB). Earlier studies attempted to quantify this PB, indicating a maximum of 6.2–11.2 Tg for synthetic P fertiliser use worldwide (Steffen et al., 2015). This PB was derived from targets for inland and offshore water quality (Steffen et al., 2015). Few studies have explored the implications of PBs for agricultural nitrogen (N) management (Yu et al., 2019) and have presented substantial impacts on local water quality and food security (Chang et al., 2021; Schulte-Uebbing, 2021). For P, such studies are scarce. We lack knowledge about the implications of P redistribution under PB guidelines for global crop calorie production while accounting for the equality in the availability of crop calories for people.

Globally, approximately 25% of fertiliser P is used for exported agricultural commodities (Barbieri et al., 2021). 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 between 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 on the impact of P redistribution on crop calorie production in countries with different levels of P trade and livestock production. Our aim is to fill these crucial knowledge gaps by i) developing P redistribution principles under PB guidelines and evaluating the impacts on crop calorie production and inequality in the availability of crop calories for people and ii) exploring possible options to increase resilience to low and probably inadequate inputs of P.

Results

P redistribution principles

For P fertiliser use, we developed four redistribution principles: (1) responsibility, (2) capability, (3) equality and (4) food security. Two levels of PB of P were used: a lower limit (6.2 Tg P) and an upper limit (11.2 Tg P) (Steffen et al., 2015) to test the variances of impacts on crop calorie production and inequality in the availability of crop calories to humans under strict or loose PB. P fertiliser application rates or reduction targets are redistributed to each of the 188 studied countries. This is done by considering their shares in the total PB of P or total required reduction targets under each principle. Currently, the global P fertiliser use rate was 19 Tg P per year during 2016 and 2018 (FAO, 2022).

The responsibility principle considered the cumulative soil apparent P surpluses per country from 1961 to 2018, and the P fertiliser reduction target was distributed to each country according to its share in the global cumulative soil apparent P surpluses during the past six decades. The capability principle builds on the ability to invest in advanced technologies to ensure food production at lower levels of P input. The P fertiliser reduction target is proportionally distributed over countries according to their shares in agricultural production but corrected by different discount factors, based on the concept of common but differentiated responsibilities (Pauw et al., 2014; Althor et al., 2016). The equality principle considered equal P fertiliser use per capita for all countries from 1961 to 2050 (i.e., the year in which the PB of P was assumed to be achieved). P fertiliser use per country will be proportionally distributed based on the shares of crop calorie production to global crop calorie production during 2016–2018 in the food security principle. A brief introduction is shown in Table 1, and for details, see the methods. The reference year for all results is 2018 for reasons of data availability.

Table 1
Description of the synthetic phosphorus fertiliser redistribution principles and categorisation of countries into four different groups.

	Redistribution principles or country groups	**Descriptions of principles and main rationales**
Redistribution principles	Responsibility	Each country shares the P fertiliser 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 fertiliser use. In addition, higher soil P surplus countries also have greater resilience to no or little P fertiliser input, since crops can utilise P from the soil.
	Capability	Each country shares the P fertiliser 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 fertiliser per capita from 1961 to 2050, instead of based on current population.
	Food security	P fertiliser use will redistribute to each country according to their share of total crop calorie production during the period 2016–2018.
Country groups *(The judgement 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.

Note that not all countries will bear their ideal reduction targets under each principle because the ideal reduction targets, in some cases, exceed the current P fertiliser application rates (since P fertiliser use 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.

To study the impacts of P redistributions on countries with different roles in agricultural product trade and level of livestock production, all the countries were categorised into four groups: 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). The livestock production level was determined by the average livestock protein production level per capita, larger or smaller than the global average level, based on three years of average data between 2016 and 2018 (Table 1).

Targets of P fertiliser use for different countries

Responsibility principle. P fertiliser reduction targets are disproportionately redistributed among countries because of differences in soil P surplus levels from 1961 to 2018 (Fig. S1). The global current P fertiliser use needs to be reduced by two-thirds under the lower-limit PB, under which the responsibility principle implies targets for ImS, ImL, ExS and ExL countries of 2.7, 0.1, 1.6 and 1.7 Tg P fertiliser, respectively (Fig. 1a). The ImL countries benefit less from the responsibility principle: their P fertiliser target is 87% lower than their current use (Fig. 2). These countries have relatively higher resilience of P fertiliser deficits or lower P input since they have extra availability of P resources embedded in the net imported agricultural products and a large amount of P in livestock manure. ExS countries benefit more from the responsibility principle with a 50% reduction target for P fertiliser use, and this may also help these countries be resilient to future low P input since they were net exports of P and have relatively lower amounts of manure P resources available for recycling (Fig. 2a).

The upper-limit PB of P is 81% higher than the lower limit; however, P fertiliser is not proportionally increased in different countries compared to the lower limit. For ImS, ImL, ExS and ExL countries, the upper-limit PB implies a 76%, 155%, 64% and 98% higher P fertiliser use than the lower-limit PB, respectively (Fig. 1a, b). This is mainly due to the transfer of P reduction targets between different country groups, with more target transfer for the lower-limit PB (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).

Capability principle. The results for actual P fertiliser use redistribution using the capability principle are similar to those for the responsibility principle (Fig. 1a, b; Fig. S3), probably because the income levels of different country groups are correlated with levels of soil P surplus. The capability principle, however, yields less intensive P fertiliser target transfer between country groups than does the responsibility principle (Fig. 1c and d).

Equality principle. The equality principle results for P fertiliser redistribution differ largely from the other principles. For example, the targets for ExL countries (0.13 Tg P fertiliser) are approximately 1/20 to 1/13 of those under the other principles (Fig. 1; Fig. S3). Small livestock production countries (ImS and ExS) only need to halve their P fertiliser use, while P fertiliser use needs to be reduced by 70% and 98% in ImL and ExL countries under lower-limit PB, respectively (Fig. 2a). This is reasonable since large livestock production is more resilient to low P input due to the large availability of P from livestock manure.

The differences in P fertiliser redistributions between lower- and upper-limit PBs are relatively large under the equality principle. Under the upper-limit PB, the small livestock production (ImS and ExS) countries barely need to reduce their P fertiliser use, with most of the reduction target distributed to countries with large livestock production (Fig. 2b). This is partly due to differences in historic P fertiliser use per capita and partly due to differences in population increases between countries in the future, for example, a more rapidly increasing population in developing countries. There were much larger transfers of P fertiliser reduction targets under the equality principle than under the other principles (Fig. 1c, d). This was due to P fertiliser use per capita being too high for a few countries during 1961–2018, and there is too short a period (from 2019 to 2050) to compensate countries with a long history of low P fertiliser use per capita. Hence, few countries need to reduce their P fertiliser application to zero, for example, most European Union countries (Fig S3c, d). There were still large differences in average P fertiliser use per capita between countries from 1961 to 2050 after massive redistribution under the equality principle, which is against the goal of individual fairness.

Food security principle. This principle largely follows the current geographical distribution patterns of P fertiliser use and yields the smallest differences in the P fertiliser reduction rate across country groups (Fig. 2). Interestingly, most African countries receive similar amounts of P fertiliser distributions compared to the current situation even under the lower-limit PB, in which global P fertiliser use needs to be reduced by two-thirds (Fig. 2). This is probably because these countries currently produce crop calories with low inputs of synthetic P fertiliser or even deplete soil P to support crop production. Targets for countries with lower crop calorie productivity, such as Brazil, China, India and Australia, are redistributed with lower amounts of P fertiliser compared to the current situation (Fig. 2e, j). This is partly due to the unique crop production structure, which is more targeted for protein production than calorie production, such as in Brazil, and in part due to over-fertilisation, such as in China (FAO, 2022). There was no transfer of P fertiliser reduction targets under the food security principle, which is different from other principles (Fig. 1c, d).

Impacts on crop calorie production and availability for people

Impacts on crop calorie production capability. Global crop calorie production could potentially decrease by 0.43–4.0*10^{15} kcal under the four different redistribution principles at the upper-limit PB, assuming there are no changes in P use efficiencies of crop production in the different countries and no improvement of P management of the entire food production-consumption system. The yield losses may be larger (4.1–6.4*10^{15} kcal) at the lower-limit PB (Fig. 3a). This means that 3–43% of the current global crop calorie production may be threatened when trying to fairly redistribute P fertiliser under PB guidelines, when there was no comprehensive improvement of P use efficiency and recycling rate. These negative impacts on crop yield could be smaller when assuming a more rational P fertiliser redistribution plan under the upper-limit PB (Fig. 3). The yield loss is smallest for the equality principle at the upper-limit PB (Fig. 3a), as a net effect of increased yields as a result of the additional distribution of P fertilisers to the ImS countries (Fig. 1–2), with much higher P use efficiency for crop production compared to other countries. The largest crop yield losses occurred using the capability principle at the lower-limit PB (Fig. 3a).

Countries react differently to the different redistribution principles and to strict or loose PBs (Fig. 3–4). ExL countries show the largest losses in crop calories for most redistribution principles (Fig. 3). This is mainly because a relatively large part of the P reduction targets are allocated to these countries. Many of the ImS and ExS countries will benefit from the food security principle, with crop calorie production doubling or tripling compared with their current situation (Fig. 4). This is because these countries are currently depleting soil nutrients for food production to some extent. These results are in line with recent studies showing that increasing P inputs to smallholder farmers in Africa could double agricultural productivity and hence reduce the global requirement of land-use change to support an 11 billion population in the future (Mogollón et al., 2021; Langhans et al., 2022).

Impacts on the availability of crop calories for the population. The current production of crop calories is unevenly distributed in the world, especially in countries with serious malnutrition (FAO, 2022). The responsibility and capability principles reduce the inequalities in per capita crop calorie production but at the cost of total crop calorie production (Fig. 3). It seems that there is a strong tradeoff between lowering crop calorie losses and increasing the per capita equality of crop calorie availability. An efficient redistribution of P fertiliser to lower losses in crop calories may increase the inequality of crop calorie production per capita, as shown for the equality and food security principles (Fig. 3).

Options to increase resilience to lower P inputs

The negative effects of P fertiliser redistribution under PB guidelines on the production of crop calories and fair availability to humans need to be alleviated. One option is to increase the international free trade of agricultural products, especially under the equality principle of upper-limit PB, since the GINI coefficient under the equality principle is higher than for the current situation (Fig. 3). Recent studies also show that rational agricultural trade patterns and recycling of P embedded in agricultural trade products in the net importing countries would increase global resilience to the deficit of P (Barbieri et al., 2021).

Our analysis also indicates that fertiliser, pesticides and energy inputs in agriculture have a strong positive correlation with crop calorie productivity in the major countries, which means that maintaining or even sustainably increasing these inputs would help to be more resilient to lower P input (Fig. 5a). Improving the crop production structure may also favour the increase in P use efficiency in a few countries (Fig. 5b). The recycling of P from existing food production systems, such as the recycling of livestock manure, human excreta and food waste, should be increased (Kanter et al., 2020; Schulte-Uebbing et al., 2021). If all countries achieved the livestock manure recycling rates of the top 5% countries in the world and collected and applied human excreta and food loss and waste to the field, an additional 27 Tg P could potentially be recycled (Fig. 5d). This amount is 2.0 or 3.4 times the amount of P fertiliser that needs to be reduced under the lower-limit and upper-limit PB, respectively (Fig. S4, S5). Increased recycling of P would also generate additional benefits for improving P use efficiency for crop production (Fig. 5b).

Discussion

Different PB limit levels and P redistribution principles yield contrasting effects on crop calorie production between countries and fairness in the availability for people. Strict PB yields stronger shifts in P fertiliser reduction responsibilities between different countries, high crop yield losses and high inequality in the availability of crop calories to humans compared to the upper- or loose-limit PB. Redistribution under the equality and food security principles showed smaller losses of crop calories, although it may increase inequality in the availability of crop calories per person. This negative effect can be alleviated through more intense agricultural product trade between countries, which is hampered by large obstacles to deglobalisation concerns in the post-pandemic world.

Limitations and uncertainties of P fertiliser use redistribution. Redistribution has been widely used in estimating national carbon dioxide (CO_2) reduction targets (Raupach et al., 2014; Pozo et al., 2020; Williges et al., 2022). This is easier than for P because the increase in CO_2 concentrations is more even across the globe (Li et al., 2022). Water pollution by P shows a large spatial variation around the world (Mekonnen et al., 2018). This may lead to a dilemma in which the redistribution principles, through considering equality or food security, may result in distributing P to regions with severe water pollution. Hence, instream or offshore water P concentration-based bottom-up modelling may help to avoid such a dilemma; for example, the Global-NEWS and IMAGE models can both be used to quantify the amount of P entering inland water and offshore at the global scale for a few fixed certain years (Mayorga et al., 2010; van Wijnen et al., 2017), and the latter model is even able to simulate P concentrations in water with a link to an extra hydrologic model (Mogollón et al., 2021; Langhans et al., 2022). However, the effects of P fertiliser redistribution on local water quality are still not covered.

Another issue is that P fertiliser redistribution rates or reduction targets for different countries may change over time. For example, China's reduction target under the responsibility principle 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 after 2015 (MARA, 2017). Likewise, the results of the equality principle may vary with the selection of the start and end years because of the fast changes in P fertiliser use and population during the past few decades (Fig. S1). P fertiliser redistribution under the food security principle may also vary when considering the role of food in terms of providing protein or other essential nutrients, and changes in crop caloric production react to changes in P input in the future.

Actions for improvement of P deficit. Global crop calorie losses and inequality in the availability of crop calories for humans could be largely decreased when there was considerable improvement of P use efficiencies of crop production and improvement of P management of the entire food production-consumption system, as illustrated in Fig. 5, of which actions towards 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 these potentials for recycling P from the food system could be achieved, partly because of the availability of cost-effective technologies, for example, the higher social economic and environmental costs (Jupp et al., 2021). In addition, partly due to the uneven geographic distribution of crop and livestock systems, for example, the uneven geographic distribution of crop-livestock systems has greatly limited the potential of manure N and P recycling in China, of which approximately 4–5 Tg P was not economically recycled (Jin et al., 2020).

Policy recommendations. Despite its 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 fair redistribution of global P fertiliser. Such a system would allow trade of the reduction targets between countries; since countries have different capabilities and motivations to achieve PB, this may allow a better achievement of PB at the global level. In addition, more rational use of P should also be strengthened after the country distribution target has been determined. In dealing with global nitrogen pollution, Gu et al. (2021) developed a unique credit system that provides new insights for the redistribution of P use more concretely to reduce water pollution without lowering food security or quality targets. 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 favour the success of fair P use, food security and clean water for all humans.

Conclusions

We argued that there is a need to redistribute P fertiliser use to reverse unfair P fertiliser use and related crop calorie production and access by humans. We developed and tested four unique principles to redistribute P fertiliser use to each country combined with the planetary boundary of P. Our study shows that there are important tradeoffs between smaller crop calorie yield losses and fair availability of crop calories to humans, especially under strict planetary boundary values. However, the majority of these negative effects can be alleviated through increased input in crop production to increase resilience to lower P input, increasing recycling of P within the food production-consumption system, and increasing agricultural product free trade. Moreover, a global, high-resolution P concentration-based water pollution model is required, not only to provide a bottom-up solution to the redistribution of P fertiliser under PB guidelines but also to provide clues for improved water quality.

Methods

P fertiliser redistribution principles

Responsibility principle. This principle considers the redistribution of P fertiliser use to the historical apparent soil P surplus from 1961 to 2018, of which the most reliable results were available. The apparent soil P surplus was defined as follows:

Soil P $_{surplus\_a}$ = Total P $_{input\_crop}$ – Crop P $_{uptake}$ (1)

where Soil P $_{surplus\_a}$ is the P surplus of crop production in a country from 1961 to 2018, in kg; Total P $_{input\_crop}$ is the total P input into croplands, including synthetic P fertiliser input, manure applied to soil, and straw applied to soil, in kg. Crop P $_{uptake}$ is the amount of P content of all crop products in one country from 1961 to 2018. This was calculated based on the total yield of 178 types of crop species 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). P fertiliser application reduction rate, either under the upper limit (11.2 Tg P) or lower limit (6.2 Tg P), will be equally distributed to each country according to their share of the global total apparent soil P surplus from 1961 to 2018. This means that countries with a higher soil P surplus receive a lower amount of redistributed P fertiliser, which is also logical since crops can benefit from residual P in the soil. The reduction target in each country should not be larger than its P fertiliser use. The rest of the reduction target will be distributed to countries that still have P fertiliser use and based on their share of soil P surplus.

Capability principle. The P fertiliser application reduction target will be distributed according to the GDP value of crop production for each country during the period 2016–2018, based on the assumption that rich countries have more capacity to invest in high tech solutions that rely on less P fertiliser. However, we do 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. These values have also been widely used in the payment of open access fees for major open-access journals. The detailed list of different countries of different groups is shown in Table S1. The crop GDP value of each country was also derived from FAOSTAT (Table S2). Similarly, the reduction target will transfer between countries by considering their corrected share of the global crop GDP value when needed.

Equality principle. The equality principle considers an equal share of P fertiliser use per capita during the period between 1961 and 2050, towards the target date of 2050 to achieve PB. The historical cumulative P use between 1961 and 2018 was collected from FAOSTAT. We assume a linear regression of PB implementation towards 2050 and predict P use for each year between 2018 and 2050. Then, the global average P use per capita could be calculated using global cumulative P use divided by the cumulative population between 1961 and 2050. The projection of the human population between 2018 and 2050 was derived from FAOSTAT (Table S2). The annual P use per country could be determined as follows:

$P\ use_{country\ i} = (P\ use\ per\ capita_{global\ average} * Cumulative\ population_{(1961–2050)\ country\ i}) − Cumulative\ P\ use_{(1961–2018)\ country\ i})/32$ (2)

where $P\ use_{country\ i}$ is the redistributed P use rate of a select country per year after 2018, in kg; $P\ use\ per\ capita_{global\ average}$ is the calculated equal average P use per capita at the global level between 1961 and 2050, in kg capita^{-1}; $Cumulative\ population_{(1961–2050)\ country\ i}$ is the cumulative population of a particular country between 1961 and 2050; $Cumulative\ P\ use_{(1961–2018)\ country\ i}$ is the cumulative P use of a select country between 1961 and 2018, in kg; and 32 is the count of years between 2018 and 2050.

Food Security principle. The target upper-limit or lower-limit PB will be directly distributed to each country according to their share of total global crop calorie production. The crop production of 178 species was collected for each country, and the total crop calorie production was calculated based on the production value and calorie content of each crop species (Renard et al., 2019).

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 N, P and potassium (K) fertiliser 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 analyse 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, manure P input on phosphorus use efficiency. The crop sown areas were calculated as the share of cereal, bean, vegetable, and fruit in total crop sown area, respectively (Table S2).

Declarations

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Author contributions

Z.B. X.C. and L.M. developed the original research question and designed the paper; L.L. performance the original data collection, data processing and preparing the figures and tables; all the authors wrote and revised the manuscript.

Competing interests

The authors declare no competing interests.

Data and code availability

All the data used in this study will be share upon the acceptance.

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Figures

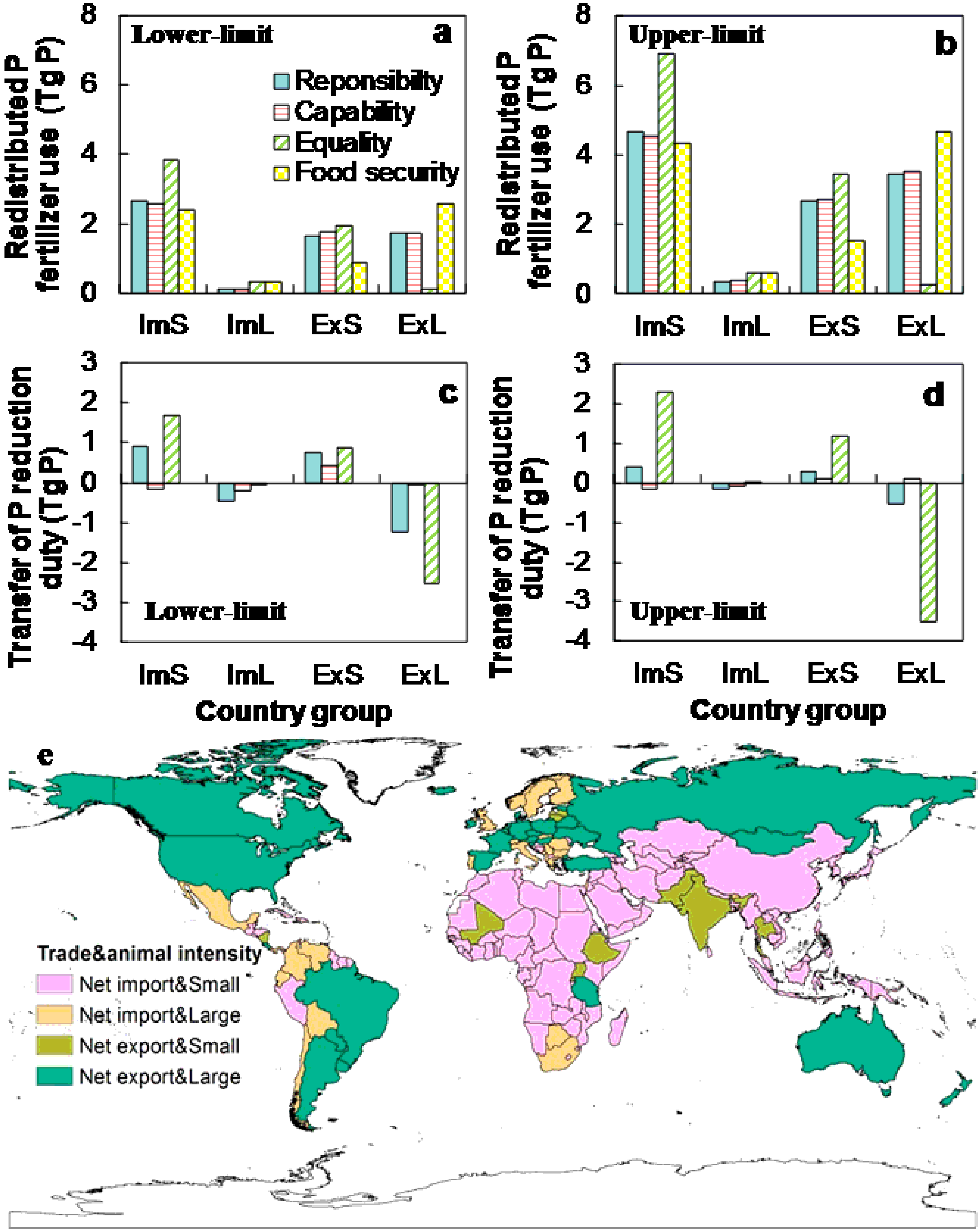

Figure 1

Synthetic phosphorus (P) fertiliser use (a, b) and their ratios to current P fertiliser use (c, d) for different country groups under four redistribution principles (responsibility, capability, equality and food security) and different levels of planetary boundaries for P (lower limit, 6.2 Tg P; upper limit, 11.2 Tg P) and the countries that belong to each country group (e).

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

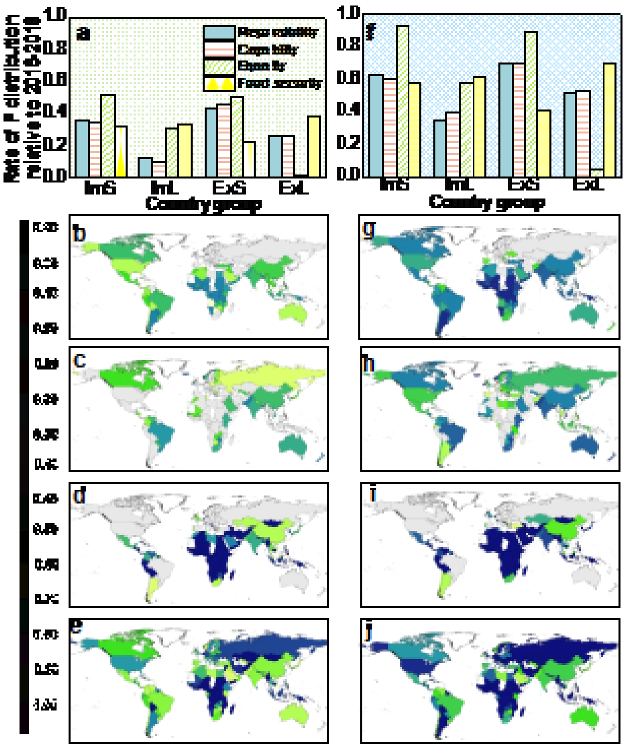

Figure 2

Ratio of redistributed P fertiliser use to current use (three-year average value between 2016–2018) for different country groups (a, f) and for different countries under four redistribution principles:

responsibility (b, g); capability (c, h), equality (d, i) and capability (e, j) under the lower-limit (left panels) and upper-limit (right panels) planetary boundaries.

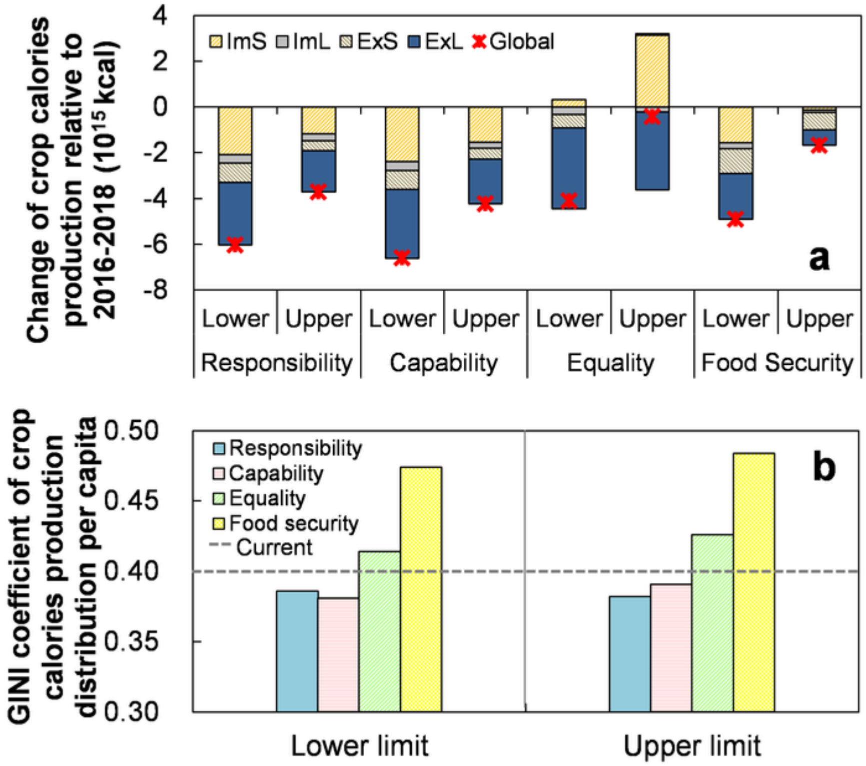

Figure 3

Potential impacts of redistribution of P fertiliser use under lower-limit and upper-limit planetary boundaries on crop calorie production relative to 2016–2018 (a) and the GINI coefficients (as an indicator of fairness for per capita crop calorie distribution) (b) under the responsibility, capability, equality and food security principles.

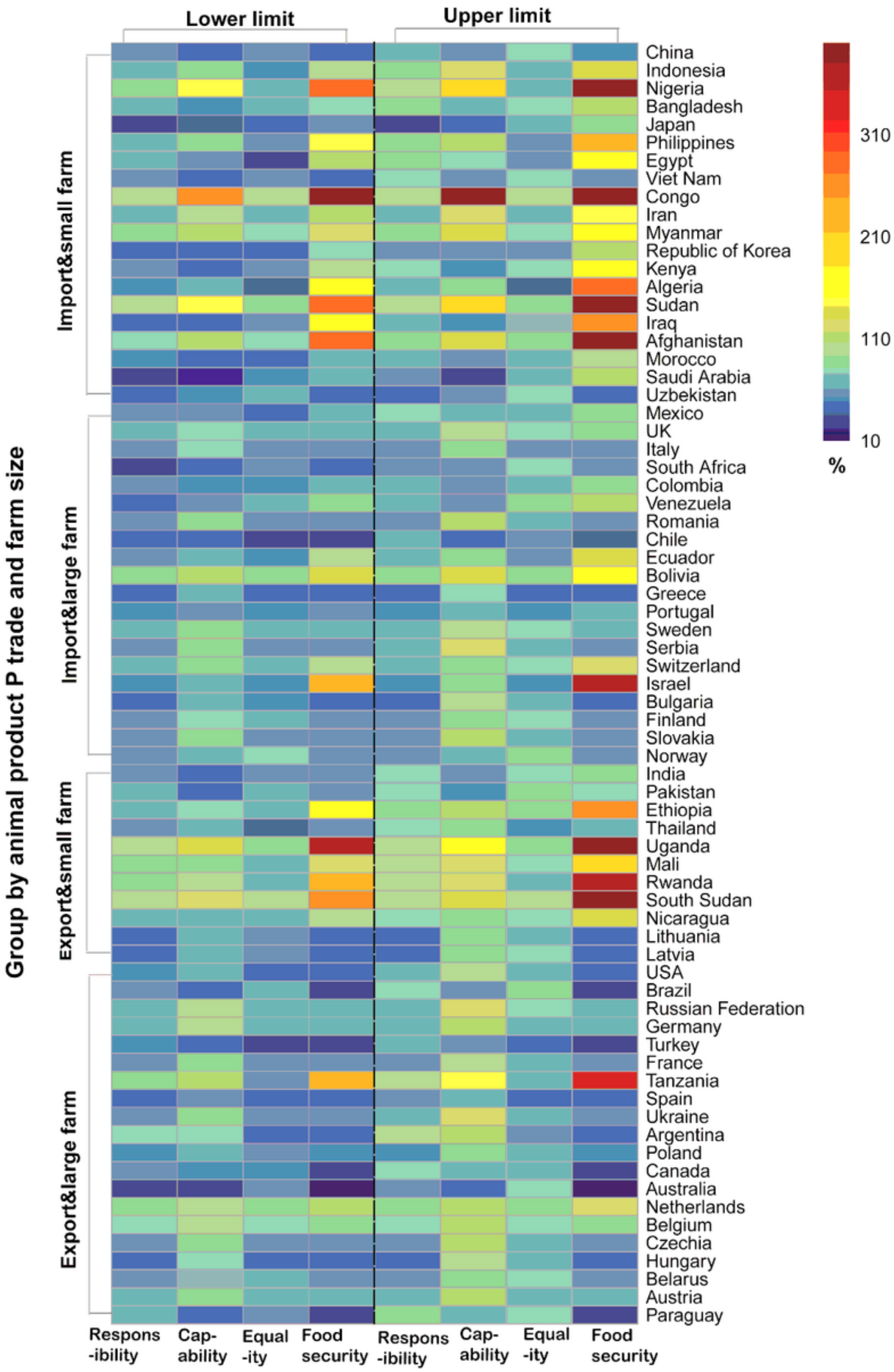

Figure 4

Potential impacts of the redistribution of P fertiliser use under lower- and upper-limit planetary boundaries on crop calorie production relative to 2016–2018 for the main representative countries within different country groups under the responsibility, capability, equality and food security principles (unit: %).

Note: Red colours represent increasing crop yields relative to 2016–2018, while green and blue colours indicate reducing crop yields.

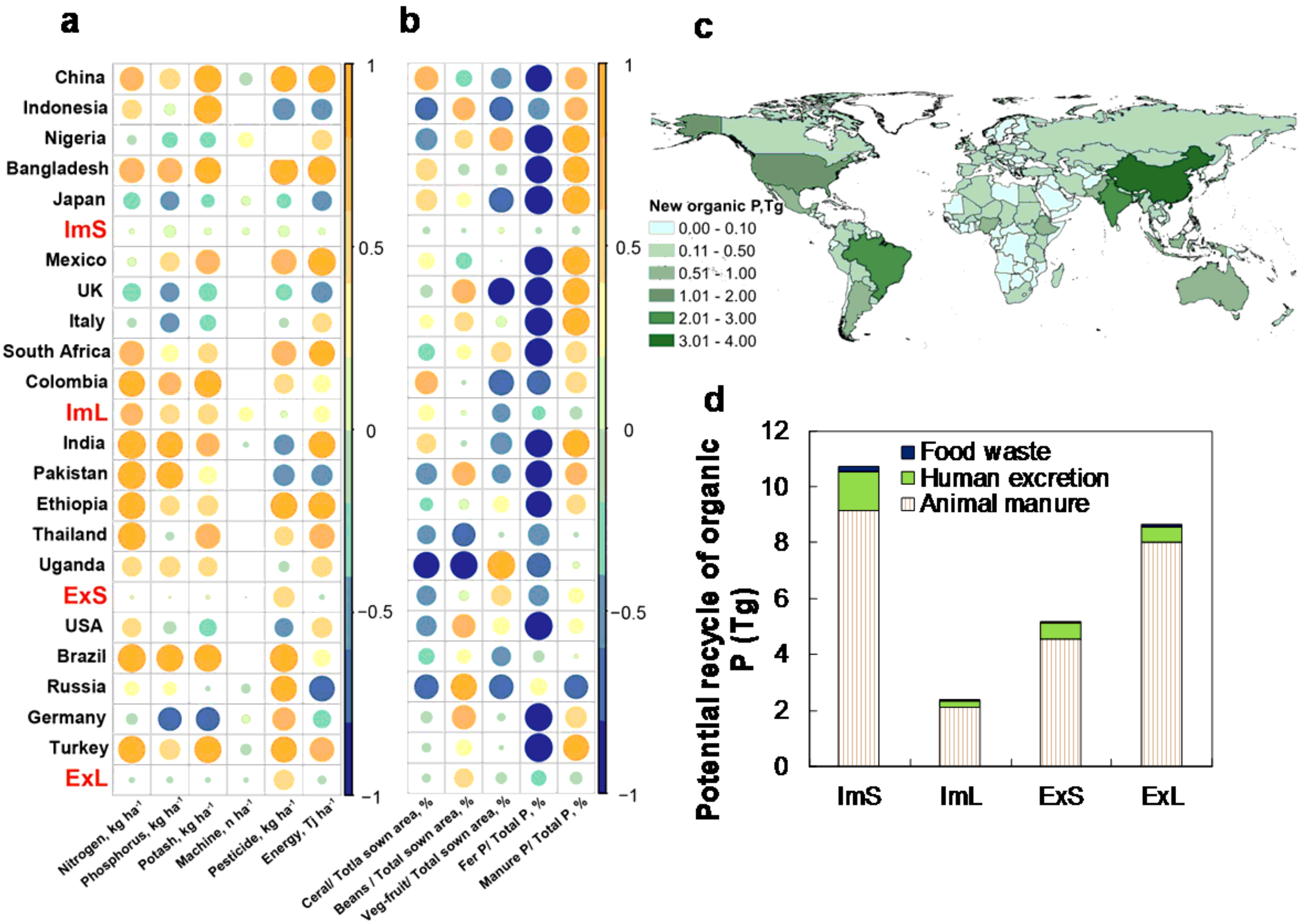

Figure 5

Pearson analysis of the main factors that impact crop energy productivity (a) and P use efficiency (b) of crop production for different country groups and their five representative countries and recycling P from livestock manure and human excreta for different countries (c) and country groups (d).

Note: Orange and blue colours represent positive and negative effects, respectively. The darker the colour is, the stronger the effects. The blank grid in fig 5a, means data not available.

Supplementary Files

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