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Enhanced mitigation in nutrient surplus driven by multilateral crop trade patterns

Hongwei Lu [1,6✉], Wei Feng[1,2,6], Pengdong Yan[3], Jiajie Kang[3], Chunfang Jiang[3], Qing Yu[1,2], Tianci Yao[4], Yuxuan Xue[1,2], Dongzhe Liang [5] & Yiming Yan[1,2]

Multilateral crop trade is likely to drive enhancement or mitigation of nutrient surpluses of the trading countries; however, the driving mechanisms are unclear. Here we explore the effects of multilateral crop trade on nitrogen and phosphorus surpluses based on two optimal multilateral crop trade models, a regional nutrient surplus model and crop trade data. Focusing on China and Central Asia, we find that optimal multilateral crop trades are effective to mitigate both nutrient surplus and footprint. Compared to the base year (2018), a single-objective-based crop trade would drive an obvious transition from nitrogen surplus enhancement (1170.5 kt) to mitigation (−705.8 kt over 2030–2034); the phosphorus surplus enhancement would be transferred from 1741.5 to mitigation of −2934 kt. Driven by the bilevel-objective-based crop trade, great mitigations in both nitrogen and phosphorus surpluses are detected, with the projected levels reaching −571 and −2809 kt, respectively. This implies that strengthening optimal multilateral crop trades across the world would facilitate global nutrient management.

[1] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China. [2] University of Chinese Academy of Sciences, Beijing, China. [3] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin, China. [4] Guangzhou Institute of Geography, Guangdong Academy of Sciences, Guangzhou, China. [5] School of Water Conservancy and Hydropower Engineering, North China Electric Power University, Beijing, China. [6] These authors contributed equally: Hongwei Lu, Wei Feng. ✉email: luhw@igsnrr.ac.cn

A projected 50–100% growth in global food demand by 2050 indicates that growing crop planting and the associated fertilizer uses would be required[1,2]. When excess nitrogen (N) and phosphorous (P) owing to overmuch fertilizer uses are released into the environment, a variety of environmental problems will be induced such as groundwater contamination[3], freshwater eutrophication[4,5], and estuarine ecosystems[6] and tropospheric pollution[7,8]. To mitigate the adverse environmental and health impacts, the United Nations has even established a set of Sustainable Development Goals (SDG 2.4, 6.4, 6.6. and 15.1, etc.)[9,10] focusing on global nutrient management. Many studies have been undertaken to investigate the N and P emissions from agricultural activities[11,12], fate and transport in the environment[13], spatiotemporal evolution[14], and pollution control[15,16] at the global or regional scales. Some researchers have also used the nutrient footprint tool for thoroughly understanding the lifecycle process of N and P contents embodied in a product or an entity's consumption activities, from the emissions to eventual fixation in the environment[17,18].

Recently, nutrient surplus (NS or PS) has received concerted attention because inappropriate surplus (maintaining as potential long-term pollution sources) may impose threat to the environment[19]. Since the nutrient surplus reflects the inputs exceeding crop and forage needs[20,21], nutrient use efficiency has been thought to be one of the most important approaches for controlling excess nutrients[22,23]. Nutrient surplus footprint (NSF or PSF) is an indicator improved based on the concepts of nutrient surplus and nutrient footprint. It can simultaneously reflect the potential environmental risk arising from the flowing-state nutrient remaining in the environment and the crop gain from the stabilized-state nutrient fixed by the crop. Moreover, more information associated with crop activities such as nutrient budget in cropland and virtual nutrient flow are implied in the indicator, creating a bridge between nutrient surplus and crop trade. This helps evaluate the nutrient surplus mitigation or enhancement given various multilateral crop trade patterns. However, it is unclear that how the nutrient surplus responds to multilateral crop trading patterns (MCTs) and which patterns have the highest potential to mitigate the surplus. Without addressing these questions, we would be short of a scientific basis when establishing policies for synergic safeguarding the food production and environmental protection.

This study attempts to gain insight into not only spatiotemporal evolution of nutrient surplus footprint at the multinational scales, but also response of nutrient surplus to anthropogenies activities such as MCT. To achieve this goal, we here i) propose an integrated nutrient surplus footprint evaluation model (INSFEM) to calculate the N and P surplus footprints for a MCT system; ii) examine the response mechanisms of nutrient surplus to current crop trade patterns: mitigation or enhancement by using the nutrient surplus tool; and iii) detect the response of N and P surpluses to a set of projected trade patterns so that the most suitable one can be identified from the perspectives of both environmental stress and economic return. Outputs from this research would probably help mitigate the local poverty to a certain degree by establishing sustainable agricultural development and environmental protection policies.

We focus our scope on the abovementioned six inter-neighboring countries. The reasons are specified as follows. (i) Food security and guaranteeing have been the major challenge across the world including Centra Asia[24–26]. Kazakhstan is one of the largest grain exporting countries in the world; Uzbekistan is the main cotton producing and exporting country; Turkmenistan is basically self-sufficient in food; Kyrgyzstan's food self-sufficiency rate is about 90%; Tajikistan is a relatively low-income country in short of food[27,28]. Strengthening crop trade cooperation within these countries will benefit to mitigating the problems of hunger and poverty in these countries[29,30]. The current scale of multilateral crop trade among the countries is relatively weak, compared to those among the countries like US, Australia, and Brazil. Nevertheless, it has shown great potential to strengthen in future years[31–33]. (ii) China and central Asian countries are facing severe N- and P-related environmental problems due to either overuse of fertilizers or loss of soil fertility in arable lands. This leads to adverse effects on environmental quality, human health, and food security[34–37]. (iii) Multilateral crop trade could be a useful tool in mitigating such environmental burdens in addition to alleviating the local poverty (by maintaining stable food supplies)[38–40]. (iv) We have accumulated abundant data and information in the past years through various means of site investigation, expert survey, and literature review. This provides us convenience in knowledge acquisition, modeling calibration, parameter estimation, performance evaluation, etc. However, it is extremely short of related understandings particularly regarding the food and environment nexus. Strengthening research on these countries would help fill the knowledge gap, which is beneficial to extend this work to future global-scale studies (Detailed presentation on this issue can be seen from section 3.1 of the Supplementary information).

Results

Spatiotemporal evolutions of NSF and PSF. We use the INSFEM to evaluate the NSF and PSF in 1992–2018 for the six countries in terms of data of 144 crops (aggregated to 12 classifications) (Fig. 1; Table S1). Note that in central Asian countries, we calculated the nutrient surplus at the national scale using the country-level data due to the lack of high-precision data. In China, the spatiotemporal characteristics of nutrient surplus are more complicated than those in the other countries so that using the country-level data could lower the precision of the results. Therefore, we initially calculated the nutrient surplus at the provincial scales and then totaled them at the national scale.

China has the NSF of about 2.0 and PSF of 2.8, which are about 67% and 22 times higher than the averages of the other five countries (1.2 and 0.12, respectively). Spatially, high NSF and PSF mainly present in the east and south China as well as Turkmenistan and Uzbekistan. As for the crops, maize contributes high NSF and PSF especially in China, Kyrgyzstan, and Uzbekistan. Turkmenistan and Uzbekistan have higher surplus footprints than the other three central Asian countries in large because maize, cotton, fruits, vegetables, and oil crops contribute increased footprints than the other crops (Fig. 1). Of particular concern should be given is that the footprints in part of central Asian countries (Kazakhstan and Kyrgyzstan) achieve negative values, implying long-term short of fertilizer use causes insufficient fertility but meanwhile mitigate the environmental degradation due to N and P. Temporally, all the six countries show consistently increasing footprints from 1992–2018 (Fig. S4), especially in China, Turkmenistan, and Uzbekistan. There is large difference in the footprints among the crops. In 2011–2018, the maize-driven footprints gradually turn to fruits-driven.

In this period, there is a rapid increase in NSF in Turkmenistan while slow in Uzbekistan (Fig. S4), attributed to the fast growth of N fertilizer use in Turkmenistan but stable use in Uzbekistan (Fig. S2). Excess fertilizer use and rather low N fertilizer use efficiency are the main mechanisms leading to high NSF in China and central Asian countries. Our estimations have shown that the average efficiencies are only about 33 and 45% in China and central Asian countries, respectively, which are much lower than those in the developed countries (about 70%) (Fig. S1). China shows a relatively rapid increase in PSF, which has grown by

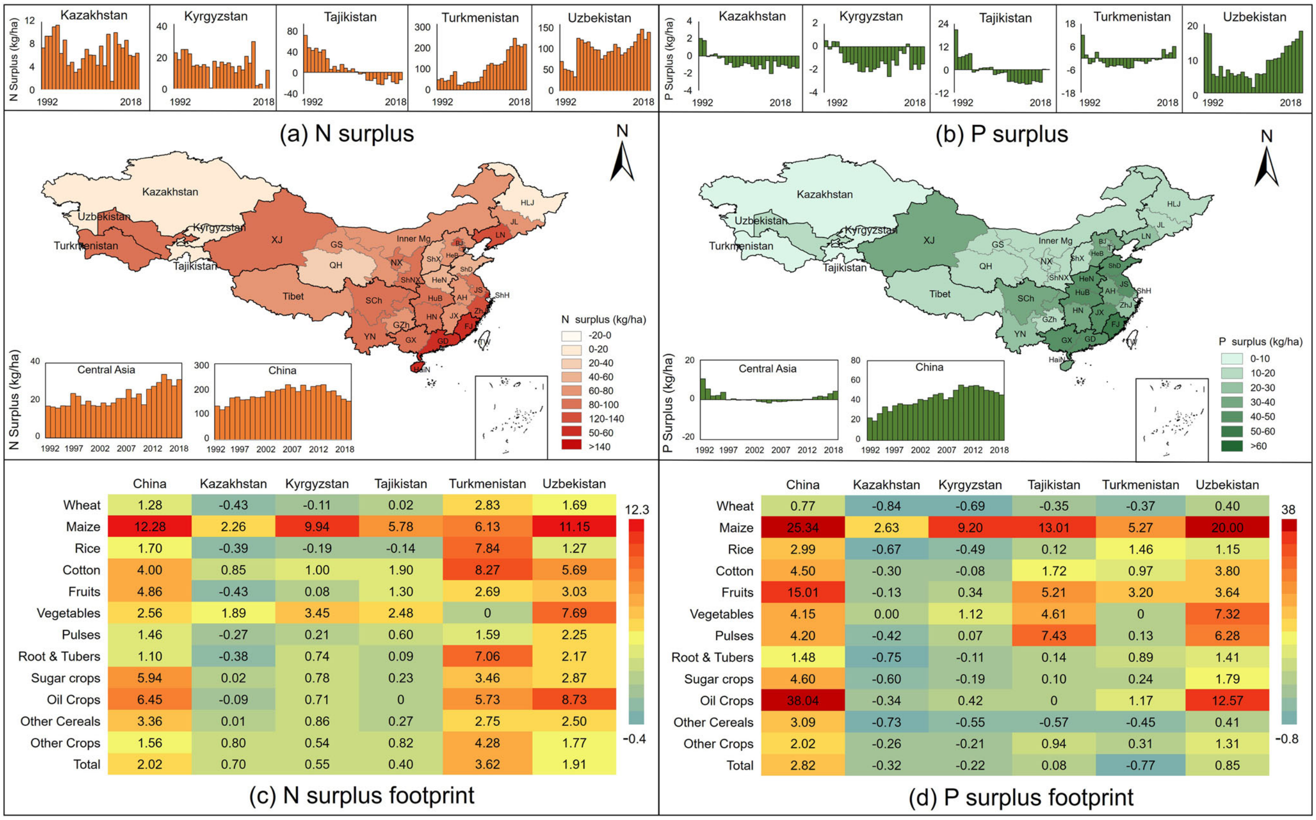

Fig. 1 Distributions of surplus footprints in China and Central Asia. (**a**) N surplus, (**b**) P surplus, (**c**) N surplus footprint, and (**d**) P surplus footprint calculated for the years of 1992–2018. The full name of acronyms on the provinces in China is shown in Table S2.

about 30% from 2.3 in 1990s to 3.0 in 2010s. Despite generally low PSFs in the central Asian countries, negative PSFs arising from part of crops (such as wheat, rice, and root and tubers) are detected, all lower than −0.5 (Fig. 1). To mitigate the adverse effect of PSF on environmental degradation, these crops would thus be attached sufficient importance and incorporated into integrated N and P management practices.

Response of surplus footprints to net crop trade amount/structure. We examined the response of NSF and PSF to the net crop trade amount and trade structure. Results showed that all the countries except Kazakhstan maintained net crop imports with the amounts keeping growing in 1992–2018. Tajikistan shows the largest crop net import amount, followed by Uzbekistan and Kyrgyzstan, with the average amounts of 346.3, 301.8, and 154.0 kt over 1992–2018, respectively (Fig. S5). Seeing from the trade structure, China imports more and more cotton from the other countries, starting from 4.5 kt in 1992, then reaching its peak of 392.9 kt in 2006, and declining gradually to 82.6 kt in 2018. Kazakhstan, as the only net exporter, maintains a small amount of import mainly focusing on vegetables and fruits, with the highest amounts of 418.9 kt and 485.314 kt in 2013, respectively. The remaining countries maintained high proportions of wheat import, accounting for 84.5% of their total imports (Fig. S6).

Further linear regression analysis is employed to test the relationships of NSF and PSF with trade amount and trade structure across the countries. On the one hand, both NSF and PSF (mainly contributed from wheat, maize, fruits, vegetables, and oil crops) show obvious relationships with trade amount and trade structure (Figs. 2, S7; Tables S8–S11). In China, trade amounts for crops including wheat, maize, fruits, and oil crops shows the highest relationships with NSF and PSF. In central Asian countries, trade amounts for crops including wheat, maize, fruits, and vegetables show relatively good relationships with NSF, while those including wheat, pulses, roots and tubers, and vegetables present good relationships with PSF (Fig. 2a, b). On the other hand, the NSF and PSF in China have good relationships with the trade structure (considering the trade proportions of wheat, maize, and oil crops). In the central Asian countries, the NSF has rather good relationships with the trade structure (considering proportions of fruits and oil crops), whereas the PSF is good with proportions of maize, cotton, and vegetables (Fig. 2c, d). Note that all the p-values above are <0.05. These results show that both NSF and PSF have obvious response to trade amount and trade structure.

Mitigation or enhancement of nutrient surplus driven by virtual nutrient trade. Moreover, we investigate the virtual N and P flows subject to crop trade from 1992 to 2018 and the resulting N and P surplus variations: mitigation or enhancement (Fig. 3). The virtual N and P flows between any two of the six countries become more and more enhanced with growing trade amount (Figs. 3a–c, S8a–c). One of the most obvious observations occurs between China and Kazakhstan, whose net virtual N flow is only 40 kt (in 1992–2000) but increased by about 4.6 times (225 kt in 2011–2018). The net virtual P flow is generally higher than the net virtual N flow. Between Kazakhstan and China, the virtual net virtual P flow increases from 40 to 413 kt (by over 10 times) and the P flows in 2001–2010 and 2011–2018 are 38 and 84% higher than N flows, respectively. These variations in net N and P virtual flows due to crop trade may correspond to temporal changes in N and P surplus mitigation or enhancement over the countries.

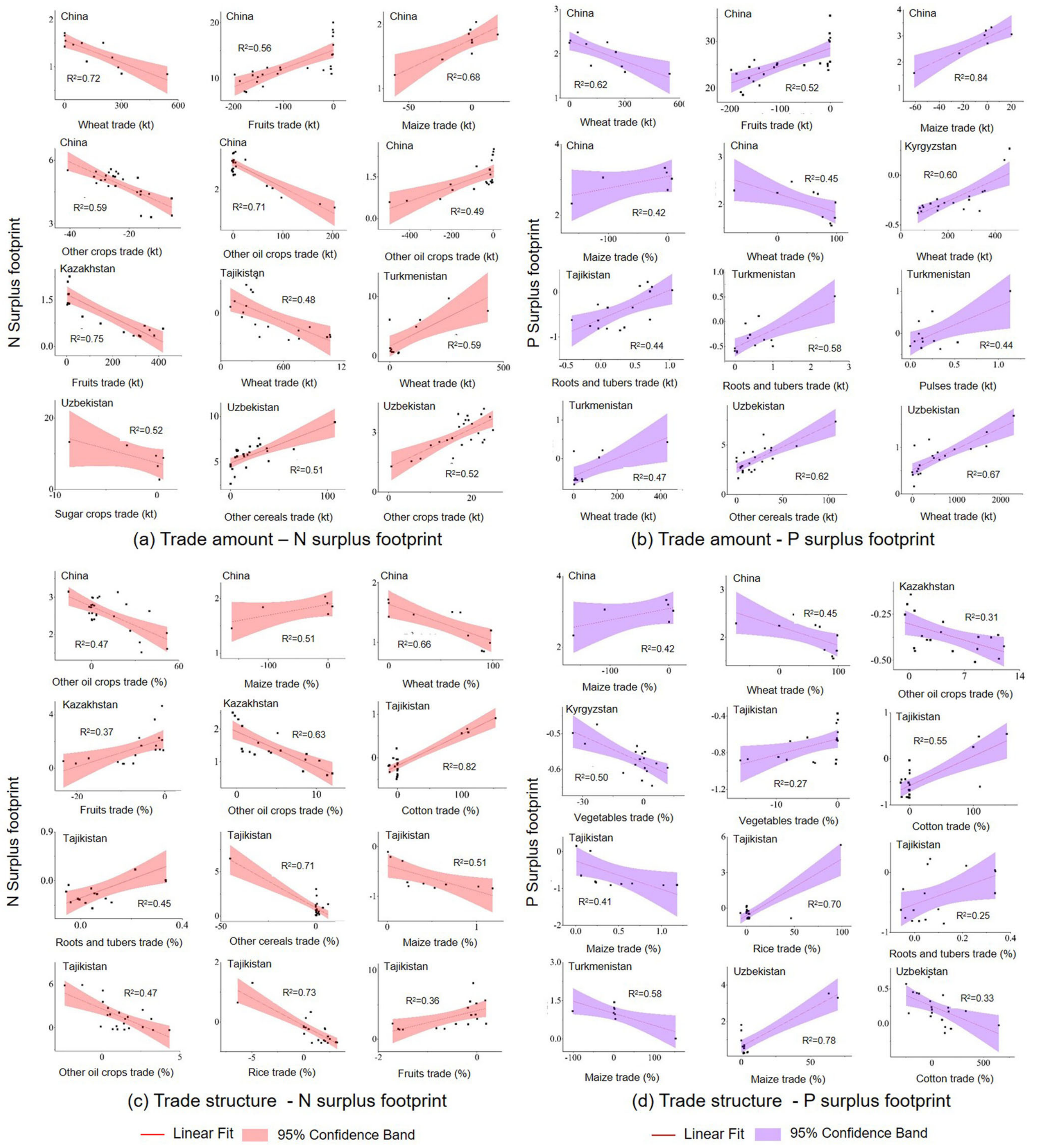

Fig. 2 Relationships between nitrogen (N) and phosphorus (P) surplus footprint and trade amount and structure. (**a**) N surplus footprint and trade amount, (**b**) P surplus footprint and trade amount, (**c**) N surplus footprint and trade structure, and (**d**) P surplus footprint and trade structure. The other crops and their associated correlation coefficient matrices are shown in Fig. S7 and Tables S8–S11.

Further observation shows that the past crop trade between China and the five central Asian countries drives obvious surplus enhancement (Fig. 3d–i; S8d–i), despite slight mitigation in the trade for wheat and oil crops. The highest total NS enhancement and PS enhancement for China occurring in 2013 (2066 and 4575 kt, respectively). The trade between China and Kazakhstan drives the highest NS enhancement and PS enhancement in 2013 (1641 and 3753 kt, respectively), and then followed by Kyrgyzstan (289 kt in 2007 and 1258 kt in 2006, respectively) and Uzbekistan (296 kt in 2015 and 323 kt in 2018, respectively). Such enhancement in N and P surpluses can be attributed to the multilateral trade for fruits, vegetables, and rice. This suggests that the past trade patterns are not generally reasonable due to the non-negligible N and P surplus enhancements from inappropriately virtual N and P flows, and there is necessity of improving the past patterns to achieve surpluses mitigation rather than enhancement.

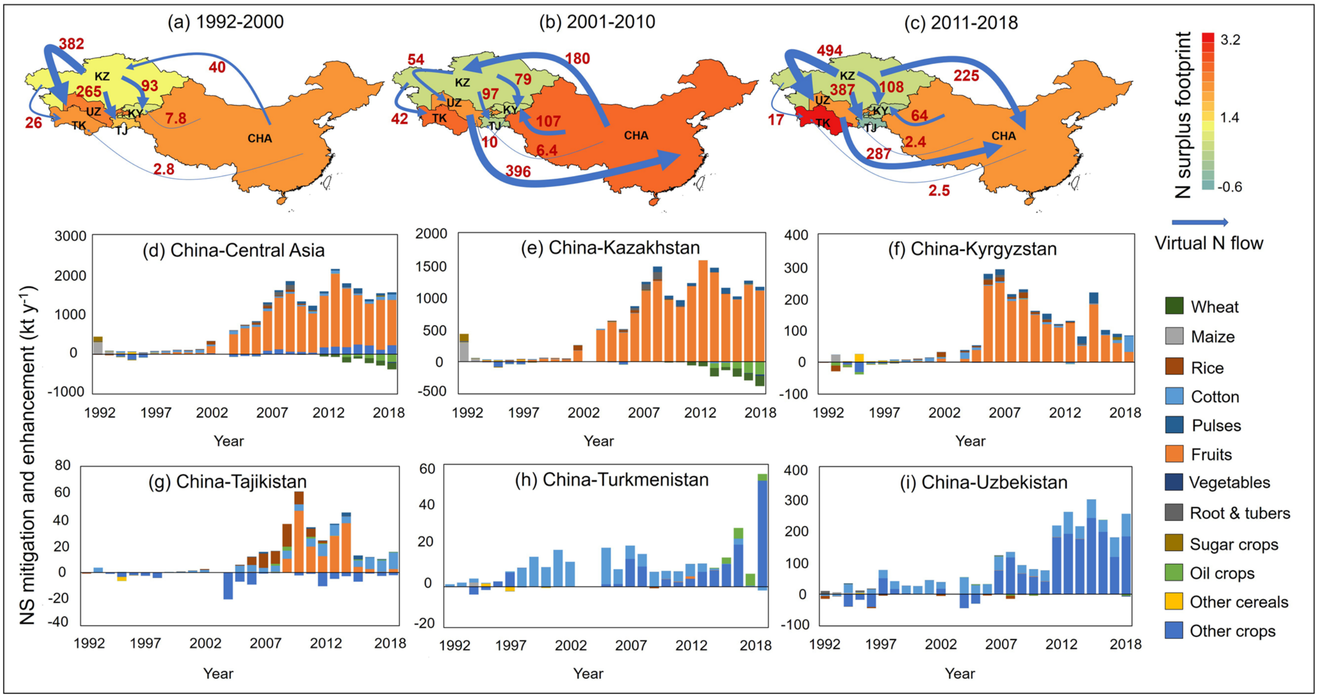

Fig. 3 Virtual nitrogen (N) and phosphorus (P) flows and resulting mitigation or enhancement of nutrient surplus. (**a**–**c**) virtual N flows, (**d**–**i**) N surplus mitigation/enhancement in China and the central Asian countries, where the positive and negative y-axis represents enhancement and mitigation, respectively. Details on virtual P flows and P surplus mitigation/enhancement are shown in Fig. S8.

Nutrient surplus mitigation/enhancement driven by MCT patterns. We therefore continue to examine the response of NSF and PSF to a set of trade patterns so that the most suitable trade patterns can be identified simultaneously from the perspectives of environmental stress and economic return. We design four types of trade patterns through simply changing trade amount, adjusting trade structure, and using outputs from our developed optimal MCTs, with all the patterns based on 2018 as the fundamental year. In specific, the first type is to change the trade amount (both exports and imports) by (i) increasing trade amount by 50% (TV1), 100% (TV2), and 150% (TV3) and (ii) decreasing the trade amount by 50% (TV4), 80% (TV5), and 100% (TV6). The second is to adjust the trade structure by (i) increasing the trading proportions of fruits and vegetables by 50% (TS1), 100% (TS2), and 150% (TS3) and (ii) decreasing the proportions by 50% (TS4), 80% (TS5), and 100% (TS6). We here only consider adjustment of fruits and vegetables because they are important crops driving N and P surpluses enhancement. Changes in the trade proportions of the two crops can facilitate N and P control in high efficiency. In these scenarios, we have not considered the constraints on demands and production capacities of each country. To accommodate more factors that need to be considered, we continue to design a set of more reliable scenarios by using mathematically based optimal MCT models. The third is generated though a linear programming model with the objective of maximizing system benefit (OP1). The fourth is to employ a bi-level programming model, where two objectives are proposed: maximizing the system benefit and minimizing the inequality level of water-land benefits (OP2). The same planning periods are assumed as the linear model. Outputs from the two models include optimal trade amount and trade structure for the six countries. The planning horizon covers the years of 2020–2034, which is divided into three planning periods, with each one representing 5 years.

Figure 4 shows the obtained NSF, PSF, NS mitigation (or enhancement) and PS mitigation (or enhancement) due to virtual flows among the countries under patterns TV1–TV6 and TS1–TS6. NSF and PSF would insensitively response to variations in both trade amount and structure. When increasing the trade amount, the NSF and PSF in China would slightly rise by about 0.001–0.002. In comparison, those in the central Asian countries would obvious decline particularly when the trade amount increases by 150%. In TV3, the NSF of central Asia would decrease slightly by about 2%, compared to 1.38 in 2018, while the PSF of central Asia would decline by about 5% from 0.3 (Fig. 4a, b). However, NS and PS would remarkably response to the change of trade amount. Driven by increased trade amount, China would have an obvious transition from NS enhancement (1170.5 kt in 2018) to NS mitigation (−530.3 kt, decreased by about 145% under TV3, and PS mitigation would reach the peak (−2131 kt) (Fig. 4c). When the trade structure changes, NSF and PSF would vary slightly owing to weak N and P flows (Fig. 4d, e), but NS enhancement would occur, and PS enhancement would be weakened (Fig. 4f). For example, under scenario TS6, NS enhancement would be changed from 1170.5 kt (in 2018) to 1228.7 kt, increased by about 5%; the PS enhancement would be weakened by about 8%, from 1741.5 kt in 2018 to 1604 kt. This shows growing trade amount is beneficial to nutrient surplus mitigation while varied trade structure leads to the enhancement. Therefore, control of the trade amount is a better tool for mitigating nutrient surplus than trade structure.

We further seek to identify the most effective trade patterns that contribute to potential mitigations in nutrient surplus under OP1 and OP2. It is obvious that both patterns would improve the footprints of the six countries (Fig. 4g, h, j, k). For example, the OP1 pattern shows that NSF and PSF in China would diminish by 3% and 2.4% from 1.36 to 1.32 and from 2.50 to 2.44, respectively. In central Asian countries, the NSF and PSF would diminish by 16 and 37% from 1.38 to 1.16 and from 0.30 to 0.19, respectively. Meanwhile, strengthened virtual N and P flows due to crop trade would also bring about a

Fig. 4 Mitigation and enhancement of nutrient surplus and footprint driven by the optimal multilateral crop trade patterns. (**a**–**c**) TV, (**d**–**f**) TS, (**g**–**i**) OP1, and (**j**–**l**) OP2, where the positive- and negative values in the *y*-axis represent enhancement and mitigation, respectively. (NSF/PSF: Nitrogen/Phosphorus surplus footprint; NS/PS: Nitrogen/Phosphorus surplus; TV: Scenarios of trade amount; TS: Scenarios of trade structure; OP1: Single-objective optimal multilateral crop trade model; OP2: Bi-level objectives optimal multilateral crop trade model).

positive effect. In period 3 under OP1, there would be a transition from 1170.5 kt of NS enhancement to −705.8 kt of NS mitigation (decreased by about 160%); the PS enhancement would be transferred from 1741 kt to mitigation of −2934 kt (Fig. 4i). Obvious NS mitigation and PS mitigation are also detected corresponding to OP2 (Fig. 4l). The NS mitigation and PS mitigation would transfer from 1170.5 kt to −571 kt and 1741 to −2809 kt, respectively. The lowering NS mitigation and PS mitigation from OP2 than that from OP1 is mainly due to the introduction of inequality objective for water and land resources benefits and a set of fairness constraints, which leads to rather conservative optimal virtual N and P flows. Notwithstanding, this analysis implies that both the optimal MCTs are more effective approaches in mitigating nutrient surplus, compared to simply adjusting trade amounts and trade structure.

Discussion

We use INSFEM to examine the response of N and P surpluses to varied multilateral crop trading patterns, focusing on China and five central Asian countries. We find the obvious response of NSF and PSF to varied trade amount and trade structure among the six countries, leading to potential N and P surpluses mitigation or enhancement. Results also reveal that growing trade amount is beneficial to surplus mitigation while varied trade structure leads to enhancement. Therefore, control of the trade amount is a better tool for mitigating nutrient surplus than trade structure. Nutrient surplus shows positive response to the optimal multilateral crop trade pattern obtained with single objective (OP1), followed by that with bi-level objectives (OP2), and then those with changing trade amount. This is reasonable because optimal MCTs consider maximizing the total system benefit and meanwhile minimizing the inequality level of water-land benefits, while simply changing trade amount and trade structure cannot guarantee optimal allocation of available water, soil, and capital resources during the trade. OP1 has demonstrated to be the best pattern for intensifying nutrient surplus mitigation; there would be an obvious transition from 1170.5 kt of N surplus enhancement to −705.8 kt of mitigation in period 3 (decreased by about 160%); the P surplus enhancement would be transferred from 1741 kt (in 2018) to mitigation of −2934 kt (in period 3). The positive but rather lower response to OP2 is mainly due to the introduction of inequality objective for maintaining the tradeoff between water and land resources benefits and fairness.

One implication in this research lies in the improvement on future crop planting patterns. Conventional patterns seldom consider environmental issues resulting from excess N and P discharging into the environment. If they are incorporated into future patterns, those cropping types contributing to low N and P surplus footprints would be preferentially planted such as wheat and root & tubers. By contrast, those with high footprint contributions (e.g., maize and oil crops) would be carefully chosen. For mitigating N and P discharges, measures would be considered either by declining their planting area to some degree[41], introducing new high productive planting technologies[42], or improving fertilizer use efficiency[43–45]. The other implication is in the reinforcement of crop trade patterns. Historical records have shown that the crop trade scale among the six countries is quite low, while it has increased by about 90 times from US$462 million to US$41539 million in the past 30 years[46]. This suggests that there would be high potential to expand future trade scale. Policies are thus desired probably by intensifying crop trading activities, opening to incorporate more countries into the trading policy framework, and developing various offline and online trading platforms to broaden the current trading approaches[47,48].

Argument has been existing on multinational commercial trading, particularly when those developed countries are included[49,50]. A set of adverse impacts of these trading patterns can hardly be overlooked such as intensified environmental degradation, overmuch resources exploitation, and unfavorable ratio of expenditure to payment among the trading countries[51,52]. Therefore, a key issue is that trading equality should be paid sufficient concern for maintaining long-term sustainable trading. Recent studies probably to provide a good means that introduces Gini-coefficient-based inequality level into policy-making framework[53]. To enhance trading efficiency and achieve maximal gains from trading, optimal multilateral crop trading models would be useful. Despite the existing optimization models to be available, there is difficulty in extending it to wider-scale applications, e.g., global trading systems. Global Trade Analysis Project (GTAP) is one of the widely used tools for assisting in developing global trading pattens[54]. However, challenges will need to be addressed including generation of dynamic optimization trading patterns under various future changing conditions and accommodating trading equality into the patterns[55–57].

The environmental implication in highly efficient nutrient management is also contributable[58,59]. Results in this research have revealed that NSF and PSF would vary with different trading patterns, with either positive or negative response. Therefore, integrated evaluation of NSF and PSF and their response to varied trading patterns are necessary before policy making on nutrient management. Based on it, suggestions on strengthening nutrient management are given as follows to mitigate the adverse environmental impacts. First, NSF and PSF, similar to N and P concentrations in the environment, are added as new indicators into the Sustainable Development Goals and their upper limits (thresholds) are determined through quantitative tools. Second, proposal of a comprehensive nutrient management framework is desired, accounting for more nutrient-related environmental and technological indicators, including nutrient footprint, surplus footprint, use efficiency, and their associated environmental and ecological risks. Third, technological advance is introduced that is beneficial to nutrient footprint mitigation; for example, scientific planting patterns and crops with high N- and P-fixation capabilities are given priority[60,61]. Fourth, incentives are quite important in mitigating nutrient surplus[62,63]. In addition to MCT, agricultural subsidies and loans may also be good ways driving farmers to select highly efficient planting technologies and enhance fertilizer use efficiency, likely causing increased decline in nutrient surplus[64–66].

As this work is initially performed, future studies will be required from various perspectives. First, the model is run at the national scale due to the limitation of data availability. Refined simulation accuracy is desired by using those input data with high resolutions, although there is difficulty in achieving high resolution gridded parameters such as field capacity, nutrient excretion rate, and deposition rate. Second, the INSFEM is proposed only for a limited number of countries, whose generalization is to be validated at the global scale. The findings would similarly exist in expanded trading systems covering more countries, although we here did not show quantitative evidence. In future studies, modeling improvement is thus expected for facilitating global N and P management. Particularly with the rising number of countries involved in the trade, the complexity of the model would be greatly enhanced so that appropriately designed modeling structures and improved solution algorithms would be desired. Third, it is unclear whether nutrient surplus would have response to climatic conditions (such as increasing precipitation)[67,68] and human activities (agricultural trade)[35,69]. Future studies will be conducted to understand how their future variations will impact on nutrient surplus and what measures will be adopted for offsetting the adverse or utilizing the positive impacts.

Methods

System boundary. This study focuses on N and P surpluses produced by crop planting for its great contribution to soil. We calculate the nutrient surplus of cropland system and its responses to various crop patterns in 1992–2018 for the inter-neighboring six countries: China, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan in terms of data of 144 crops and aggregate them to 12 classifications (Table S1). The concepts and the acronyms used in this study are shown in Table 1.

Integrated nutrient surplus footprint evaluation model (INSFEM). The INSFEM is an integrated model to estimate the nutrient surplus footprint of crop planting systems. The total N input of the INSFEM refers to the addition of N to cropland in forms of synthetic fertilizer application (IN_{fer}), animal N manure (IN_{man}), atmospheric N deposition (IN_{dep}) and biological N fixation (IN_{fix}). The N output in INSFEM is the N withdrawal from the field through crop harvesting (N_{har} and P_{har}). In this study, we compute annual nutrient surplus and the surplus footprints of cropland in China and Central Asia from 1992 to 2018 based on INSFEM. Detailed calculation of the budget terms is discussed in Section I of the Supplementary Information.

Table 1 Concepts and the acronyms used in this study.

Concepts	Acronyms
Integrated nutrient surplus footprint evaluation model	INSFEM
Multilateral crop trade	MCT
Nitrogen surplus	NS
Phosphorus surplus	PS
Nitrogen surplus footprint	NSF
Phosphorus surplus footprint	PSF
Single-objective optimal multilateral crop trade model	OP1
Bi-level objectives optimal multilateral crop trade model	OP2
Scenarios of trade amount	TV1–TV6
Scenarios of trade structure	TS1–TS6

Calculated by the INSFEM, a nutrient surplus is the difference between the total nutrient input (e.g., fertilizer, animal manure, legumes fixation and atmospheric inputs) and the output (crop products) of the national cropland budget. Nutrient surplus footprint is defined as nutrient surplus per unit N/P harvest from crop production. Virtual nutrient flows occur when nutrient surplus is transferred from one area to another due to crop trade.

Nitrogen Surplus (NS) and Phosphorus Surplus (PS). A nutrient balance describes the difference between all nutrient inputs and outputs on cropland. Nutrient surplus occurs when not all the fertilizers, animal manure and other nutrient inputs applied to the land are absorbed by the plants or removed during harvest. Negative value indicates soil N or P depletion, and can induce soil depletion, soil degradation. NS is calculated by the following equation:

$$NS = IN_{fer} + IN_{man} + IN_{fix} + IN_{dep} - N_{har} \quad (1)$$

For P, the same approach is used, with P inputs being animal manure, fertilizer, and atmospheric deposition.

$$PS = IN_{fer} + IN_{man} + IN_{dep} - P_{har} \quad (2)$$

Nutrient Surplus Footprint (NSF and PSF). It is defined as the ratio of the amount of nutrient surplus to that of nutrient harvested by the crop within a same area of the cropland:

$$NSF = \frac{NS}{N_{har}} \quad (3)$$

$$PSF = \frac{PS}{P_{har}} \quad (4)$$

Nutrient surplus mitigation and enhancement. In terms of evaluation results for NSF and PSF, we continue to investigate the impacts of crop trade on nutrient surplus variations: mitigation or enhancement. Nutrient surplus mitigation can be used to evaluate the sustainability of soil nutrient, that is, the direction of virtual nutrient flow from areas with low surplus footprint to areas with high surplus footprint. Oppositely, there would be nutrient surplus enhancement. Thus, the mitigation options are calculated by the following equations:

$$NS\,mitigation_{i,j,x} = T_{i,j,x} \times (NSF_{i,x} - NSF_{j,x}) \quad (5)$$

$$PS\,mitigation_{i,j,x} = T_{i,j,x} \times (PSF_{i,x} - PSF_{j,x}) \quad (6)$$

where i, j and x correspond to the import country, the export country and traded crops, respectively; $T_{i,j,x}$ is the amount of crop x traded from country j to country i; $NSF_{i,x}$ ($PSF_{i,x}$) and $NSF_{j,x}$ ($PSF_{j,x}$) refer to the NSF of import country i and export country j, respectively. The negative values of NS $mitigation_{i,j,x}$ (PS $mitigation_{i,j,x}$) (<0) indicates that crop x traded from country i to country j could lead to nutrient surplus mitigation; conversely, the positive values (>0) indicate this trade could lead to nutrient surplus enhancement (NS enhancement and PS enhancement). Thus, the total nutrient surplus mitigation between China and the central Asia countries can be calculated as the following equation:

$$NS\,mitigation = \sum_x \sum_{(i,j)} NS\,mitigation_{i,j,x} \quad (7)$$

$$PS\,mitigation = \sum_x \sum_{(i,j)} PS\,mitigation_{i,j,x} \quad (8)$$

Optimal multilateral crop trade models. The trade was modeled considering the market competition (price, cost, benefit, distance), resources transfer (water, soil, etc.), and virtual mass flow (N and P). If a certain trade pattern is selected, governmental regulations at the national levels will be important in stimulating and assisting in the implementation of the pattern.

(1) Single-objective-based optimal multilateral crop trade model:

Objective: to maximize the total system benefit
Constraints:

i. Water and soil resource constraints: including irrigation water demand constraints and planting area constraints.
ii. Trade amount constraints: including demand amount constraints and import and export balance constraints.
iii. Water and soil resources benefit equalization constraints, including the equalization constraints for water and soil resources.
iv. Nonnegative Constraints

Decision variables: planting area, crop import of a country involved in the trade, and export amount involved in the trade.

(2) Bi-level objective-based multilateral crop trade model:

Upper-level objective: to minimize the inequality level of water-land benefits
Upper-level constraints:

(i) Constraint of the Upper Limit of the Inequality Coefficient
(ii) Constraint of Virtual Water Efficiency

Lower-level objective: to maximize the total system benefit.
Low-level constraints:

(iii) Planting area constraint
(iv) Constraint of Irrigation Water Consumption
(v) Trading Constraints
(vi) Nonnegative Constraints

Decision variables: planting area, crop import of a country involved in the trade, and export amount involved in the trade.

Data availability

All datasets used in this current study were acquired from the following open sources: The agricultural data from Food and Agriculture Organization of the United Nations, FAO (https://www.fao.org/faostat/en/#data); the fertilizer data from the International Fertilizer Industry Association, IFA (http://ifadata.fertilizer.org/ucSearch.aspx); the meteorological data from the Data Center for Resources and Environmental Science, Chinese Academy of Sciences (https://www.resdc.cn) and National Tibetan Plateau Data Center (http://data.tpdc.ac.cn).

Code availability

The regional nutrient surplus model can be performed in Microsoft Office Excel 2010 by following the steps and equations in Methods. The codes to run the optimal multilateral crop trades are available from the corresponding author upon reasonable request.

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H.L. and W.F. equally contributed to this work, who designed the research and wrote the paper. H.L., W.F., P.Y., C.J., J.K., and Q.Y. performed calculations and results analysis. T.Y., Y.X., D.L., and Y.Y. collected the data and conducted data processing.

Competing interests
The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Hongwei Lu.

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