

Research article

Potential for improving micronutrient supply and environmental sustainability by using underutilized crops in China

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ABSTRACT

Rice and wheat provide the bulk of calories in diets globally. However, foods made from these cereals are commonly in refined forms and are low in micronutrients and dietary fiber. Increasing the consumption of more nutrient-dense, underutilized cereals and beans (UCBs), such as millet, sorghum, mung bean, along with unrefined rice and wheat, could improve diet quality. Compared with rice and wheat, UCBs are generally cultivated using less intensive methods, resulting in a lower environmental impact, though their productivity is generally lower. This study explores how reallocating rice and wheat areas to UCBs, either alone or combined with greater use of unrefined rice and wheat, could potentially enhance micronutrient supply (iron, thiamin, riboflavin, calcium, zinc), while reducing water use and greenhouse gas emissions in China. A strategy combining area reallocation and greater use of unrefined rice and wheat increased micronutrient supply and dietary fiber by 12–82%, reduced environmental impact by 11–12%, and slightly increased energy supply (3%). These outcomes were achieved by reallocating 7.9 million hectares (Mha) of rice area (26% of the current total) and 1.7 Mha of wheat area to sorghum (+5.5 Mha), millet (+2.5 Mha), beans (+1.4 Mha), and oats (+0.2 Mha). As a result, the supply of UCBs and unrefined rice and wheat products increased, supporting healthier diets. Reallocating only 5% of the rice area would still yield improvements, especially for dietary fiber and iron (>27%). These findings offer insights for rethinking the value of UCBs and supporting their integration into future food system strategies.

1. Introduction

The global food system relies on a few high-yielding crops (e.g., rice, wheat) to provide 60% of the dietary energy intake of the world population (Willett et al., 2019; Siddique et al., 2021). The focus on high-yield crops has greatly increased global dietary energy availability and reduced the number of undernourished people in recent decades (Pingali, 2012). However, imbalanced diets, micronutrient deficiencies, and nutrition-related chronic diseases are widespread globally (Black et al., 2013; Willett et al., 2019). The cultivation of high-yield and high-input crops depends on intensive use of agricultural inputs (e.g., irrigation), resulting in water resource depletion and substantial GHG emissions (Galloway and Cowling, 2002; Rockström et al., 2007; Willett

et al., 2019). Moreover, the overreliance on a limited number of crop species also reduced agricultural and dietary diversity, weakening food system resilience (Khoury et al., 2014). To build more sustainable and resilient food systems, we need solutions that improve nutrient supply, reduce environmental impact, and enhance agricultural and dietary diversity.

Increasing the supply and consumption of crops that are nutrient-dense and require low resource inputs can be a win-win strategy for human health and environmental sustainability (van Zonneveld et al., 2023; Siddique et al., 2021). Among these crops, so-called underutilized cereals and beans (UCBs) are potentially valuable alternatives to the

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major staple crops rice and wheat (Davis et al., 2019). The term “underutilized” reflects their limited cultivation and consumption, as well as the lack of sufficient research investment and policy support compared to crops that dominate current food systems (Li et al., 2020b). However, UCBs are rich in vitamins and minerals, and are drought-tolerant and relatively well adapted for cultivation on poor soils (Li et al., 2020b; Siddique et al., 2021). Thus, promoting the use of UCBs can help combat micronutrient deficiencies, support healthy diets, and increase agricultural and dietary diversity, thereby strengthening food system resilience (Siddique et al., 2021).

Previous studies showed that promoting the use of UCBs in local food systems can theoretically enhance micronutrient intake or the production of micronutrient-dense food while reducing environmental impact (Yin et al., 2024; Davis et al., 2018, 2019). These previous studies analyzed the same topic from two perspectives, consumption and production. From the consumption perspective, Yin et al. (2024) proposed healthier diets than baseline with increased intake of UCBs and unrefined grains while reducing intake of refined grains to improve micronutrient intake and lower environmental impact. However, realizing such a large-scale dietary change, e.g., a 3.9-times increase in consumption of unrefined grains compared to baseline, requires adjustments on the supply side as indicated for further study by Yin et al. (2024). From the supply perspective, area reallocation is a promising strategy to support healthy diets, increase nutrient supply, reduce environmental impact, and increase farmers’ income (Davis et al., 2018, 2019; Xie et al., 2023; Shi et al., 2024). Davis et al. (2018, 2019) found that reallocating areas from major staple crops to UCBs in India can enhance the production of micronutrient-dense foods and reduce environmental impact. However, their analysis did not account for food trade, or regional differences in crop demand driven by factors such as population density, which were suggested as topics for future research (Davis et al., 2018, 2019). If decisions about where to grow which crops only consider cultivation while ignoring where the crops will be used, such isolated adjustments may unintentionally increase the distance between production and consumption, increase transport-related GHG emissions (Zuo et al., 2023), and offset emission reduction gains achieved during cultivation. Therefore, we propose an integrated analysis that links production, food trade (via transportation), and regional consumption needs, while assessing broader nutritional indicators (including dietary fiber, minerals, and vitamins) beyond iron and zinc analyzed in the prior studies. This approach enables a more comprehensive assessment of the potential for expanding UCB cultivation to support healthy diets and benefit both human nutrition and the environment.

Expanding UCB areas at the expense of major staple crops could be a promising strategy to enhance nutrient supply, reduce environmental impact, and support diverse and healthier diets. This strategy can provide insights for countries that have limited agricultural diversity, an overreliance on major staple crops, and insufficient supply and intake of micronutrients. In this study, we focus on China, where rice and wheat are the staples that dominate the agricultural and food systems, while the potential of UCBs remains largely untapped (Diao, 2017). China faces dual pressures from both limited sustainability of agricultural production and unbalanced dietary consumption, calling for solutions that can support nutritious diets with a lower environmental impact. The agricultural system faces challenges like water resource depletion and over-application of nitrogen and phosphorus. Dietary patterns are characterized by insufficient intake of whole grains, alongside excessive intake of refined grains and red meat (He et al., 2018). Although energy and macronutrient needs are generally met, dietary fiber intake is low, and micronutrient deficiencies persist (Yu et al., 2016; Zhang et al., 2018; Yu et al., 2021; Ayling et al., 2023). These challenges underscore the importance of exploring how expanding the cultivation of UCBs could help improve both nutrition and environmental outcomes. Furthermore, underutilized cereals are typically consumed as whole grains, while rice and wheat are mainly processed and consumed in refined

forms in China. Greater use of unrefined rice and wheat is therefore an alternative option to decrease nutrient loss and improve nutrient supply (NDRC and NFSRA, 2025).

A more sustainable and healthier food system requires actions across the food supply chain. As one of these steps, we explore here for China options to improve micronutrient supply and environmental sustainability by reallocating rice and wheat cultivated areas to six UCBs (millet, sorghum, buckwheat, oats, mung bean, and adzuki bean) while making greater use of unrefined rice and wheat flour. Nutrient supply focuses on dietary energy, protein, dietary fiber, and five micronutrients (thiamin, riboflavin, calcium, iron, zinc), as their intake in China falls below the recommendations and UCBs generally have higher nutrient density for these nutrients than rice and wheat, especially in their refined forms (Yu et al., 2021; NINH, 2018). Environmental sustainability is evaluated by total weighted water use during cultivation and GHG emissions from cultivation and food trade (i.e., transportation). The total weighted water use (TWWU) was based on each province’s water use adjusted by the related water stress index (Zhao et al., 2015), giving greater weight to water use in water-scarce provinces, which reflects the environmental burden. Crop uses for feed, non-food purposes, and international trade remain at baseline levels. Any increase in UCB supply from reallocating rice and wheat areas is assumed to be fully dedicated to food consumption use. Scenario S1 (baseline) evaluates the current nutrient supply and environmental impact of all considered crops and serves as a benchmark. Scenario S2 analyzes the impact of increased use of unrefined rice and wheat. Scenario S3 explores reallocating rice and wheat areas to UCBs, while scenario S4 combines a greater use of unrefined rice and wheat and area reallocation. All scenarios use linear programming or compromise programming (a specific form of linear programming) that aims to optimize multiple objectives simultaneously. In reality, implementing area reallocation among crops requires considering more factors, such as consumer acceptance, producer incentives, and the agronomic feasibility of switching crops. Therefore, the potential presented here represents a theoretical potential based on the crops considered.

2. Methods

2.1. Model outline and scenario description

This study considered six UCBs for which provincial-level production data are available in China, namely millet, sorghum, oats, buckwheat, mung bean, and adzuki bean, along with the two major staple crops (rice, wheat). These six UCBs accounted for 62% of the total cultivated area of all UCBs in China in 2022 (NBS, 2018-2022). Barley is also considered a UCB, but only 7% of the barley supply is used for food (FAO, 2018-2021), hence we did not include barley in our analysis. The cultivated area, production amount, nutrient supply, and environmental impact of the other UCBs were assumed to remain unchanged. The potential implications of excluding other UCBs will be addressed in the discussion section.

We developed a linear programming model linking crop production, trade (international and interprovincial), and regional consumption, while accounting for crop uses and food loss and waste. A baseline scenario (S1) was established to assess the current performance of the considered eight crops in China, using indicators such as per capita supply of energy, protein, dietary fiber, and micronutrients (thiamin, riboflavin, calcium, iron, zinc), total weighted water use, and total GHG emissions from cultivation and food trade (via transportation). The linear programming model was applied to quantify transport-related GHG emissions and to estimate the per capita supply for food consumption in each province (see Supplementary Materials Section 1.3 for details). Because per capita crop supply for food consumption (except rice) was estimated using a modeling approach rather than observed data, we will discuss the potential impact of this estimation in the discussion section.

Table 1

Scenarios. The scenarios differ in optimization objective, reallocating rice and wheat areas to underutilized cereals and beans (UCBs), UCB area restrictions per province, and unrefined rice and wheat proportions. Other elements that influence the nutrient supply and environmental indicators, such as international trade, feed, or non-food use, were kept at the 2022 level for crops in all scenarios. 'NA' stands for 'not applicable'.

	Scenario S1	Scenario S2	Scenario S3		Scenario S4
	Baseline	Greater use of unrefined rice and wheat	Reallocating areas		Reallocating areas and greater use of unrefined rice and wheat
			S3a	S3b	
Objective	Transport cost	NA	Nutrition & environment indicators	Nutrition & environment indicators	Nutrition & environment indicators
Reallocate rice and wheat areas to UCBs	NA	NA	Yes	Yes	Yes
UCB area restriction in each province	NA	NA	Historical maximum	Two times the historical maximum	Two times the historical maximum
Unrefined rice and wheat proportions	Current	Increased	Current	Current	Increased
Indicators can perform worse than baseline	NA	NA	No	No	No

We then first explored the improvement ranges of indicators by reallocating crop areas. Each indicator was optimized individually, while ensuring others were not worse than the baseline. We did a supplementary analysis to analyze trade-offs among indicators (Supplementary Materials section 3).

Finally, three alternative scenarios (S2, S3, S4) were analyzed to improve nutrition and the environment (Table 1). Scenario S2 (Greater use of unrefined rice and wheat) assessed the impact of reverting the unrefined proportions of rice and wheat from their baseline levels (5% for rice and 25% for wheat, based on 2013 market shares, the most recent year with available data) to their 2002 levels (12% for rice and 35% for wheat) (Yu et al., 2020). Scenario S3 (Reallocating areas) used multi-objective optimization to explore how reallocating rice and wheat areas to UCBs within each province could improve the indicators. To align area expansion with agronomic feasibility and farmer experience, scenario S3a limited the cultivated area of each UCB to its historical maximum over the past 45 years (or from the earliest year with available data to 2022) and allowed cultivation only for crops already grown in each province. Given the wide adaptability of growing UCBs, scenario S3b relaxed the area constraint, allowing expansion to twice the historical maximum area. Scenario S4 (Reallocating areas and greater use of unrefined rice and wheat) estimated the potential of a combined strategy.

The mathematical notations, optimized objective functions, constraints, and decision variables for each optimization and the four scenarios are outlined in this section, and details are given in Supplementary Materials 1.1 and 1.3–1.7. All optimizations were solved using the docplex package in Python with IBM CPLEX version 12.9.0.

2.2. Estimating baseline supply for feed and non-food uses

At the national level, millet, sorghum, and oats were used for food and feed (FAO, 2022). Sorghum served multiple purposes, food, feed, and brewing, with approximately 10% of domestic production used for food in China (CFIIN, 2024). In this study, we assumed 10% of sorghum production to be allocated to food, while the rest of the domestic supply (production plus net import) was used for feed and brewing. Buckwheat, mung bean, and adzuki bean were used solely for food (Liu, 2018). Over 90% of rice and 70% of wheat supplies were used as food; non-food uses account for less than 4% (FAO, 2022).

Due to limited provincial data on feed and non-food crop uses in the baseline, we estimated these amounts as detailed in Supplementary Materials section 1.2. Feed use of each crop per province was estimated from provincial meat production and crop-to-meat conversion factors, while non-food use was allocated proportionally to each province's share of the national population.

2.3. Performance indicators in the baseline scenario

Per capita nutrient supply. The baseline per capita nutrient supply in demand province j for nutrient k ($TSupply_{kj}^{base}$) was calculated based on supply of crop m for food consumption (S_{mj}^{food}) (Eq. (1)). To more accurately reflect nutrient supply, the calculation incorporated food waste (θ_m^{waste}) (Xue et al., 2021), the allocation of grain supply to refined grains ($\mu_m^{refined}$; 95% for rice, 25% for wheat) and whole grain forms (μ_m^{wg}) (Yu et al., 2020), and conversion factors from harvested grains to either refined ($\phi_m^{refined}$, 0.5 for refined rice and 0.74 for refined wheat flour) or whole grains (ϕ_m^{wg} , 0.76 for unrefined rice) (SAC, 2009), and nutrient content (n_{mk} for underutilized cereals and beans, $n_{mk}^{refined}$ for refined rice and wheat and n_{mk}^{wg} for whole grains) (NINH, 2018). We assumed that all harvested grains are transported to demand locations, where they are then processed into refined or unrefined forms. This assumption may overestimate transport-related GHG emissions, as inter-provincial trade involves both raw and processed products and China aims to shift away from transporting raw grains (NDRC and NFSRA, 2017). We used the nutrient content of minimally processed and uncooked food.

$$\begin{aligned}
 TSupply_{kj}^{base} = & \sum_{m \in M_{ucb}} \left[S_{mj}^{food} \cdot n_{mk} \cdot 10^6 \cdot (1 - \theta_m^{waste}) \right] \\
 & + \sum_{m \in M_{major}} \left[S_{mj}^{food} \cdot (\mu_m^{refined} \cdot \phi_m^{refined} \cdot n_{mk}^{refined} \right. \\
 & \left. + \mu_m^{wg} \cdot \phi_m^{wg} \cdot n_{mk}^{wg}) \cdot 10^6 \cdot (1 - \theta_m^{waste}) \right] \\
 & \forall k \in \mathcal{K}, j \in \mathcal{J} \setminus \{0\}
 \end{aligned} \quad (1)$$

Total weighted water use at the national level. The total weighted water use ($TWWU^{base}$) was calculated by multiplying water use in each supply province i by its water stress index (ws_i) (Zhao et al., 2015) and summing across all provinces (Eq. (2)). Each province's water use was quantified at cropland level by multiplying the unit total water footprint (wf_{mi} , $m^3 \text{ ha}^{-1}$, precipitation + irrigation) and the cultivated area of crop m (a_{mi}), and then adding up water use of all crops (Eq. (2)).

$$TWWU^{base} = \sum_{i \in I \setminus \{0\}} ws_i \cdot \sum_{m \in M} wf_{mi} \cdot a_{mi} \quad (2)$$

The unit total water footprint of each crop in every province (expressed in $m^3 \text{ tonne}^{-1}$) was obtained from Mialyk et al. (2024). We converted this into area unit total water footprint (wf_{mi} , $m^3 \text{ ha}^{-1}$) by multiplying by the corresponding provincial yield of each crop (tonne ha^{-1}).

Total GHG emissions at the national level. Total GHG emissions (TGE) from crop production and transportation were quantified in carbon dioxide equivalents (Eq. (3)). Production emissions were calculated by multiplying the crop-specific carbon intensity of cultivation (e_{mi}^0 , $\text{kg CO}_2\text{e ha}^{-1}$) by the cultivated area (a_{mi}). This intensity includes upstream emissions (e.g., fertilizer production) and in-field production (e.g., application and machinery use) (Liu et al., 2018; Ma et al., 2021; Chen et al., 2021). Transportation stage emissions included domestic and international transport, the transport amount (X_{mij}), and distance (l_{ij}). We treated all importing and exporting countries as a single overseas point, located 20,000 km east of China's coast, following the assumption in Zuo et al. (2023). Using a shorter distance (2000 km, 5000 km, 10,000 km) had little impact on GHG emissions reduction (Supplementary Table S1). This can be explained as the import and export quantities were maintained as the baseline in all analyses, and international transport (maritime transport) has a low emission intensity, $0.0035 \text{ kg CO}_2\text{e tonne}^{-1} \text{ km}^{-1}$ (Zuo et al., 2023). X_{mi0} was the export flow from provinces in China to the overseas point, X_{m0j} was the import flow. e_m^1 denotes the emission intensity of domestic transport ($\text{kg CO}_2\text{e t}^{-1} \text{ km}^{-1}$), while e_m^2 denotes the emission intensity of international transport.

$$TGE^{base} = \sum_{m \in \mathcal{M}} \left(\sum_{i \in \mathcal{I} \setminus \{0\}} e_{mi}^0 \cdot a_{mi} + \sum_{i \in \mathcal{I} \setminus \{0\}} \sum_{j \in \mathcal{J} \setminus \{0\}} e_m^1 \cdot X_{mij} \cdot l_{ij} \right) + \sum_{i \in \mathcal{H}} e_m^2 \cdot X_{mi0} \cdot l_{i0} + \sum_{j \in \mathcal{H}} e_m^2 \cdot X_{m0j} \cdot l_{0j} \quad (3)$$

2.4. Constraints in optimization models

The optimization models were developed to estimate baseline transport-related GHG emissions and per capita supply for food consumption and to explore strategies to improve nutrition and environmental sustainability. The models incorporate four types of constraints (full models and details about the constraints are provided in Supplementary Materials 1.3-1.7).

International trade constraints. To ensure that crop flows between China and overseas match the baseline amounts of import and export.

Flow balance constraints. At the national level, crop supply (production + imports – exports), after accounting for food loss, should match domestic supply for food consumption, feed, and non-food uses. The loss per crop was assumed to occur before crops were delivered to provinces for local use. For each province, net supply was calculated as local production plus inflow from other provinces, minus outflow to other provinces and food loss. This net supply should match the supply for provincial food consumption, feed, and non-food uses.

Cultivated area constraints. These constraints served three purposes, (1) to ensure UCBs area expansion came from reductions in rice and wheat, (2) reallocation was limited to crops already grown in each province, (3) in scenarios S3 and S4, crop area per province was further constrained by the historical maximum (or twice the maximum) from 1978 to 2022 (NBS, 1978-2022) to align expansion of UCB areas with farmer experience.

Sustainability performance constraints. In scenarios S2-S4, no indicators were worse than the baseline. Per capita nutrient supply did not decline in any province, total weighted water use in each province did not exceed baseline levels, and national GHG emissions did not surpass the baseline.

2.5. Multi-objective optimization

To simultaneously optimize all indicators in scenarios S3 and S4, we applied compromise programming, which identifies solutions closest to the best value of each indicator (Romero and Rehman, 2003). Each indicator F_t was normalized using its best value (F_t^* , from single-objective optimization) and baseline value (F_t^{base} , from scenario S1), then combined into a composite objective function.

All nutrition-related indicators were combined into a single metric, called total nutrient supply (TNS). We minimized the distance function (formula (4)) to find a set of alternative solutions by considering TNS, total weighted water use (TWWU), and TGE together. The indicators of TNS, TWWU, and TGE were assigned a user-defined weight w_t , reflecting their relative importance. A higher weight means the corresponding indicator contributes more to the total distance, causing the optimization process to prioritize improving that indicator. We applied equal weights for TNS, TWWU, and TGE, and tested multiple weight combinations (details in Supplementary Materials section 2 and Supplementary Fig. S1).

$$OBJ_L = \sum_{t \in \mathcal{T}} w_t \cdot \frac{(F_t^* - F_t)}{(F_t^* - F_t^{base})} \quad (4)$$

3. Results

3.1. Baseline performance and crop contribution (Scenario S1)

In the baseline scenario (S1), per capita nutrient supply varied across provinces. On average across provinces, the considered crops provided 1090 kcal of dietary energy per capita per day, 31 g of protein, 7 g of dietary fiber, 0.7 mg of thiamin, 0.2 mg of riboflavin, 59 mg of calcium, 6 mg of iron, and 4 mg of zinc (Supplementary Table S2). Rice and wheat together accounted for 94%-98% of the average supply of dietary energy and seven nutrients, while contributing 98% of total GHG emissions (mainly from cultivation) and 95% of total weighted water use (Supplementary Table S2). This is because rice and wheat together occupied 95% of the total cultivated area of 56 million hectares (Mha), comprising 30 Mha for rice, 24 Mha for wheat, and around 3 Mha for the combined six UCBs (Supplementary Table S3).

3.2. Improvement ranges among indicators

Reallocating rice and wheat areas to UCBs without area restrictions substantially improved nutrient supply and reduced environmental impact (Fig. 1(a)). Average increase (population-weighted across provinces) in iron supply quadrupled, that in dietary fiber, riboflavin, and calcium supplies more than doubled, and thiamin increased by 75% compared to the baseline. A lower increase was obtained for energy, protein, and zinc than for other nutrients (< 46%). However, if only reallocating areas among six UCBs, the improvements for all indicators were less than 8% (Fig. 1(b)). Optimizing different indicators resulted in different solutions for reallocating areas, while all solutions generally required reallocating 20–29 Mha of rice areas and 4–17 Mha wheat areas to sorghum (9–41 Mha), millet, oats, and beans (Supplementary Table S4).

3.3. Performance of scenarios S2, S3, and S4

We compared three scenarios (S2, S3, S4) with the baseline (S1) to assess nutrient supply and environmental outcomes. Greater use of unrefined rice and wheat alone (S2) improved nutrient supply but hardly reduced environmental impact, whereas reallocating areas alone (S3a, b) or combined with greater use of unrefined rice and wheat (S4) simultaneously improved nutrient supply and reduced environmental impact (Fig. 2(a)). Among all scenarios, the combined strategy (S4) achieved the greatest improvements in all nutritional indicators. The average supply of iron across all provinces improved substantially in all scenarios compared to baseline (14%–82%), followed by dietary fiber (22%–57%), calcium (5%–38%), riboflavin (7%–32%), thiamin (8%–25%), and zinc (2%–12%) (Fig. 2(a)). Energy and protein supplies were slightly above the baseline (0%–7%). Meanwhile, total weighted water use and total GHG emissions decreased by up

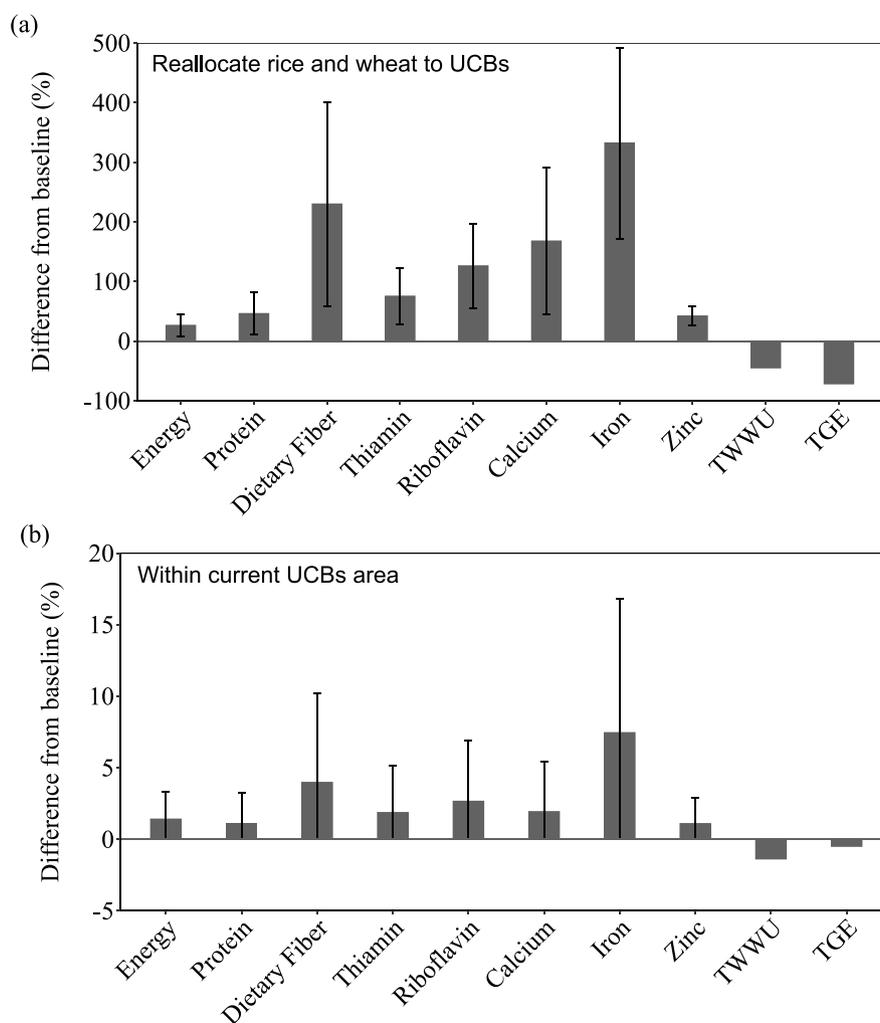


Fig. 1. Changes in per capita nutrient supply, total weighted water use (TWWU), and total GHG emissions (TGE) when optimizing each indicator separately. (a) When reallocating rice and wheat cultivated areas to UCBs without restriction on the expansion of cultivated area. (b) When area reallocation was only allowed within the cultivated areas of the considered UCBs. For nutritional indicators, each bar shows the population-weighted average of provincial percentage change relative to the baseline when that indicator was optimized. Error bars represent the standard deviation of the percentage change across provinces. The changes of TWWU and TGE were evaluated at the national level.

to 12%. Energy supply increased by no more than 3% in all scenarios, while micronutrient supply improved substantially, indicating that more micronutrient-dense foods can be provided with these strategies.

Allowing UCBs to exceed historical area limits (S3b) improved nutrient supply (except energy) and environmental outcomes compared to scenario S3a (Fig. 2(a)), indicating that expanding UCB areas beyond historical levels can be encouraged in regions with suitable climatic and resource conditions to increase nutrient supply while lowering environmental impact. Compared to area reallocation (S3a and S3b), greater use of unrefined rice and wheat (Scenario S2) performed equally well or better in terms of energy, protein, dietary fiber, thiamin, and zinc supply, but showed smaller improvement in riboflavin and calcium, and environmental impact.

To achieve better nutrient supply and environmental outcomes, sorghum area increased most (2.9–5.5 Mha) in scenarios S3 and S4, followed by millet (1.8–2.5 Mha), while mung bean (1.1–1.4 Mha), oats (0.1–0.3 Mha) and adzuki bean areas (0.1–0.3 Mha) increased slightly compared to the baseline (Fig. 2(b)). The total cultivated areas of buckwheat remained nearly unchanged from the baseline. In contrast, rice areas would have to be reduced by 4.9–7.9 Mha (17%–26% of the national baseline rice area), and wheat areas by 0.9–2 Mha (4%–9% of the national baseline wheat area).

3.4. Provincial area change and environmental benefit in scenario S4

To simultaneously improve nutrient supply and environmental sustainability with the combined strategy (Scenario S4), rice area was mainly dedicated to growing sorghum, millet, and mung bean in certain regions (Fig. 3(a)). Although six UCB species were included as options, only some were selected by the model for cultivation expansion. Specifically, sorghum and millet areas increased by 0.5 to 2 Mha in Northeast China, sorghum area expanded by 0.15 to 2 Mha in North China, while mung bean, adzuki bean, sorghum, and millet areas increased by around 0.15 Mha in most southern and southwestern provinces (Fig. 3(a)). In contrast, 19 of the 31 provinces showed relatively small changes in crop areas (< 0.15 Mha). This is partly because, in 15 provinces, the historical maximum area for the six UCBs does not exceed 0.1 Mha, limiting the area expansion of UCBs in these provinces in our optimization.

The changes in crop areas substantially reduced local water use during cultivation (Fig. 3(b)). Among provinces where the total reallocated area exceeded 10% of the baseline, total weighted water use in eight provinces was reduced by more than 16% compared to baseline after reallocating areas, namely Beijing (–49%), Tianjin (–42%), Heilongjiang (–41%), Ningxia (–37%), Liaoning (–34%), Jilin (–23%), Hebei (–16%), and Guizhou (–16%).

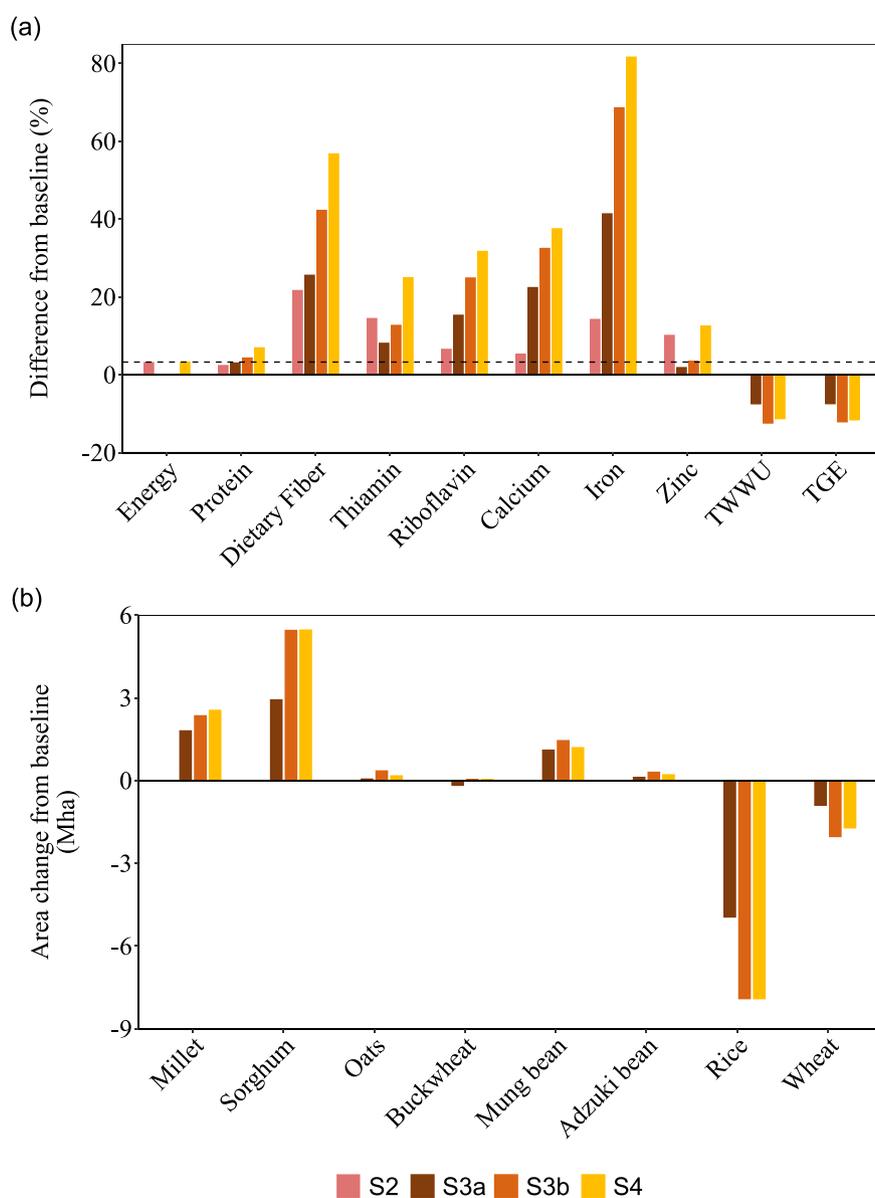


Fig. 2. Changes in indicators (a) and in national area per crop (b) compared to the baseline (S1) in scenarios S2, S3a, S3b, and S4. TWWU stands for total weighted water use, and TGE stands for total GHG emissions. Scenario S2: greater use of unrefined rice and wheat. Scenario S3 (Reallocating areas), with S3a restricting areas of UCBs to their historical maximum in each province, while S3b allowed two times the historical maxima. Scenario S4 (Reallocating areas and greater use of unrefined rice and wheat) combined two strategies. Panel (a) shows the difference from baseline in each scenario. Nutrient supply improvement is the population-weighted average for provincial increase percentages, while TWWU and TGE show the changes at the national level. The dashed line represents the increase in energy supply (+3%) under scenario S4. For each nutrient, the improvement in scenario S4 that exceeds this line reflects an increase in nutrient density per unit of energy. Panel (b) shows the national area change for each crop in scenarios S2–S4.

3.5. Food supply and nutrient supply from each crop in scenario S4

Reallocating rice and wheat areas to UCBs and increasing the use of unrefined rice and wheat enhanced the average supply of UCBs (mainly sorghum, millet, mung bean), brown rice, and whole wheat across all provinces compared to the baseline (Fig. 4(a)). Average UCB supply across provinces increased substantially, rising from 7 to 73 g/capita/day. Brown rice supply increased by 68% (from 13.2 to 22.3 g) and whole wheat flour by 28% (46.9 to 59.9 g). The total food supply amount increased by 3% compared to the baseline, while average energy and nutrient supply increased by 3%–82%, TWWU and TGE decreased by 11%–12% (Fig. 2).

Comparing food supply baskets among provinces showed different optimized diets, but also similarities (Fig. 4(b)). Refined rice and wheat

products still contributed over half to local diets, while two UCB crops, sorghum and millet, accounted for more than 25% of the diets in 17 provinces based on the considered crop products.

The increased supply of UCBs and unrefined rice and wheat products resulted in more diverse sources of nutrient supply. In scenario S4, the substantially increased supply of iron, dietary fiber, thiamin, riboflavin, and calcium was primarily driven by a higher share of diverse unrefined grains, including brown rice, whole wheat flour, sorghum, and millet (Fig. 5). On average, unrefined grains contributed 53%–85% of the total supply of iron, dietary fiber, thiamin, riboflavin, and calcium across provinces in scenario S4, whereas this share (except for dietary fiber) was less than 46% in the baseline.

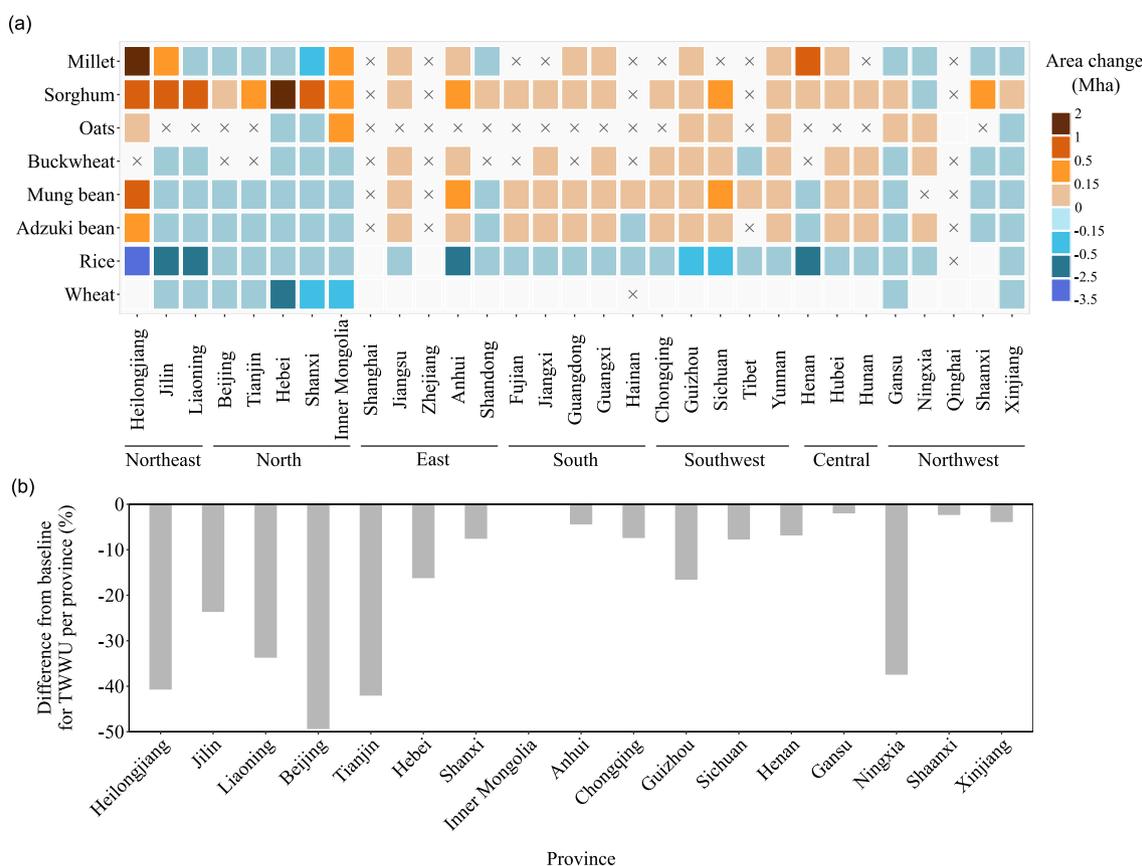


Fig. 3. Changes in cultivated areas and total weighted water use (TWWU) compared to baseline at the provincial level under scenario S4. (a) Area change for each crop relative to the baseline in every province. The blank (uncolored) areas indicate provinces where the crop's cultivated area remains unchanged from baseline levels. Provinces marked with crosses (×) in panel (a) represent regions where the crop was not grown during 2018–2022. Divisions of regions refer to a previous study (Li et al., 2020a). (b) Percentage change in TWWU during cultivation are shown for provinces where the total reallocated area exceeds 10% of the baseline.

4. Discussion

Our results indicate that expanding UCBs while reducing rice and wheat cultivation, combined with greater use of unrefined rice and wheat products, can offer dual benefits of enhancing nutrient supply and lowering environmental impact. Under this combined strategy, the average supply of micronutrients across provinces increased by 12%–82%, while total weighted water use and GHG emissions declined by 11%–12%, with dietary energy supply maintained at baseline levels. This indicates that more micronutrient-dense foods can be provided without jeopardizing the security of the calorie supply. Moreover, the combined strategy increases the availability of UCBs (mainly sorghum, millet, mung bean) and unrefined rice and wheat, providing options for a wider consumption of these foods and thereby a shift towards healthier diets. However, the implementation of these strategies and translation to healthier diets may face several challenges. Overcoming these challenges is essential to achieving the mentioned benefits. In the following discussion, we will reflect on the implications of improved nutrient supply for next steps along the food chain, the potential obstacles to implementing these strategies, and possible interventions to address these obstacles. For this, we will systematically go through the food system, moving from nutrition to production.

The scenarios showed substantial improvements in micronutrient supply, with iron having the largest increase, on average 82% above the baseline. In scenario S4, unrefined grains (e.g., sorghum, millet, whole wheat flour) contributed 73% to the total iron supply. Although a higher share of unrefined grains greatly enhanced iron supply, the actual improvement in bioavailable amount for the human body

may be lower when accounting for bioavailability due to compounds (e.g., phytate and tannins) that hinder iron absorption from unrefined grains (Samtiya et al., 2020). Iron bioavailability is estimated at 10% in vegetarian diets and 18% in omnivorous diets (IOM, 2001). Because in all scenarios diets remain omnivorous, iron bioavailability is expected to change only slightly from scenarios S1 to S4. To further assess the effect of lower bioavailability on efficiency of iron supply, we estimated the average per capita iron supply adjusted for assumed bioavailability (range of 10%–18%) in scenario S4 (Supplementary Fig. S2). The supplementary analysis showed that with a bioavailability of 14% (the midpoint of 10%–18%), iron supply adjusted for bioavailability increased by 41% relative to the baseline. Further enhancing nutrient bioavailability through improved food preparation and processing could help translate increased supply into better nutritional outcomes. Traditional foods, such as fermented porridge made from underutilized cereals, offer practical examples for solutions (Xue et al., 2013). Compared to other nutrients, the improvements in protein and zinc were smaller due to the lower yield of UCBs and similar density of these nutrients compared to major staples. However, using more unrefined rice and wheat more than doubled zinc supply. Increasing zinc bioavailability from unrefined grains will also require appropriate processing methods (Lopez et al., 2003).

The strategy of using more unrefined rice and wheat faces challenges such as the need for improved packaging and storage to extend shelf life, shifts in dietary preferences of consumers, and, related to the latter, processing technologies to enhance the taste and texture. Additionally, the environmental benefits of shifting towards more unrefined rice and wheat are limited, as processing contributes less than 5% of total GHG emissions in rice and wheat supply chains (Goucher et al.,

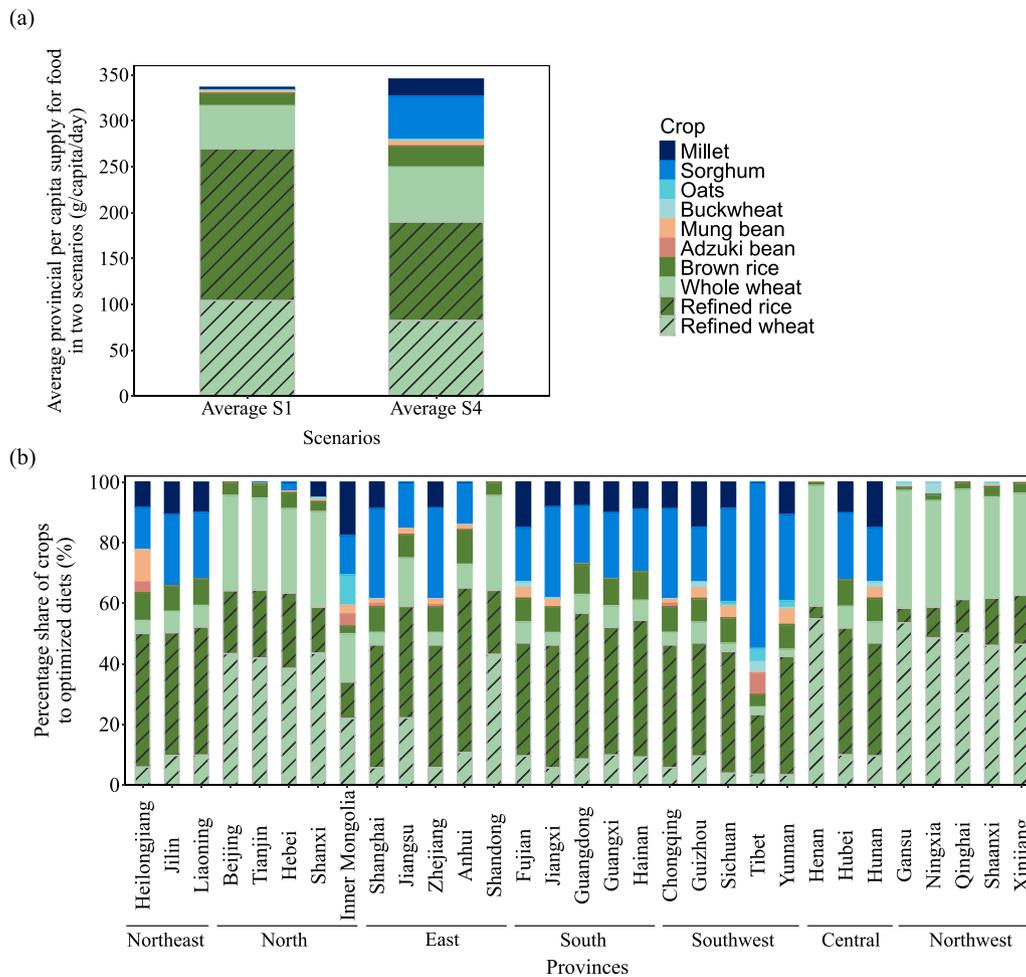


Fig. 4. The average per capita supply for food under scenarios S1 and S4 (a), and percentage share of each crop in the optimized diets across provinces under scenario S4 (b). In panel (a), the average per capita supply for food per crop product was calculated as a population-weighted average across all provinces. Supplementary Tables S5 and S6 show the daily per capita supply for food (g/capita/day) from each crop product in all provinces under two scenarios: S1 (Baseline) and S4 (Reallocating areas and greater use of unrefined rice and wheat). The supply for food under the setting of scenario S4 when using alternative assumptions about the baseline is shown in Supplementary Table S7.

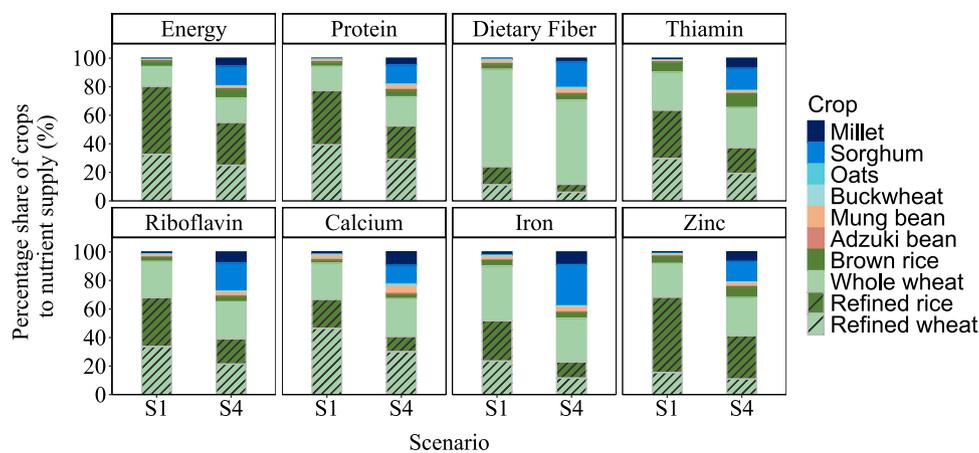


Fig. 5. The average share of each crop to nutrient supply under scenarios S1 (Baseline) and S4 (Reallocating areas and greater use of unrefined rice and wheat). For each nutrient, we first computed the population-weighted average supply from each crop across provinces and then expressed each crop's share as a proportion of the total nutrient supply.

2017; Poore and Nemecek, 2018). This highlights the advantages of reallocating areas to UCBs, which can simultaneously improve nutrient supply and reduce environmental impact. Additional benefits, such as

enhanced crop diversity and biodiversity, can be achieved by reallocating areas from major staple crops to UCBs, contributing to a more robust and resilient food system (Aramburu Merlos and Hijmans, 2020).

Achieving gains in nutrient supply and environmental sustainability requires coordinated transitions in production and consumption. However, both transitions face multiple challenges. Here, we discuss the challenges and propose potential policy interventions for food system transition trajectories. The first challenge is the agronomic feasibility of reallocating areas, which depends on factors such as soil type, irrigation suitability, and farmer knowledge and skills (Xie et al., 2023). Two sets of constraints in scenarios S3 and S4 were intended to make agronomic feasibility plausible, namely, restricting cultivated area expansion up to historical maximum areas and allowing cultivation only for crops already grown in a province. However, it remains uncertain whether reallocating rice or wheat areas to UCBs is feasible in all provinces. Lessons may be drawn from India's Odisha state, where millet area has been expanded successfully in low-yielding upland and midland rice areas since 2017, demonstrating the viability of such an area reallocation strategy (Kumar et al., 2024). In designing transition trajectories, local expertise can be used to select the most appropriate cultivated areas.

The second challenge is the lack of economic incentives for farmers to shift from high-yielding crops like rice and wheat to lower-yielding UCBs. A recent study in India showed that harvest price significantly affected area change for underutilized cereals, but there was little impact on rice, as rice had a minimum support price and procurement targets set by the country (Wei et al., 2025). To promote the integration of UCBs into production systems, expanding research to enhance their yield and effective subsidy schemes are essential. Investment in yield improvement without reducing the gains made in environmental sustainability can enhance benefits in nutrient supply and mitigate trade-offs between dietary energy, calcium supply, and environmental outcomes. Subsidy policies and procurement targets can incentivize farmers to shift crop cultivation in the short term (Wei et al., 2025; Islam and Nathan, 2025), and the societal value of UCBs should be assessed, including their nutritional and environmental benefits beyond calorie production. Such analyses would then require translation into subsidy or pricing schemes that allow farmers to reap the fruits of the production of more societally valuable products. In the long term, promoting consumption and ensuring stable demand will be crucial, which leads to the third challenge, the consumer acceptance of unrefined grains and UCBs.

Recent consumer surveys in eight provinces in China indicate that awareness of health is the major driver of consumption of underutilized cereals, and more nutrition education increases awareness of health (Huang et al., 2022). Specific information and education interventions can refer to successful cases in Singapore and Denmark, used to promote the consumption of whole grains (HPB, 2010; Suthers et al., 2018) (as underutilized cereals in China are mainly consumed as whole grains and thus can be promoted as a type of whole-grain products). The implemented intervention includes specifying recommendations of whole-grain consumption in dietary guidelines, standardizing labels for whole-grain products, launching education and media campaigns to raise health awareness, and helping consumers identify and prepare whole-grain food products (HPB, 2010; Suthers et al., 2018). Including UCBs in public feeding programs such as school meals and government canteens is also a way to ensure a stable demand for UCBs, as has been implemented in a state in India (Islam and Nathan, 2025).

As rice plays a significant cultural and food security role in China, we also assessed the consequences and potential gains by setting provincial limits on rice area reduction, ranging from 5% to 100% of the baseline. This supplementary analysis showed that allowing larger rice reduction led to greater gains in the supply of all micronutrients (except zinc) and in environmental sustainability (Supplementary Fig. S3(a)). In fact, already a large improvement can be expected by reallocating a mere 5% of the rice area. Sorghum, oats, and mung bean areas expanded under all settings, while more millet and adzuki bean would be grown as rice decreased, contributing to improved nutrition and environmental sustainability (Supplementary Fig. S3(b)). We emphasize that the changes in allowed rice area reallocation are

policy decisions, and the theoretical potential presented in this study provides a view on directions food system transformation could take, while further work is needed to explore transition trajectories, policy strategies, and agendas.

We used total weighted water use (weighted by each province's water stress index) as an indicator to assess environmental sustainability. Although this indicator cannot distinguish between reductions in precipitation and irrigation, provinces showing reduced total weighted water use (−16% or even lower) in scenario S4, such as Beijing, Tianjin, Ningxia, Heilongjiang, and Hebei, are regions where irrigation supplements rainfall (Zhang et al., 2022) and where water scarcity and competition among water uses are severe (Zhao et al., 2015). Thus, the optimized results by using total weighted water use as an indicator reflect a reduction in irrigation demand, but might under- or overestimate the potential of water saving via reallocating major crop areas to UCBs. Future research could use higher-resolution data to distinguish precipitation and irrigation in UCB production.

Assuming that all harvested rice and wheat are transported to consuming provinces and then processed into refined or unrefined grains is a simplification of reality and may overestimate transport-related GHG emissions from these crops. In practice, China aims to shift away from transporting raw grains towards a system in which a higher share of inter-provincial food trade consists of primary-processed products (NDRC and NFSRA, 2017). The GHG emissions generated in transporting rice and wheat accounted for 1.7% of total GHG emissions (cultivation + transport) from rice and wheat in our study (Supplementary Table S2), and only part of these transport-related GHG emissions would be reduced if only processed grains were transported. Therefore, refining this assumption of transporting harvested or processed grains would have a minor effect on the estimated improvements in environmental sustainability. Future studies could consider processing locations and explicitly model trade in refined and unrefined grains.

The baseline supply of food (except rice, for which data were available from earlier years before the baseline) was estimated using a modeling approach due to a lack of information on actual consumption. Sensitivity analysis showed that different assumptions related to provincial baseline supplies for food did not change the order or magnitude of improvements of indicators (Supplementary Table S8). However, the optimized diets in each province did change when the baseline crop supply was changed (Supplementary Tables S6 and S7). The sensitivity analysis results highlight that, although the potential of expanding UCBs and using more unrefined rice and wheat to improve nutrition and reduce environmental impact is robust, realizing these improvements requires more complete information on food consumption so that the proposed strategies can incorporate local food preferences and dietary culture to support gradual dietary shifts.

We analyzed six underutilized cereals and beans, but there are at least 15 crop species of underutilized cereals and beans produced in China (e.g., barley, broad bean, faba bean, chickpea) (Chai et al., 2007). The data lacking for the crops we have not included are mainly yield per unit land, cultivated area, and resource use and environmental impact at the province, city, and county levels. Because only a subset of UCBs was analyzed, our study may underestimate the potential of using UCBs to enhance nutrient supply and environmental sustainability. Future efforts can focus on collecting and compiling data for a broader range of crop species, which would support both research and policy making to promote UCBs and whole grains, and enhance crop and dietary diversity.

In summary, this study addressed where in China to grow what kind of UCBs to achieve better nutrient supply and environmental benefits, accounting for food trade and regional differences in consumption needs. Our findings suggest that expanding UCB cultivation can help address imbalances in micronutrient supply while lowering environmental pressures. Combining this approach with increased use of unrefined rice and wheat may help overcome nutrient supply bottlenecks that cannot be solved by expanding UCB production alone. To

enable the expansion of UCBs, challenges need to be addressed such as their lower yield, economic incentives for farmers, and consumer acceptance of UCBs compared to major staple crops. Therefore, the potential and solutions presented here represent theoretical potentials, while transition trajectories towards these potentials require considering broader dimensions and addressing the challenges mentioned above. Our interdisciplinary analysis quantifies the potential benefits of expanding UCBs and increasing the use of unrefined grains, offering insights into why to revalue UCBs and integrate them into future food systems.

CRedit authorship contribution statement

Yijun Li: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Johanna C. Gerdessen:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Wopke van der Werf:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Anneleen Kuijsten:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Sander de Leeuw:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Wen-Feng Cong:** Writing – review & editing, Supervision, Conceptualization. **Shenggen Fan:** Writing – review & editing, Supervision, Conceptualization. **Edith J.M. Feskens:** Writing – review & editing, Supervision, Conceptualization. **Tjeerd Jan Stomph:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.gfs.2026.100907>.

Data availability

I have shared the link to my data at the ‘Attach file step’. The data will be made publicly available upon publication of the paper.

[Improving micronutrient supply and environmental sustainability by using underutilized crops in China \(Reference data\) \(Zenodo\)](#)

References

- Aramburu Merlos, F., Hijmans, R.J., 2020. The scale dependency of spatial crop species diversity and its relation to temporal diversity. *Proc. Natl. Acad. Sci.* 117 (42), 26176–26182. <http://dx.doi.org/10.1073/pnas.2011702117>.
- Ayling, K., Li, R., Muhandi, L., Melse-Boonstra, A., Sun, Y., Chen, W., Kudla, U., 2023. Systematic literature review of the nutrient status, intake, and diet quality of Chinese children across different age groups. *Nutrients* 15 (6), 1536. <http://dx.doi.org/10.3390/nu15061536>.
- Black, R.E., Victora, C.G., Walker, S.P., Bhutta, Z.A., Christian, P., De Onis, M., Ez-zati, M., Grantham-McGregor, S., Katz, J., Martorell, R., et al., 2013. Maternal and child undernutrition and overweight in low-income and middle-income countries. *Lancet* 382 (9890), 427–451. [http://dx.doi.org/10.1016/S0140-6736\(13\)60937-X](http://dx.doi.org/10.1016/S0140-6736(13)60937-X).
- CFIIN, 2024. Feed Ingredients: Sorghum. URL: <https://m.feedtrade.com.cn/nav/10/1711/2019456#/>, CFIIN stands for China Feed Industry Information Network. (Accessed 06 June 2025).
- Chai, Y., Feng, B., Sun, S., 2007. *Varieties of Chinese Minor Grain Crops*, first ed. China Agricultural Science and Technology Press, Beijing, China, (in Chinese).
- Chen, X., Ma, C., Zhou, H., Liu, Y., Huang, X., Wang, M., Cai, Y., Su, D., Muneer, M.A., Guo, M., et al., 2021. Identifying the main crops and key factors determining the carbon footprint of crop production in China, 2001–2018. *Resour. Conserv. Recycl.* 172, 105661. <http://dx.doi.org/10.1016/j.resconrec.2021.105661>.
- Davis, K.F., Chhatre, A., Rao, N.D., Singh, D., Ghosh-Jerath, S., Mridul, A., Poblete-Cazenave, M., Pradhan, N., DeFries, R., 2019. Assessing the sustainability of post-green revolution cereals in India. *Proc. Natl. Acad. Sci.* 116 (50), 25034–25041. <http://dx.doi.org/10.1073/pnas.1910935116>.
- Davis, K.F., Chiarelli, D.D., Rulli, M.C., Chhatre, A., Richter, B., Singh, D., DeFries, R., 2018. Alternative cereals can improve water use and nutrient supply in India. *Sci. Adv.* 4 (7), eaao1108. <http://dx.doi.org/10.1126/sciadv.aao1108>.
- Diao, X., 2017. Production and genetic improvement of minor cereals in China. *Crop. J.* 5 (2), 103–114. <http://dx.doi.org/10.1016/j.cj.2016.06.004>.
- FAO, 2018–2021. Food balance sheet, food and agriculture organization of the united nations. URL: <https://www.fao.org/faostat/>, (Accessed 01 September 2024).
- FAO, 2022. Food balance sheet, food and agriculture organization of the united nations. URL: <https://www.fao.org/faostat/>, (Accessed 01 September 2024).
- Galloway, J.N., Cowling, E.B., 2002. Reactive nitrogen and the world: 200 years of change. *AMBIO: A J. Hum. Environ.* 31 (2), 64–71. <http://dx.doi.org/10.1579/0044-7447-31.2.64>.
- Goucher, L., Bruce, R., Cameron, D.D., Lenny Koh, S., Horton, P., 2017. The environmental impact of fertilizer embodied in a wheat-to-bread supply chain. *Nat. Plants* 3 (3), 1–5. <http://dx.doi.org/10.1038/nplants.2017.12>.
- He, P., Baiocchi, G., Hubacek, K., Feng, K., Yu, Y., 2018. The environmental impacts of rapidly changing diets and their nutritional quality in China. *Nat. Sustain.* 1 (3), 122–127. <http://dx.doi.org/10.1038/s41893-018-0035-y>.
- HPB, 2010. Health Promotion Board National Report 2009/10. URL: https://www.hpb.gov.sg/docs/default-source/annual-reports/hpb-annual-report-2010.pdf?sfvrsn=48c3ec72_2.
- Huang, Y., Liu, K., Zhao, M., 2022. Awareness of health or group mentality? — Analysis on the motives of residents’ consumption of miscellaneous grain based on PSM model. *J. Agrotech. Econ.* 2, 110–125. <http://dx.doi.org/10.13246/j.cnki.jae.20210728.001>.
- IOM, 2001. Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc. National Academies Press (US), Washington, DC, <http://dx.doi.org/10.17226/10026>, URL: <https://www.ncbi.nlm.nih.gov/books/NBK222310/>, Available from <https://www.ncbi.nlm.nih.gov/books/NBK222310/>.
- Islam, M.S., Nathan, H.S.K., 2025. Elements of Effective Public Policy: Evidence From Odisha Millets Mission, India. *Rev. Policy Res.* <http://dx.doi.org/10.1111/ropr.70035>.
- Khoury, C.K., Bjorkman, A.D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., Rieseberg, L.H., Struik, P.C., 2014. Increasing homogeneity in global food supplies and the implications for food security. *Proc. Natl. Acad. Sci.* 111 (11), 4001–4006. <http://dx.doi.org/10.1073/pnas.1313490111>.
- Kumar, S., Das, A., Afari-Sefa, V., Sawargaonkar, G., Roul, P.K., Padhee, A.K., 2024. Advancing the Mainstreaming of Millet in Odisha’s Agrifood System. ICRISAT, URL: <https://oar.icrisat.org/12919/>.
- Li, X., Wu, C., Lu, J., Chen, B., Li, Y., Yang, Y., Hu, S., Li, J., 2020a. Cardiovascular risk factors in China: a nationwide population-based cohort study. *Lancet Public Health* 5 (12), e672–e681. [http://dx.doi.org/10.1016/S2468-2667\(20\)30191-2](http://dx.doi.org/10.1016/S2468-2667(20)30191-2).
- Li, X., Yadav, R., Siddique, K.H., 2020b. Neglected and underutilized crop species: the key to improving dietary diversity and fighting hunger and malnutrition in Asia and the Pacific. *Front. Nutr.* 7, 593711. <http://dx.doi.org/10.3389/fnut.2020.593711>.
- Liu, H., 2018. *Research on the Development of Coarse Grains Industry in China – From the Perspective of Planting Structure Adjustment*, first ed. Economic Science Press, Beijing, China.
- Liu, W., Zhang, G., Wang, X., Lu, F., Ouyang, Z., 2018. Carbon footprint of main crop production in China: Magnitude, spatial-temporal pattern and attribution. *Sci. Total Environ.* 645, 1296–1308. <http://dx.doi.org/10.1016/j.resconrec.2021.105661>.

- Lopez, H.W., Duclos, V., Coudray, C., Krespine, V., Feillet-Coudray, C., Messenger, A., Demigné, C., Rémy, C., 2003. Making bread with sourdough improves mineral bioavailability from reconstituted whole wheat flour in rats. *Nutrition* 19 (6), 524–530. [http://dx.doi.org/10.1016/s0899-9007\(02\)01079-1](http://dx.doi.org/10.1016/s0899-9007(02)01079-1).
- Ma, H., Wang, S., Yang, Y., Feng, X., Zeng, Z., Ren, C., Zang, H., Hu, Y., 2021. Intercropping of oat with mungbean, peanut, and soybean: Yield advantages, economic benefits, and carbon footprints. *J. China Agric. Univ.* 26 (8), 23–32. <http://dx.doi.org/10.11841/j.issn.1007-4333.2021.08.03>, (in Chinese)..
- Mialyk, O., Schyns, J.F., Booi, M.J., Su, H., Hogeboom, R.J., Berger, M., 2024. Water footprints and crop water use of 175 individual crops for 1990–2019 simulated with a global crop model. *Sci. Data* 11 (1), 206. <http://dx.doi.org/10.1038/s41597-024-03051-3>.
- NBS, 1978-2022. National data, national bureau of statistics of China. URL: <https://data.stats.gov.cn/>, (Accessed 01 September 2024).
- NBS, 2018-2022. National data, National Bureau of Statistics of China. URL: <https://data.stats.gov.cn/>, (Accessed 01 September 2024).
- NDRC and NFSRA, 2017. The 13th five-year plan for the development of the grain logistics industry. URL: https://www.ndrc.gov.cn/xgk/zcfb/ghwb/201703/t20170310_962230.html, NDRC stands for National Development and Reform Commission, NFSRA stands for National Food and Strategic Reserves Administration. (in Chinese).
- NDRC and NFSRA, 2025. The national whole grain action plan (2024-35). URL: https://www.gov.cn/zhengce/zhengceku/202412/content_6997625.htm, NDRC stands for the National Development and Reform Commission, NFSRA stands for the National Food and Strategic Reserves Administration.
- NINH, 2018. China Food Composition, Sixth ed. Peking University Medical Press, Beijing, China, NINH stands for National Institute for Nutrition and Health, Chinese Center for Disease Control and Prevention (in Chinese).
- Pingali, P.L., 2012. Green revolution: impacts, limits, and the path ahead. *Proc. Natl. Acad. Sci.* 109 (31), 12302–12308. <http://dx.doi.org/10.1073/pnas.0912953109>.
- Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360 (6392), 987–992. <http://dx.doi.org/10.1126/science.aag0216>.
- Rockström, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. *Proc. Natl. Acad. Sci.* 104 (15), 6253–6260. <http://dx.doi.org/10.1073/pnas.0605739104>.
- Romero, C., Rehman, T., 2003. Multiple Criteria Analysis for Agricultural Decisions. Elsevier.
- SAC, 2009. GB 1350-2009: Paddy. Chinese National Standard, SAC stands for Standardization Administration of China (in Chinese).
- Samtiya, M., Aluko, R.E., Dhewa, T., 2020. Plant food anti-nutritional factors and their reduction strategies: an overview. *Food Prod. Process. Nutr.* 2 (1), 6. <http://dx.doi.org/10.1186/s43014-020-0020-5>.
- Shi, W., Wang, M., Tao, F., Xu, X., Deng, X., Liu, L., Kong, X., Zuo, L., Lei, M., Shi, X., et al., 2024. Wheat redistribution in Huang-Huai-Hai, China, could reduce groundwater depletion and environmental footprints without compromising production. *Commun. Earth Environ.* 5 (1), 380. <http://dx.doi.org/10.1038/s43247-024-01547-9>.
- Siddique, K.H., Li, X., Gruber, K., 2021. Rediscovering Asia's forgotten crops to fight chronic and hidden hunger. *Nat. Plants* 7 (2), 116–122. <http://dx.doi.org/10.1038/s41477-021-00850-z>.
- Suthers, R., Broom, M., Beck, E., 2018. Key characteristics of public health interventions aimed at increasing whole grain intake: a systematic review. *J. Nutr. Educ. Behav.* 50 (8), 813–823. <http://dx.doi.org/10.1016/j.jneb.2018.05.013>.
- Wei, D., Castro, L.G., Chhatre, A., Tuninetti, M., Davis, K.F., 2025. Swapping rice for alternative cereals can reduce climate-induced production losses and increase farmer incomes in India. *Nat. Commun.* 16 (1), 2108. <http://dx.doi.org/10.1038/s41467-025-57420-6>.
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., et al., 2019. Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *Lancet* 393 (10170), 447–492. [http://dx.doi.org/10.1016/S0140-6736\(18\)31788-4](http://dx.doi.org/10.1016/S0140-6736(18)31788-4).
- Xie, W., Zhu, A., Ali, T., Zhang, Z., Chen, X., Wu, F., Huang, J., Davis, K.F., 2023. Crop switching can enhance environmental sustainability and farmer incomes in China. *Nature* 616 (7956), 300–305. <http://dx.doi.org/10.1038/s41586-023-05799-x>.
- Xue, J., Chen, Y., Yu, H., Zhang, H., 2013. Analysis of chemical and microbiological composition in naturally fermented acidic-gruel from western areas of Inner Mongolia. *Food Sci. Technol.* 38 (7), 10–14, (in Chinese).
- Xue, L., Liu, X., Lu, S., Cheng, G., Hu, Y., Liu, J., Dou, Z., Cheng, S., Liu, G., 2021. China's food loss and waste embodies increasing environmental impacts. *Nat. Food* 2 (7), 519–528. <http://dx.doi.org/10.1038/s43016-021-00317-6>.
- Yin, J., Lin, J., Zhang, X., Wang, L., Liu, M., 2024. A balanced staple food structure effectively curbs the environmental impact and counters the nutrient losses from elevated CO₂. *Resour. Conserv. Recycl.* 205, 107545. <http://dx.doi.org/10.1016/j.resconrec.2024.107545>.
- Yu, D., He, Y., Guo, Q., Fang, H., Xu, X., Fang, Y., Li, J., Zhao, L., 2016. Trends of energy and nutrients intake among Chinese population in 2002–2012. *J. Hyg. Res.* 45 (4), 527–533, (in Chinese).
- Yu, D., Zhao, L., Ju, L., Guo, Q., Fang, H., Xu, X., Li, S., Piao, W., Cheng, X., Cai, S., Ding, G., 2021. Status of energy and primary nutrients intake among Chinese population in 2015–2017. *Food Nutr. China* 27 (04), 5–10, (in Chinese).
- Yu, D., Zhao, L., Zhao, W., 2020. Status and trends in consumption of grains and dietary fiber among Chinese adults (1982–2015). *Food Nutrition China* 78 (Supplement_1), 43–53. <http://dx.doi.org/10.1093/nutrit/nuz075>.
- Zhang, C., Dong, J., Zuo, L., Ge, Q., 2022. Tracking spatiotemporal dynamics of irrigated croplands in China from 2000 to 2019 through the synergy of remote sensing, statistics, and historical irrigation datasets. *Agricult. Water. Manag.* 263, 107458. <http://dx.doi.org/10.1016/j.agwat.2022.107458>.
- Zhang, J., Wang, H., Wang, Z., Du, W., Su, C., Zhang, J., Jiang, H., Huang, F., Jia, X., Ouyang, Y., Wang, Y., Li, L., Zhang, B., 2018. Dietary fiber intake status among Chinese adults in 15 provinces in 2015. *Food Nutr. China* 24 (10), 10–12, (in Chinese).
- Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., Hubacek, K., 2015. Physical and virtual water transfers for regional water stress alleviation in China. *Proc. Natl. Acad. Sci.* 112 (4), 1031–1035. <http://dx.doi.org/10.1073/pnas.1404130112>, arXiv:https://www.pnas.org/doi/pdf/10.1073/pnas.1404130112, URL: <https://www.pnas.org/doi/abs/10.1073/pnas.1404130112>.
- van Zonneveld, M., Kindt, R., McMullin, S., Achigan-Dako, E.G., N'Danikou, S., Hsieh, W.-h., Lin, Y.-r., Dawson, I.K., 2023. Forgotten food crops in sub-saharan africa for healthy diets in a changing climate. *Proc. Natl. Acad. Sci.* 120 (14), e2205794120. <http://dx.doi.org/10.1073/pnas.2205794120>.
- Zuo, C., Wen, C., Clarke, G., Turner, A., Ke, X., You, L., Tang, L., 2023. Cropland displacement contributed 60% of the increase in carbon emissions of grain transport in China over 1990–2015. *Nat. Food* 4 (3), 223–235. <http://dx.doi.org/10.1038/s43016-023-00708-x>.