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Conflicting stakeholder priorities produce sustainability tradeoffs for cereal production in Northeast China

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Abstract

Northeast China (NEC) as one of the primary breadbaskets of China plays an essential role in achieving sustainable agriculture to provide sufficient and nutritious food while minimizing resource consumption and environmental costs. Growing evidence indicates crop switching is a promising solution for achieving sustainable agriculture. Comprehensively assessing synergies and tradeoffs among competing objectives for stakeholders is essential for crop switching implementation but not well documented in NEC. We examine tradeoffs and synergies among multi-objectives—nutritional yields, water demand, greenhouse gas emissions (GHGs), and benefits—from policymakers' and farmers' perspectives for cereals in NEC using the most recent data available, and assess potential sustainability changes from implementing the policy of crop switching. We find no single cereal can achieve all objectives of sustainable agriculture in most regions of NEC for stakeholders and synergies and tradeoffs have obviously spatial heterogeneity. Overall, rice has the best performance on energy and protein yield but the worst on iron yield, water requirement, and GHGs. Coarse cereals (sorghum and millet) have better desirable attributes on iron yield 223% and 66% more, blue water requirement 91% and 90% less, and GHGs 84% less than rice, but not for energy and protein yield because of lower yields. From the farmers' perspective, rice can produce more revenue than dryland cereals by 32%–58% due to higher price and yield. Nevertheless, the sustainability of cereal production in NEC will be improved from crop switching with a 33% increment in iron production, a 24% and 3% decrease in irrigation water demand and GHGs, and a 4% increment in farmers' revenue on existing cultivation area without compromises in rice production. Our study indicates that comprehensively assessing the synergies and tradeoffs among multiple objectives and stakeholders will provide more opportunities to align policymakers with practitioners to make crop switching feasible and achieve sustainable agriculture.

1. Introduction

Sustainable agriculture aims to provide sufficient, affordable, and nutritious food while minimizing water exploitation and greenhouse gas emissions, and increasing land use efficiency, climate resilience and biodiversity (Davis *et al* 2019, Rising and Devineni 2020, Wang *et al* 2021, He *et al* 2023). Since 2000, global crop production increased 54% through a combination of increased yields from irrigation and fertilizer inputs, cropland expansion, and crop shifts from more lower-yielding nutritious cereals to higher-yield cereals (DeFries *et al* 2015, Wang *et al* 2021, Potapov *et al* 2022, Food and Agriculture Organization 2023, Meng *et al* 2024). This increase in crop production was essential for reducing hunger and stunting but it also resulted in ~80% increase in freshwater consumption, 15%–25% greenhouse gas emissions, and persisting malnutrition (Hoekstra and Mekonnen 2012, Vermeulen *et al* 2012). Such unsustainable agricultural production led to water overexploitation, a decrease in crop diversity, and unhealthy diets in some regions. Growing evidence demonstrates that crop switching provides a promising solution to achieve sustainable agriculture on multiple objectives (Davis *et al* 2017, 2019, Rising and Devineni 2020, Xie *et al* 2023, Wei *et al* 2025). Comprehensively assessing the synergies and tradeoffs of crops across multiple objectives for policymakers and farmers is essential for implementing the crop-switching policies.

China, as one of the most populous countries, has followed the same patterns of agricultural development (Hu *et al* 2020, Qi *et al* 2022). After 2004, crops gradually switch to high-yielding staple crops such as rice, wheat, and maize particularly in the main breadbaskets of China—Northeast, and North Plain China (Liu *et al* 2022). Such shifts help to reduce hunger especially for rural and low-income populations since cereals are the main source of food intake, accounting for 71% of their energy intakes and approximately 45% of iron intakes (He *et al* 2016, Li and Shangguan 2012). Such crop specialization has likely pushed the diversity of cereal intakes loss since rice and wheat become the main cereals intake (He *et al* 2019, Wang *et al* 2020). Moreover, with increasing incomes and social development, consumers' demands for food shifted from having enough calories to having enough nutritious food with diverse cereals and food intakes. However, previous studies mainly limited on assessing the yield and calorie yield of crop cultivation from the producers' side in China (Zhang *et al* 2016, Cui *et al* 2018). The nutritional yield provides a new metric to help link nutrition supply from crop production with the human requirements for nutrients (DeFries *et al* 2015).

Irrigation and crop switches to high-water demanding crops in water scarce regions led to unsustainable water use (Deng *et al* 2025). For example, the intensification of irrigation on the wheat-maize system caused the overexploitation of groundwater in the North Plain of China (Famiglietti 2014, Aryal *et al* 2020, Zhang *et al* 2020). The dramatic expansion of rice fields mainly from dryland exacerbates the water scarcity in Northeast China since the long flooding of rice makes its water consumption much higher than dryland crops (Zhang *et al* 2020, Qi *et al* 2022).

To address these issues, the Chinese government implemented China's National Sustainable Agriculture Development Plan (2015–2030), which emphasized the importance of crop mix shifts to ensure self-sufficient grain production while minimizing environmental costs (Xie *et al* 2023). Implementation of such sustainable agriculture policies needs the cooperation of different sectors that have different top priorities, which can sometimes be contradictory. For instance, a series of 'water-saving' programs and policies in agriculture have been implemented by the central government and the Ministry of Water Resources to control the amount of irrigation water (Yang *et al* 2022). In 2015, the Ministry of Agriculture and Rural Affairs released the Zero Increase Action Plan in Chemical Fertilizer Use aiming to cease the increase of fertilizer use in 2020 without yield losses (Jiao *et al* 2018). Nevertheless, practitioners (such as farmers) who actually manage the cropland tend to prioritize economic benefits over environmental costs (Scown *et al* 2019). However, the differing priorities of stakeholders likely result in misaligned target crop choices, which hinders the implementation of crop switching. Therefore, it is necessary to comprehensively evaluate the synergies and tradeoffs of sustainable goals in crop cultivation for stakeholders. This is helpful for not only making prudent and evidence-based policy decisions but also for making crop switching policies feasible. Along these lines, recent work has demonstrated that crop switching across China can realize substantial co-benefits for farmer incomes and a suite of environmental outcomes (Xie *et al* 2023). However, it remains unclear the extent to which crop switching might be implemented to be sensitive to nutritional outcomes—in addition to farmer incomes and environmental variables—and how such recommendations might need to be tailored to specific contexts in the breadbasket regions of China. Our study here provides an important advance in this regard, establishing an example case for Northeast China that can be modelled for other agricultural regions of the country. Indeed, understanding the extent to which crop switching can provide co-benefits for income, nutrition, and the environment is in direct alignment with meeting multiple national initiatives in China, including the 2035 Food Security Initiative, the National Nutrition Plan, and the Agricultural Green Development strategy.

Here we comprehensively evaluate the synergies and tradeoffs for multiple objectives of sustainable agriculture of cereals from the perspectives of policymakers and practitioners and assess potential sustainability changes from crop switching in Northeast China. Specifically, we aim to (1) analyze nutritional yield (limited here to energy, protein, and iron), water demands using a process-based model, and GHGs using an empirical method among cereals (limited here to rice, wheat, maize, sorghum, and millet) (https://data.stats.gov.cn/) from policymakers' perspectives using the most recent data available from 2010 to 2014; (2) compare farmers' revenue by combining price and yields of cereals from 2010 to 2014 from farmers' perspectives; (3) assess the

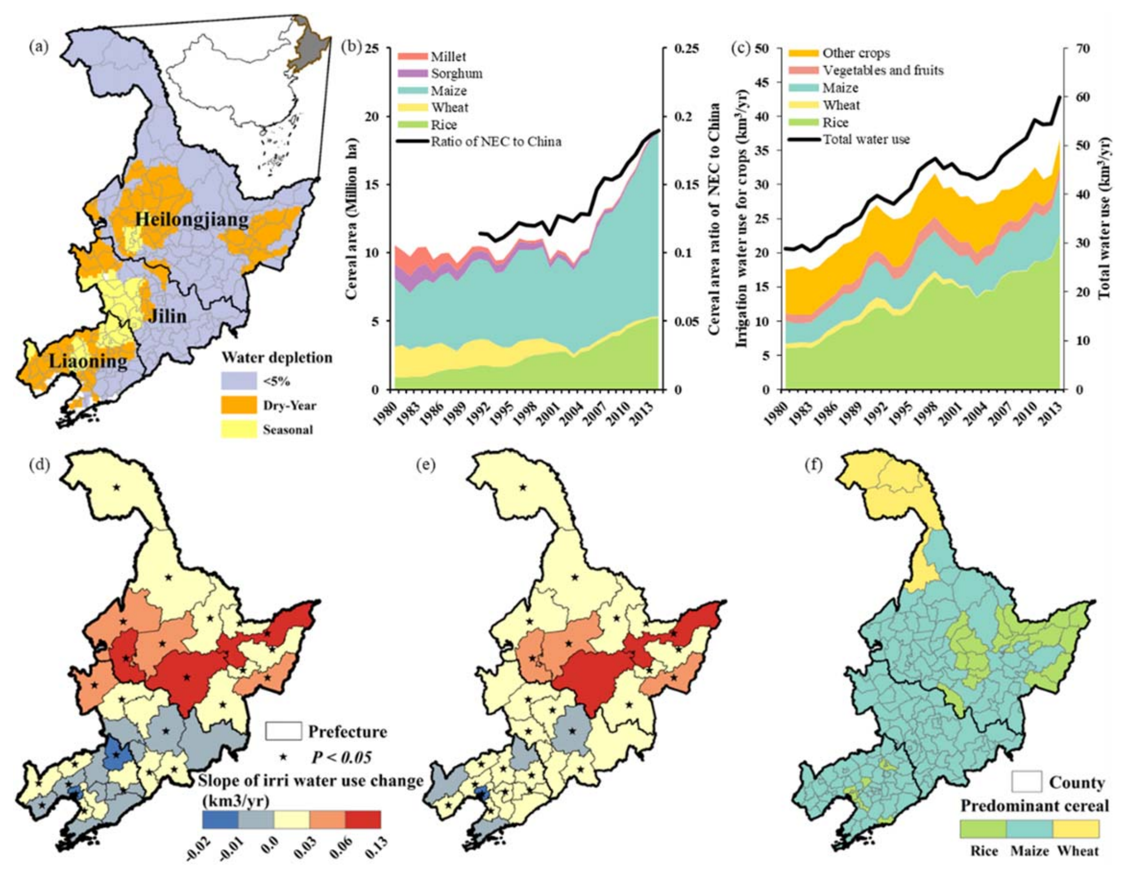

Figure 1. Cereal area and water use in Northeast China. (a) Water depletion for watersheds in Northeast China, which is defined by the ratio of long-term (1971–2000) average annual water consumption to renewable available water. Watersheds are defined as 'seasonal depletion' when annual depletion is below 75% but at least one month more than 75% depletion, and 'dry-year' depletion when one month more than 75% depletion in at least 10% of years during 1971–2000 but on average are not annually or seasonally depletion (Brauman *et al* 2016). (b) Area of cereals and the fraction of cereal area in Northeast China to that of China. Data are publicly available from the National Bureau of Statistics of China (http://www.stats.gov.cn/). (c) Annual irrigation water use for cropland and the total water use for all sectors in Northeast China from 1980 to 2013 (Zhou *et al* 2020). Slope of irrigation water use change for cropland (d) and rice (e) in 1980–2013 at the prefecture level (Zhou *et al* 2020), and stars mean the slopes are significant at the 0.05 level. (f) The predominant cereal with the largest average sown area among the five cereals (rice, maize, wheat, sorghum, and millet) from 2010 to 2014 in Northeast China.

extent and locations of synergies and trade-offs for cereals by identifying target cereals that can achieve multiple objectives simultaneously; (4) evaluate sustainability outcome changes of potential crop switching. Our research provides insights on how crop switching offers promise to align policymaker and practitioner priorities and achieve agricultural sustainability in Northeast China.

2. Materials and methods

2.1. Study area

Northeast China, encompassing Heilongjiang, Jilin, and Liaoning provinces, is one of the main breadbaskets covering 19% of the harvested area of China and producing 20% of crops in the 2010s (https://data.stats.gov.cn/) (figure 1(a)). Northeast China is characterized by a temperate, semi-humid (dry) climate with 450–1070 mm average annual precipitation mainly received in summer (Liu *et al* 2012). The crops in Northeast China are harvested once a year from April to September (spring wheat from April to July, rice, maize, millet, and sorghum from May to September).

The main cereal area in Northeast China increased 8.62 million hectares from 1980 to 2014 (figure 1(b)). The maize and rice area experienced dramatic expansion by 8.55 (1.72 times) and 4.37 (5.15 times) million hectares while the area of wheat, millet (foxtail millet), and sorghum shrunk substantially by 2.13 (93%), 1.29 (94%), and 0.87 (82%) million hectares, respectively from 1980 to 2014 (figure 1(b)). The obvious expansion of rice mainly happened in northern and northeastern Northeast China and maize area increased mainly in western Northeast China (figure S1). Millet and sorghum areas decreased in the western and northeastern parts of Northeast China, where millet planting was already minimal in 2014 (figure S1). The area of wheat in the northwest of Northeast

China declined and southern Heilongjiang and eastern Northeast China have minimal wheat planted in 2014 (figure S1).

Expansion of rice possibly exacerbated water scarcity in Northeast China. The fraction of total water consumed by irrigation is around 61% in 2013 with irrigation for cropland increasing water demand by 109% from 1980 to 2013 (figure 1(c)). The predominant increment of irrigation water use is for rice accounting for 87%, followed by maize, vegetable and fruits, other crops, and wheat for 26%, 2%, −12% and −3%, respectively (figures 1(c)–(e)). The significant increase in irrigation for rice occurred mainly in the south and northeast of Heilongjiang province (figure 1(e)). Most of the increment of irrigation water consumption happened in water basins that experienced dry-year or seasonal water depletion, which will exacerbate water scarcity in these regions.

2.2. Nutritional yield

Nutritional yield incorporates nutrient content and dietary requirements as a metric to quantify crop production required to fulfill nutritional needs. Nutritional yield is defined as the number of adults who can obtain 100% of the annually recommended daily dietary reference intake (DRI) for nutrients from a given cereal produced on each hectare annually (DeFries *et al* 2015). Nutritional yield is calculated as:

$$NY_{ij} = \frac{Food\ Composition_{i,j}}{DRI_i} \times Yield_j/365 \times 10^4 \tag{1}$$

NY_{ij} is the nutritional yield of nutrient i from cereal j (adult/ha/year). $Food\ Composition_{i,j}$ means the nutrient content of nutrient i in 100 g cereal j (g/100 g). We average the content of nutrient i of food items produced by cereal j in China (Yang *et al* 2004). DRI_i means reference daily intake of nutrient i for an adult (average for male and female between 18 and 49) (g/day/adult) (Chinese Nutrition Society 2013). $Yield_j$ is the production of cereal j per hectare of cropland each year (tonnes/ha/year). We calculate nutritional yields at the county level for rice, maize, sorghum, millet (foxtail millet), and wheat.

2.3. Crop water requirement

We use the WATNEEDS model to calculate the daily crop water requirement that each crop requires to compensate for the loss from evapotranspiration. In summary, the WATNEEDS model is based on the theory of daily soil water balance for each grid and separates crop water requirement into blue water requirement from irrigation and green water requirement from precipitation (Chiarelli *et al* 2020). For each grid, for each day, the potential evapotranspiration (PET) is the total water requirement of the well-watered crop calculated by reference evapotranspiration (ET_0) and crop coefficients (k_c) (equation (2)). The actual evapotranspiration ($AET_{i,t}$) of each crop is the water requirement when the crop suffers from water stress by multiplying the water stress coefficient (k_s) and $PET_{i,t}$ (equation (3))—equal to the green water requirement of the crop. The blue water requirement is calculated as the difference between the unstressed actual evapotranspiration $PET_{i,t}$ and $AET_{i,t}$. We then take a summation of the daily green and blue water requirement across each crop's growing season for each year from 2010 to 2014 and average those values across five years. Our results of green and blue water requirements for crops are consistent with previous studies (figure S2).

$$PET_{i,t} = k_{c,i,t} \times ET_{0,t} \tag{2}$$

$$AET_{i,t} = k_{s,i,t} \times PET_{i,t} \tag{3}$$

$$k_{s,i,t} = \begin{cases} \frac{S_{i,t}}{(1 - p_{i,t})TAW_i} & if \quad S_{i,t} < (1 - p_{i,t})TAW_i \\ 1 & if \quad S_{i,t} \geqslant (1 - p_{i,t})TAW_i \end{cases} \tag{4}$$

$$TAW_i = TAWC \times rd_i \tag{5}$$

$$p_{i,t} = p_{std,i} + 0.04 \times (5 - PET_{i,t}) \tag{6}$$

where $S_{i,t}$ means the soil moisture for crop i in the day of t. TAW_i is the total available soil water capacity in the root zone (mm). $TAWC$ means the total available water capacity of soil (mm/m). rd_i means the depth of the crop root (m). The depletion fraction $p_{i,t}$ is the fraction of TAW that crop i can uptake from the root zone without suffering water stress. The depletion fraction is a function of crop type and PET (equation (6)). $p_{std,i}$ I is the value of depletion fraction for crop for PET of around 5 mm day^{-1} obtained from (Allan *et al* 1998) and (Siebert and Döll 2010).

$$S_{i,t} = S_{i,t-1} + \Delta t(P_{eff,i,t} + I_{i,t} - AET_{i,t} - D_{i,t} - R_{i,t}) \tag{7}$$

$$D_{i,t} = \begin{cases} F_{\max} \times \frac{S_{i,t} - (1 - p_{i,t})TAW_i}{p_{i,t} \times TAW_i} & if\ (1 - p_{i,t})TAW_i \leqslant S_{i,t} < TAW_i \\ 0 & if\ S_{i,t} < (1 - p_{i,t})TAW_i \end{cases} \tag{8}$$

where $S_{i,t-1}$ is the water content of the end of the previous step. Δt refers to the time steps of one day. $P_{eff,i,t}$ is the effective precipitation that 5% of the precipitation is assumed as surface runoff $R_{i,t}$ (Chiarelli *et al* 2020). $D_{i,t}$ represents the deep percolation below the root zone, which occurs when soil moisture exceeds field capacity (Chiarelli *et al* 2020). $F_{\max}$ is the soil-specific maximum infiltration rate depending (mm/day).

2.4. GHGs assessment

We calculate averaged CH_4 and N_2O emissions from nitrogen input of cereals in Northeast China from 2010 to 2014 since these two GHGs are the predominant sources accounting for more than 90% of GHGs of cropland in China in the 2010s (https://www.fao.org/faostat) (equation (9)).

$$GWP_{i,j} = 273 \times N_2O_{i,j,ave} + 27.2 \times CH_{4,j,ave} \tag{9}$$

$$N_2O_{i,j,ave} = \frac{1}{n}\sum_t N_2O_{N,t} \times F_{i,j,t,N} \tag{10}$$

Where $GWP_{i,j}$ is the 100-year global warming potential of cereal *i* per hectare per year in county *j* (CO_2eq tonne/ha/year). $N_2O_{i,j,ave}$ and $CH_{4,j,ave}$ represent the average N_2O emission of cereal *i* and CH_4 emission of rice per hectare of county *j* from 2010 through 2014 respectively. $N_2O_{N,t}$ refers to the direct and indirect N_2O emission of 1 kg of nitrogen input in year *t* of China. Both $CH_{4,j,ave}$ and $N_2O_{N,t}$ are obtained from FAOSTAT calculated under the IPCC guidelines (https://www.fao.org/faostat). $F_{i,j,t,N}$ is the total nitrogen application of cereal *i* in year *t* for county *j*. Since crop-specific nitrogen input data are not available, we used the area-weighted method to obtain nitrogen use of each cereal at the county level based on the crop area, agricultural nitrogen inputs at the county level and ratio of crop-nitrogen input in China (Mueller *et al* 2012, Zuo *et al* 2018) (Supplementary information). Our results for GHGs for crops are consistent with previous studies (table S1).

2.5. Farmers' revenue

We calculate farmers' average revenue from certain cereal cultivation from 2010 to 2014 by combining its price and yield (equation (11)).

$$Revenue_{i,j} = \frac{1}{N}\sum_t^N (Price_{i,t} \times Yield_{i,j,t}) \tag{11}$$

Where $Revenue_{i,j}$ is farmers' revenue from the production of cereal *i* per hectare per year of county *j* (RMB/ha). $Price_{i,t}$ is the price of cereal *i* per tonne in year *t* (RMB/tonne). $Yield_{i,j,t}$ is the yield of cereal *i* per hectare in year *t* of county *j* (tonne/ha). *N* means the number of years.

2.6. Synergies and tradeoffs analysis

We assess the sustainability synergies and tradeoffs for cereals regionally and spatially from 2010 to 2014 by the Z-score method and selecting the target cereals. We normalize values for attributes of nutritional yields, blue water requirement, GHGs, and farmers' revenue for cereals by the Z-score method (Raudsepp-Hearne *et al* 2010, DeFries *et al* 2016, Zuo *et al* 2018, Carter Berry *et al* 2020, Shen *et al* 2020). Spatially, we select the target cereals for each county, which are defined as cereals that have the best performance for achieving a single objective or multiple objectives simultaneously for policymakers and farmers. For instance, cereal *i* that has maximum nutritional yields with the minimum blue water requirement and GHGs is defined as the target cereal for achieving all objectives for policymakers.

$$Z_{i,j} = \frac{x_{i,j} - \bar{x}_j}{\sigma_j} \tag{12}$$

Where $Z_{i,j}$ is the normalized value of cereal *i* for attribute *j*. $x_{i,j}$ is the value of cereal *i* for attribute *j*. $\bar{x}_j$ and σ_j are the mean value and standard deviation of all cereals for attribute *j*.

2.7. Optimization model

We evaluate the changes of sustainability outcomes from potential crop switching in Northeast China using a multi-objective optimization model. Here, we aim to achieve the maximum sustainability of cereal cultivation in Northeast China by using the weighted sum method to combine all dimensions of sustainability (equation (13)). Because Northeast China is one of the primary breadbaskets, we set strict constraints to ensure food security with no losses in rice production and any nutritional production after crop switching (equations (21)–(24)). Meantime, it is limited in expansion of areas under cereal cultivation (equation (20)), irrigation consumption (equation (25)) due to water endowment stress, and farmers' revenue (equation (26)) for each county after crop switching.

$$Maximum\ f_{energy} + f_{protein} + f_{iron} - f_{irri} - f_{GHG} + f_{revenue} \tag{13}$$

Where:

$$f_{energy} = \sum_i \sum_j Area_{i,j} * NY_{energy,i,j} \tag{14}$$

$$f_{protein} = \sum_i \sum_j Area_{i,j} * NY_{protein,i,j} \tag{15}$$

$$f_{iron} = \sum_i \sum_j Area_{i,j} * NY_{iron,i,j} \tag{16}$$

$$f_{irri} = \sum_i \sum_j Area_{i,j} * RI_{i,j} * BW_{i,j} \tag{17}$$

$$f_{GHG} = \sum_i \sum_j Area_{i,j} * GWP_{i,j} \tag{18}$$

$$f_{revenue} = \sum_i \sum_j Area_{i,j} * Revenue_{i,j} \tag{19}$$

$Area_{i,j}$ is the area under cereal j in county i. $NY_{energy,i,j}$, $NY_{protein,i,j}$, and $NY_{iron,i,j}$ show the energy, protein, and iron yield of cereal j in county i. $RI_{i,j}$ and $BW_{i,j}$ mean the ratio of the irrigated area of cereal j in county i and the volumetric irrigation consumption per hectare.

Subject to:

$$\sum_j Area_{i,j,opt} \leqslant \sum_j Area_{i,j,current}\ \forall\ i \in I \tag{20}$$

$$\sum_i Area_{i,rice,opt} * yield_{rice,i,j} \geqslant \sum_i Area_{i,rice,current} * yield_{rice,i,j} \tag{21}$$

$$f_{energy,opt} \geqslant f_{energy,current} \tag{22}$$

$$f_{protein,opt} \geqslant f_{protein,current} \tag{23}$$

$$f_{iron,opt} \geqslant f_{iron,current} \tag{24}$$

$$\sum_j Area_{i,j,opt} * RI_{i,j} * BW_{i,j} \geqslant \sum_j Area_{i,j,current} * RI_{i,j} * BW_{i,j}\ \forall\ i \in I \tag{25}$$

$$\sum_j Area_{i,j,opt} * Revenue_{i,j} \geqslant \sum_j Area_{i,j,current} * Revenue_{i,j}\ \forall\ i \in I \tag{26}$$

2.8. Data sources

Cereal yield, crop planting area, and nitrogen and compound fertilizer inputs from 2010 to 2014 are the most recently available data at the county level obtained from the China Statistical Yearbook and the China Rural Statistical Yearbook published by China's National Statistical Bureau and the Agricultural Statistics of China by the Ministry of Agriculture and Rural Affairs of China. Cereal yield is used to calculate nutritional yield and water footprint, while planting area and nitrogen and component fertilizer inputs of crops are used to evaluate GHGs. Cereal prices at the state level from 2010 to 2014 are the most recently available data from the China Agricultural Cost and Return Yearbook.

Crop water requirement simulation is based on daily reference evapotranspiration dataset, daily precipitation datasets, and soil datasets. Daily reference evapotranspiration datasets from 2010 to 2014 are obtained from (Singer *et al* 2021), which were calculated using the FAO's Penman-Monteith equation based on hourly ERA5-Land reanalysis meteorological variables datasets. Daily precipitation datasets are collected from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset (Funk *et al* 2015), which spans 50°S-50°N and 180°W-180°E with a spatial resolution of $0.05° \times 0.05°$ from 2010 to 2014. The missing data in regions over 50°N are substituted by CPC Global Unified Gauge-Based Analysis of Daily Precipitation from 2010 to 2014 with $5° \times 5°$ resolution (Chen *et al* 2008). Maximum soil available water capacity and maximum infiltration rate are from the ISRIC-WISE dataset (Batjes 2012) and the groundwater resources and recharge dataset (Jones 2011). Crop calendars are obtained from the dataset of monthly irrigated and rainfed crop areas around the year 2000 (MIRCA2000) and China's agricultural meteorological station observations collected from the China Meteorological Administration (Portmann *et al* 2010). Rainfed and irrigated information for each cereal is from the Spatial Production Allocation Model (SPAM) datasets in 2010 (Yu *et al* 2020).

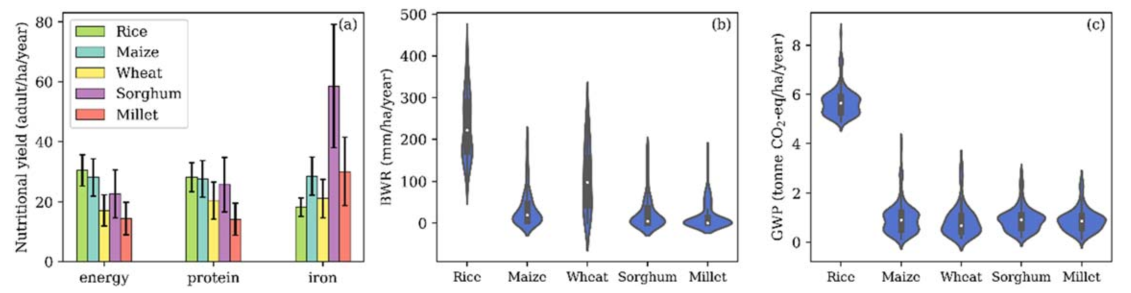

Figure 2. Nutritional yield (a), blue water requirement (BWR) (b), and global warming potential (GWP) (c) of cereals from 2010 to 2014 in Northeast China. Error bars mean the standard deviation for the nutritional yield of cereals across counties in Northeast China.

3. Results

3.1. Nutritional yield, water demands, and GHGs of cereals

Rice, maize, and sorghum are advantageous in terms of average yields of energy and protein from 2010 to 2014 (figure 2(a)). Coarse cereals (sorghum and millet) have higher yields of iron. Energy and protein yield for rice is the highest with 30.50 and 28.27 adults/ha/year because of the high production yield (tonnes/ha/year), followed by maize with 28.16 and 27.67 adults/ha/year and sorghum with 22.68 and 25.76 adults/ha/year, respectively (figures 2(a), S3f). Iron yield for sorghum is the highest with 58.51 adults/ha/year because of its high iron content per 100 g of dry weight edible portion, followed by millet and maize, which are 3.23, 1.66, and 1.58 times of rice's iron yield (figures 2(a), S4). Wheat has relatively low nutritional yields for energy, protein, and iron yield because of low production yield in Northeast China (figures 2(a), S3f, S4). Moreover, the nutritional yield has a large variation across counties. The nutritional yield is higher in the south of Heilongjiang, west of Jilin, and Liaoning province (figure 3).

The blue water requirement varies substantially between rice and dryland cereals and across counties. The blue water requirement for rice is the highest (231$\pm$75.25 mm), followed by wheat (106.33$\pm$77.62 mm). Sorghum, millet, and maize require 9%, 10%, and 15% of the blue water requirement for rice and 15%, 22%, and 32% of wheat, respectively (figure 2(b)). Spatially, the blue water requirement of cereals in the west of NEC (Songnen plain and Liaohe plain) is the highest because of high evapotranspiration, followed by the northeast of NEC (Sanjiang plain) (figure 3).

The GHG emissions are disparate between rice and dryland cereals and between the south and north NEC. The GHGs released per hectare of rice paddy are the highest, with 5.66 tonne CO_2-eq/ha/year. The GHGs from dryland cereals are similar at approximately 16% of those from rice (figure 2(c)). Spatially, cereals sown in the south of NEC release more GHGs than those in the north of NEC (figure 3).

3.2. Revenue of cereal production

The average revenue per hectare for farmers across 183 counties was highest for rice because of both high yield and price from 2010 to 2014 (figures 4 and S3f). In comparison, revenues from wheat, sorghum, maize, and millet were 58%, 56%, 34%, and 32% lower, respectively (figure 4(b)). These discrepancies are largely due to lower yields for millet and wheat—54% and 45% less than that of rice, respectively. Additionally, maize price was 28% lower than that of rice, while sorghum had both lower prices and yields, at 38% and 28% less, respectively (figures 4 and S3f). These findings highlight the potential for increasing cereal yields—especially for millet and wheat—as a mean to help mitigate the trade-offs in benefits among crops for farmers.

3.3. Synergies and tradeoffs

Overall, each cereal has its desirable attributes and conflicting priorities between policymakers and farmers that would limit the potential of crop switching implementation (figure 5). From policymakers' perspectives, rice has the highest energy and protein yields but the lowest iron yields with the highest blue water demands and GHGs. Maize has better performance in energy and protein yields, blue water demand, and GHGs except for iron yield. Sorghum has the highest iron yield and high energy and protein yield as well as lower blue water requirement and GHGs. Millet yields the least energy and protein but the second most iron with lower blue water requirement and GHGs. Wheat has poor performance in all dimensions. Notably, most of the dryland cereals in Northeast China are rainfed (figure S5). However, from farmers' perspectives, rice is most valuable for revenue.

Here we identify target cereals that can achieve single objective or multiple objectives simultaneously across stakeholders spatially. Synergies and tradeoffs across objectives for cereals are spatially heterogeneous, and

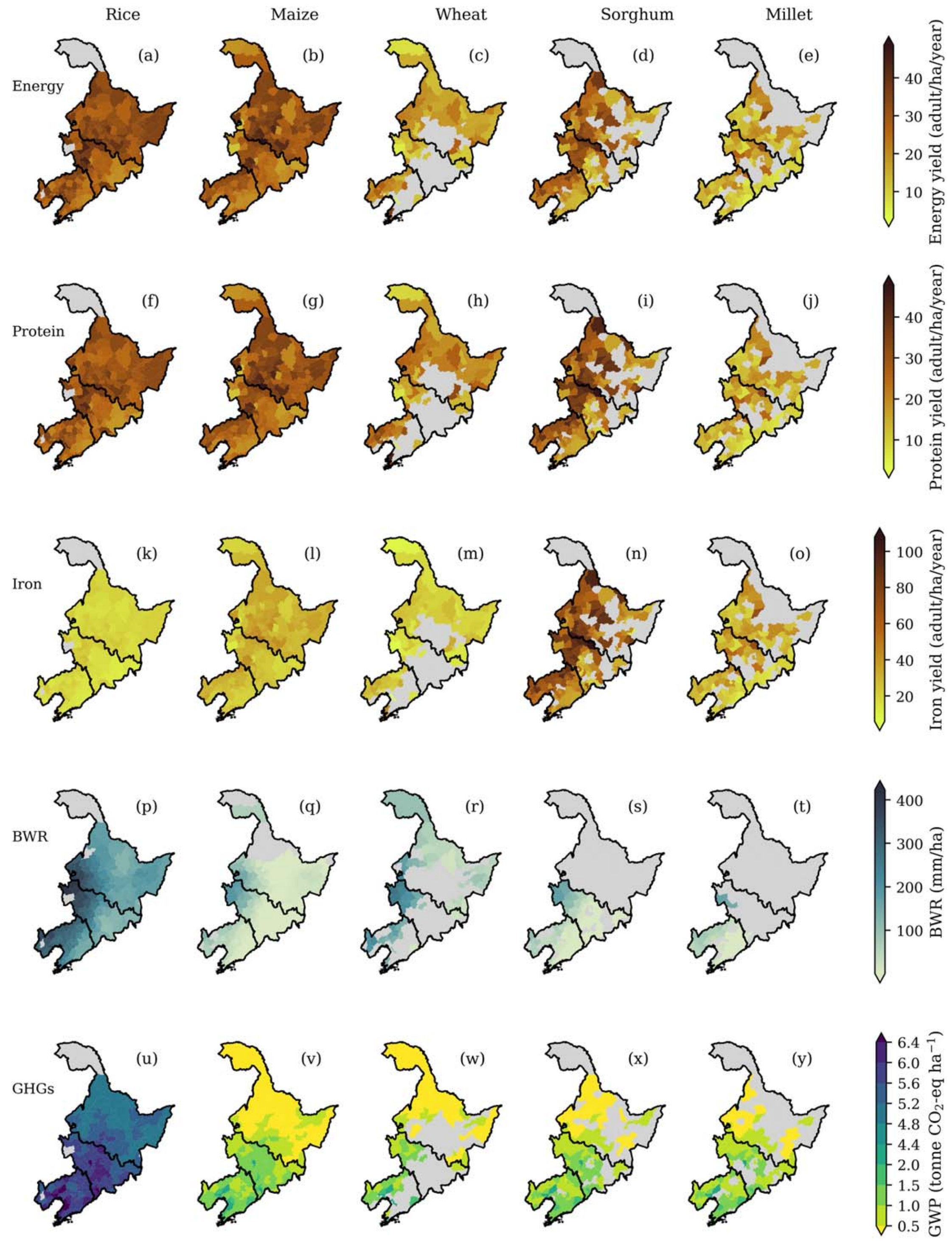

Figure 3. Geographic distribution of average nutritional yield, blue water requirement (BWR), and greenhouse gas emissions (GHGs) of cereals from 2010 to 2014 in Northeast China. (a)–(e): Energy yield, (f)–(j): protein yield, (k)–(o): iron yield, (p)–(t): BWR, and (u)–(y): GHGs.

priorities among stakeholders are often misaligned spatially (figure 6). Spatially, approximately 10% of counties currently achieve all objectives of sustainable agriculture. The policymakers considered maximizing nutritional yields while minimizing irrigation water requirement and GHGs by selecting the target cereals (maize, sorghum, and millet) (figure 6(f)). However, the target cereal is mismatched with most of the current predominant cereals (figures 1(f) and 6(f)). In these 10% of counties, the target crop for maize accounts for 78%, while the current predominant cereals are maize, rice, and wheat. The target crops for sorghum and millet account for 17% and 6%, respectively, while the current predominant cereal is maize (figures 1(f) and 6(f)). Notably, these counties are primarily located in regions with relatively low rice yields. Only two counties can simultaneously achieve all the sustainable goals that both policymakers and farmers are interested in (figure 6(h)).

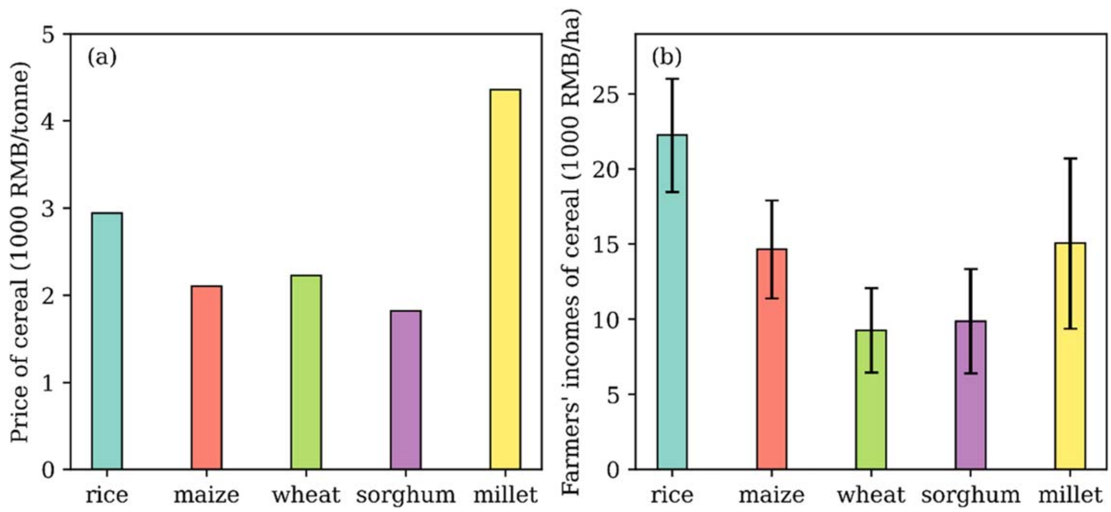

Figure 4. Average price and revenue of cereals in Northeast China from 2010 to 2014. (a) Average price from 2010 to 2014 per tonne for cereals in Northeast China. (b) Average and standard deviation across counties for benefits from 2010 to 2014 per hectare combining price and yield of cereals.

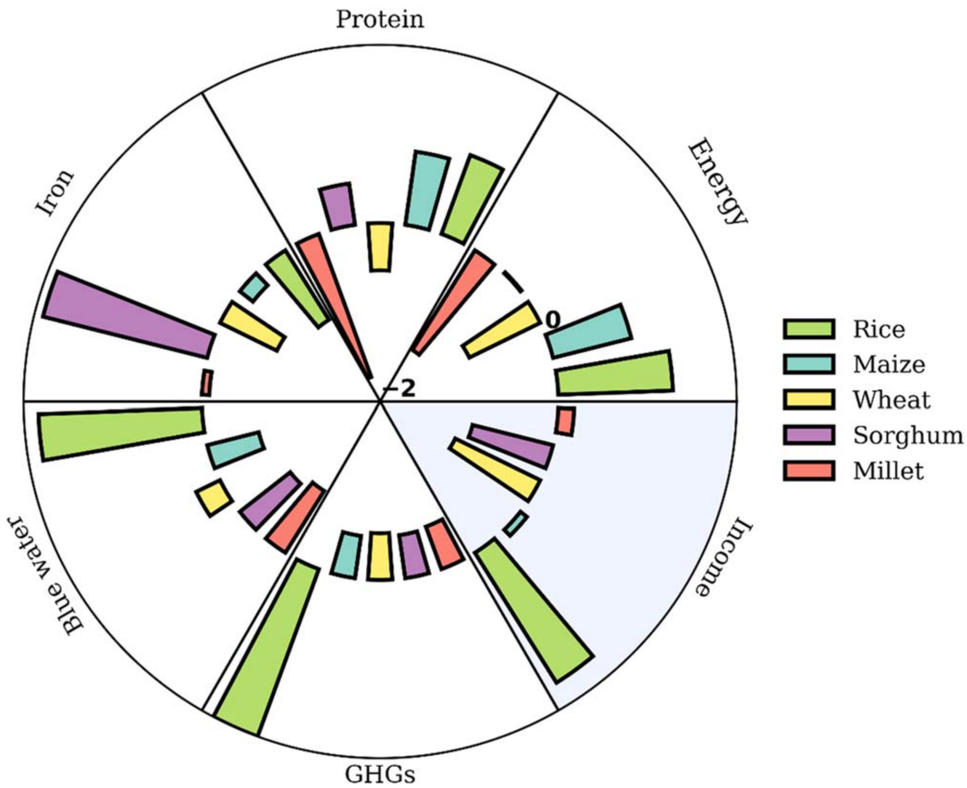

Figure 5. Comparison of average nutritional yields, blue water requirement (BWR), greenhouse gas emissions (GHGs), and farmers' revenue (combining yield and price per hectare) for the five cereals per unit cropland from 2010 to 2014 for all 183 counties in Northeast China. Values are normalized by Z-score for all cereals for each category. Cereals with higher nutritional yields and farmers' revenue perform better, but is the opposite for BWR and GHGs. Zero shows the mean values for nutritional yields, BWR, GHGs, and farmers' revenue of cereals in Northeast China.

3.4. Outcome changes from potential crop switching

Cereal production sustainability in Northeast China can be improved through strategic crop switching (figure 7). By shifting from rice, maize, and wheat to sorghum and millet—while maintaining rice production, preserving farmer revenue, and avoiding increases in cereal cultivation area and irrigation demand—iron and protein production are projected to rise by 33% and 2%, respectively. Simultaneously, irrigation water requirement will decrease by 24% (−345.68 million tonnes/year), and GHGs will be reduced by 3% (167.95

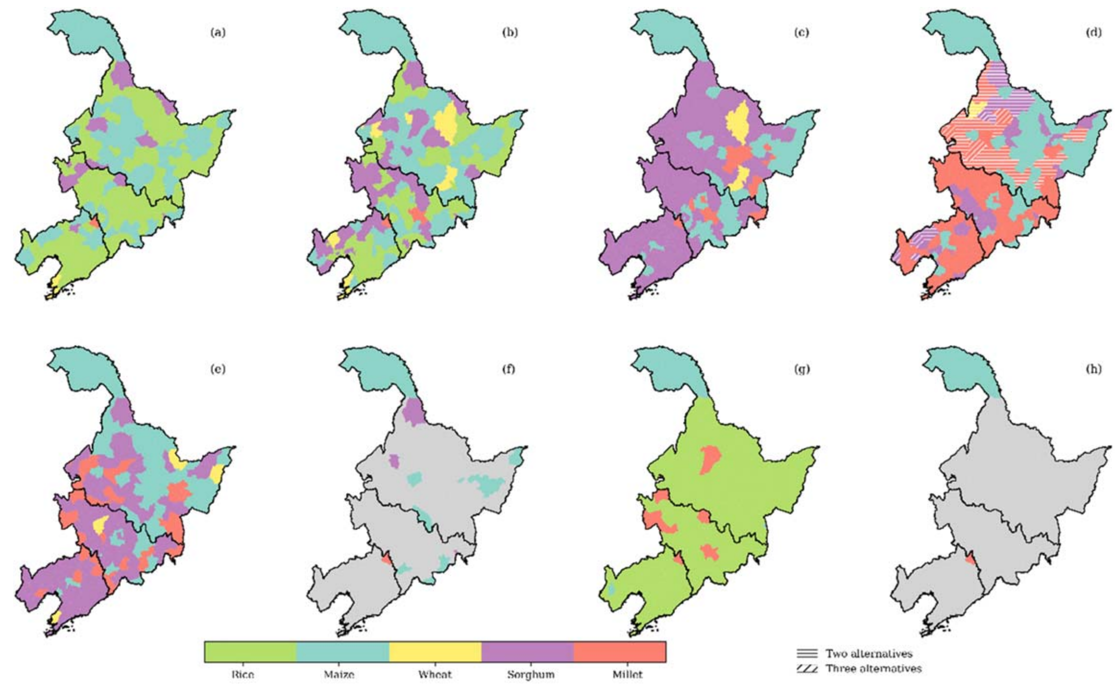

Figure 6. The target cereals to achieve sustainability objectives for each county in Northeast China from 2010 to 2014. The target cereals for achieving maximum energy yield (a), maximum protein yield (b), maximum iron yield (c), minimum blue water requirement (d), and minimum greenhouse gas emissions (GHGs) (e) of the average from 2010 to 2014. The target cereals that can achieve all objectives the policymakers considered, including maximum all nutritional yields and minimum blue water requirement and GHGs per unit area simultaneously (f). The most valuable cereals from the farmers' perspective (g). The target cereals that can achieve all goals from both policymakers and farmers (h). Regions under grey mean there are tradeoffs in different situations, which indicates that efforts should be made in the future.

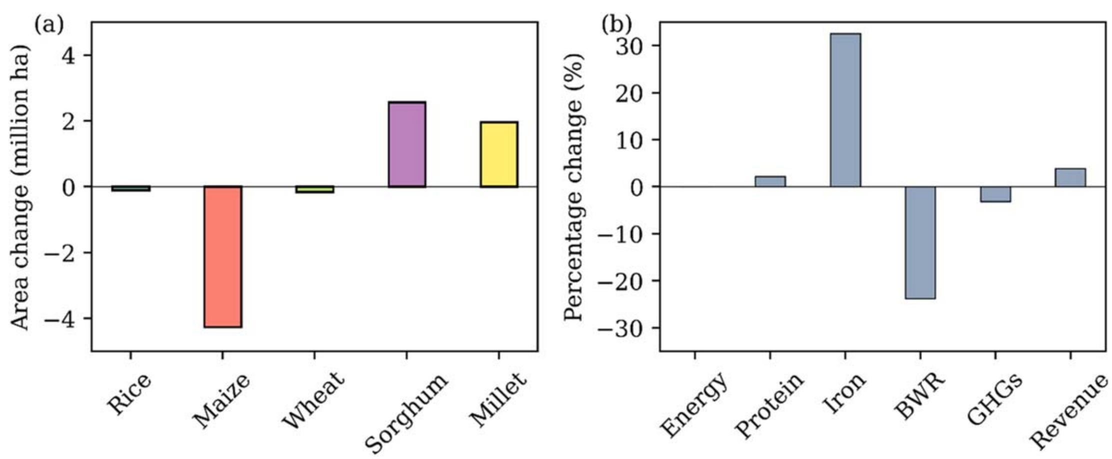

Figure 7. Changes in cereal areas and outcomes from crop switching in Northeast China. (a) Total area changes for cereals before and after crop switching. (b) Changes in outcomes from stakeholders' perspectives, including energy production, protein production, iron production, volumetric irrigation water requirement (BWR), greenhouse gas emissions (GHGs), and farmers' revenue before and after crop switching in Northeast China. The optimization is conducted under the constraints of maintaining rice production and nutritional production levels, avoiding expansion of cereal cultivation areas, and ensuring no additional irrigation water requirement for each county in Northeast China.

million tonnes of $CO_2eq/year$), without compromising energy production (figure 7). Notably, farmers' revenue across the region would also increase by 4%.

4. Discussion

Our study provides a pragmatic approach to assess synergies and tradeoffs among multiple objectives of stakeholders for sustainable agriculture for cereals. We comprehensively assess a semi-humid study region with dramatic historic crop pattern shifts in Northeastern China as a case study to examine the attributes of nutrient supply, water requirement, GHGs, and farmers' revenue for cereals from 2010 to 2014 and evaluate the potential effects on achieving sustainability from crop switching. Our results illustrate the synergies and tradeoffs among different cereal choices that farmers and policymakers face regionally and locally and highlight the plausibility of crop switching to achieve agricultural sustainability.

No single cereal can obtain all the co-benefits in most counties. While maize is the dominant cereal in this region, it has a relatively good average performance in all attributes, but still has some compromises in each attribute. For instance, it has 7% and 1% lower nutritional yields for energy and protein than rice, and 51% less than sorghum for iron, respectively (figure 2). Rice, with the highest increasing rate in harvest area from 1980 to 2014 and leading to sub-regional water scarcity, has the poorest performance in iron yield, water requirement, and GHGs per unit cropland than the other cereals we considered but has the best performance in energy, protein yield and farmers' revenue in most regions (figures 1(b), 5 and 6). Sorghum and millet perform better than rice, maize, and wheat in iron yield and irrigation water requirement, but with minor or moderate compromise on protein and energy yield and shrinking of planting area.

However, synergies and tradeoffs for different objectives have significant spatial heterogeneity. For achieving the single objective, dryland cereals are the best choices for reducing irrigation water requirement and GHGs and increasing iron yield in most counties while rice yields the most energy in 57% of counties such as in central south of Heilongjiang, most of Jilin and Liaoning province because of higher yield (figures 6 and S3). Such spatial heterogeneity provides the potential to achieve the sustainability of cereal cultivation through crop switching. Our results demonstrate that regional sustainability will improve from the perspectives of both policymakers and farmers without compromise on rice production, cropland use, and environmental burdens after crop switching from rice, maize, and wheat to sorghum and millet (figure 7).

Yield increase, economic policy incentives, and market demands are essential to crop shifts. Policies need to put more attention on increasing yields of dryland cereals, such as increasing investment in breeding new varieties and improving technology and agronomy practices without increasing fertilizer inputs on the integrated soil–crop system management program such as precision fertilization (Cui *et al* 2018). New varieties have successfully improved the genetic gains for crop yield in the past decades. For example, improved varieties of maize from 1960 to 2011 increased maize yields by 54%–98% in Lishu County, Jilin Province (Lv *et al* 2015). The average yield of newly adapted millet cultivars in 2015 was higher than that of 2005 and 2010 by 13% and 8% in Northeast China (Li *et al* 2017). The sorghum yield increased significantly with increased plant density in Gongzhuling, Jilin Province (Gao *et al* 2022). However, the investments of governments are more for stable cereals instead of coarse cereals.

Meanwhile, incentive policies such as building a comprehensive price-adjustment and subsidy incentive system for crops could help align policy goals with farmers' revenue and increase the probability of crop switching. Since 2004, the Chinese government has adopted a portfolio of price intervention programs to ensure the production of staple crops through increasing farmers' revenue. For example, the minimum procurement price program has been implemented for rice since 2004 and wheat since 2006, and the minimum procurement price for targeted crops is increased at a steady rate each year; the temporary storage program was started in 2008 for maize, soybean, and rapeseeds (Gale 2013, Huang and Yang 2017). These price-incentive policies achieved their initial goals successfully and additionally made great contributions to crop shifts. However, the current price-support system limitedly covers *Kouliang* (rice and wheat) and other main crops, while other crops such as coarse cereals and most vegetables are not included. Such a policy imbalance probably narrows farmers' choices, which would limit the implementation of the crop-switching strategy and crop diversity.

Incentive policies on shifting consumer diets are essential for facilitating feasible crop switching. As economies grow, dietary preferences tend to shift from plant-based to meat-based options. This transition increases the demand for crops primarily used as animal feed, often at the expense of historically nutritious food like millet. This shift can have significant environmental repercussions. For instance, the energy and protein yield of maize, when primarily grown for feed, is considerably lower than when it is grown for direct human consumption. This inefficiency is exacerbated by the substantial losses incurred during the conversion of crops to animal products (see figures S6 and 2a). The dense water footprint and GHGs costs will come with (Mekonnen and Hoekstra 2012, Gerber 2013). Incentives in increase fraction for food of crop production, improvement of crop quality and taste, and updating of plant-based diet recipes are necessary not only to change market preference but to encourage dietary shift to healthier and more sustainable lifestyles.

This analysis has some limitations. Our study analyzed the sustainability trade-offs and synergies in cereal production among stakeholders in Northeast China, utilizing static panel data primarily from 2010 to 2014, while assuming that changes in international food trade and other crop areas remained constant. The food compositions we used from the latest China food composition table are the average values of China. However, food compositions may vary according to growing conditions, varieties of crops, and the way of processing and cooking. We also do not consider the CO_2 from energy use for tillage, pumping, and harvest, which probably underestimates the GHGs for cereals (figure S8b). Because of limited detailed cost data of cereal production, we only collected detailed costs and net profits data for rice, maize, and wheat (figures S7 and S8). Nevertheless, we have consistent conclusions for the historical revenue comparison of cereals with that for net profits (figure S8).

5. Conclusion

This exploratory study comprehensively assessed the synergies and tradeoffs of multiple objectives of sustainable agriculture from policymakers' perspectives—nutrient output, water requirement, and GHGs—and farmers' revenue for cereals in Northeast China and the potential effect of crop switching on sustainability. Our results indicate that no single cereal can achieve all objectives of sustainable agriculture for stakeholders in most counties, and synergies and tradeoffs have obviously spatial heterogeneity. Overall, rice has the highest energy, protein yield, and income, but performs most poorly on iron yield, water requirement, and GHGs. Sorghum and millet have the highest iron yield 223% and 66% more than rice, and the lowest blue water demand 91% and 90% less than rice. The sustainability of cereal production in NEC will be improved from crop switching with a 33% increment in iron production, a 24% and 3% decrement in irrigation water requirement and GHGs, and a 4% increment in farmers' revenue on existing cultivation area without compromises in rice production. Increasing investments in the yield increment of dryland cereals, building a comprehensive price-adjustment system, and making incentives for diet shifts will help eliminate tradeoffs across objectives and stakeholders and make crop switching feasible. Our study highlights that comprehensively assessing the synergies and tradeoffs among multiple objectives and stakeholders will provide more opportunities to align policymakers and practitioners for crop switching and achieve sustainable agriculture.

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Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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