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Promoting potato as a substitute in low-yield regions for grain crops can achieve multiple benefits in China

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Potato cultivation in China grew only modestly after the 2015 Potato as Staple Food policy, amid grain crop prioritization. Here, we identified grain crop low-yield regions and compared grain crop versus potato performance in productivity, economics, and carbon emissions using the crop model and life cycle impact assessment model. We found that planting potato in these regions would increase crop productivity by 2%–119%, lower greenhouse gas emissions and intensities by 6%–85% and 26%–92%, respectively, while the economic returns increased from generally lower than $600 for the original crops to over $1600 per hectare. However, switching to potato in low-yield wheat and maize regions would reduce calorie supply by over 70%, though these reductions would not affect overall caloric provision at the national level. Our results show that substituting traditional crops with potato offers multiple benefits, enhancing productivity and economic returns while simultaneously reducing carbon emissions, with minimal trade-offs in China.

Although we are more than halfway through the implementation of the 2030 Agenda for Sustainable Development, the goals related to food and agriculture have stagnated or even regressed[1]. This is mainly because agricultural production is facing severe challenges in eradicating poverty and hunger, improving nutrition and health, and addressing climate change. Meanwhile, continuous population growth, limited arable land resources, and intensifying agricultural inputs are also threatening food security and agricultural sustainability, particularly in developing countries[2–5]. Producing more grain on limited arable land with low environmental impact is a key measure to address these challenges. In recent years, a growing number of studies have demonstrated that optimizing crop distribution is an effective means to enhance crop yield and economic return while reducing environmental impact[6,7]. For example, replacing rice with millet and sorghum can improve agricultural productivity and water use efficiency, especially in water-scarce regions in India[8]. In the United States, optimizing the spatial allocation of six major crops could boost farmers' economic returns[7]. To reduce greenhouse gas emissions, substituting wheat with chickpea is suggested in Australian cropping systems[9], while optimized planting configurations for rye and rapeseed in Germany can strengthen agricultural climate resilience[10].

China's agricultural production feeds nearly 22% of the world's population with about 9% of the world's arable land[11]. The planting area and total production of maize, rice, and wheat in China account for 11%-21% and 17%-27% of the global totals, respectively, highlighting their crucial roles in ensuring global food security[1]. However, in some cultivation regions for staple grain crops, adverse climatic or soil conditions result in low and highly variable grain yields in China (e.g., 2.9−5.9 t ha^{-1} for wheat in the Loess Plateau, 3.7−6.7 t ha^{-1} for maize in Guanzhong Plain, 1.9−2.7 t ha^{-1} for rice in southern hilly regions in China)[12–14]. Low crop yields in these regions lead to economic losses for farmers, while increasing water/fertilizer inputs for improving crop yields generate severe environmental impacts[15,16]. Therefore, breaking the 'triple dilemma' of low yield, low income, and high environmental impact in low-yield regions of staple grain crops is crucial for maintaining livelihood stability, safeguarding national food security, and

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environmental protection[17]. Previous studies have primarily focused on enhancing agricultural productivity by optimizing planting date, cultivar, agronomic management practice, and soil improvements[18,19]. However, in regions where climatic conditions are unfavorable for the growth of staple grain crops, these strategies may fall short of high productivity gains. In such cases, introducing climate-resilient crops as alternatives to traditional staple grain crops presents a promising approach to improving crop yields and fostering more sustainable agricultural production.

Potato, the fourth largest global food crop after wheat, maize, and rice, plays a key role in China's agricultural sector, contributing 32% of the world's total potato planting area and 26% of global production[1]. Despite the Chinese government's Potato as the Staple Food policy initiated in 2015, the anticipated expansion in potato planting area has yet to be fully achieved[20,21]. Recent studies confirm that potato plays a vital role in ensuring food security [22], improving resource use efficiency [23], reducing agricultural carbon emissions[24], and promoting climate-smart agricultural development[25,26]. Moreover, potatoes are rich in vitamin C, anthocyanins, and carotenoids, making them well-suited for improving dietary diversity and nutritional balance[22]. Compared to staple grain crops, potato produces higher dry yields while emitting fewer greenhouse gases under similar hydrothermal conditions[24]. Therefore, assessing the adaptability of potato cultivation in low-yield regions of staple grain crops is essential for promoting potato planting without compromising the domestic production of staple grain crops in China.

Recent studies have investigated the impacts of optimizing agronomic management practices and selecting suitable cultivars on potato yield, water use efficiency, greenhouse gas (GHG) emissions, and economic benefits across China's potato planting regions[20,23,27]. However, the comparative advantage of potato cultivation to staple grain crops in their suboptimal regions remains unclear. This knowledge gap calls for a comprehensive assessment that considers multiple factors, including crop yields, economic benefits, and ecological and environmental impacts. Crop models are typically used to explore optimal combinations of crop cultivars, environment, and agronomic management for high-yield and high-efficiency production, while the life cycle assessment model quantifies greenhouse gas emissions from different cropping systems[20,28–30]. However, due to limitations in data and methodological compatibility, few studies have integrated both approaches to comprehensively evaluate the overall performance of crop cultivation in terms of yield, economic returns, and environmental impact. Therefore, this study firstly identified suboptimal regions for staple grain crops (maize, rice, and wheat) in China based on their actual yield levels. Then, a hybrid model integrating a crop growth model and a life cycle impact assessment model was developed to compare the yields, economic benefits, ecological efficiency, and greenhouse gas emissions of potato with three staple grain crops[31]. Our results will provide insights into the feasibility and advantages of promoting potato cultivation in suboptimal regions of staple grain crops, thereby supporting the implementation of the 'Potato as Staple Food' policy and advancing towards a more sustainable agricultural system.

Results

Yield and cost-return of alternative potato planting in China

The suboptimal planting regions of three staple grain crops in China were determined, where actual yields were within the 10th percentile across all planting regions for each crop in this study (see details in the "Methods" section). Figure 1a–c shows that low-yield regions of maize were primarily distributed in southwest China, southern Shaanxi and Gansu, the center part of Xinjiang, eastern Inner Mongolia, and the hilly region of south China. The low-yield regions of rice were located in southwest China and western Xinjiang, while those of wheat were in southwest China, southern Gansu, Shaanxi, the center part of Xinjiang, eastern Inner Mongolia, and the hilly region of South China. As rice in southern China is primarily planted in well-irrigated regions, the area of suboptimal planting regions for rice (0.3 million ha), mainly concentrated in southwest China, was much smaller than that for maize (1.6 million ha) and wheat (1.1 million ha).

The simulated dry yields of the original grain crops and potato in these low-yield regions were compared using the calibrated APSIM model. Without water limitation, simulated regional average yields of maize, wheat, and rice were 6.2 t ha^{-1}, 4.4 t ha^{-1}, and 2.8 t ha^{-1}, respectively (Supplementary Fig. S7a–c). After switching to potato cultivation, simulated potential dry yields would increase by 119%, 41%, and 2% compared to potential yields of rice, wheat, and maize, respectively (Fig. 2a–c). Under rainfed conditions, simulated dry yields of staple grain crops were generally less than 4 t ha^{-1} (Supplementary Fig. S7d–f), while planting potato could increase yields by 19%–89% relative to three grain crops (Fig. 2d–f). Overall, the low-yield regions for maize, rice, and wheat in southwest, northeast, and northwest China should be prioritized for promoting potato cultivation in terms of achieving high yields. Under potential and rainfed conditions, potato cultivation in low-yield regions of rice increased calorie production by 46% and 27%, respectively. In contrast, replacing maize and wheat with potato in their low-yield regions led to calorie supply reductions of 76% and 66%, and 70% and 72% under potential and rainfed conditions, respectively. However, these calorie decreases in suboptimal regions only account for a minor proportion relative to the national crop calorie supply (Supplementary Fig. S8).

The total cost and return of planting these crops were calculated based on the national compilation data of agricultural products. Despite the costs of planting staple grain crops being less than \$500 ha^{-1} regardless of potential and rainfed conditions (Fig. 3a), the economic return (sale price of harvested crop yield minus planting cost) was below \$600 ha^{-1}. Never-

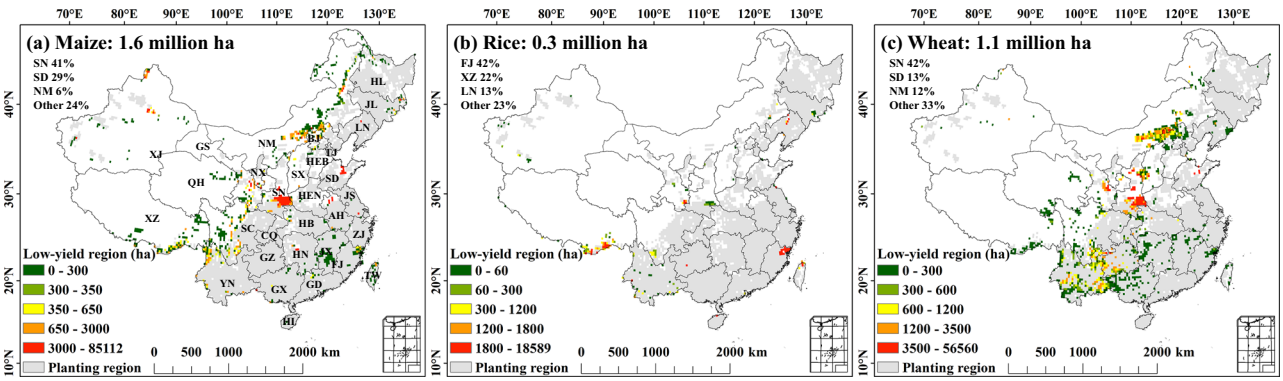

Fig. 1 | Distribution of low-yield regions for staple grain crops. The spatial maps of low-yield regions (**a**–**c**) of maize, rice, and wheat based on the actual yield level. The abbreviations corresponding to the provinces can be found in the supplementary Fig. S6. The percentages in the figure represent the proportion of the top three provinces with the largest low-yield areas relative to the total low-yield area.

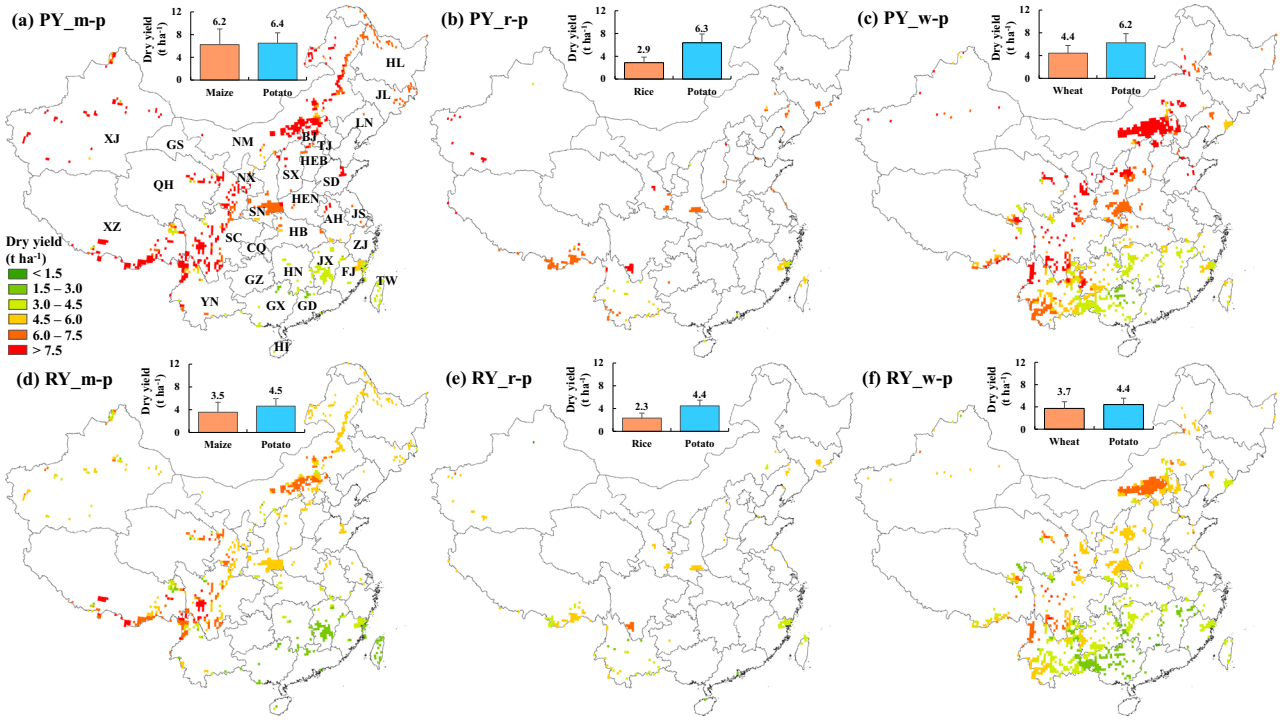

Fig. 2 | Yield performance of potato cultivation in low-yield staple grain crop regions. Simulated dry yield of switching maize to potato (m–p), switching rice to potato (r–p), and switching wheat to potato (w–p) under potential (PY) (**a**–**c**) and rainfed (RY) (**d**–**f**) conditions. The histogram on each map shows the average potato yield in these suboptimal regions compared with the yields of three major grain crops. The error bar shows the interannual variation for each crop. The abbreviations corresponding to the provinces can be found in the supplementary Fig. S6. The legend in each map is consistent with (**a**).

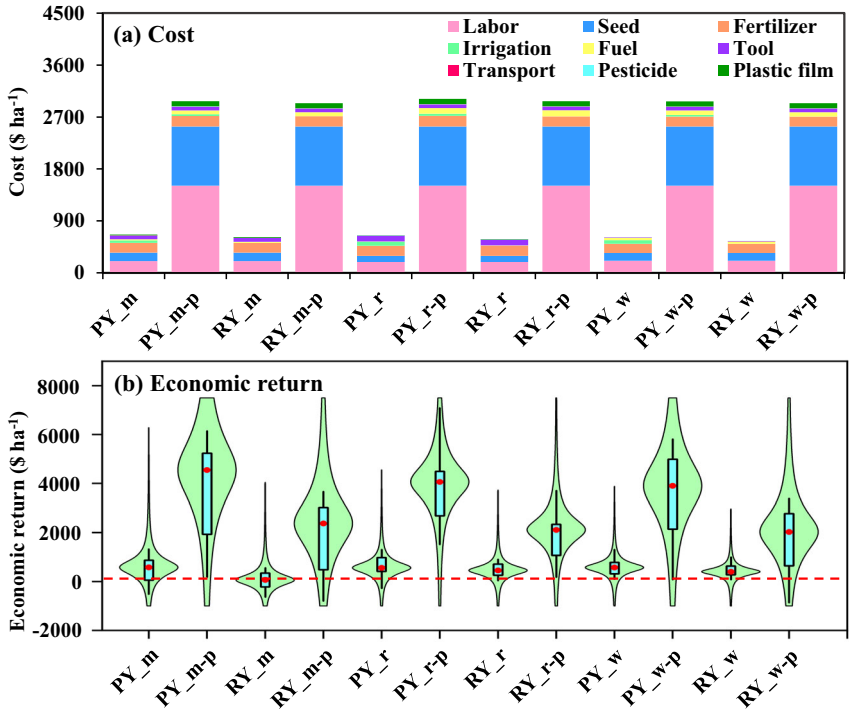

Fig. 3 | Cost-benefit analysis of staple grain crops versus potato cultivation. The cost-return of maize (m), rice (r), wheat (w), and switching maize to potato (m–p), switching rice to potato (r–p), and switching wheat to potato (w–p) under potential (PY) and rainfed (RY) conditions. The cost (**a**) includes the sum of each agricultural input per hectare. Economic return (**b**) refers to the benefit generated from the sale of harvested crop yields minus all associated costs. The box whiskers show the maximum and minimum values; the upper and lower box edges of boxes show the 75th and 25th percentiles, respectively; the red point shows the average value.

theless, the economic return from planting potato exceeded \$3500 ha^{-1} and \$1600 ha^{-1} under potential and rainfed conditions, respectively, despite the planting costs being 3–4 times higher than grain crops (Fig. 3b). High potato yields lead to great economic returns, particularly because potato is typically sold based on their fresh weight.

Carbon emissions of alternative potato planting in China

Overall, GHG emissions exhibited large spatial variations, primarily driven by differences in agricultural inputs, particularly nitrogen fertilizer application across regions. Under potential conditions, maize cultivation in central and northern Jiangsu emitted the highest GHG emissions, at 5098 kg

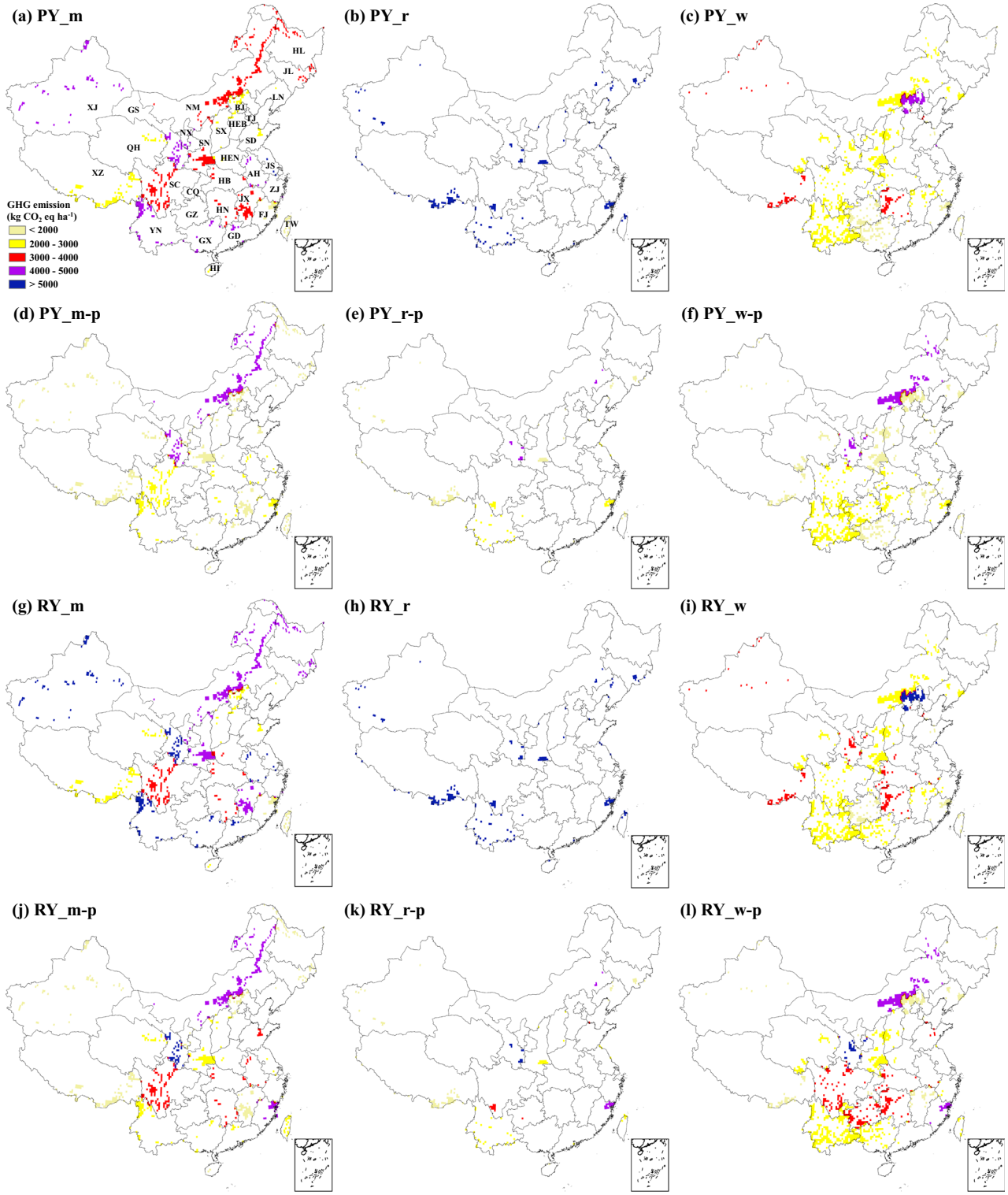

Fig. 4 | GHG emission amount of staple grain crops versus potato cultivation. The GHG emission amount per hectare of maize (m), rice (r), wheat (w), and switching maize to potato (m–p), switching rice to potato (r–p), and switching wheat to potato (w–p) under potential (PY) (**a**–**f**) and rainfed (RY) (**g**–**l**) conditions. GHG emissions include the indirect CO_2 emissions from the production and transportation of agricultural inputs, farming operations and harvest, and the direct seasonal CH_4 and N_2O emissions from crop planting. The abbreviations corresponding to the provinces can be found in the supplementary Fig. S6. The legend in each map is consistent with (**a**).

CO_2 eq/ha, while maize in suboptimal regions of Xinjiang under rainfed conditions produced even higher emissions, at 6753 kg CO_2 eq/ha (Fig. 4a, j).

For rice, southern provinces including northern Jiangsu, Yunnan, and southern Guangdong had the highest emissions per hectare under potential condition, ranging from 10,762 to 11,960 kg CO_2 eq/ha (Fig. 4b). Under rainfed condition, northern Jiangsu, Yunnan, and northern Shandong exhibited the highest emissions per hectare, ranging from 9868 to 11,757 kg CO_2 eq/ha (Fig. 4h). For wheat, northern Hubei, Jiangsu, and Xinjiang produced the highest emissions per hectare under potential condition, with

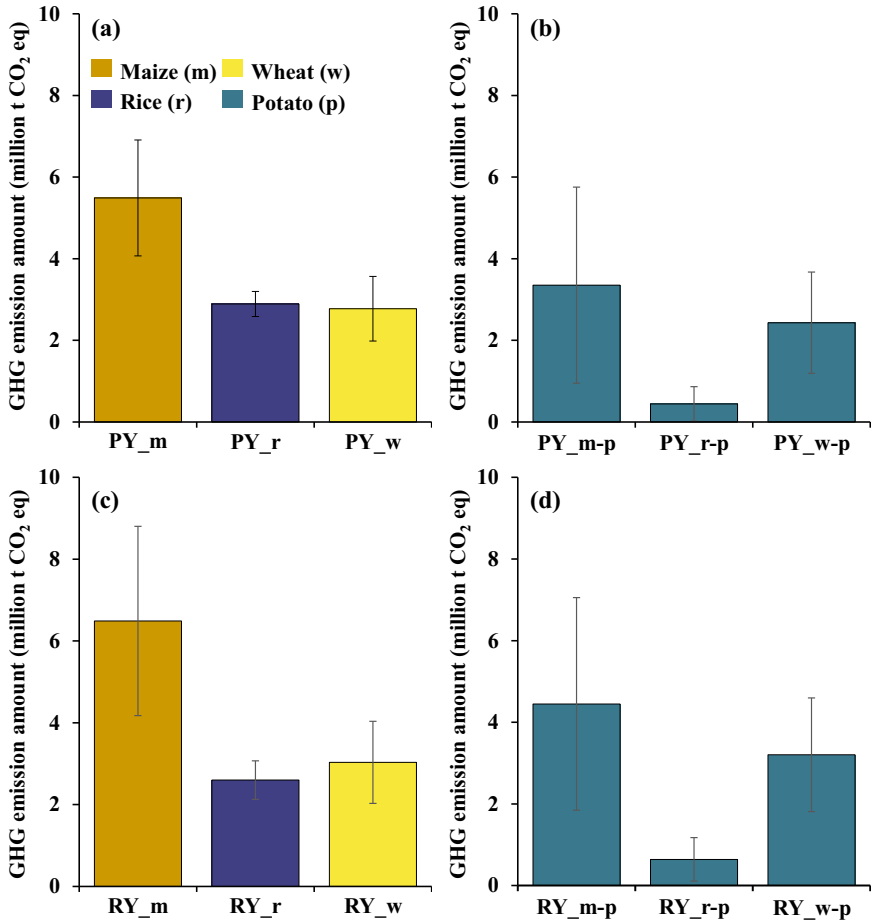

Fig. 5 | Total GHG emission amount of staple grain crops versus potato cultivation. Total GHG emission amount of maize (m), rice (r), wheat (w), and switching maize to potato (m–p), switching rice to potato (r–p), and switching wheat to potato (w–p) under potential (PY) (**a** and **b**) and rainfed (RY) (**c** and **d**) conditions. The error bar shows the interannual variation for each crop. The legends in (**b**–**d**) are consistent with (**a**).

values of 5517, 5456, and 3954 kg CO_2 eq/ha, respectively. Under rainfed conditions, northern Hubei, Jiangsu, and Tianjin had the highest emissions per hectare of 4672, 4657, and 3455 kg CO_2 eq/ha, respectively (Fig. 4c, i).

Our findings indicated that potato cultivation could substantially reduce GHG emissions, particularly in suboptimal rice regions, where emissions decreased by 85% under potential conditions and 75% under rainfed conditions (Fig. 4e, k). In suboptimal maize regions, potato cultivation led to a reduction in emissions by 39% and 31% under potential and rainfed conditions, respectively (Fig. 4d, j). Although potato cultivation in suboptimal wheat regions resulted in a small increase of 6% in GHG emissions per hectare compared to wheat under rainfed conditions, it lowered emissions by 12% under potential conditions (Fig. 4f, l).

In terms of total GHG emissions, maize accounted for the largest suboptimal planting areas, which contributed to the highest GHG emissions —5.5 and 6.5 million t CO_2 eq under potential and rainfed conditions, respectively, followed by wheat at 2.8 and 3.0 million t CO_2 eq, and rice at 2.6 and 2.9 million t CO_2 eq (Fig. 5a, c). Planting potato in suboptimal maize regions emitted the highest GHG emissions of 3.4 million t CO_2 eq and 4.4 million t CO_2 eq followed by suboptimal wheat regions of 2.4 and 3.2 million t CO_2 eq, and suboptimal rice regions of 0.4 and 0.6 million t CO_2 eq, under potential and rainfed conditions, respectively (Fig. 5b, d).

GHG emission intensity and eco-efficiency of alternative potato planting in China

Our analysis showed that under potential condition, rice planting exhibited the highest GHG_i (3.7 t CO_2 eq t^{-1}), followed by maize (0.8 t CO_2 eq t^{-1}), and wheat (0.6 t CO_2 eq t^{-1}) in the respective suboptimal regions (Fig. 6a). The GHG_i of potato was substantially reduced compared to the original crops, with all the values below 0.3 t CO_2 eq t^{-1} (Fig. 6a). Planting potato in Jilin, Xinjiang, and Jiangxi provinces had lower GHG_i than other regions under potential condition, while potato planting in most regions of Xizang presented an absorption of the GHG emissions (Supplementary Fig. S9c, g, k). Under rainfed conditions, the GHG_i of potato had increased compared to the potential condition. However, it remained lower than the GHG_i of grain crops (Fig. 6b). Overall, the suboptimal regions of staple grain crops in the northeast and southwest China should be prioritized for potato cultivation with lower GHG_i compared to other regions (Supplementary Fig. S9d, h, l).

Furthermore, potato planting in suboptimal regions of wheat achieved the highest eco-efficiency (E_{GHG}) at 6.9 \$ CO_2 eq kg^{-1}, followed by maize and rice of 6.0 \$ CO_2 eq kg^{-1} and 4.6 \$ CO_2 eq kg^{-1}, respectively (Fig. 6c) under potential conditions. Under rainfed condition, the ranking of E_{GHG} for potato planting in the suboptimal regions of wheat, maize, and rice remained consistent with the values of 1.6, 1.2, and 1.0 \$ CO_2 eq kg^{-1}, respectively (Fig. 6d). The E_{GHG} of planting potato under rainfed condition was highest in the suboptimal maize planting regions of Xinjiang, the rice regions of Jilin and Liaoning provinces, and the wheat regions of Xizang (Supplementary Fig. S10d, h, l). Overall, these results suggest that switching low-yield regions of staple grain crops to potato planting can considerably enhance agricultural sustainability.

Discussion

The implementation direction of the Potato as Staple Food policy

Sustainable agriculture seeks to enhance agricultural productivity, improve resilience to climate change, and mitigate environmental impacts, particularly in developing countries[2,6]. Crop switching has been recognized as an effective approach to achieving agricultural sustainability[32,33]. In 2015, the Chinese government launched the 'Potato as Staple Food' policy with objectives to boost agricultural productivity, conserve water and fertilizer resources, and promote healthier dietary options. Despite these efforts, the

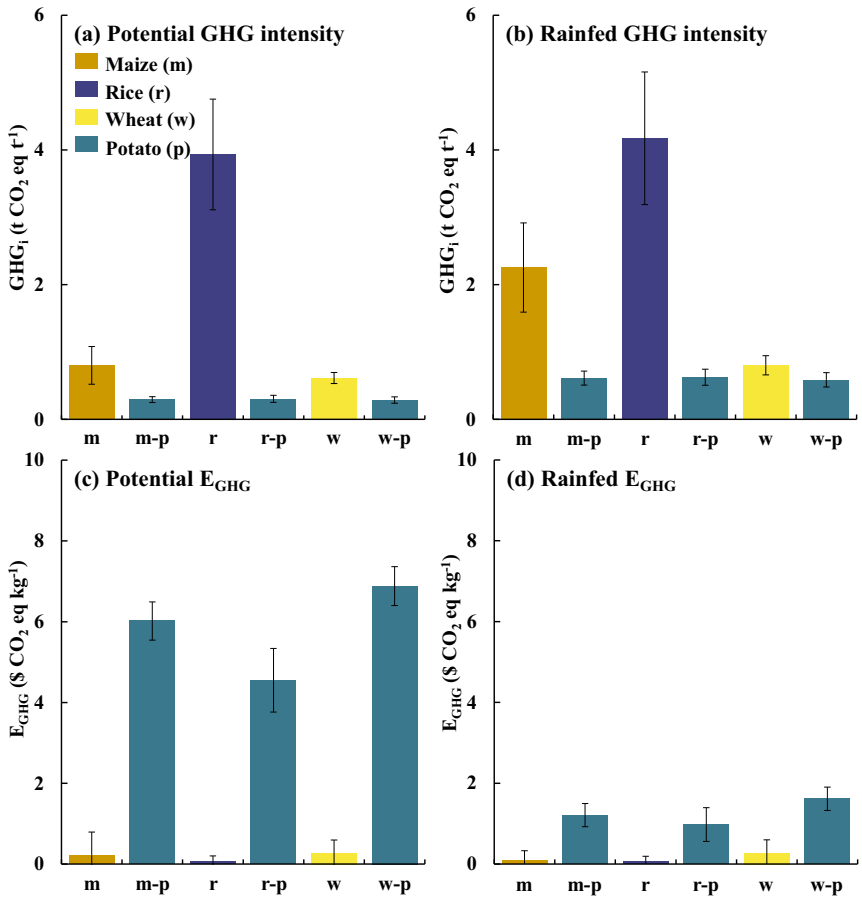

Fig. 6 | GHG emission intensity and eco-efficiency of staple grain crops versus potato cultivation. GHG emission intensities (**a**, **b**, GHG_i) and eco-efficiency (**c**, **d**, E_{GHG}) of maize (m), rice (r), wheat (w), and switching maize to potato (m–p), switching rice to potato (r–p), and switching wheat to potato (w–p) under potential (PY) and rainfed (RY) conditions. GHG_i (t CO_2 eq t^{-1}) is the GHG emissions per unit yield. E_{GHG} ($ CO_2 eq kg^{-1}) is the economic return per unit GHG emission. The error bar shows the interannual variation for each crop. The legends in (**b**–**d**) are consistent with (**a**).

expansion of potato cultivation area remains limited, largely due to the focus on securing the national supply of staple grains. Previous studies have indicated that in several grain-producing regions of China, yield improvements are unlikely to be achieved solely through optimized agronomic management practices or the selection of existing cultivars[34,35]. Our study is the first to identify suboptimal grain-producing areas that could be effectively converted to potato cultivation, thereby allowing the promotion of potato crops without jeopardizing the production capacity of essential staple grains.

Comprehensive benefit analysis of potato cultivation

Crop switching could increase agricultural productivity. In the United States, optimizing the crop distribution of maize and wheat can increase yields by more than 10%[36]. Potato, with tubers developing underground, can achieve fresh yields exceeding 70 t ha^{-1} under optimal hydrothermal conditions[21]. Under similar high-yield and high-efficiency cultivation modes, the yields of maize, wheat, and rice ranged between 10−12 t ha^{-1}, 7.5−8.5 t ha^{-1}, and 8.1−8.3 t ha^{-1}, respectively[37–39]. Even in regions with limited hydrothermal resources unsuitable for crop cultivation, potato yields remain higher than those of staple grain crops. For example, in rainfed systems, the average dry matter yields for potato, rice, spring wheat, and spring maize were 3.6 t ha^{-1}, 2.0 t ha^{-1}, 2.4 t ha^{-1}, and 3.0 t ha^{-1}, respectively[40,41]. We also found that the low-yield regions for staple grain crops are primarily located in the plateau, mountainous, and hilly areas. These cool regions provide favorable climatic conditions for potato growth, as demonstrated by field trials in Switzerland and South Korea[42,43]. However, potato yields in the mountainous areas of south and southwest China (e.g., Yunnan, Guizhou, and Guangxi provinces) are lower than in other regions. Although water availability is not a limiting factor, low solar radiation during the potato growing season constrains yield potential for these areas[44]. To address this, efforts should focus on improving radiation use efficiency by adjusting planting dates and selecting cultivars with longer growth durations[20,44].

Previous studies reported that potatoes had lower GHG emission amounts and emission intensities than other staple grain crops[24]. They found that GHG emissions from potato cultivation accounted for only 4% of the total emissions generated by rice, wheat, and maize. In addition, studies from the United States[26], China[45], and Denmark[46] indicated that optimizing agronomic management can further reduce greenhouse gas emissions during potato cultivation. Our study found that planting potatoes in low-yield regions of rice resulted in the greatest reduction in greenhouse gas emissions per hectare. This is because rice production generates higher GHG emissions than other crops, particularly methane[47,48]. In contrast, potatoes have been found to absorb remarkable amounts of methane emissions, resulting in a substantial reduction in greenhouse gas emissions[45,49]. Previous study also demonstrated that the single-season rice cultivation emitted 304 kg ha^{-1} of CH_4, while potato cultivation demonstrated an absorption of 29 kg ha^{-1} of CH_4 in India[50]. Meanwhile, extensive water and fertilizer inputs in low-yield regions further exacerbate the negative environmental impacts[24,51]. Specifically, potato cultivation in southern regions such as Xizang, Yunnan, and Guangxi exhibits lower greenhouse gas emissions compared to other areas. On the one hand, the cooler climate during spring or autumn-winter potato planting in these regions suppresses soil microbial activity, which reduces nitrous oxide emissions[52]. On the other hand, higher precipitation during the potato growth period minimized the need for irrigation, labor, and machinery inputs. Additionally, crop rotations with maize, soybeans, barley, and forage further reduce emissions compared to monoculture systems[53]. However, there are still regions where switching to potato cultivation results in relatively high greenhouse gas emissions due to excessive fertilizer inputs and

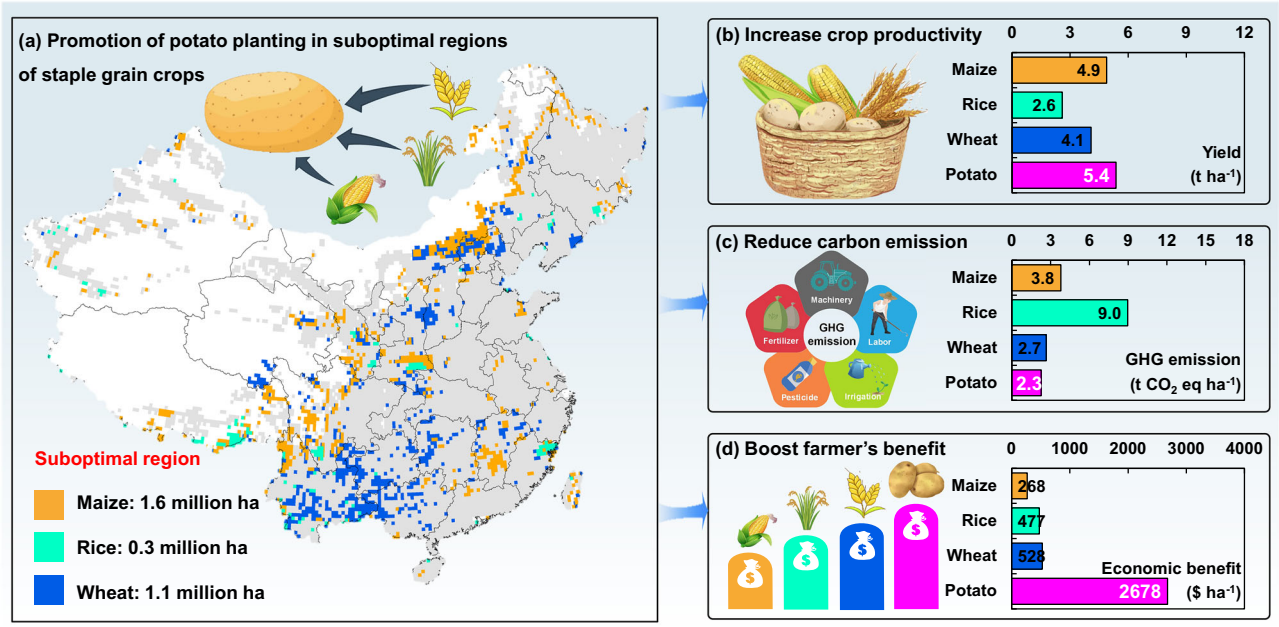

Fig. 7 | The overall effects of crop switching. a Conversion of low-yield maize, rice, and wheat areas to potato cultivation. Impacts of potato cultivation in low-yield staple grain crop regions on productivity (**b**), carbon emissions (**c**), and economic returns (**d**).

low fertilizer use efficiency among smallholders in Inner Mongolia and Gansu[45,54]. These regions may achieve further GHG reductions through optimized fertilizer management strategies. Additionally, switching to potato cultivation in low-yield staple grain regions may still pose certain negative environmental impacts. Our further analysis indicated that greenhouse gas emissions from nitrogen leaching during potato cultivation were higher than those from staple grain crops (Supplementary Fig. S11). Although this portion represented a small share of total greenhouse gas emissions, practical production should prioritize precise nitrogen application strategies to further reduce GHG emissions in potato fields.

It is undeniable that staple grain crops yield substantial economic returns when cultivated in their primary production region. However, research findings from these staple crop primary production regions cannot reflect the economic returns of cultivation in low-yield regions[55,56]. Our analysis reveals that traditional cropping patterns in the suboptimal regions of staple grain crops have low economic returns, with maize at \$268 ha^{-1}, rice at \$477 ha^{-1}, and wheat at \$528 ha^{-1}. In contrast, potato cultivation in these regions offers a much higher economic return, averaging around \$2700 ha^{-1}. Similar cases of crop switching increasing farmers' economic returns have also been observed in other countries. For example, switching from rice to millet or sorghum cultivation can increase farmers' profits by 140% in India[8], while adding oilseed and legume crops to traditional single-season grain cultivation can increase the economic returns of farmers by 10%–20% in Canada[57]. However, we also found that potato planting in southern China (e.g., parts of Guangdong, Guangxi, Jiangxi, and Hainan provinces) may incur economic losses due to low yields under rainfed conditions. In these areas, potato growing season overlaps with the dry season, resulting in low rainfed yields[58]. Additionally, low solar radiation during the growth period further constrains yield increases, as confirmed by our previous research[59].

Our findings indicate that switching to potato cultivation in low-yield staple grain regions may lead to some calorie loss (Supplementary Fig. S8). In fact, China's current total crop-derived energy supply can essentially meet population requirements. Therefore, cultivating potatoes in low-yield grain regions would not affect overall caloric provision. Especially, with rising consumption shares of dietary fiber and meat products, optimizing nutritional structure in diets has become particularly crucial[22,24]. Potato tubers contain a variety of nutrients essential to the human body, such as lysine, vitamin C, and carotenoids, etc.[60]. Thus, the cultivation of potato as an alternative crop for staple grain crops in suboptimal regions not only enhances dry matter production, but also provides more nutrients, which in turn contributes to improving the nutritional level of the population's diet.

The potential implications of this study's findings

In 2016, China's agricultural sector issued the Guiding Opinions on Promoting the Development of the Potato Industry, setting a goal to expand the potato planting area to over 6.7 million hectares by 2020. However, by 2022, the potato planting area in China reached 5.7 million hectares, falling approximately 15% short of the target[1]. Our findings indicate that planting potatoes as an alternative to staple grain crops in their suboptimal regions aligns with the objectives of the Potato as Staple Food policy while offering multifaceted benefits. These include improving agricultural productivity, increasing economic returns of farmers, reducing carbon emissions and enhancing ecological efficiency (Fig. 7). Furthermore, based on the observational data, the potato cultivation could expand by up to 39% (an additional 3.0 million hectares) from the current level, with a reduction in total staple grain crop yield of less than one percent (Supplementary Fig. S12). However, while this study demonstrates distinct advantages of planting potatoes in yield enhancement, economic profitability, and emission mitigation, it is important to recognize that grain crops remain nutritionally irreplaceable due to their protein, iron, and other essential nutrient content. Consequently, the current findings are specifically applicable to low-yield grain production regions, and potatoes' comparative advantages in other agricultural areas necessitate further validation through a comprehensive multi-factor assessment.

Countermeasures for the development of China's potato industry

The Chinese potato industry faces several challenges that constrain its productivity and broader adoption. Low yields remain a critical issue, driven by poor seed quality, limited mechanization, and suboptimal agronomic practices[59]. Addressing these constraints requires the development and promotion of high-yield, disease-resistant cultivars, improved irrigation and fertilization techniques, and the adoption of precision agriculture technologies. Enhancing farmer training programs and expanding access to modern farming equipment could further optimize management practices. Additionally, the short storage life of potato tubers, coupled with inadequate

storage, transportation, and marketing infrastructure, leads to high post-harvest losses and market inefficiencies[22]. Investments in cold storage facilities, transportation networks, and regional processing hubs are essential to minimize losses and improve year-round availability. Furthermore, the perception of potatoes as a staple food remains weak in Chinese diets, limiting their consumption[21]. Promoting the nutritional benefits of potatoes and diversifying downstream production lines with processed products such as potato flour, noodles, and ready-to-eat meals could enhance their role as a staple food[61]. Integrating these pathways will be critical to unlocking the full potential of the Chinese potato industry and ensuring its sustainable growth.

The limitation of this study

Our study has several limitations and uncertainties. Firstly, while the hybrid model demonstrates comprehensive analyses, its inherent uncertainties and limitations need to be emphasized. Crop and management data used in the LCA model were spatially interpolated from site-scale observations, introducing uncertainties between stations that require higher-resolution grid data for improvement. Most data used in the LCA model for greenhouse gas estimation (e.g., production inputs and emission factors) remained fixed throughout the historical period, resulting in constant GHG emission values for each crop across different years. In reality, GHG emissions for each crop would vary across years due to differences in agronomic management practices. Subsequent studies should therefore investigate long-term environmental impacts using more precise crop production datasets based on refined LCA modeling. Moreover, crop models, including APSIM, could not well simulate the impacts of extreme weather events (e.g., hail, heavy wind, and heat stress) on crop growth, which likewise constrains the model's precision. Secondly, the identification of suboptimal regions for staple grain crops in this study is based on areas characterized by low yield levels. However, this approach may not accurately represent current planting conditions due to the limited availability of yield data. To improve accuracy, future research should focus on refining the identification of these suboptimal regions by incorporating a broader range of datasets, including gridded soil data and land resource utilization information. Thirdly, the cost and price data at the provincial level used in our study were treated as fixed, whereas agricultural input costs and crop sale prices are subject to regional variations driven by fluctuations in market supply and demand during actual production. Future research should involve a more detailed examination of factors such as soil types, land use change, climate change, and policy directions to better understand their impacts on potato cultivation in China. Finally, our modeling approach compared potato and grain crop systems in terms of yield performance, economic returns, and greenhouse gas emissions. However, comprehensive agricultural environmental impacts extend beyond GHG emissions to include factors such as soil acidification and water pollution. Future investigations of cropping system sustainability should incorporate these additional environmental dimensions.

Methods

Crop planting regions, soil, and meteorological data

In this study, gridded planting regions and actual yields of maize, rice, wheat, and potato with a resolution of 0.1° × 0.1° (averaged for the period of 2009–2011) for China were available from the Spatial Production Allocation Model (SPAM2010), which is a widely used dataset[21,62,63]. Gridded soil data (0.08° × 0.08°) included soil layer depth, bulk density, saturated water content, field capacity, and wilting moisture were obtained from the Global Gridded Soil Information driven by ISRIC. Daily meteorological data with a resolution of 0.25° × 0.25° during 1981–2010 were obtained from the AgMIP Climate Forcing Datasets driven by NASA, including daily maximum temperature (°C), minimum temperature (°C), mean temperature (°C), precipitation (mm), and solar radiation (MJ m^{-2} d^{-1}). The gridded data of soil and planting region were upscaled to 0.25° × 0.25° for simulating crop yields and calculating the GHG emissions at the grid level.

Definition of suboptimal planting regions of staple grain crops

There are low-yield regions for the staple grain crops in China due to the limitations of geographical, climatic, and soil conditions[18,37,64]. Based on the gridded average actual yields of maize, rice, and wheat with a resolution of 0.1° × 0.1° obtained from the SPAM dataset, we first divided the yield into 10th, 20th, …, 100th percentiles. The grids with yields lower than the 10th percentile of the yield were defined as the low-yield grids. Secondly, the low-yield grids were mapped to the planting regions of each crop with a resolution of 0.1° × 0.1°, which were defined as the suboptimal regions of each crop. Finally, the suboptimal regions were upscaled to 0.25° × 0.25° for simulating crop yields and estimating the GHG emission amounts for each crop (Fig. 1a–c).

Crop model and life cycle impact assessment model

An integrative assessment framework for evaluating the yield, economic benefit, and carbon emission of crop planting was developed by combining the life cycle impact assessment model with a crop model using multiple sources of data (Supplementary Fig. S5). Crop yields were simulated using the APSIM (Agricultural Production Systems sIMulator), which could simulate the interaction of genetic, environment, and management on crop growth and development. Specifically, the well-calibrated APSIM-Maize, Rice, Wheat, and Potato models were used to simulate the yields under potential and rainfed conditions across the staple crops' suboptimal planting regions[30,65]. Based on previous parameter calibration results of various models, we validated the performance of APSIM-Maize, APSIM-Potato, APSIM-Rice, and APSIM-Wheat in simulating phenology and yields across different cultivation zones by collecting field experimental data from the literature and agricultural meteorological experiment stations. The crop data for model validation (including field experimental locations, observed indicators, irrigation/fertilization amounts and methods, and references for each crop cultivar) were summarized in supplementary Tables S11–14. The validation results showed that the APSIM model achieved root mean square errors (RMSE) of 1.2–7.4 days for simulating phenology of maize, potato, rice, and wheat, with relative RMSEs of 7%–12% for yield simulations compared to observed values (Supplementary Fig. S13). The cultivar parameters for maize, potato, rice, and wheat in different regions of China were detailed in supplementary Tables S15–18.

The life cycle impact assessment model (LCA model) employed in this study is recognized as the most scientific and effective method for environmental evaluation to date[28,29,47]. Its fundamental framework (goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation) is established by the ISO 14040 series[28]. Currently, LCA models are widely applied to assess environmental impacts across domains, including resource consumption, climate change, atmospheric environment, and industrial production. In agriculture, this model is primarily used to evaluate the environmental effects of crop cultivation, such as maize[66], wheat[53], and potato[45]. In this study, the LCA model was used to estimate the GHG emissions for maize, rice, wheat, and potato. The system boundary of LCA model used in this study was shown in Fig. 8. This study considered the GHG emissions including the indirect CO_2 emission from the production and transportation of inputs (such as fertilizer, pesticide, plastic film, labor, and energy), farming operation and harvest (E_p), and the direct seasonal CH_4 (E_c) and N_2O (E_n) emissions from crop planting. The total GHG emission, including CO_2, CH_4, and N_2O, was expressed in kg CO_2 eq ha^{-1}. The global warming potentials (GWP) of 29.8 ± 11 for CH_4 and 273 ± 130 for N_2O were used in the latest IPCC Report. However, most previous studies on greenhouse gas emissions from staple grain crop production in China[51,67] have consistently used GWPs of 25 for CH_4 and 273 for N_2O. Given our study focusing on China, these conventional values were also used in our study to facilitate comparison with other research findings:

$$\mathrm{GHG} = E_p + E_C + E_N \quad (1)$$

$$E_p = \sum (I_i \times f_i) \quad (2)$$

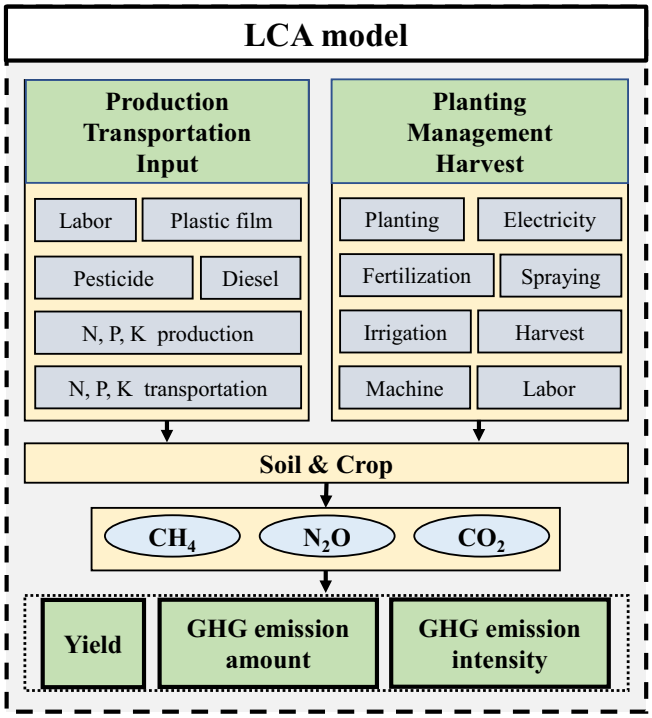

Fig. 8 | System boundary of the life cycle assessment model. This system primarily includes indirect emissions from all inputs during the entire crop cultivation process, as well as direct emissions such as methane and nitrous oxide from farmland.

where I_i is the amount of each agricultural input, including the production and transportation of fertilizers (nitrogen, phosphatic, potassium), plastic film, pesticide, diesel, and labor. All these data are sourced from the National Compilation of Agricultural Product Cost-Benefit Data. f_i is the GHG emission coefficient of each agricultural input shown in Supplementary Table S1.

The seasonal CH_4 emission (E_c) from the crop field is calculated as[24]:

$$Ec = Fc \times A \times D \tag{3}$$

where F_c is the seasonal CH_4 emission rate (kg CH_4 ha^{-1} d^{-1}), A is the harvesting area (ha), and D is the length of the crop growth period (d). The F_c for rice (1.19) was adopted from a previous study[68], while the negative value of F_c for potato (−0.76) reflects consistent findings of methane uptake across various water-nitrogen application conditions in prior studies[24,45]. Therefore, in the study, the seasonal CH_4 emissions from rice and potato were directly calculated based on the observed harvesting area (Fig. 1) and the length of crop growth period (Supplementary Table S7). For maize and wheat, the CH_4 emission amounts per unit area were calculated based on the linear relationship between the nitrogen application rate and CH_4 emission amount due to the lack of reference values of seasonal CH_4 emission rates of maize and wheat (Supplementary Table S6 and Fig. S1). The total N_2O emission is expressed in kg CO_2e kg^{-1} (E_N) according to the following equation:

$$E_N = N_2O_t \times \frac{44}{28} \times 298 \tag{4}$$

where the N_2O_t is the total N_2O emission (kg ha^{-1}) including the indirect N_2O emission and direct N_2O emission in the cropland, the 44/28 is molecular weight ratio of N_2O to N[66], and 298 is the equivalent coefficient of N_2O emission for global warming potential (kg CO_2e kg^{-1} N_2O)[67].

Previous studies verified the reliability of the LCA model in estimating both direct and indirect GHG emissions[24,69]. For estimating the direct GHG emission for each crop, the collected data, including nitrogen application rates, N_2O and CH_4 emission amounts, NH_3 volatilization amounts, and nitrate leaching amounts during crop production, were used to fit the emission factors. Direct N_2O emissions during crop cultivation were determined by collecting literature-based fitted relationships between nitrogen application rates and N_2O emission amounts under different water and fertilizer conditions:

$$y_m = 0.2735 \times e^{0.0075 \times N} \tag{5}$$

$$y_p = 0.33 \times e^{0.0067 \times N} \tag{6}$$

$$y_r = 0.187 \times e^{0.0074 \times N} \tag{7}$$

$$y_w = 0.6151 \times e^{0.005 \times N} \tag{8}$$

where y_m, y_p, y_r, and y_w are the N_2O emission amounts of maize, potato, rice, and wheat during planting, respectively (kg ha^{-1}), N is the nitrogen application rate during the growth period of each crop (kg ha^{-1}). The field experimental datasets and fitted curves for nitrogen application rates and N_2O emission amounts of maize, potato, rice, and wheat are shown in Supplementary Fig. S2 and Table S8.

Subsequently, this study further validated the performance of the LCA model used for estimating N_2O, CH_4, and total greenhouse gas emissions by collecting field experimental datasets independent of those used for fitting emission factors. The field trial datasets applied for each crop are presented in Supplementary Table S19. The results showed that the root mean square errors (RMSE) between the CH_4 emission for maize, potato, and wheat, CH_4 emission for rice, N_2O emission for four crops, and total greenhouse gas emissions estimated by the LCA model used in this study and the field-measured values were 0.28 kg ha^{-1}, 31.1 kg ha^{-1}, 0.33 kg ha^{-1}, 0.65 t ha^{-1}, respectively (Supplementary Fig. S14). Gridded crop and agricultural input data (0.25° × 0.25°) were aggregated from the county- and site-level statistical yearbooks and literature of each crop with the inverse distance weighting interpolation method and then used to estimate the GHG emission amounts with a resolution of 0.25° × 0.25°. Detailed emission items, emission factors, and data resources for estimating the direct and indirect GHG emissions are shown in Supplementary Methods.

Simulating crop dry yield under different water supply conditions

Typically, water variability during the crop growth period is the primary factor driving notable fluctuations in crop yield and GHG emissions[45,49]. To address this, the well-validated APSIM model was employed to simulate the potential and rainfed yields of maize, rice, wheat, and potato at the grid scale. The potential yields of each crop were determined solely by climate factors (temperature and solar radiation) without water and nitrogen stresses. Nitrogen fertilizer was applied automatically when the total mineral nitrogen within 60 cm depth in the soil was less than 300 kg ha^{-1} for each crop to avoid any nitrogen stress even for the very wet years. The nitrogen application rate simulated by the APSIM model under the potential condition was used to estimate the GHG emission amount. Irrigation was applied automatically if the soil water content in the root zone was lower than the field capacity when simulating the potential yield of each crop. The rainfed yield was quantified as the maximum yield that can be achieved under local rainfall condition[20]. Nitrogen application rate for each crop in different provinces under rainfed conditions was collected from previously published articles and statistical yearbooks (see information in Supplementary Methods). To reduce the impact of spatial heterogeneity in cultivars on simulation results, we selected widely cultivated representative cultivars from different planting regions for modeling (Supplementary Tables S15−18). The planting dates for each crop under potential and rainfed conditions were sourced from statistical yearbooks and published literature (Supplementary Table S7). The

planting depth and planting density of each crop in different provinces were also obtained based on the statistical yearbooks and the previous literature[18,45].

Cost-economic return analysis and GHG intensity

This study estimated the gridded cost and economic return of maize, rice, wheat, and potato based on the gridded crop price and agricultural inputs across staple crops' suboptimal planting regions under potential and rainfed conditions. The economic return (ER, $ ha^{-1}) of each crop under different water supply conditions is calculated as:

$$ER = Y \times P - C \tag{9}$$

where ER is the net income of each crop planted in the staple crops' suboptimal planting regions under potential and rainfed conditions, Y is the crop yield (t ha^{-1}), P is the price of each crop ($ kg^{-1}), C is the cost of agricultural inputs such as seed, fertilizer, labor, tool, water, fuel, transport, pesticide, and plastic film ($ kg^{-1}). Detailed price of each input is shown in the Supplementary Table S20.

For comparing the carbon emission impact and eco-efficiency of planting maize, rice, wheat, and potato in staple crops' suboptimal planting regions, the GHG emission intensity per unit dry yield (GHG_i) and the economic return per kg CO_2 (E_{GHG}) are calculated as follows:

$$GHG_i = \frac{GHG}{Y} \tag{10}$$

$$E_{GHG} = \frac{ER}{GHG} \tag{11}$$

Finally, the gridded yield, economic benefit, GHG emission amount, and GHG emission intensity were used to compare the advantages and limitations of planting potatoes in the suboptimal regions of maize, rice, and wheat in China.

Data availability

Data that support the findings of this study are available at https://doi.org/10.5281/zenodo.17389289.

Code availability

Code used for this analysis is available at https://doi.org/10.5281/zenodo.17389289.

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Author contributions

J.W. and B.W. designed the research and revised the paper. Y.L. and R.C. ran the crop model and estimated the GHG emissions. Y.L., P.W., Q.H., M.H., and A.S. contributed to writing the manuscript. H.Y. and J.Z. collected and analyzed the data. All authors critically reviewed and approved the final manuscript and are accountable for all aspects of the work.

Competing interests

The authors declare no competing interests.

Additional information

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