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Climate-smart planting for potato to balance economic return and environmental impact across China

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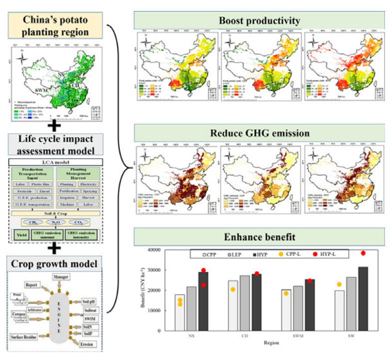
HIGHLIGHTS

- GHG emissions were estimated by life cycle impact assessment model and crop model.
- Climate-smart management practice was identified to reduce GHG and increase yield.
- Climate-smart planting could increase yield by 13 % and reduce GHG emission by 36 %.

GRAPHICAL ABSTRACT



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ABSTRACT

Potato production plays an important role in safeguarding food security in China since the central government implemented the 'Potato-as-Staple-Food' policy in 2015. However, a key challenge facing China's potato production is to realize a tradeoff between economic return and environmental impact. Effective strategies for reducing carbon emission without compromising potato yield remain to be developed. This study conducted a comprehensive assessment by integrating climate, soil, crop, and agricultural input data, crop model and life cycle impact assessment model to quantify potato yields, GHG emission amounts and intensities (GHGI), and economic benefits under the conventional planting pattern (CPP), the lowest GHG emission pattern (LEP), and the highest yield pattern (HYP) across China's potato planting regions including four sub-regions, i.e., North Single planting region (NS), Central Double planting region (CD), South Winter planting region (SW), and Southwest Mixed planting region (SWM). Averaged fresh potato yield, GHG emission amount, and GHGI under the CPP were 21.7 t ha^{-1}, 2815.1 kg CO_2eq ha^{-1}, and 137.3 kg CO_2eq t^{-1}, respectively, in China's potato planting region. Compared with the CPP, averaged GHG emission amount and GHGI under the LEP could be decreased by 48.2 % and 51.5 % respectively while the fresh potato yield and economic benefit could be enhanced by 8.1 % and 18.5 %, respectively. For the HYP, averaged GHG emission amount and GHGI could be decreased by 24.2 % and 39.8 % respectively while the fresh potato yield and economic benefit could be enhanced by 18.7 % and 39.6 %, respectively, compared with the CPP. Across the four potato planting regions, SW had the largest potential in reducing GHG emissions owing to a high reduction amount of nitrogen application rate. Our study demonstrates that optimizing agronomic management could reduce environmental impact without compromising economic benefit and provides a scientific method for assessing crop potential to realize the climate-smart planting.

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1. Introduction

Agriculture accounted for 10 %–12 % of the global anthropogenic emissions of GHG (Li et al., 2016). As the largest agricultural country and carbon dioxide emitters, nearly 15 % of the total GHG emission, 90 % of N_2O emission, and 60 % of CH_4 emission were produced by the agricultural production in China (Wang et al., 2010a; Zhang et al., 2013; Li et al., 2016). For achieving high and stable crop yields, farmers have used a large amount of water and N fertilizer in the agricultural production (Wang et al., 2021b; Li et al., 2022a). Previous studies pointed out that the consumption of water for agriculture accounted for 63 % of the total water consumption while nearly 1/3 of the global chemical nitrogen fertilizer was applied in China's agricultural production (Wang et al., 2010b; FAO, 2018). However, a large amount of water and nitrogen application has caused serious environment problems, such as increased reactive N (nitrous oxide emissions, ammonia volatilization, and N leaching) loss, greenhouse gas (GHG) emission, soil acidification, groundwater depletion, and loss of biodiversity (Rockstrom et al., 2009; Cui et al., 2013; Xia et al., 2016). Therefore, reducing environmental impact without compromising crop yield and economic benefit is a key challenge for the arable land over the world (Huang et al., 2021; Ma et al., 2021). Developing climate-smart agriculture has been recognized as a solution to increase crop productivity, reduce GHG emission, and improve resilience to climate change (Lipper et al., 2014; Peng and Guan, 2021).

China is now the largest potato producer in the world accounting for 25.1 % and 29.6 % of the world total production and planting area, respectively (FAO, 2016; Li et al., 2022a). In 2015, Chinese government implemented the ‘Potato-as-Staple-Food’ policy because of its importance in Chinese dietary structure, high environmental adaptability, and nutritional value (Gao et al., 2019a; Liu et al., 2021; Li et al., 2022a). However, relative low potato yield, low water and nitrogen use efficiency, and high GHG emission still existed in China's potato production due to excess water and nitrogen application together with suboptimal agronomic management practices (Cui et al., 2013; Xiao et al., 2013; Wang et al., 2021b).

Although the GHG emission in potato production is lower than that in wheat and maize production in China (Kong and Zhu, 2016; Gao et al., 2019a), there may be still a large potential in reducing the GHG emission in China's potato production by optimizing agronomic management practices (Li et al., 2019; Liu et al., 2021). Previous studies mainly focused on the impacts of climate change and agronomic management on potato yield, yield gap, water and nitrogen use efficiency across China's potato planting regions (Wang et al., 2018; Zhang, 2018; Li et al., 2021, 2022b; Tang et al., 2019, 2021). Meanwhile, researchers also found that optimizing agronomic management could reduce GHG emission in China's potato production (Gao et al., 2017; Wan et al., 2018; Yang et al., 2019). However, a comprehensive analysis on the effects of optimizing agronomic management practices on potato yield, GHG emission, and economic benefit at the national scale is still lacking. What strategies to realize a tradeoff between potato yield, GHG emission, and economic benefit in China's potato production remain unclear (Garnett et al., 2013; Lipper et al., 2014; Xin and Tao, 2020, 2021).

Therefore, the objectives of the study are to: 1) develop a framework to assess the potential of climate-smart management practices for potato planting in China based on a combined approach of the life cycle assessment (LCA) model and crop model; 2) quantify the GHG emission (N_2O and CH_4), potato yield, and economic benefit under different patterns of agronomic management; 3) identify the optimum agronomic management practices for potato to reduce the GHG emission and increase yield and economic benefit in China.

2. Materials and methods

2.1. Study area, historical climate, crop, and soil data

Based on the climate conditions and the types of representative cropping systems, China was divided into four potato planting regions including North Single planting region (NS), Central Double planting region (CD), Southwest Mixed planting region (SWM), and South Winter planting region (SW) (Table S1) (Jansky et al., 2009; Li et al., 2022a). Potato planting area available with the resolution of 0.1° × 0.1° (average for the period of 2009–2011) were from the Spatial Production Allocation Model (SPAM2010) (You et al., 2014; Wang et al., 2018). Within the distance of 50 km to potato planting area, 477 meteorological sites were selected to investigate the impacts of different agronomic management practices on potato yield across China's potato planting regions (Fig. 1). Daily meteorological data, including daily maximum and minimum temperatures (°C), precipitation (mm), and sunshine hours (h) at these meteorological sites during 1981 to 2020 were obtained from China Meteorological Administration (http//www.cma.gov.cn/). Daily solar radiation (MJ m^{-2}) was estimated with sunshine hours using the Angström equation, which showed a good agreement between observed and calculated solar radiation in China (Wang et al., 2015a; He et al., 2020).

For simulating the fresh potato yield at each meteorological site, 15 types of typical soil were used in this study because our previous study demonstrated that these types of soil could reflect the differences in physical and chemical characteristics of soil across China's potato planting regions (Li et al., 2022a). The physical and chemical characteristics of the 15 types of soil were obtained from the China Soil Scientific Database (http://www.soil.csdb.cn/) and the detailed hydraulic characteristics of each soil type were shown in Fig. S1.

2.2. Assessment framework of economic benefit and environmental impact of potato planting

Based on climate, soil, crop, and agricultural input data, an assessment framework of the economic benefit and environmental impact of climate-smart potato planting across China's potato planting regions was developed by combining the life cycle impact assessment model and process-based crop growth model (Fig. 2).

Yields, GHG emissions, and economic benefits at the grid level (0.1° × 0.1°) across China's potato planting regions were compared under different agronomic management practices. Simulated gridded yields were aggregated from simulated site-level yields by APSIM-Potato model with the inverse distance weighting (IDW) interpolation method (He et al., 2017; Wang et al., 2021a; Li et al., 2022b). Actual potato yields recorded in the statically yearbooks were used to validated the model accuracy in simulating the fresh potato yield under the conventional planting pattern (CPP). Gridded GHG emission amounts were estimated with LCA model based on gridded planting area (0.1° × 0.1°) from SPAM dataset and gridded agricultural inputs aggregated from site-level data recorded by the literature with the IDW interpolation method. Gridded GHG emission intensities were calculated by gridded GHG emission amounts and gridded yields. Gridded economic benefits were calculated based on the price of gridded production and agricultural inputs interpolated from the county- and site-level data by using the IDW interpolation method. Detailed data resources could be referred to Supplementary Table S2.

2.2.1. Life cycle impact assessment model

The gridded GHG emissions (0.1° × 0.1°) across China's potato planting regions were estimated by the Life Cycle impact Assessment (LCA) model, a common method for evaluating the impact of production and transport of agricultural input, farming operation, and harvest (from cradle to grave). The system boundary of LCA model used in this study was shown in Fig. 3. The GHG emissions included the indirect CO_2 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 potato planting (Mosier et al., 2006; Gao et al., 2019a). The total GHG emission including CO_2, CH_4, and N_2O was expressed in kg CO_2e kg^{-1}, with the global warming potential (GWP) of CH_4 and N_2O being 25 and 298, respectively (Chen et al., 2020):

$$GHG = E_p + E_C + E_N \tag{1}$$

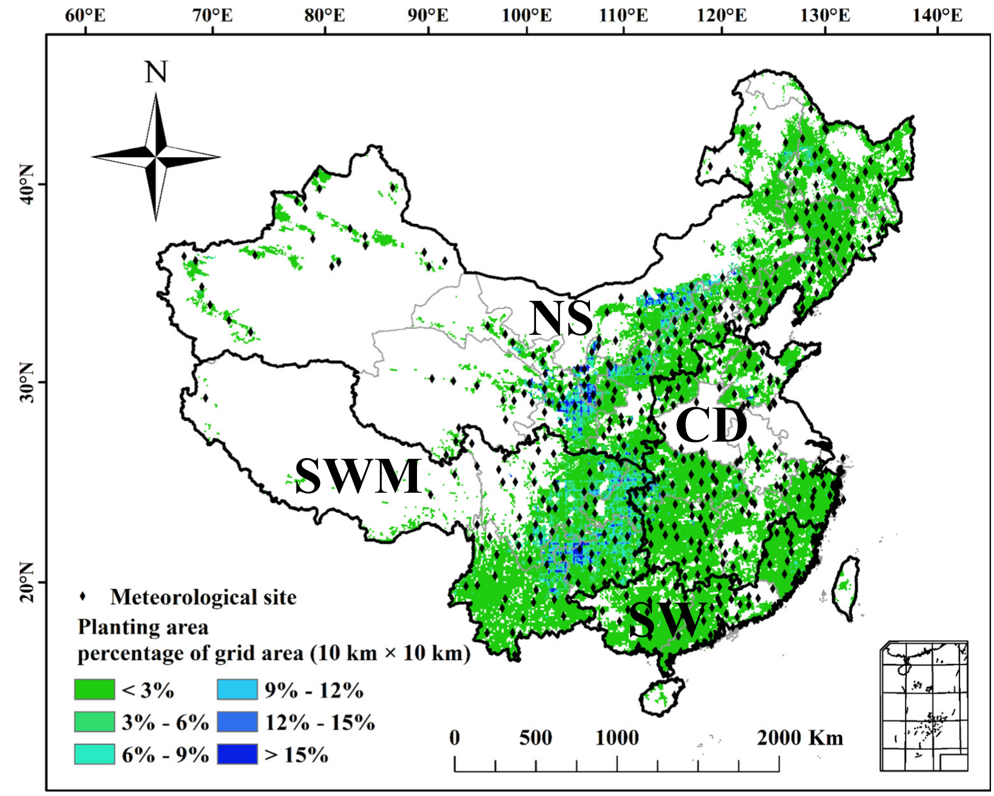

Fig. 1. Potato planting area (averaged from 2009 to 2011) represented by the percentage of the potato planting area within each grid (100 km^2) in four sub-regions including North Single planting region (NS), Central Double planting region (CD), Southwest Mixed planting region (SWM), and South Winter planting region (SW), and the distribution of the 477 meteorological sites.

Previous studies verified the reliability of LCA model in estimating both direct and indirect GHG emissions (Djomo and Blumberga, 2011; Liu et al., 2021). In this study, both direct and indirect GHG emissions were estimated by the LCA model to unify the calculation method for both direct and indirect emissions. For estimating the direct GHG emission in potato field, the collected data including nitrogen application rates, N_2O and CH_4 emission amounts, NH_3 volatilization amounts, and nitrate leaching amounts during potato production were used to fit the emission factors (Gao et al., 2019a). The indirect GHG emission was estimated by collecting the application amounts and their emission factors of each emission item from the

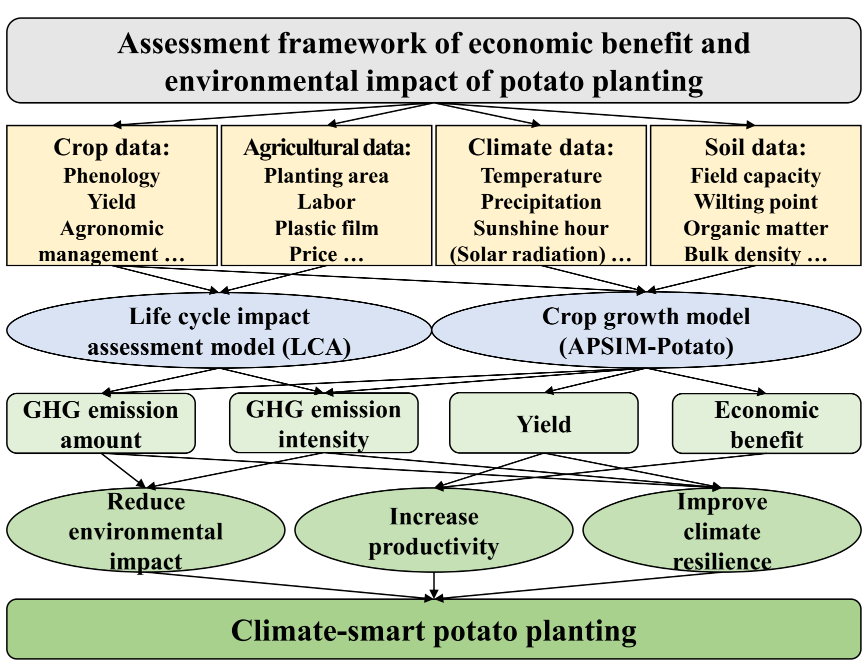

Fig. 2. Assessment framework of economic benefit and environmental impact of potato planting.

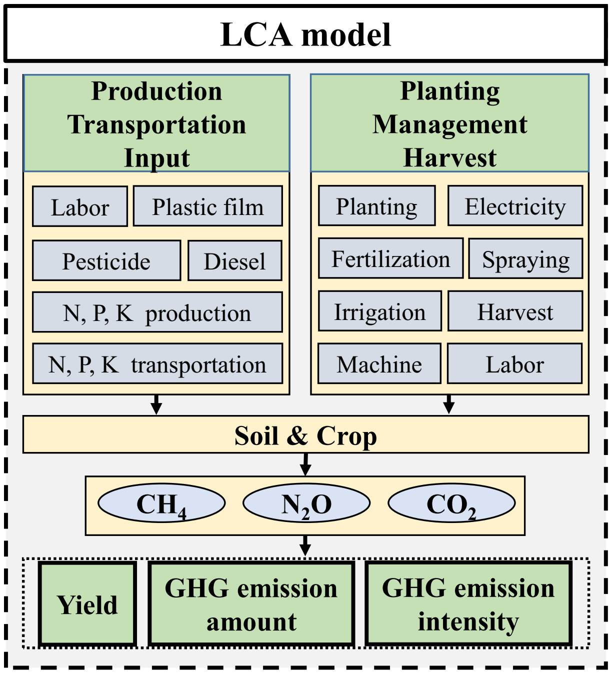

Fig. 3. System boundary of the life cycle assessment (LCA) model for potato production.

statistical yearbooks and previous literature. Detailed emission items, emission factors, and data resources for estimating the direct and indirect GHG emissions were shown in Supplementary S1.

Gridded GHG emission intensities (GHGI) were calculated by gridded GHG emission amounts and gridded yields:

$$\mathrm{GHGI} = \frac{\mathrm{GHG}}{Y} \tag{2}$$

where Y was gridded fresh potato yield (kg ha^{-1}).

2.2.2. APSIM-Potato model and its parameterization

APSIM-Potato (version 7.6) model was used to simulate potato yield under different combinations of planting date, cultivar maturity, irrigation schedule, and nitrogen application rate at each study site. Our previous studies have tested APSIM-Potato in simulating phenology (the root mean square errors (RMSEs) < 6.3 days), LAI (the relative root mean square errors (RRMSEs) < 23 %), biomass (RRMSEs <29 %), soil water content in 1 m depth (RRMSEs <32 %), N uptake by potato (RRMSEs <21 %), mineral N content in 1 m depth (RRMSEs <33 %), and yields (RRMSEs <24 %) for different cultivars and planting dates at typical sites in North Single planting region (Tang et al., 2018, 2019, 2021; Li et al., 2021). For further testing the performance of APSIM-Potato across China's potato planting regions, we evaluated the responses of potato growth and development to different representative cultivars used in different potato plating regions. The results showed that the model could reproduce the response of phenology (RMSEs <5 days), yield (RRMSEs <19 %), and water use efficiency (R^2 = 0.71) of potato to variations in cultivar (Li et al., 2022a). The representative cultivars and their genetic parameters for each planting region were shown in Table S10.

2.3. Long-term simulation setting

First, sensitivity analysis was conducted to investigate the response of potato yield, GHG emission amount and intensity, and economic benefit to the individual change in planting date, cultivar maturity, irrigation schedule, and nitrogen application rate in different planting regions (Figs. S4-S7). Potato yield and economic benefit were more sensitive to change in nitrogen application rate than that in planting date, cultivar maturity, and irrigation amount across the four planting regions except NS, where potato yield and economic benefit were also sensitive to change in irrigation amount. For all the planting regions, continuous increase in irrigation and nitrogen application amounts did not increase potato yield and economic benefit remarkably. GHG emission amount and intensity increased with the nitrogen application rate while increasing irrigation decreased GHG emission intensity and its variation in NS.

Based on the sensitivity analysis, 108 scenarios including three planting dates, three cultivar maturities, three nitrogen application rates, and four irrigation amounts were simulated during 1981–2020 at each site to investigate the combined effects of different agronomic management practices on potato yield and GHG emission (Fig. 4). The conventional planting date, cultivars, nitrogen application rate were collected based on the statistical yearbooks and the literature. The early- and late-planting dates were set at an interval of 10 days before and after the conventional planting date (middle planting date) (Table S1). The setting of planting date, nitrogen application rate for each province were shown in Table S11. The high and low nitrogen application amounts were set as 50 % and 150 % of the conventional nitrogen application amount, which was the most commonly used to optimize nitrogen application rate (Wang et al., 2020; Ban et al., 2022). Based on water resources carrying capacity and our previous studies in exploring the water-saving potential across China's potato planting regions, four irrigation scenarios were applied under each combination of planting date, cultivar maturity, and nitrogen application rate: 30 mm for planting (I_1); 30 mm for planting, and 60 mm for emergence (I_2); 30 mm for planting, 60 mm for emergence, and 60 mm for earlytuber (I_3); 30 mm for planting, 60 mm for emergence, 60 mm for earlytuber, and 60 mm for senescing (I_4) (Li et al., 2022a). Detailed model settings could be referred to Table S12.

Second, fresh potato yields, GHG emission amounts and intensities under different combinations of planting date, cultivar maturity, irrigation schedule, and nitrogen application rate were compared based on the long-term simulation. From the 108 simulation scenarios, two patterns of the lowest GHG emission pattern (LEP) and the highest yield pattern (HYP) were chosen as the target planting patterns relative to the conventional planting pattern (CPP). The LEP and HYP planting patterns meant the optimized agronomic management practices (planting date, cultivar maturity, irrigation schedule, and nitrogen application rate) under which the lowest GHG emission amount and the highest fresh potato yield could be realized, respectively. Finally, simulated fresh potato yields, total GHG emission amounts, and GHG emission intensities under the CPP, LEP, and HYP were compared to explore the potential of yield enhancement and GHG emission reduction across China's potato planting regions.

2.4. Cost-benefit analysis and ecological sustainability

Gridded economic benefits were calculated based on the price of gridded yields and agricultural inputs. The economic benefits under different agronomic management practices were calculated as:

$$I = Y \times P - C \tag{3}$$

where I was the net income under each combination of planting date, cultivar maturity, irrigation schedule, and nitrogen application rate, Y was the fresh potato yield, P was the price of fresh potato, C was the cost of agricultural inputs such as seed, fertilizer, labor, tool, water, and plastic film. Detailed prices of each input were shown in Table S13.

An ecological efficiency index (EEI) defined as the ratio of economic benefit to GHG emission amount was used to evaluate the ecological sustainability of China's potato production (Zhang et al., 2021). A high EEI value represented a high ecological sustainability of potato production (Kaplan and Norton, 1996).

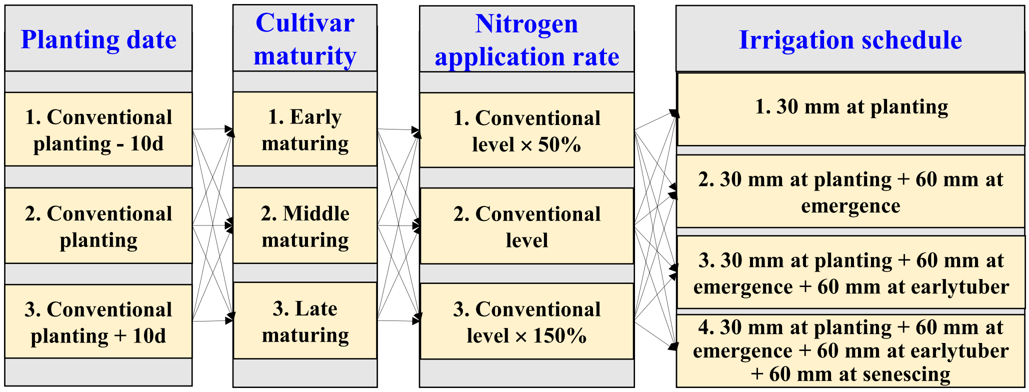

Fig. 4. The scenario setting for the long-term simulation.

3. Results

3.1. Fresh potato yield and nitrogen application rate

Fig. 5 showed that optimizing planting date, cultivar maturity, irrigation schedule, and nitrogen application rate could enhance potato yield and reduce nitrogen application rate significantly. Simulated fresh potato yield of China's potato planting region averaged from 1981 to 2020 was 21.7 t ha^{-1} under the conventional planting pattern (CPP). The highest yield of 24.8 ± 6.9 t ha^{-1} occurred in Southwest Mixed planting region (SWM) followed by 22.7 ± 5.1 t ha^{-1} in North Single planting region (NS), 22.3 ± 3.3 t ha^{-1} in Central Double planting region (CD), and 16.9 ± 2.3 t ha^{-1} in South Winter planting region (SW) (Fig. 5a). Actual nitrogen application rate under the CPP was 152.8 ± 24.9 kg ha^{-1} in SWM, 175.7 ± 54.1 kg ha^{-1} in NS, 195.8 ± 39.3 kg ha^{-1} in CD, and 224.1 ± 56.4 kg ha^{-1} in SW (Fig. 5b). Under the lowest GHG emission pattern (LEP), fresh potato yield could be increased by 12.8 %, 8.8 %, 5.9 %, and 4.8 %, respectively, in NS, SW, CD, and SWM (Fig. 5c). The nitrogen application rate could be reduced by 49.6 %, 49.8 %, 49.5 %, and 49.1 %, respectively, in NS, SW, CD, and SWM (Fig. 5d). Compared with the CPP, fresh potato yield under the highest yield pattern (HYP) could be enhanced by 38.6 % in NS followed by 16.2 % in SWM, 12 % in SW, and 8.1 % in CD (Fig. 5e). The nitrogen application rate could be decreased by 22.7 % in SWM, 49 % in SW, 34.6 % in CD, respectively, but it would be increased by 12.5 % in NS (Fig. 5f). For the top three provinces of potato planting area, i.e., Inner Mongolia, Guizhou, and Sichuan, the fresh potato yields under the LEP could be increased by 16 %, 2 %, 3 % and under the HYP they could be increased by 33 %, 12 %, and 12 %, respectively, compared with those under the CPP (Fig. S8a). In total, the fresh potato yield could be enhanced by 8.1 % under the LEP and 18.7 % under the HYP, compared with that under the CPP. Detailed optimal combinations of planting date, cultivar maturity, irrigation schedule, and nitrogen application rate under the lowest emission pattern and the highest yield pattern were showed in Fig. S9.

3.2. GHG emission amount and intensity

Total GHG emission amount was 2815.1 kg CO_2eq ha^{-1} under the conventional planting pattern (CPP). Compared with the CPP, optimizing agronomic management could reduce 48.2 % and 24.2 % of the total GHG emission amount, respectively, under the lowest emission pattern (LEP) and the highest yield pattern (HYP) (Fig. 6a, c, e). Under the CPP, the highest GHG emission amount of 3100.9 kg CO_2eq ha^{-1} occurred in SWM followed by CD (2845.4 kg CO_2eq ha^{-1}), SW (2722.3 kg CO_2eq ha^{-1}), and NS (2591.5 kg CO_2eq ha^{-1}) (Fig, 6a). Under the LEP, the GHG emission amount could be decreased by 58.8 %, 49.3 %, 48.8 %, and 36 %, respectively, in South Winter planting region (SW), Central Double planting region (CD), North Single planting region (NS), and Southwest Mixed planting region (SWM), compared with that under the CPP (Fig. 6c). Under the HYP, the GHG emission amount in SWM, CD, and SW could be decreased by 17 %, 34.4 %, and 57.8 %, respectively, compared with that under the CPP (Fig. 6e). However, the GHG emission amount could be increased by 12.4 % in NS. The GHG emission amount under the LEP could be decreased by 34 % while it would be increased by 13 % under the HYP in Inner Mongolia compared with that under the CPP (Fig. S8b). For Guizhou and Sichuan, the GHG emission amount under the LEP and HYP could be decreased by 26 % and 24 %, 32 % and 17 %, respectively. Total GHG emission amount of China's potato production was 1.67 × 10^{10} kg CO_2eq ha^{-1}, 1.63 × 10^{10} kg CO_2eq ha^{-1}, and 1.01 × 10^{10} kg CO_2eq ha^{-1}, respectively, under the CPP, HYP, and LEP.

Fig. 6b, d, and f indicated that optimizing agronomic management has a large potential to reduce the GHGI. Averaged GHGI was 137.3 kg CO_2eq t^{-1} under the CPP. Averaged GHGI under the LEP and HYP could be decreased by 51.5 % and 39.8 %, respectively, compared with that under the CPP. Under the CPP, the GHGI of 159 kg CO_2eq t^{-1} was highest in SW followed by SWM (134.9 kg CO_2eq t^{-1}), CD (131.3 kg CO_2eq t^{-1}), and NS (124 kg CO_2eq t^{-1}) (Fig. 6b). The GHGI under the LEP could be decreased by 62.3 %, 53.9 %, 52.4 %, and 37.5 %, respectively, in SW, NS, CD, and SWM compared with that under the CPP (Fig. 6d). The GHGI under the HYP could be decreased by 62.5 %, 40.2 %, 30.1 %, and 26.6 %, respectively, in SW, CD, SWM, and NS compared with that under the CPP (Fig. 6f). The GHG emission intensity under the LEP and HYP could be decreased by 42 % and 17 % in Inner Mongolia, 29 % and 33 % in Guizhou, 33 % and 27 % in Sichuan, compared with that under the CPP (Fig. S8c).

3.3. Cost-benefit analysis and ecological sustainability

Fig. 7 showed that compared with the CPP, optimization of planting date, cultivar maturity, irrigation schedule, and nitrogen application rate could boost economic benefit in most of potato planting regions under both the LEP and HYP. Farmers could achieve the highest economic benefit under the HYP, which could be enhanced by 61.8 % in NS, 58.8 % in SW, 25.3 % in SWM, and 12.6 % in CD compared with that under the CPP. Under the LEP, economic benefit could be enhanced by 33.4 % in SW, 22.3 % in NS, 9.7 % in CD, and 8.5 % in SWM compared with that under the CPP. In total, averaged economic benefit in China's potato planting region could be enhanced by 18.5 % under the LEP (24,348.7 CNY ha^{-1}) and 39.6 % under the HYP (28,394.2 CNY ha^{-1}) compared with that under the CPP (20,668.4 CNY ha^{-1}). The economic benefit under the LEP and HYP could be increased by 27 % and 53 % in Inner Mongolia, 7 % and 22 % in Guizhou, 5 % and 19 % in Sichuan, compared with that under the CPP (Fig. S8d).

The highest ecological efficiency index (EEI) was achieved under the LEP followed by the HYP and CPP in all the planting regions (Fig. 8), which suggested higher ecological sustainability of China's potato production under the LEP and HYP compared with that under the CPP.

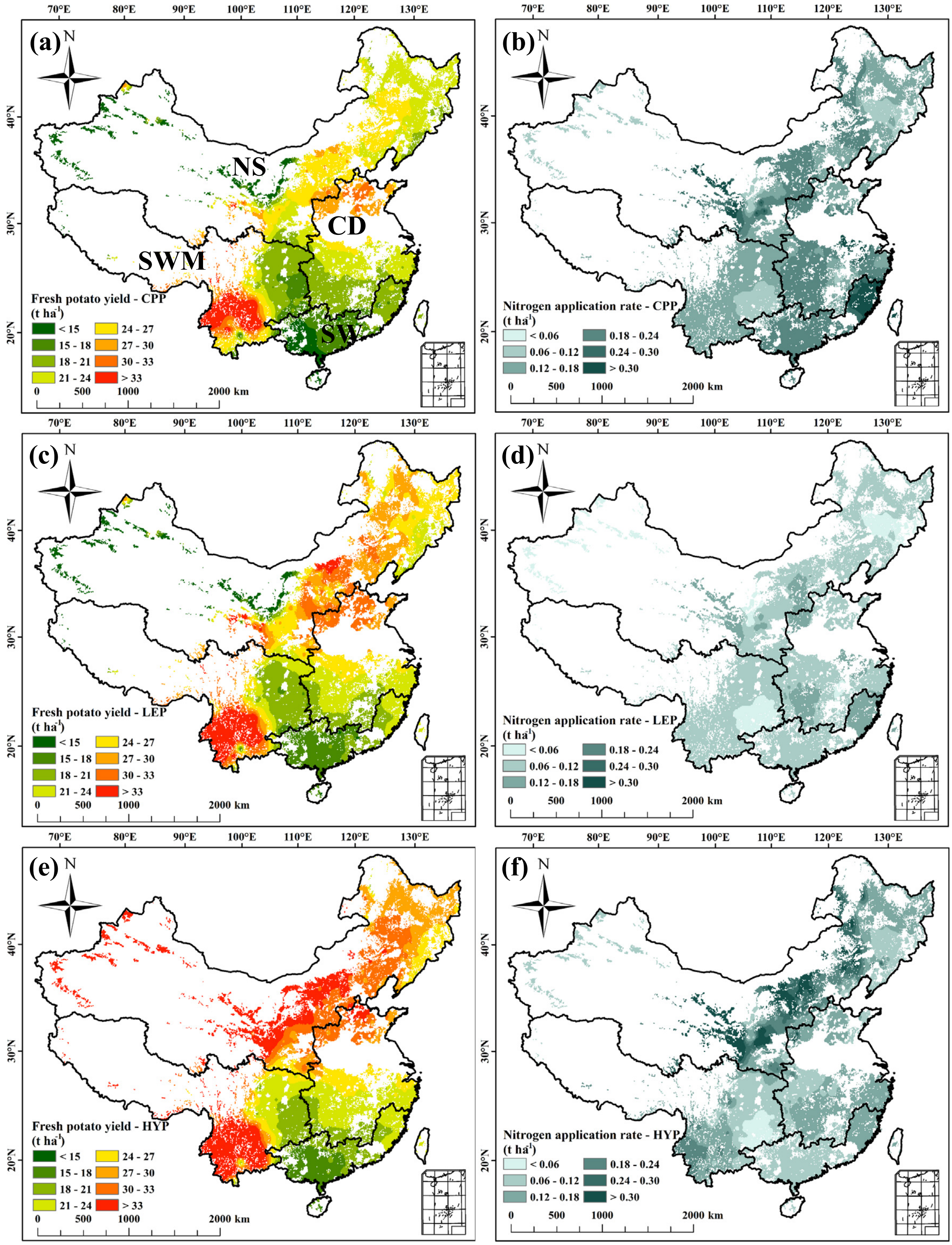

Fig. 5. Fresh potato yield and nitrogen application rate under the conventional planting pattern (CPP, a-b), the lowest emission pattern (LEP, c-d), and the highest yield pattern (HYP, e-f) in the North Single planting region (NS), Central Double planting region (CD), Southwest Mixed planting region (SWM), and South Winter planting region (SW).

4. Discussion

4.1. Assessment method of economic benefit and environmental impact of climate-smart potato production

Safeguarding food security is still a global priority especially under the pressure of climate change and the COVID 19 pandemic (Falkendal et al., 2021). Compared with three staple grain crops, potato as the fourth largest food crop has a large yield-increasing potential (Wang et al., 2018; Li et al., 2022a). Reducing the environmental impact without compromising crop productivity is a key task in realizing the sustainable development of China's potato production (Huang et al., 2021; Liu et al., 2021). Quantitatively assessing the productivity and environment impact of crop production is a prerequisite for developing optimal agronomic management

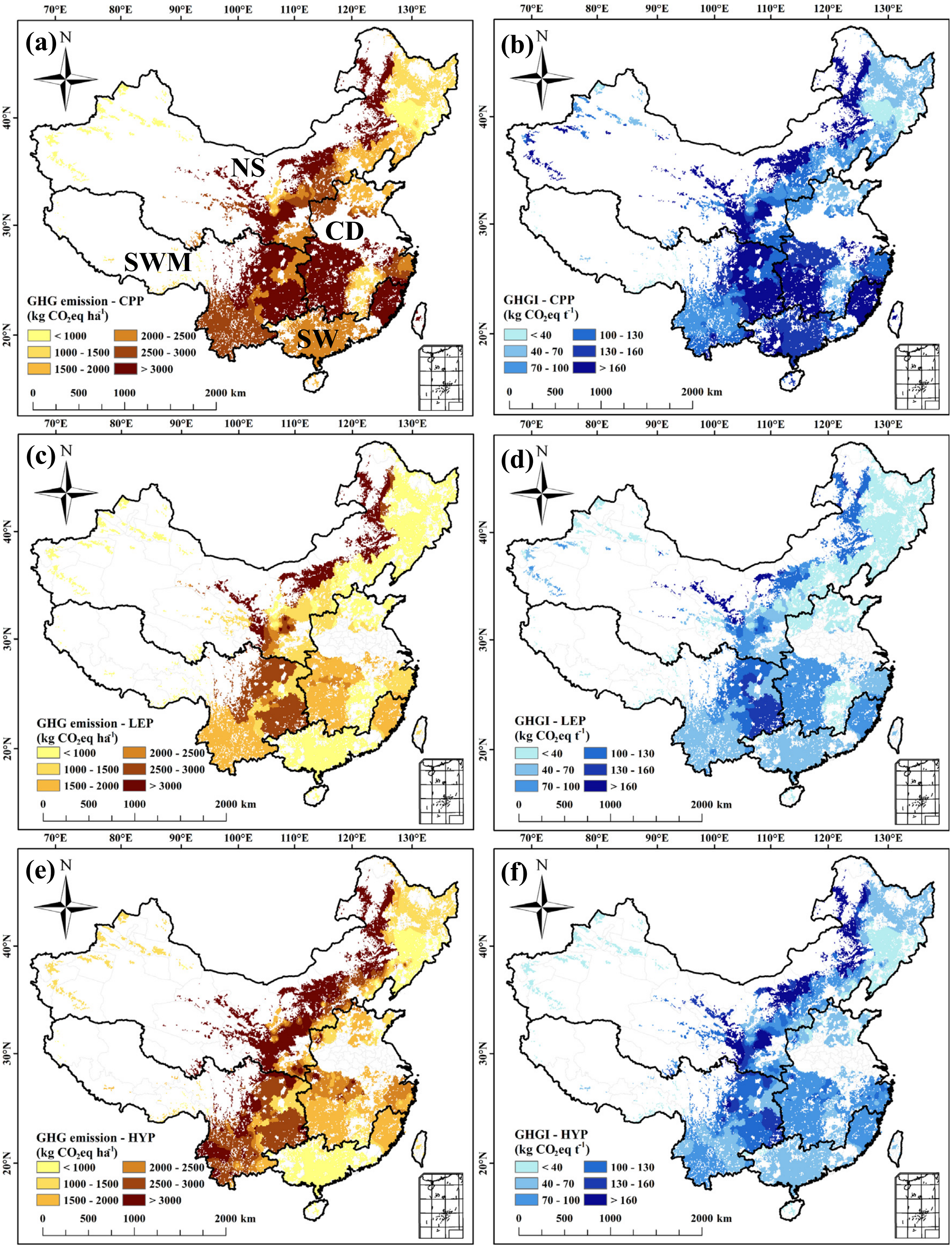

Fig. 6. Total GHG emission amount (a, c, e) and intensity (GHGI, b, d, f) under the conventional planting pattern (CPP, a-b), the lowest emission pattern (LEP, c-d), and the highest yield pattern (HYP, e-f) in the North Single planting region (NS), Central Double planting region (CD), Southwest Mixed planting region (SWM), and South Winter planting region (SW).

strategies. Life cycle impact assessment model could evaluate the environmental implications during crop production, but it could not consider the interaction of genotype (G), environment (E), and management (M) on crop yields (Djomo and Blumberga, 2011; He et al., 2016; Liu et al., 2021). However, process-based crop growth models have been applied widely in evaluating the interaction of G × E × M on crop yield, water and nitrogen use efficiency (He et al., 2017; Tang et al., 2018, 2019, 2021; Li et al., 2022a). Therefore, our study developed an assessment framework of economic benefit and environmental impact of potato planting by combing LCA model and process-based crop growth model driven by climate, soil, crop, and agricultural input data. Our study demonstrated that optimizing agronomic management could realize climate-smart potato production, i.e., increasing productivity, decreasing GHG emission, and improving climate resilience (Lipper et al., 2014). Under the lowest emission pattern and the highest yield pattern, the fresh potato yield could be increased by 8.1 % and 18.7 %, respectively, relative to that

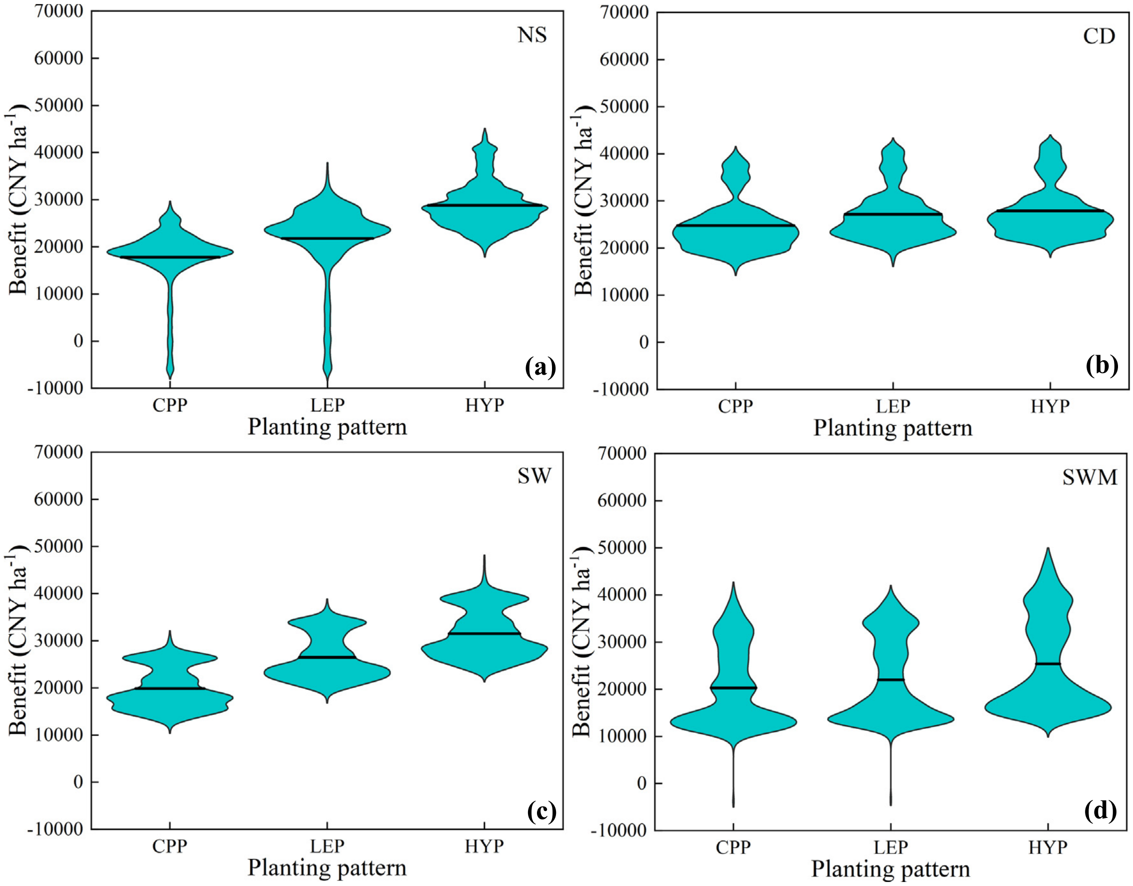

Fig. 7. Economic benefit of potato planting under the conventional planting pattern (CPP), the lowest emission pattern (LEP), and the highest yield pattern (HYP) in the North Single planting region (NS), Central Double planting region (CD), Southwest Mixed planting region (SWM), and South Winter planting region (SW).

under the CPP while the nitrogen application rate could be decreased by 49.5 % and 23.5 %, respectively. Consequently, economic benefit could be enhanced with the increased potato yield and decreased agricultural inputs (Fig. S10).

Currently, Chinese government proposes a "Double-carbon" strategy to realize the goal of reduce GHG emissions (Zhang and Liu, 2022). Climate-smart potato planting presented in our study could help achieve this goal

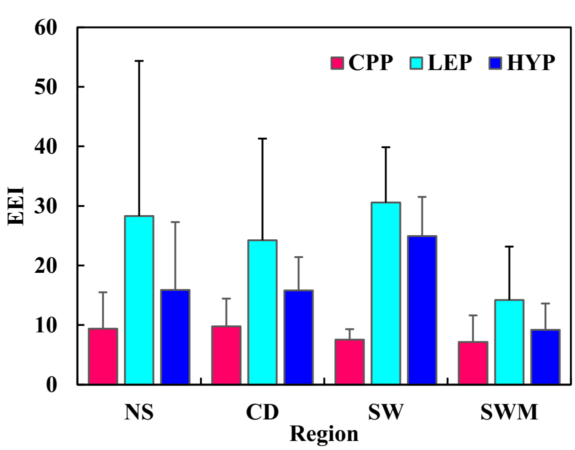

Fig. 8. Ecological efficiency index (EEI) of potato planting under the conventional planting pattern (CPP), the lowest emission pattern (LEP), and the highest yield pattern (HYP) in the North Single planting region (NS), Central Double planting region (CD), Southwest Mixed planting region (SWM), and South Winter planting region (SW).

to some extent (Huang et al., 2021). The GHG emission amount of potato production is lower than that of rice, wheat, and maize because potato field is a CH_4 sink (Liu et al., 2021). The GHG emissions in the potato production include the indirect CO_2 from the production and transportation of inputs, farming operation and harvest, and the direct seasonal CH_4 and N_2O emissions from potato planting (Gao et al., 2019a). Besides decreasing nitrogen fertilizer application, reducing the use of pesticide and plastic film, increasing the operation efficiency, applying the new energy farm machinery could help reduce the GHG emissions in China's potato planting regions (Li et al., 2020; Lombardi and Berni, 2021; Qin et al., 2022).

4.2. Effects of optimizing agronomic management on GHG emission and climate resilience

Optimizing agronomic management has a large potential in reducing the GHG emission amounts and intensities across China's potato planting regions. Total GHG emission amount of China's potato planting region was 1.67×10^{10} kg CO_2eq under the conventional planting pattern with the major emissions from the provinces along the Hu line (Hu, 1935; Liu et al., 2021). This result was similar with previous studies (Huang et al., 2021; Liu et al., 2021). Higher GHG emission amount in SWM was caused by higher CO_2 emission amount from more inputs of plastic film and energy for potato production compared with other three potato planting regions. However, the GHG emission amount estimated in our study were about 17 % lower than that estimated by Gao et al. (2019a). The possible reason was that our study used a fixed emission factor of -0.76 for CH_4 emission during potato growing season (Liu et al., 2021). Previous study also demonstrated that the potato field was a CH_4 sink, especially under the rainfed condition (Wang et al., 2015b). We further analyzed the absorption capacity of CH_4 in potato field under the CPP, HYP, and LEP. The results showed that absorption amount of the CH_4 in potato field was equal to 59 %, 70 %, and 88 % of the total GHG emission respectively under the CPP, HYP, and LEP, which suggested the increase in absorption capacity of CH_4 in potato field by optimizing agronomic management (Fig. S11).

Optimizing agronomic management also improved the resilience to climate change mainly by adjusting planting date and shifting cultivar maturity. Adjusting potato growth period by optimizing planting date and cultivar maturity could make potato growing under suitable climate condition and decrease hydrothermal stress (Van Duinen et al., 2015; Li et al., 2022b). Especially for the rainfed cropping system, optimization of planting date could mitigate water stress by matching crop demand with supply of precipitation resources (Tang et al., 2018; Li et al., 2020, 2021, 2022b). Our previous studies found that late planting could increase climate resilience of potato planting by avoiding high precipitation variation in the front of growing season in North Single planting region (NS) under rainfed condition while planting date should be advanced with increased irrigation (Li et al., 2021, 2022b). Optimizing cultivar increased climate resilience by utilizing growing season fully while avoiding high risk of water stress and frost during the reproductive period (Haverkorta and Struikb, 2015; Li et al., 2021). In this study, selecting middle-late maturing cultivars could achieve the higher potato yield in most of China's potato planting regions, which was consistent with our previous study (Li et al., 2022a).

Our previous studies have investigated the yield potential, yield gap, optimal cultivar and agronomic management practice at the site-level across China's potato planting regions (Tang et al., 2018, 2019, 2021; Li et al., 2021, 2022a). These give us a high confidence in scaling the study results from site to region level. In this study, we further conducted the regional variation of potato yield, GHG emission amount and intensity scaled from site-level results simulated by APSIM-Potato model with the inverse distance weighting (IDW) interpolation method. For validating the reliability of the scaling method from site to region, we did a comparison of the province-level fresh potato yields recorded by the statistical yearbooks and aggregated from site-level fresh potato yields simulated by APSIM model with the IDW interpolation method. The comparison results verified the reliability of the scaling method from site to region with a good agreement between the simulated and observed fresh potato yield in each potato planting region under the conventional planting pattern ($R^2 > 0.43$) (Fig. S12). Simulated fresh potato yields were slightly higher than the observed ones in SWM. This might be because the actual potato production in SWM often suffered from the pests and diseases while the APSIM-Potato did not consider their negative effects (Gao et al., 2019b).

Our study showed that the highest enhancement potential in yield and economic benefit occurred in NS followed by SW, SWM, and CD. This is because the potential yield in NS is higher than other regions due to higher solar radiation and optimizing agronomic management increases potato yield more significantly than other regions, especially by adjusting the irrigation schedule (Li et al., 2022a). Low yield gap between the highest yield pattern and the conventional planting pattern in SW and CD also suggested that current agronomic management practices in the two regions were close to the high-yielding management practices. The study results also showed a large spatial heterogeneity in optimized agronomic management practices. NS should select the LEP because the GHG emission under the HYP was 12.4 % higher than that under the CPP (Fig. 9a). However, the HYP was better for SW because potato yield and economic benefit under the HYP were higher than that under the LEP while the GHG emission amount and intensity under the HYP were similar with those under the LEP (Fig. 9c). For CD and SWM, both the LEP and the HYP could realize a win-win for reducing environment impact and increasing economic benefit where farmers could choose the optimal planting pattern according to their planting arrangement and the government's policy (Fig. 9b, d).

4.3. Implementing the climate-smart planting for a sustainable potato production in China

Implementing the climate-smart planting could realize the sustainable development of potato production in China. Our results showed that the increase in potato yield was the result of combined effects of optimizing planting date, cultivar, irrigation, and nitrogen fertilization while the reduction in GHG mainly depended on decreasing nitrogen application rate. In NS, irrigation amount was needed to increase under the HYP compared with that under the CPP. This is because water shortage is a major limiting factor of crop production especially in the northwest arid region (Tang et al., 2019). However, the recommended irrigation amount even under the HYP is still within local water resource carrying capacity (Li et al., 2022a). Moreover, compared with staple cereals crops, potato is more drought-resistant with higher water use efficiency (Wang et al., 2018; Li et al., 2022b).

In NS, increasing irrigation is a major practice in improving potato yield, which is consistent with previous studies (Zhang, 2018; Tang et al., 2021; Li et al., 2022a). Therefore, increasing irrigation together with early planting and selecting late-maturing cultivar are recommended as the climate-smart potato planting in NS. In the other three planting regions, early planting coupled with middle- to late-maturing cultivars and supplemental irrigation at planting achieve higher potato yield compared with the conventional planting pattern (Sang et al., 2014; Li et al., 2019). Reducing nitrogen application rate has been recognized as one of the most effective practices in reducing GHG emissions in all the planting regions (Wang et al., 2015b; Wan et al., 2018). However, there are still some constraints in the popularization of climate-smart potato planting. For example, increasing irrigation may be not feasible in NS where surface water resource is limited and agricultural irrigation has resulted in serious decline in ground water (Tang et al., 2019, 2021; Qin et al., 2022). Adjusting plating date could be constrained by the next season crop in the double cropping system and potential late frost during the reproductive growth period in CD (Wang et al., 2020). For shifting cultivar, our study only considered the difference in maturity of cultivar. However, resistance of cultivar to drought and disease may be a priority in selecting cultivar in some arid and disease susceptible areas (Gao et al., 2019b; Zhao et al., 2012; Li et al., 2021).

4.4. Limitation of the study

There were several limitations in our study. Firstly, the latest available China's potato planting area for calculating the GHG emission amount and intensity was averaged from 2009 to 2011. However, the government's policy such as returning farmland to forests and grasslands, protecting wetlands, and ‘Potato-as-Staple-Food’, may have an important impact on the potato planting area (Qin et al., 2022). Statistical data reported by FAO showed that China's potato planting area increased during the past ten years (FAO, 2018; Gao et al., 2019a; Qin et al., 2022), which indicates that there may have a higher potential in improving potato yield and reducing GHG emission amount and intensity by the climate-smart potato planting. Therefore, the updated potato planting area data are urgently needed for estimating regional GHG emissions. Secondly, our study optimized planting date, cultivar maturity, irrigation schedule, and nitrogen application rate to enhance potato yield and decrease GHG emissions across China's potato planting regions. Actually, other agronomic management practices such as ridge-furrow with film or straw mulching, conservation tillage, and selection of drought-resistance cultivar could also increase potato yield and decrease the GHG emissions, which needs to be considered in the future study (Saluzzo et al., 1999; Zhao et al., 2012; Tang et al., 2019). Thirdly, we collected the price of fresh potato from previous studies, without considering the price variation caused by supply and demand of market (Lun et al., 2020). Lastly, our simulation results did not consider the impacts of biotic and abiotic stresses (such as hail, insects, diseases, and weeds) on potato growth and development (Li et al., 2021).

These damages occurred during the actual potato production would impact negatively on the growth and yield of potato. For example, early blight (*Alternaria solani*) and late blight (*Phytophthora infestans*) almost occur in all the potato planting regions while scab (*Streptomyces scabies*) and bacterial wilt (*Pseudomonas solanacearum*) often appear in the arid and humid regions, respectively (Ren et al., 2015; Gao et al., 2019b; Xiang et al., 2019).

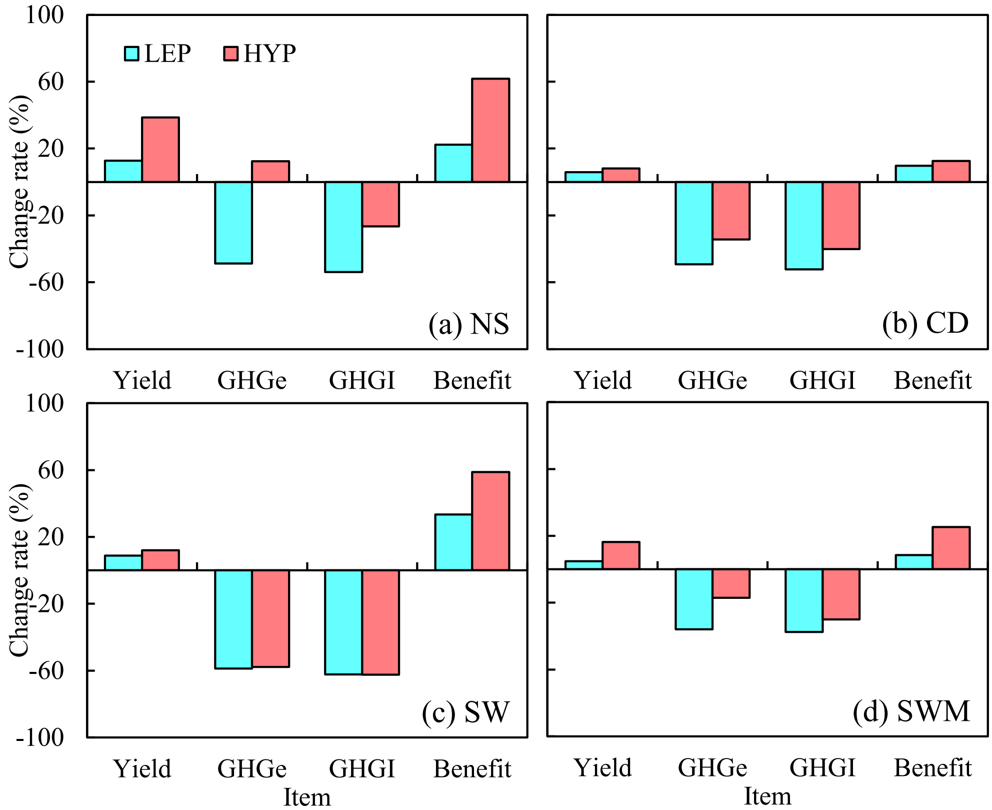

Fig. 9. Comparison of change rate (%) of potato yield, GHG emission amount (GHGe), GHGI, and economic benefit under the lowest emission pattern (LEP) and the highest yield pattern (HYP) relative to the conventional planting pattern (CPP) in the North Single planting region (NS), Central Double planting region (CD), Southwest Mixed planting region (SWM), and South Winter planting region (SW).

5. Conclusion

Low potato yield, high inputs of irrigation and nitrogen fertilizer, suboptimal agronomic management practices are severely threatening the sustainable development of China's potato production. Optimizing agronomic management could realize the climate-smart potato planting by not only boosting potato fresh yield and economic benefit but also reducing the GHG emission. Both the lowest emission pattern and the highest yield pattern could reduce the amount and intensity of GHG emission and increase potato yield and economic benefit compared with the conventional planting pattern in China's potato planting regions. The study provides an assessment method on economic benefit and environmental impact of crop planting to realize a trade-off between crop yield, GHG emission, and economic benefit. Further work will be focused on identifying climate-smart management practices of potato planting for a win-win strategy under future climates.

CRediT authorship contribution statement

Yang Li: Writing - review & editing, Methodology, Writing - original draft, Formal analysis and data processing. **Jing Wang:** Writing - review & editing, Methodology, Supervision, Conceptualization. **Renwei Chen:** Methodology, Visualization. **Enli Wang:** Conceptualization, Supervision. **Bin Wang:** Conceptualization, Methodology. **Qiang Yu:** Methodology, Resources. **Qi Hu:** Methodology, Resources. **Zhihua Pan:** Conceptualization, Funding acquisition. **Xuebiao Pan:** Conceptualization, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare no conflict of interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.158013.

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