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Research Paper

Stagnating rice yields in China need to be overcome by cultivars and management improvements

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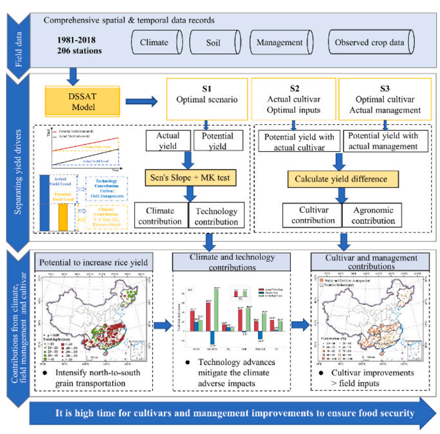
HIGHLIGHTS

- Potential yields declined in Yangtze River region but increased in Northeastern China.
- Differences in the yield trends could intensify north-to-south grain transportation.
- Technology advances are pivotal in mitigating the adverse impacts from climate.
- Cultivars improvements contribute more largely to yield increases than field inputs did.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Understanding the dynamics of potential yields, actual yields, and their drivers is vital for developing sustainable agricultural management practices. Previous studies on rice in China, focusing on either limited experiments, limited driving factors, or short-term periods, reached inconsistent conclusions.
OBJECTIVE: We tried to investigate annual dynamics of rice potential yields, actual yields, and their gaps to distinguish the contributions of climate and technology to yield increases in major rice cultivation areas across China.
METHODS: Herein, using valuable field trials from 1981 to 2018 across 205 agro-meteorological stations and the crop model CERES-Rice, we explored the spatiotemporal trends of rice yields and quantitively separated the contributions of various factors to yield increases across mainland China.

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RESULTS AND CONCLUSIONS: A contrasting trend in potential yields was observed, with a decline in the Middle and Lower Reaches of the Yangtze River (MLRYR, −22.4 kg ha^{-1} y^{-1}) and an increase in the Northeastern China Plain (NECP, 20.0 kg ha^{-1} y^{-1}). Despite varying regional trends, the national yield gap narrowed to 27 % in 2018. Technological advances were the primary drivers (37.3 kg ha^{-1} y^{-1}) of yield increases in most areas compared to climate impact (−2.6 kg ha^{-1} y^{-1}). Particularly in the MLRYR, technological improvements have offset the negative impacts of climate change. Cultivars improvement contributed (14 %–22 %) more than water and fertilizer management did in the main rice-producing regions.

SIGNIFICANCE: Our findings discover the evolving patterns of potential rice yields across China and the underlying drivers, providing scientific evidence for hindering rice yield stagnations by cultivars improvements and field management optimizations.

1. Introduction

By 2050, the rapidly increasing global population requires double crop production to meet the escalating food demand (Tilman et al., 2011). As a vital cereal crop, rice sustains over half of the world's population as a staple food (Seck et al., 2012). China, contributing 28 % to the global rice supply with the biggest annual production (206 million metric tons), plays a crucial role in this context. Even a minor decrease in China's rice productivity could significantly affect global food security. However, the global increasing rates of rice yield have been gradually slowing down in recent years, with an annual rate of only 1 % since 2000 (Grassini et al., 2013). A similar trend is observed in main rice planting areas of China, even ceilings in some areas (Zhang et al., 2014a; Wei et al., 2015; Xu et al., 2016), further threatening grain supply and global food security. Therefore, pinpointing the potential drivers of yield growth is crucial.

Yield potential (Yp) serves as a key indicator for gauging room for yield growth, defined as the maximum yield per unit area under optimal conditions without limitations from water, nutrients, weeds, etc., and is typically considered to be 80 % attainable (Cassman et al., 2003). Potential yields and yield gaps (Ygp) can be estimated by field experiments, yield contests, surveys, and crop model simulations at global, regional, and local scales (Lobell et al., 2009; van Ittersum et al., 2013). Among these, crop modeling, which considers interactions among weather, soil, cultivars, and management practices, is deemed the most reliable method (van Ittersum et al., 2013; Tao et al., 2015). Unlike previous static assessments of Ygp (Mueller et al., 2012; Van Oort et al., 2017; West et al., 2014) based on limited sites, recent studies have shown that the Yp dynamics deepen understanding of production possibilities. For example, Gerber et al. (2024) revealed that 84 % of rice-growing areas face 'ceiling pressure' indicated by closing yield gaps, implying the possible risks for the areas even currently experiencing yield growth. However, studies revealed conflicting trends in potential yields, e.g., both increases and decreases were observed in northeastern China (Chen et al., 2017; Wang et al., 2018). Addressing these inconsistencies requires reliable estimates of potential yield trends based on high-quality local observations (e.g., weather and field trial data), which are fully lacking in many cropping systems.

Climate change significantly impacts rice production (Lobell et al., 2011; Peng et al., 2009; Zhang et al., 2016). Decreases in solar radiation and increases in extreme events have negatively impacted rice productivity in recent decades, although climate warming increased the growing degree-days for rice production (Tao et al., 2013; Zhang et al., 2014a, 2014b). Despite these challenges, technological advances, including water and fertilizer management and adoption of better cultivars and hybrid seeds, have raised a silver lining because of their mitigation roles (Paleari et al., 2022; Abramoff et al., 2023). However, the current yield assessments do not sufficiently recognize technology drivers. Aggarwal et al. (2019) found that the increased yields observed are higher than those declines projected by climate change assessment due to incomplete consideration of technological growth. Both climate and technology impacts exhibit high heterogeneity in China; however, previous studies mainly focused on the impacts of individual factors, rather than comprehensive all factors. All these highlight the urgent need to enhance our overall understanding of yield impacts.

Two important measures, water and fertilizer management, and cultivars improvements, have contributed significantly to yield growth in China. However, the application of nitrogen fertilizer has shown two-sided effects on rice yields: positive impacts on productivity alongside negative consequences from land degradation due to overuse, coupled with other field management issues such as overusing pesticides and degradation of irrigation infrastructure (You et al., 2011; Sun et al., 2019; van Wesenbeeck et al., 2021; Yu et al., 2022). Cultivars improvements have received increasing attention as a means to improve yields (Zhang et al., 2022), but some studies also pointed out that their roles in yield increases are more limited than what had been expected (Ladha et al., 2021; Rizzo et al., 2022). Thus, clarifying the relative contributions of different measures to yield growth is urgent for us to determine the direction of investment in technology.

This study tackles the risk of yield stagnation by simulating and evaluating potential yields and their trends across mainland China based on a processes-based crop model and extensive field trials. The objectives of this study are to (1) identify the potential of yield increases, (2) clarify the contributions of climate and technology to yield growth, and (3) compare the effectiveness of key agricultural practices (water and fertilizer management versus cultivars improvements) in enhancing yield sustainability.

2. Material and methods

2.1. Study areas

The major rice cropping areas in China were categorized into six agro-ecological zones (AEZs) based on a range of ecological factors, including soil, climate, geographical environments, cultivar characteristics, management practices, and cropping systems (Fig. 1). The dominant rice cropping systems in China are categorized into two types: single rice and double rice systems. The single rice system is prevalent in four AEZs: the Northeastern China Plain (NECP), the northern parts of the Middle and Lower Reaches of the Yangtze River (NMLRYR), the Sichuan Basin (SB), and the Yunnan-Guizhou Plateau (YGP). These areas, spanning nine provinces and one municipality, cover approximately 17.2 million hectares and are responsible for about 49.2 % of China's rice production. The double rice cultivation areas comprise the southern parts of the Middle and Lower Reaches of the Yangtze River (SMLRYR) and southern China (SC). This system is operational in nine provinces across about 16.8 million hectares, contributing to 47.1 % of the national rice production. Details on each AEZ are presented in Table S1.

2.2. Field experimental observation, soil and weather data

Rice yield experimental observations data were collected from 205 national agro-meteorological stations maintained by the Chinese Meteorological Administration (CMA), covering the period from 1981 to 2018. All selected stations have over ten years of records, robustly ensuring long-term analysis. These observations included key rice phenological dates, rice types, cultivar maturity characteristics, management practices, and recorded yields. For each AEZ and rice type, three cultivars representing three maturity traits, widely promoted and sown for over three years, were selected. Each of these cultivars was consistently used throughout the entire period in simulations to isolate the effects of climate change. Soil properties data, such as soil texture, bulk density, pH, organic carbon content, and hydraulic properties, were sourced from the Global High-Resolution Soil Profile Database (https://doi.org/10.7910/DVN/1PEEY0). Daily weather data, including precipitation, sunshine hours, and temperature extremes, were obtained from weather stations located within 10 km of the experimental sites accessed through the CMA's climate data-sharing service system (http://data.cma.cn//). Sunshine hours were converted to solar radiation for CERES-Rice simulation using the Angstrom-Prescott equation (Angstrom, 1924; Prescott, 1940).

2.3. Calibrating and validating CERES-Rice model

The CERES-Rice model, as part of the Decision Support System for Agro-technology Transfer version 4.5 (Jones et al., 2003), was employed to simulate rice growth, development, and potential yields from 1981 to 2018. Recognized as a widely-used process-oriented crop model, CERES-Rice incorporates climate, cultivar characteristics, fertilizer application, and soil properties to simulate rice growth and soil water and nitrogen dynamics daily (Tao et al., 2008a; Kim et al., 2013; Xiong et al., 2014). An agricultural model inter-comparison study highlighted that DSSAT's outputs were closely aligned with the median of many models' outputs (Rosenzweig et al., 2014). Finally, our simulations were based on month-specific atmospheric CO_2 concentration from the Keeling Curve to account for CO_2 fertilization effects on rice yield (Harris, 2010; Nordebo et al., 2020).

We selected 24 commonly used cultivars representing each region and rice system. Data from agro-meteorological stations (2013–2018) were used to calibrate and validate observed heading dates, maturity dates, and yields. The crop cultivars were updated every 3 to 5 years, and data from the first four years were used for calibration, with the remainder for validation. After calibration, each selected cultivar was consistently used throughout the entire period to simulate yield. Calibration involved two steps: (i) setting initial parameters for three popular cultivars in each AEZ using GLUE (Generalized Likelihood Uncertainty Estimation) with 6000 samples, based on Xiong et al. (2008), (ii) stepwise calibration using GENCALC (Genotype Coefficient Calculator in DSSAT) in DSSAT, optimizing both phenological (P1, P2O, P2R, P5) and growth parameters (G1, G2, G3, G4), with PHINT set at the default value of 83.00. Three commonly used statistical metrics, including the Root Mean Square Error (RMSE), relative Root Mean Square Error (rRMSE), and Index of Agreement (d-index), were calculated to evaluate model performance (Text S1).

The model achieved a high overall accuracy across different cultivars (Text S2, Fig. S1) with d-indexes exceeding 0.96. Simulation errors were within six days for anthesis dates and nine days for maturity dates, respectively (rRMSE <3 % and < 4 %). Yield estimates closely matched observed data, with RMSE less than 643 kg ha^{-1} and rRMSE under 10 %.

2.4. Simulating Rice yields under multi-scenarios

In the multi-scenario simulation using the calibrated CERES-Rice model, we examined three scenarios at each site: (S1) optimal scenario, (S2) actual cultivar with optimal water and fertilizer management, and (S3) optimal cultivar with actual water and fertilizer management (Fig. 2). Planting dates, planting densities, row spacing,

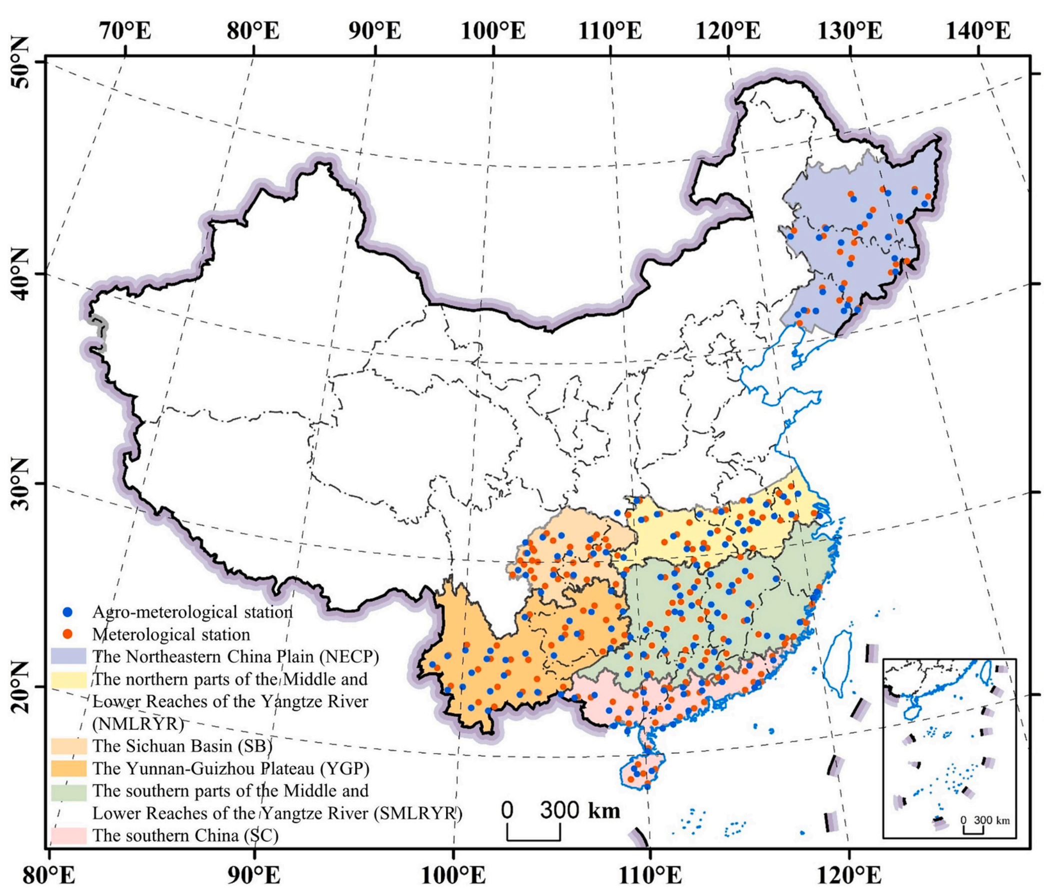

Fig. 1. Locations of agro-meteorological and meteorological stations in the six agro-ecological zones.

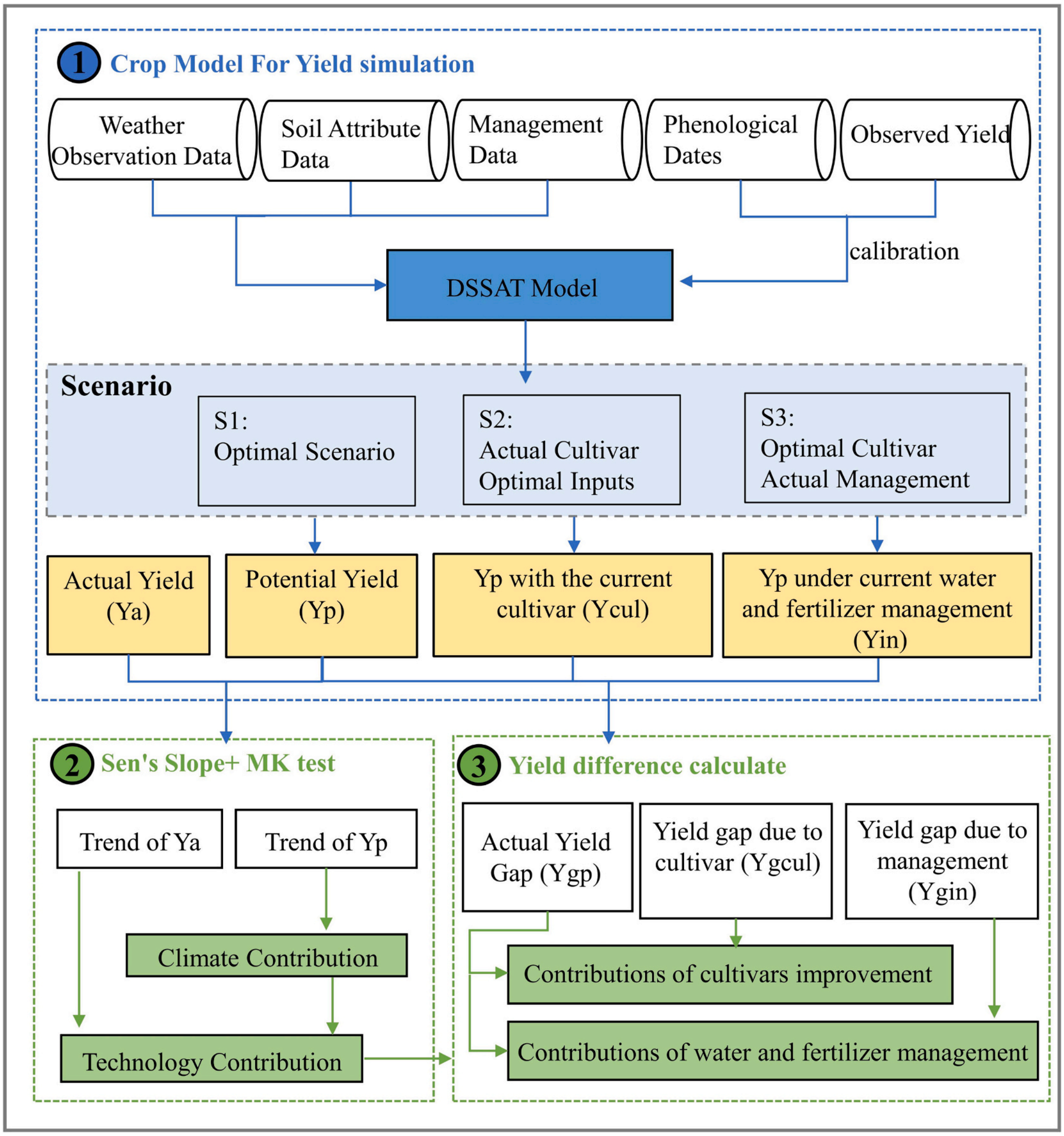

Fig. 2. Framework for investigating dynamics of yields and distinguishing the contributions of climate and technology.

and other management practices were averaged from 1981 to 2018. The optimal cultivar at each site was defined as the one with the highest potential yield (Silva et al., 2022) among all cultivars in each AEZ. Optimal water and fertilizer management means no stresses from water and fertilizer during the crop growth period.

The yield gaps were quantified as follows: the actual yield gap (Ygp), the yield gap due to the cultivar (Yg_{cul}) and yield gap due to water and fertilizer management (Yg_{in}) were calculated using the following Eq. (1)–(3):

$$Ygp = Y_p - Y_a \tag{1}$$

$$Yg_{cul} = Y_p - Y_{cul} \tag{2}$$

$$Yg_{in} = Y_p - Y_{in} \tag{3}$$

where Y_a is the actual yield, Y_p is the potential yield (S1), Y_{cul} is the potential yield achievable with the current cultivar (S2), Y_{in} is the potential yield under current water and fertilizer management (S3). Yg_{cul} and Yg_{in} represent the potential yield gaps due to cultivar and water/fertilizer management, respectively.

2.5. *Calculating contributions of climate and technology change*

We applied the non-parametric Mann-Kendall test and Sen's Slope (Mann, 1945; Sen, 1968) for trend analysis to calculate contributions of climate and technology to yield at each site and region (Text S3). Contribution of climate change was indicated by the trend of simulated potential yields, since Yps reflect the yield changes from climate factors under the assumption of constant management and cultivars over time (Rizzo et al., 2022). Contribution of technological change was then calculated as the differences in trends of Yas and Yps.

2.6. *Calculating contributions of water and fertilizer management and cultivars improvement*

Among the technological drivers, the relative contribution of cultivars improvements and water and fertilizer management to yield can be expressed by the relative values of yield gap by the following Eq. (4)–(5):

$$Con_{cul} = Yg_{cul}/(Yg_{cul} + Yg_{in}) \tag{4}$$

$$Con_{in} = Yg_{in}/(Yg_{cul} + Yg_{in}) \tag{5}$$

where Con_{cul} and Con_{in} are the relative contribution of cultivar and water and fertilizer management to yield increase, respectively.

3. Result

3.1. The potential to increase rice yield

Potential yields from 1981 to 2018 were simulated using the calibrated model, and their averages of potential yields, actual yields, and yield gaps in 2018 are indicated by site and region (Fig. 3). On average, national potential, and actual yields are 11.1 and 7.1 tons per hectare (t ha^{-1}) for single- and double-rice systems, respectively, with an averaged gap of 3.0 t ha^{-1} (27 % of potential yield) in 2018. Considering the thresholds for attainable yields set within 75 %–80 % of Yp, the fact that the average yield reached 73 % of Yp in 2018 may indicate a potential risk of stagnation in future yield improvements.

The yields in AEZs further identify large differences, with the Yps ranging from 9.7 to 13.3 t ha^{-1} across AEZs and from 6.0 to 8.2 t ha^{-1} for Yas (Fig. 3d). Larger spatial variation in Yas and Yps resulted in a wider range of Ygps (20 %–33 % across the 6 AEZs). The highest values for Yas (8.2 t ha^{-1}), Yps (13.3 t ha^{-1}), and Ygps (4.5 t ha^{-1}, 33 %) were observed in the NECP. Particularly for some sites, the Ygps even reached 40 %–52 % because of relatively higher Yps (> 12.7 t ha^{-1}) together with lower Yas (< 7.9 t ha^{-1}) there. The gaps in NMLRYR (2.1 t ha^{-1}, 20 %) are the lowest.

We then found all Yas showed a consistent and significant ($P < 0.05$) increase (13.9–60.6 kg ha^{-1} y^{-1}) in all the zones (Fig.4). However, Yps trends varied by site and region, with both decreasing and increasing trends (−27.9–20.0 kg ha^{-1} y^{-1}) (Fig. 4a, c). For example, the most significant increases were observed in the NECP (20.0 kg ha^{-1} y^{-1}), while significant decreases for single rice in the NMLRYR (−27.9 kg ha^{-1} y^{-1}) and double rice in the SMLRYR (−16.9 kg ha^{-1} y^{-1}) (Fig. 4a). As Yas increased more hugely than Yps did, Ygps narrowed over time at most sites (74 %) (Fig. 4d).

Interestingly, all above findings plot us the potential hotspots for rice production in future. For example, the NECP, with its increasing Yp trend and larger Ygp, was distinctly identified as a hotspot for future increases in rice production. Conversely, the NMLRYR, with a smaller Ygp and declining Yp (61 % sites < −30 kg ha^{-1} y^{-1}), is expected to face significant challenges due to the decline in Yp.

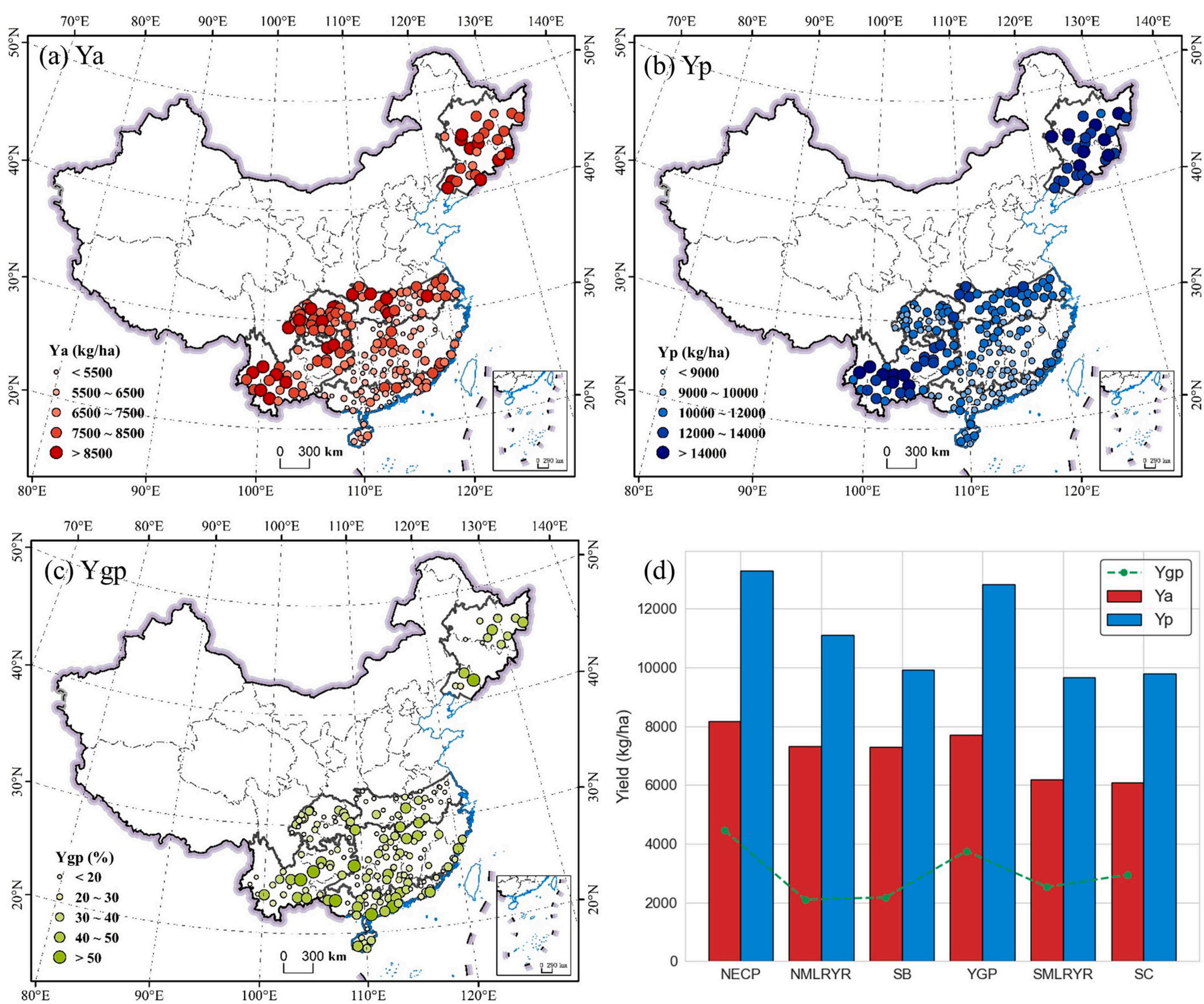

Fig. 3. Averaged actual yields (a), potential yields (b) from 1981 to 2018, yield gaps in 2018 (c), and summary of averaged yields from 1981 to 2018 and yield gaps for 2018 (d) of rice in China.

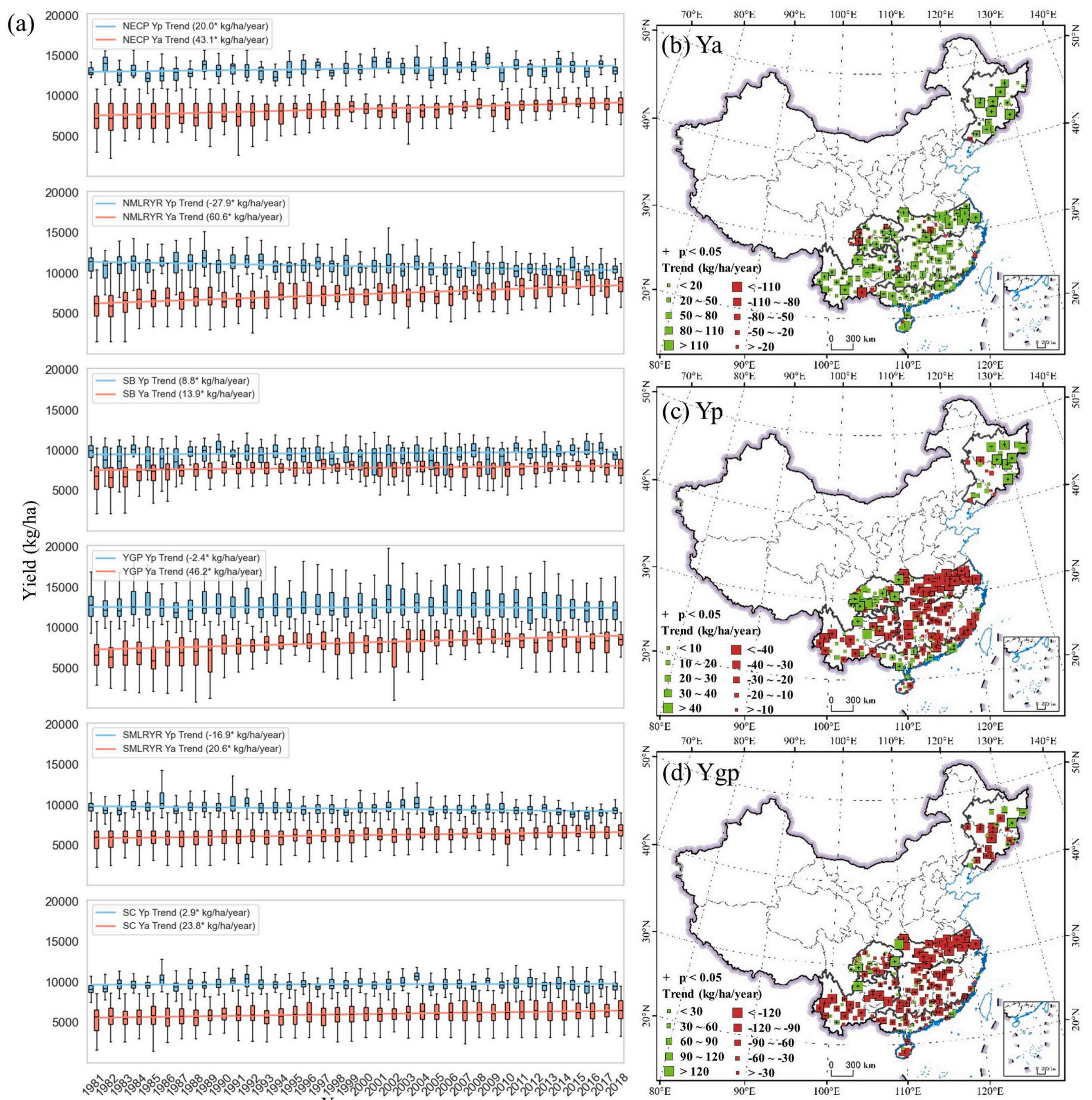

Fig. 4. Trends of actual yields, potential yields for each region (a), and spatial trends of actual yields (b), potential yields (c), and yield gaps (d) of rice in China from 1981 to 2018.

3.2. Contributions of climate and technology

We found that the contribution of climate change to rice yields was negative (-2.6 kg ha^{-1} y^{-1}), while the contribution of technologies change was consistently positive (37.3 kg ha^{-1} y^{-1}) across all regions ($P < 0.05$) (Fig. 5). This suggests that actual yield increases were primarily due to improvements in cultivars and agronomic technologies.

Although technological advancements have had a more pronounced impact than climate change at the national level, it is important to acknowledge that the various climate effects at a regional scale may neutralize each other when considered collectively. For example, positive contributions of climate for single rice were observed in the SB (63 %), NECP (46 %), and double rice in the SC (12 %) (Fig. 5a), while negative contributions for double rice in the SMLRYR (-82 %), single rice in the NMLRYR (-46 %) and YGP (-5 %). Such opposite impacts further demonstrated huge spatial heterogeneity in climate change effects in China. This heterogeneity could be attributed to the regional variations in climatic trends (Fig. S2) (Tao et al., 2013), and the differential sensitivities of rice to climatic variables across these regions (Wang and Hijmans, 2019).

The positive impact of technology was distinctly indicated for the MLRYR (63.0 kg ha^{-1} y^{-1}) and YGP (48.6 kg ha^{-1} y^{-1}). Therefore,

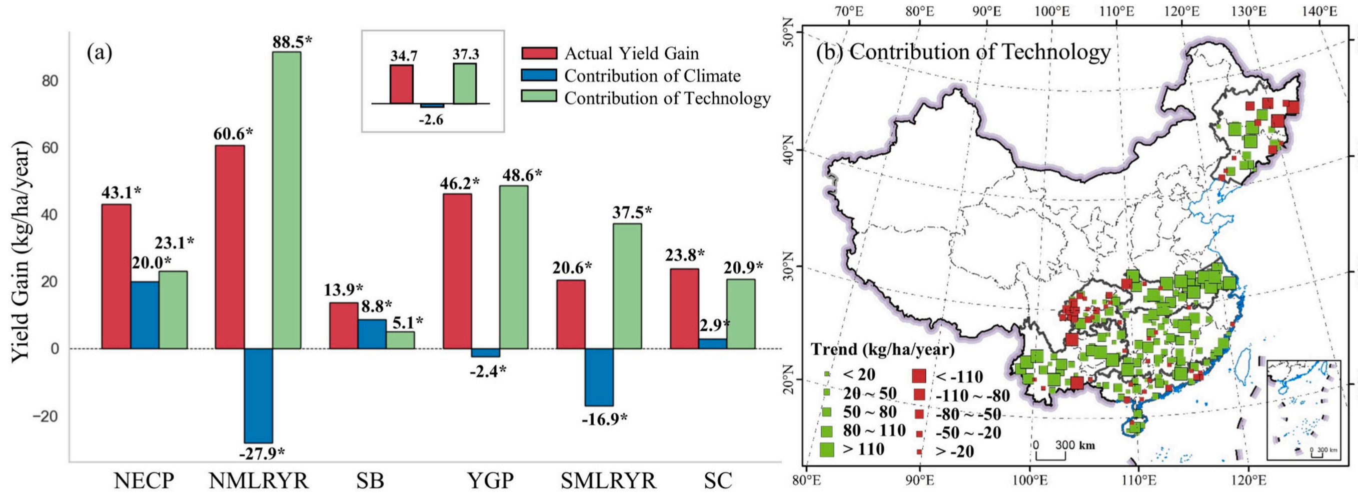

Fig. 5. Comparative analysis of actual yield increase, climate contributions, and technologies contributions across regions (a), and spatial distribution of technologies contributions (b).

despite the adverse effects of climate, interestingly, the NMLRYR still showed notable yield increases because of the developed economy, advanced management techniques, and successful breeding of superior cultivars there (Cao et al., 2010; Tang et al., 2017). As the only zone with less technological contributions than climate, the SB was characterized by the lowest technology contributions (5.1 kg ha^{-1} y^{-1}). Nevertheless, technology showed positive impacts on yield increases at most sites (Fig. 5b) with exception of several sites in SB and NECP, which might be caused by overuse of water and fertilizers (Sun et al., 2019).

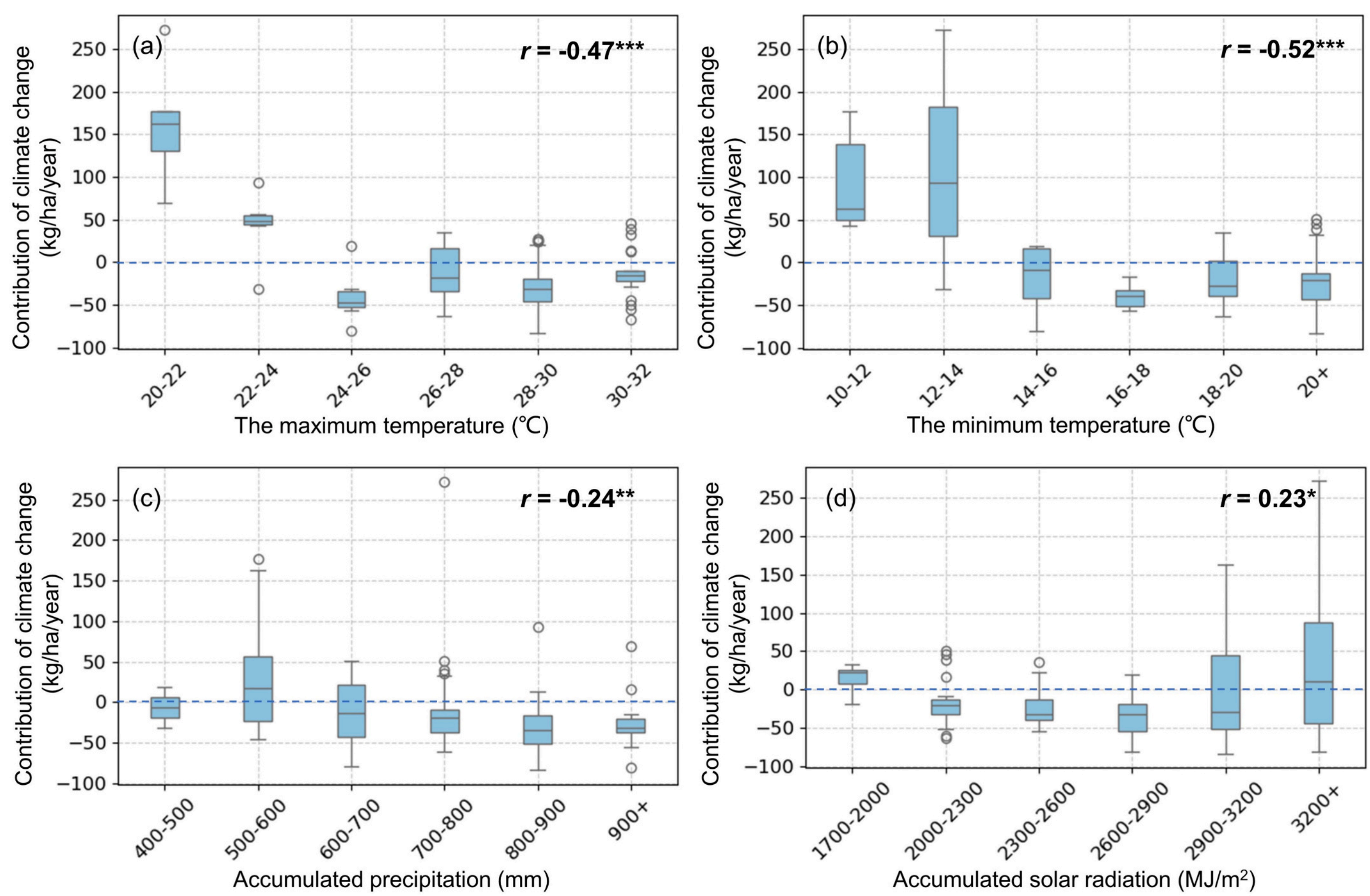

Fig. 6. Correlations between climatic contributions and key environmental factors during the growing seasons from 1981 to 2018: maximum temperature (a), minimum temperature (b), annual precipitation (c), and total solar radiation (d). The box represents the interquartile range (IQR), including the first quartile (Q1, 25th percentile), the third quartile (Q3, 75th percentile), and the horizontal line inside the box for the median (Q2, 50th percentile). The "whiskers" extend to the smallest and largest values within 1.5 times the IQR from Q1 and Q3, respectively. Individual points beyond the whiskers represent outliers. Significance levels are indicated as follows: "***" for $P < 0.001$, "**" for $P < 0.01$, and "*" for $P < 0.05$.

3.3. Relationship between climate contributions and environmental factors

The contribution of climate change to yield varies significantly across regions, primarily caused by the huge heterogeneity in meteorological conditions. Across the whole areas studied, climatic contributions were significantly and negatively correlated with both maximum ($r = -0.47$, $P < 0.001$) and minimum temperatures ($r = -0.52$, $P < 0.001$). Specifically, climate contributions were positive at most sites with maximum temperatures <24 °C and minimum temperatures <14 °C but negative in most warmer areas, indicated by adverse effects due to increased heat stress and excessive moisture loss (Wang et al., 2019; Xu et al., 2021) (Fig. 6a, b). Additionally, the relationship between annual accumulated precipitation and climatic contributions was also significantly negative ($r = -0.24$, $P < 0.01$), with the highest positive effect in areas with 500–600 mm precipitation and increasing adverse impacts in areas with more than 700 mm precipitation (Fig. 6c). In contrast, a significantly positive correlation was observed between total solar radiation and climatic contribution ($r = 0.23$, $P < 0.05$), showing a positive impact at radiation levels above 2900 MJ/m^2 (Fig. 6d). This suggests that enhanced photosynthetic activity, driven by increased solar input, positively influences crop productivity.

3.4. Comparative benefits of water and fertilizer inputs and cultivars improvements

Although technological improvements have substantially contributed to yield increases over the past four decades, their relations are indicated by a negative coefficient (insignificant $r = -0.14$) and more adverse impacts in the areas with higher yields (Fig. 7a). Particularly, at sites with yields exceeding 8000 kg ha^{-1}, a notable decline in technological contributions is observed, suggesting a potential bottleneck of technology for higher-yield sites. The relationship between technological contributions and nitrogen applications (Fig.7b) further demonstrates an initial increase followed by a decrease in technological benefits as nitrogen applications exceed around 300 kg ha^{-1}. This implies the diminishing returns from increasing nitrogen inputs, the threshold for no proportionately increased yields after additional inputs.

To better understand the specific contributions of key technological interventions, we compared the impacts of cultivars improvements and water-fertilizer inputs on yield enhancement (Fig. 7c, d). Nationally, both contributions were comparable, with 54 % and 46 % for water-fertilizer inputs and cultivars improvements, respectively (Fig. 7c). The dominant technology factor varied by area, with a more significant role from cultivars improvements in the main rice-producing regions, such as NECP (57 %), SMLRYR (61 %), and the majority of sites in SC, compared to other regions where water and fertilizer inputs contribute more (62 %–66 %) (Fig. 7c, d). Although increasing water-fertilizer inputs improves yield to some degree, it will simultaneously diminish

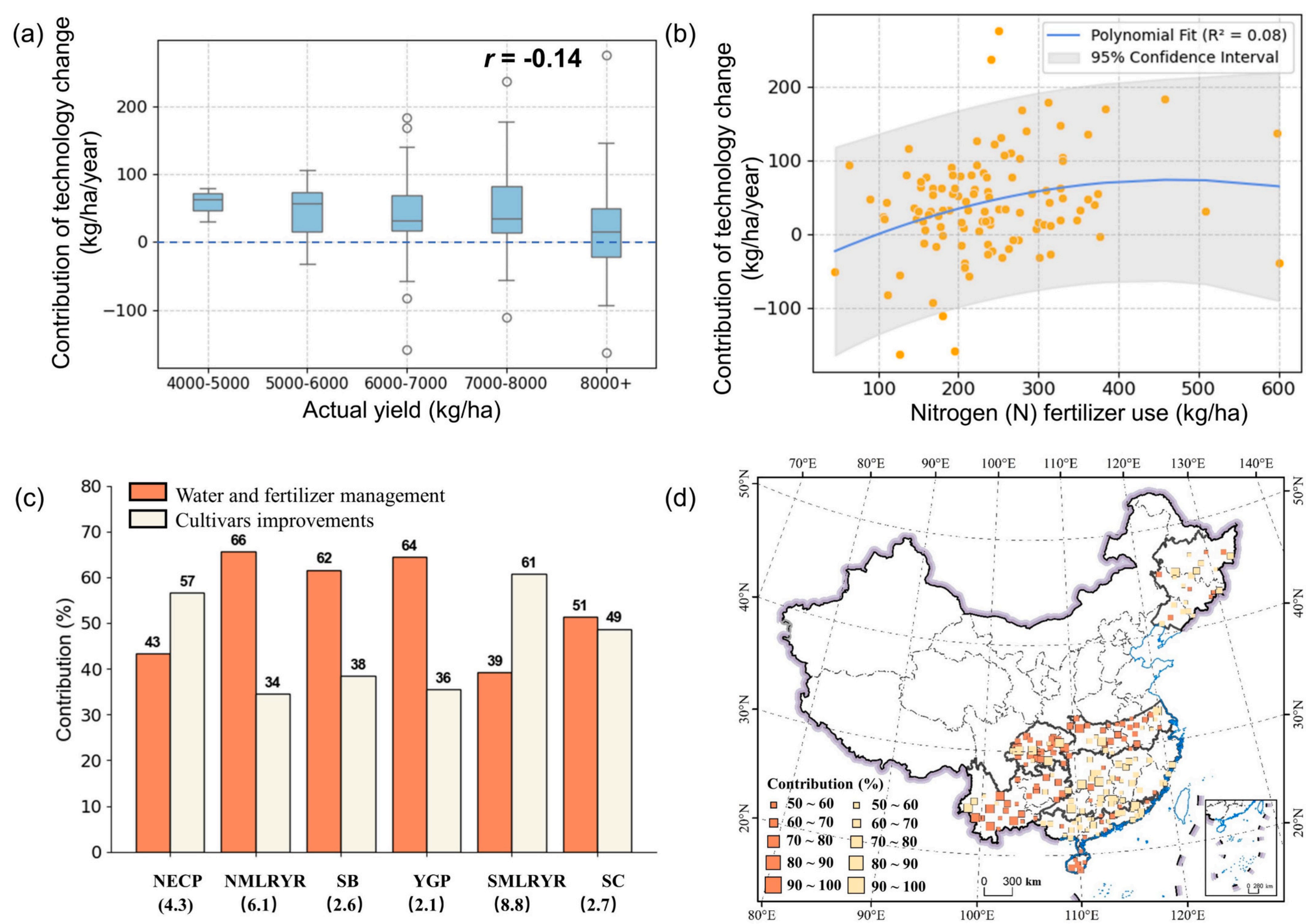

Fig. 7. Summary of technological contributions to rice yield: (a) variability in technological contributions with different levels of actual yields, (b) relationship between nitrogen fertilizer applications and technological contributions, (c) comparative impacts of water-fertilizer management vs. cultivars improvements across regions (a) and their dominant factors at each site (d). Note: The numbers below the regions indicate the rice cultivation area in units of 1×10^4 km^2.

environmental benefits and elevate costs.

4. Discussion

4.1. Impact of potential yield trends on food security: A Chinese perspective

The influence of rice production trend in China on global rice market highlights the critical need for precise Yp estimates. While Yas typically achieve 75 %–85 % of their potential (Lobell et al., 2009; van Ittersum et al., 2013), many future food security assessments neglect the annual dynamics of Yps driven by climate variability, thus introducing uncertainties in future yield projections (Deng et al., 2019; Yuan et al., 2022). For instance, the NECP demonstrates increasing Yps with notable Ygps, suggesting an optimistic hotspot for improving yield increase in the future. Conversely, the MLRYR shows decreasing Yps with smaller Ygps, implying a yield ceiling and limited room for yield improvements. Such zonal differences could exacerbate the current north-to-south grain transportation trend in China. The trends not only affect zonal agricultural productivity but also have deep implications for regional self-sufficiency and environmental impact due to increasing grain transportation (Liu et al., 2023; Zuo et al., 2023).

A recent study revealed complex challenges facing rice yield growth. Gerber et al. (2024) found that 84 % of rice planting areas are experiencing 'ceiling pressure' with closing Ygps, suggesting potential limitations for future growth. This phenomenon is also evidenced in China, with 34 % of rice planting areas approaching the yield ceiling, further highlighting the urgent need to develop new rice cultivars in the AEZs with declining Yps. Moreover, it should be noted that global food security assessments might be miscalculated if only recent yield trends or even a static state are used as a proxy without considering longer-term annual dynamics (Rizzo et al., 2022).

4.2. Contributions from climate, field management, and cultivars improvements

Our findings highlight the diverse impacts of climate change on rice production across China (Liu et al., 2020). Global warming has led to favorable conditions for crop growth in the NECP, whereas the SMLRYR faces big challenges from increasing heat damage (Tao et al., 2008b; Sun and Huang, 2011). Notably, technological advancements, particularly in the MLRYR, have mitigated these adverse impacts, emphasizing the crucial role of technology. This underscores the importance of continuous technological innovation to maintain current yield growth rates (Bracho-Mujica et al., 2024; Zhou et al., 2024).

Comparative analysis of technological interventions reveals that cultivars improvements contribute more significantly to yield increase than enhanced water and fertilizer inputs in the main rice-producing regions (e.g., NECP, SMLRYR). This discrepancy can largely be attributed to the diminishing marginal returns from overusing these inputs in Chinese agricultural land (Mueller et al., 2012; Cui et al., 2018). Additionally, optimizing water-fertilizer inputs has shown potential for significant yield improvements (He et al., 2020; Elrys et al., 2023; Kang et al., 2023). Therefore, a strategic shift towards improving water and fertilizer use efficiency and adoption of better cultivars is crucial, both for enhancing yields and mitigating environmental challenges such as air pollution and water eutrophication (Schulte-Uebbing et al., 2022; Luo et al., 2024). Thus, prioritizing the breeding and promoting high-yielding, region-specific cultivars is a key strategy for reducing the risk of future rice yield stagnation in China (Paleari et al., 2022). Our study supports the global focus on cultivar improvements and optimizing water-fertilizer inputs as key drivers for providing enough food continually and sustainably, and for adapting to climate change, which has been evidenced by research on various crops across different countries (Kassie et al., 2014; Li et al., 2019; Senapati, 2020).

4.3. Uncertainties and limitations

While this study offers valuable insights into rice yield trends and influencing factors in China, we acknowledge its limitations. The reliance on historical weather data and the CERES-Rice model might not fully capture the future impact of climate change on rice production. The CMA database indeed benefits our study because of the large number of sites and extensive information on rice crop phenology and yield. However, it has been argued that data collected from farmer fields which did not reflect optimal management practices for potential yields. Nevertheless, our main objectives are to identify the trends of potential yields and the spatial heterogeneity across six rice planting zones in China, which have been well matched by the detailed field data with huge heterogeneities provided by the CMA.

Additionally, we acknowledge that our approach for calculating the technological contribution by the difference may introduce errors from some yield-reducing (non-technological) factors, such as pest infestations. We did not further identify such negative impacts by an additional scenario simulating actual cultivar and actual management due to unavailability of all field management records throughout the study period (1981–2018) across the entire study area. Nevertheless, the method used in the study remains valuable for exploring trends and assessing technological contribution and integrated impacts from all climate-related factors over time.

Our analysis primarily focused on the integrated contributions of cultivars improvements and water-fertilizer inputs to increased yields rather than growth-stage-specific impacts. We also did not consider spatial variations in CO_2 concentrations, and although industrial development may create hotspots, such spatial differences generally have limited effects on agricultural fields because of uniform CO_2 concentrations on a national scale and their uniform fertilizing effects on rice production (Agnolucci et al., 2020). Considering potential negative impacts from other atmospheric components (e.g., increasing O_3 concentration), moreover, we did not separate the yield contributions from such changing concentrations of air components, but instead focused on their integrated impacts, including temperature, precipitation, solar radiation, CO_2, and other negative factors (e.g., extreme climate events). Finally, our focus on biophysical factors did not fully address socio-economic influences such as market dynamics and policy changes. Therefore, our results should be interpreted cautiously, and future research should broaden its scope to include more dynamic climate modeling and a deeper examination for socio-economic factors.

5. Conclusion

Our study on rice yield trends in China, integral to global food security, reveals a complex interplay among regional variability, climatic influences, and technological interventions. The observed trends in rice production of China shed significant implications to global food security. The contrasting trends in potential yields, such as the increase in the NECP (20.0 kg ha^{-1} y^{-1}) versus the decline in the MLRYR (−22.4 kg ha^{-1} y^{-1}), highlight the high requirement for accurately assessing yield trends with more valuable field experiments during longer-term period. Importantly, technological advancements (37.3 kg ha^{-1} y^{-1}) have been pivotal in mitigating the adverse effects of climate change (−2.6 kg ha^{-1} y^{-1}). Cultivars improvements and efficient agronomic practices emerged as key contributors to yield increases, surpassing the common viewpoint that only emphasized water and fertilizer inputs. Our study highlights the continuous efforts in rice cultivar improvement and innovation technology together with regional agricultural policies for sustainable production. These findings enhance our understanding of rice yield dynamics in China and provide insights for global agricultural strategies amidst environmental challenges.

CRediT authorship contribution statement

Huimin Zhuang: Writing – original draft, Visualization, Methodology. **Zhao Zhang:** Writing – review & editing, Validation, Methodology. **Jichong Han:** Conceptualization. **Fei Cheng:** Visualization. **Shaokun Li:** Validation. **Huaqing Wu:** Validation. **Qinghang Mei:** Writing – review & editing. **Jie Song:** Writing – review & editing. **Xinyu Wu:** Validation. **Zongliang Zhang:** Writing – review & editing. **Jialu Xu:** Methodology.

Declaration of competing interest

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

Data availability

All data needed to evaluate the conclusions in the paper are present in the paper and in Supplementary Materials.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.104134.

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