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Research article

Global rice land suitability and adaptation strategies under climate change

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ABSTRACT

Rice is a vital dietary staple for over half the global population, especially in Asia, Africa, and Latin America, underpinning food security. Rising temperatures and shifting precipitation patterns due to climate change threaten rice production, necessitating adaptive measures to sustain agricultural systems. This study evaluates rice land suitability across 19 sub-regions under current and future climate scenarios, assessing sowing adjustments to counter these impacts. The analysis utilized high-resolution climate data from WorldClim, encompassing historical (2001–2021) and future (2041–2060) projections based on CMIP6 models under medium-emission (SSP245) and high-emission (SSP585) scenarios. Soil data were obtained from the FAO Harmonized World Soil Database, with rice areas mapped using SPAM2020. Liebig's Law of the Minimum identified limiting factors during a standardized growing season, defined by regional sowing and harvest dates. Early sowing (ES) and late sowing (LS) adaptations were modeled to optimize climatic alignment, with suitability categorized into weakly, marginally, suitable and very suitable. Climate change significantly alters rice land suitability across 19 sub-regions, with tropical areas like South-Eastern Asia, Southern Asia, and Eastern Africa experiencing declines in suitable land for both irrigated and rainfed systems due to heat stress and irregular rainfall. In contrast, temperate regions such as Eastern Asia, South America, and Eastern Europe see gains in suitable land, driven by extended growing seasons. Marginal land challenges emerge in Southern and South-Eastern Asia. Late sowing proves the most effective adaptation strategy in major rice-producing regions like Eastern Asia, South-Eastern Asia, and Southern Asia, enhancing land suitability for irrigated systems by aligning with cooler periods and improving rainfed suitability in monsoon-dependent zones.This study highlights the varied impact of climate change on rice land suitability, with tropical regions facing greater losses and temperate zones gaining potential. Late sowing emerges as a key adaptation in Eastern and South-Eastern Asia, offering a sustainable approach to maintain rice production. These findings advocate for region-specific policies promoting timely sowing adjustments and resilient practices to ensure global food security amid escalating climate challenges.

1. Introduction

Rice (*Oryza sativa* L.) serves as a primary dietary staple for over half the global population, supplying 20–50 % of caloric intake in numerous Asian regions and sustaining nutritional security (Muthayya et al., 2014). Its role has expanded beyond Asia, emerging as a critical crop in Africa, Latin America, and the European Union due to diversification and demographic shifts, solidifying its position within the global agro-food system (Seck et al., 2012). With population projections exceeding 8.8 billion by 2100 (Vollset et al., 2020), rice demand is anticipated to rise significantly (Prasad et al., 2017). However, anthropogenic climate change imposes pronounced constraints on production, driven by rising temperatures, altered precipitation patterns, and intensified extreme weather events that abbreviate growing seasons and impair yield potential (IPCC, 2022). These disruptions undermine agricultural productivity and destabilize socioeconomic systems in rice-dependent regions, amplifying risks to food security and rural livelihoods and necessitating adaptive interventions (Wu et al., 2020).

Rice exhibits pronounced susceptibility to climatic variability, with physiological responses exacerbating its exposure to environmental stressors. Elevated temperatures in irrigated systems accelerate phenological development, reducing grain yields by disrupting photosynthesis

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and grain filling, as demonstrated in a synthesis of climate impacts across rice-growing regions (Rezvi et al., 2023). Similarly, experimental data from China reveal that temperature increases above 32 °C diminish rice productivity by shortening the reproductive phase, though adaptive measures like heat-tolerant varieties show partial mitigation potential (Saud et al., 2022). Rainfed systems face amplified water deficits from drought intensification, while coastal zones experience degradation from sea-level rise and salinity intrusion, with life-cycle assessments indicating significant reductions in cultivable land due to water scarcity and soil salinization in Thailand's deltas (Silalertruksa et al., 2017). Regional studies, such as an analysis of yield and water footprint in Thailand's large-scale and individual farms, highlight declines under future climate scenarios but remain confined to national scales (Arunrat et al., 2020). Global agro-ecological zoning efforts map crop vulnerability across multiple species, yet lack rice-specific resolution due to their broad, annualized climate focus (Fischer et al., 2021). Adaptation trials in northern Ghana demonstrate irrigation's efficacy in mitigating heat stress for rice, though scalability remains constrained by water resource availability (Koide et al., 2021a). Sowing date adjustments, validated across agroecosystems, optimize climatic alignment—soybean trials in the U.S. show yield gains from earlier planting (Mourtzinis et al., 2019), while wet direct-seeded rice in Thailand benefits from delayed sowing under water-saving regimes (Santiago-Arenas et al., 2022). Sub-Saharan African data indicate sowing shifts enhance resilience to erratic rainfall (Waha et al., 2013), with Mediterranean wheat trials (Bassu et al., 2009), chickpea disease management (Landa et al., 2004), and dryland crop efficiency studies (Turner, 2004) reinforcing this strategy's versatility. Wheat yield improvements in India via sowing adjustments suggest analogous potential for rice, though global rice-specific applications remain underexplored (McDonald et al., 2022a).

This investigation assesses global rice land suitability under SSP245 and SSP585 climate scenarios, integrating high-resolution climate and soil datasets. Distinct from prior research, it confines analysis to climate parameters within the rice growing period, extracted from sowing and harvest date maps, enhancing precision over annualized or multi-crop models (Fischer et al., 2021; Koide et al., 2021b). It employs Liebig's Law of the Minimum to pinpoint restrictive climatic and edaphic factors, refining suitability estimates by isolating rice-specific limitations during critical phenological stages. This dual approach identifies early and late sowing as effective adaptations to preserve cultivation zones, addressing a scientific gap where global, crop-centric studies remain scarce. By linking climate-driven suitability shifts to socioeconomic outcomes, this study elucidates pathways to bolster food security and agricultural resilience (Tang et al., 2023), with potential to inform policy frameworks and farmer practices in rice-dependent regions facing climatic pressures.

2. Materials and methods

2.1. Data collection (Input)

This study evaluated the land suitability of irrigated and rainfed rice cultivation under current and projected climate change scenarios for the year 2050 on a global scale. As illustrated in Fig. 1, the climate and soil factors utilized for this purpose were obtained from the WorldClim website (https://www.worldclim.org/) and represent the historical monthly weather data for the period between 2001 and 2021 (https://worldclim.org/data/monthlywth.html). Moreover, future climate projections were sourced from the same source for the period 2041 to 2060 (centered around 2050).The projections are based on mean value of ten Global Climate Models (GCMs) from the CMIP6 dataset and two scenarios (SSP245 and SSP585), including models such as ACCESS-CM2, CanESM5-CanOE, EC-Earth3-Veg, FIO-ESM-2-0, GISS-E2-1-H, HadGEM3-GC31-LL, INM-CM4-8, IPSL-CM6A-LR, MRI-ESM2-0, and UKESM1-0-LL (https://worldclim.org/data/cmip6/cmip6_clim2.5m.html). The future climate scenarios were developed using a new set of integrated assessment models (IAMs) that incorporate the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). Two integrated scenarios were considered in this study. SSP245 (a combination of SSP2 with RCP4.5) and SSP585 (a combination of SSP5 with RCP8.5). SSP2 represents a scenario characterized by a continuation of existing social, economic and technological trends, with minimal deviation from historical patterns. In contrast, SSP5 depicts a pathway of fossil-fuelled development, characterized by rapid technological advancement and human capital growth. With regard to

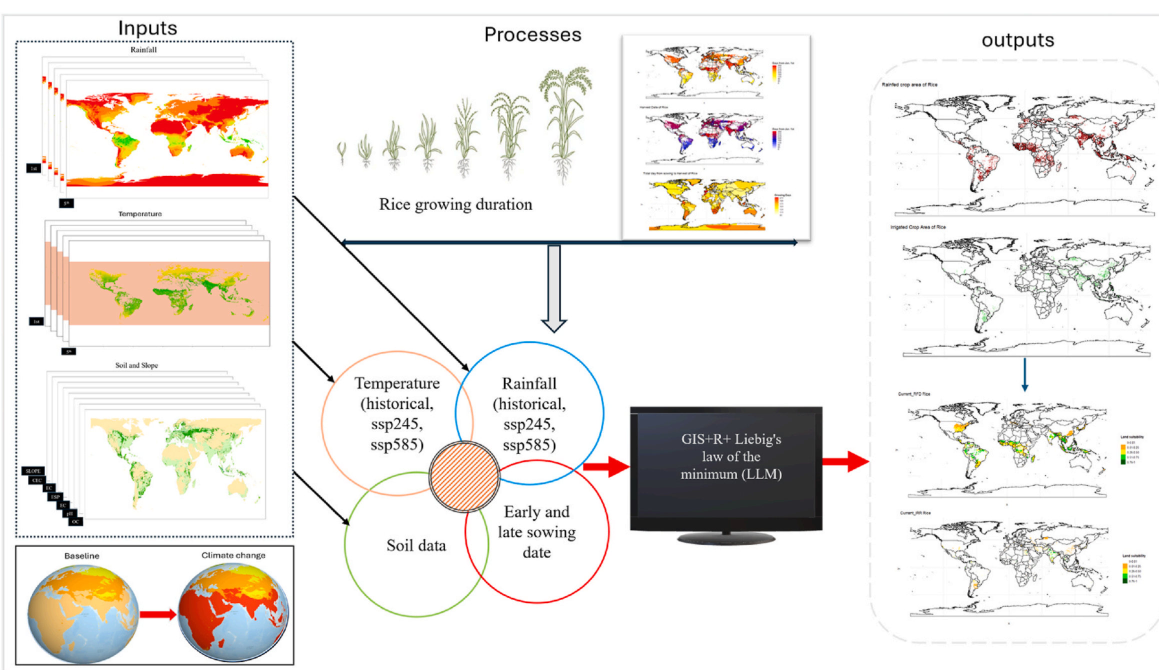

Fig. 1. Schematic diagram illustrating the analysis framework. The suitability for irrigated and rainfed rice indicates land that is suitable for rice cultivation, based on the environmental conditions specific to each period and climate scenario.

radiative forcing, RCP4.5 represents a medium scenario (4.5 W m^{-2} by 2100), whereas RCP8.5 represents a high-emission scenario (8.5 W m^{-2} by 2100). To ensure the highest possible spatial accuracy, 2.5 min (~21 km^2 at the equator) spatial resolution was applied to all maps. Furthermore, maps of rice cultivation area were obtained from the MAP SPAM2020 (Spatial Production Allocation Model) website (https://www.mapspam.info), which provides detailed spatial data on global rice production.

2.2. Uncertainty analysis

Uncertainty analysis of climate change projections was conducted using the standard deviation (SD) of General Circulation Models (GCMs) for precipitation, maximum temperature (Tmax), and minimum temperature (Tmin) across 12 months at the global scale. This analysis utilized outputs from 10 CMIP6 models under two shared socioeconomic pathways: SSP2-4.5 and SSP5-8.5. The results are presented in the supplementary material (Figs. 10–15). As shown in Figs. 10 and 11, the monthly SD values varied; however, overall uncertainty was relatively low. For precipitation, the range across months spanned from 0 to 468 mm, with the highest SD appearing in July under the SSP2-4.5 scenario. Despite this, the majority of global values ranged from 0 to 80 mm, corresponding to light green areas on the maps, indicating low uncertainty. The SSP5-8.5 scenario showed a similar spatial pattern and magnitude of uncertainty in precipitation. In contrast, the uncertainty for Tmax and Tmin ranged from 0 to 5 °C, with global average uncertainty across the 12 months generally falling between 0 and 2 °C, as illustrated in Figs. 12–15 of the supplementary material.

Regarding the selection of Shared Socioeconomic Pathways (SSPs), we chose SSP245 and SSP585 to represent moderate and high-emission scenarios, respectively, as they are most relevant to the medium-term climate impacts (2041–2060) on rice production, a crop highly sensitive to temperature and precipitation changes. SSP245 reflects a plausible mid-range pathway with moderate socioeconomic development and mitigation efforts, aligning with current agricultural policy trends, while SSP585 captures a worst-case scenario critical for evaluating adaptation limits in vulnerable regions like South Asia (36.51 Mha irrigated rice) and South-eastern Asia (20.07 Mha rainfed rice). SSP126 was excluded because its low-emission pathway assumes rapid global decarbonization unlikely by 2041–2060, given current policy trajectories, and would offer limited insights into adaptation needs for rice under realistic warming scenarios. SSP370, a high-emission scenario with heavy fossil fuel reliance, was omitted due to its lower socioeconomic plausibility compared to SSP585 and because its temperature and precipitation projections overlap significantly with SSP585, adding minimal value to rice suitability analysis while increasing computational demands (IPCC et al., 2021). This focused SSP selection ensured computational efficiency and relevance to rice production challenges.

Soil parameters were then determined for each point using soil information obtained from the FAO soil map. The FAO soil map provided vital parameters such as organic carbon (OC), exchangeable sodium percentage (ESP), cation exchange capacity (CEC), CaCO3, pH, EC which extracted from the Harmonized World Soil Database (HWSD) at a scale of 1:5,000,000, sourced from the FAO Soil Portal website. (Supplementary Fig. 2). The slope map was created using the digital elevation model. The SPAM2020 for rainfed and irrigated rice was used to intersect the climate zones and soil layers, focusing specifically on the areas dedicated to this area.

2.3. Processes

As illustrated in Fig. 1, the selection of climate data for the rice growing period and the assessment of land suitability on a global scale necessitate meticulous consideration of regional disparities in sowing dates. In order to address these discrepancies, a standardized growing season was defined, comprising a five-month interval from sowing to harvest for each region. To accommodate both early and late sowing adaptations in the context of climate change, specific monthly weather data were selected. In the case of early sowing, weather data from one month prior to the normal sowing date and one month before the harvest period were employed. Similarly, for late sowing, weather data from one month after the normal sowing date and one month beyond the harvest period were considered. The climatic factors employed in this study comprise seasonal rainfall, namely the cumulative rainfall for each of the first, second, third, fourth, and fifth months of the rice-growing season, as well as the total rainfall over the five months, which represents the total water requirement under rainfed conditions. Furthermore, the mean, maximum, and minimum temperatures for each month of the rice-growing season were subjected to analysis. In order to ascertain the pertinent climate data, sowing and harvesting date maps were employed to divide the global rice-growing area into 12 sections, each corresponding to a specific month. For each section, the mean values of the climatic parameters were calculated over the five-month growing season. The aforementioned averages were subsequently aggregated into a single map based on regional sowing and harvesting dates, thereby representing the rice-growing season on a global scale. In order to ascertain the suitability of land for a given purpose, it is necessary to consider the optimal range of climatic and soil parameters, as indicated in Table 1. This table presents the suitability classes for climate and soil requirements for rainfed and irrigated rice with a growing cycle of 90–150 days. The range of land suitability was considered unchanged for current and future conditions. In irrigated conditions, where the water requirement of the crop is not met by rainfall, the precipitation layers are excluded from the land suitability assessment (then precipitation ignored to be limited factor in irrigation system). The table delineates the climate and soil variables with varying ranges and distinct suitability classes. This optimal variable was documented in multiple reports, including those by Naidu (2006) and Sys et al. (1993).

In irrigated systems, rainfall was not considered a limiting factor, while in rainfed systems, precipitation during the growing season was a key determinant of suitability. The analysis framework ensured these classifications were consistently maintained across climate scenarios and adaptation strategies.

2.4. Determining the suitability index based on Liebig's law of the minimum

Climate and soil parameters layers were standardized to a scale of 0–1 using predefined minimum and maximum thresholds based on range of Table 1. This standardized enabled the generation of distinct response renge for each variable, as illustrated in S1 Fig. 2 (soil data) and Figs. 3–9 (climate data) for current climate conditions, soil, and topography, reflecting their relationships with crop performance. During the land suitability assessment, classification was applied in order to define different suitability classes for each climate and soil layer (see Table 1). The response of the suitability index to each variable was determined by specific thresholds. Additionally, climate change parameters are depicted in S1 Figs. 3–9. For each pixel in raster, the variable with the lowest suitability score was identified as the most limiting factor for cultivation, regardless of the scores of the other variables. After determining the suitability index for each variable, the min function was applied to derive the final overall suitability index for the region.

$$\text{Suitably class (SC)} = \min(S(Pn))$$

In this equation, SC represents the numerical suitability value for each pixel of the raster and Pn refers to the variables from 1 to n used in the land suitability analysis. The variable with the lowest suitability value was recognised as the most limiting factor for cultivation in the region. Finally, the overall suitability index for the region was classified into the following categories: weakly suitable, marginally suitable, suitable, and very suitable.

Table 1
Suitability classes for climate and soil requirements for rainfed and irrigated rice with a growing cycle of 90–150 Days.

Parameter	very Suitable (1)	Suitable (0.75)	Marginally Suitable (0.5)	Weakly Suitable (0.25)	Non suitable
Total rainfall in growing season (mm)	1110–1250	1000–1110	800–900	750–800	<750
Precipitation of 1st month (mm)	300–200	200–175	175–125	125–100	<100
	300–400	400–500	500–650	650–750	>750
Precipitation of 2nd month (mm)	300–200	200–175	175–125	125–100	<100
	300–400	400–500	500–650	650–750	>750
Precipitation of 3rd month (mm)	300–200	200–175	175–125	125–100	<100
	300–400	400–500	500–650	650–750	>750
Precipitation of 4th month (mm)	300–200	200–175	175–125	125–100	<100
	300–400	400–500	500–650	650–750	>750
Precipitation of 5th month (mm)	150–200	200–300	300–500	500–600	>600
	150–70	70–50	50–30	<30	
Mean temperature of the growing cycle (°C)	31–30	30–24	24–18	18–10	<18
	31–32	32–36	>36		–
Mean maximum temperature of warmest month G.C (°C)	35–36	36–40	40–45	45–50	>50
	35–33	33–40	30–26	26–21	<21
Mean temperature crop development stage (2nd month) (°C)	29–26	26–24	24–18	18–10	<10
	29–32	32–36	36–42	42–45	>45
Mean min temperature ripen. Stage (5th month) (°C)	20–18	18–14	14–10	10–7	<7
	20–22	22–25	25–28	28–30	>30
slope	<2	2–4	4–8	8–25	>25
Soil Organic Carbon (OC)	≥2 %	1.5 %–2 %	1 %–1.5 %	0.8 %–1 %	–
Slope	0 %–2 %	2 %–4 %	4 %–8 %	8 %–16 %	–
CEC	>24	24–16	<16(−)	<16(+)	–
CaCO3	<3	3–6	6–15	15–25	>25
pH	6.5–6.0	6.0–5.5	5.5–5.0	5.0–4.5	>8.8
	6.5–7.0	7.0–8.2	8.2–8.5	8.5–8.8	
EC (ds/m)	0–1	1–2	2–4	4–6	6–12
					>12
ESP	0–10	10–20	20–30	30–40	>40

2.5. Output

The final land suitability map was generated by overlaying the suitability output with raster files representing both irrigated and rainfed harvested areas, thus creating a composite map of land suitability (see output section in Fig. 1). This stage ensured the precise delineation of areas suitable for rice cultivation. Following the creation of land suitability maps for a variety of scenarios and adaptation strategies, the results were compared in order to identify the optimal strategy. The final map identifies the most efficacious adaptation strategy for enhancing land suitability in each region in the context of projected climate change. Also, The overview of the status of rainfed and irrigated rice worldwide. Actual yields, water-limited potential yields for rainfed conditions, and potential yields for irrigated conditions were extracted from various data sources, including MapSPAM. The potential yields were based on GYGA results as reported by Aramburu-Merlos et al. (2024). All raster files were prepared using ArcGIS Pro, and RStudio was subsequently employed for land suitability analysis.

3. Results

3.1. Current rainfed and irrigated rice systems

Overview of irrigated and rainfed rice in Fig. 2 indicated that total rainfed area in the world is equal to 62.5 million hectares (Mha) (Fig. 2A) while for irrigated rice area is equal to 102 Mha (Fig. 2B) which in total is equal 164.5 Mha in both. Highest area of **rainfed** rice is located in India, Myanmar, Bangladesh, Indonesia, Thailand, Cambodia, Nigeria with harvest area of 18.84, 6.40, 5.97, 5.85, 4.41, 2.04 Mha, respectively and other countries were less than this area. **Irrigated** rice dominates the global production and highest harvest area are related to China, India, Thailand, Vietnam, Bangladesh, Indonesia and Pakistan with 30.02, 25.53, 7.13, 6.21, 5.70, 5.21 and 3.09 Mha, respectively and other countries was less than these (Fig. 2A and B). The actual yield range in rainfed condition is relatively variable and we found it was between 0.1 and 6.5 t/ha. Also, the highest value was related to the North Macedonia, Albania, Croatia, France, Japan, and China with an averages of 5.11, 4.84, 4.53, 4.49, 4.8 and 4.19 t/ha, while the lowest values for Ya rainfed was related to the Zimbabwe, Cameroon, Mauritania, and Senegal, which an average of 0.21, 0.27, 0.29, 0.35 t/ha (Fig. 2C), respectively. While the range of water limited potential yield of rice was between 4 and 10 t/ha which indicated in Fig. 2E. In irrigated system actual yield value was more than rainfed and reached values between 0.2 and 8.43 t/ha which highest values was related to the Nicaragua, Argentina, Uruguay, Sudan and United States with an average of 8.43, 8.38, 8.31, 8.26 and 8.16 t/ha and other countries was lest then these values also the lowest yield was related to the Trinidad and Tobago, Mozambique, Somalia and Zambia which an averages of 0.92, 1.33, 1.77 and 1.95 t/ha (Fig. 2D). While potential yield of rice in irrigated system was between 6 and 16 t/h (Fig. 2F).

3.2. Land suitability of irrigated rice under climate change conditions

A global land suitability analysis in current condition (2001–2021) for irrigated rice, which encompasses a total area of 102 Mha, has yielded the following classification: A total of 30.12 million hectares are classified as weakly suitable, 36.87 million hectares as marginally suitable, 21.21 million hectares as suitable, and 14.10 million hectares as very suitable (Fig. 3G and).

Fig. 3 presents a series of maps (Fig. 3A–H) illustrating the suitability of global land for irrigated rice under current conditions, projected climate change scenarios (SSP245 and SSP585), and the impact of adaptation strategies involving early and late sowing dates. In the present scenario (Fig. 3G), the most favourable areas for the cultivation of irrigated rice are situated in South and Southeast Asia, with smaller areas of suitability in South America and parts of Africa. Maps in Fig. 3A and B illustrate the projected land suitability under SSP245 and SSP585, respectively, in the absence of adaptation. Both scenarios demonstrate a reduction in the extent of highly suitable areas, particularly in Asia, where some regions are reclassified as marginal or weakly suitable as a consequence of climate impacts. Fig. 3B, which represents a more severe climate scenario (SSP585), demonstrates a slightly greater reduction in suitable areas in comparison to SSP245 (Fig. 3A). This highlights the increased stress on agricultural suitability under more extreme climate

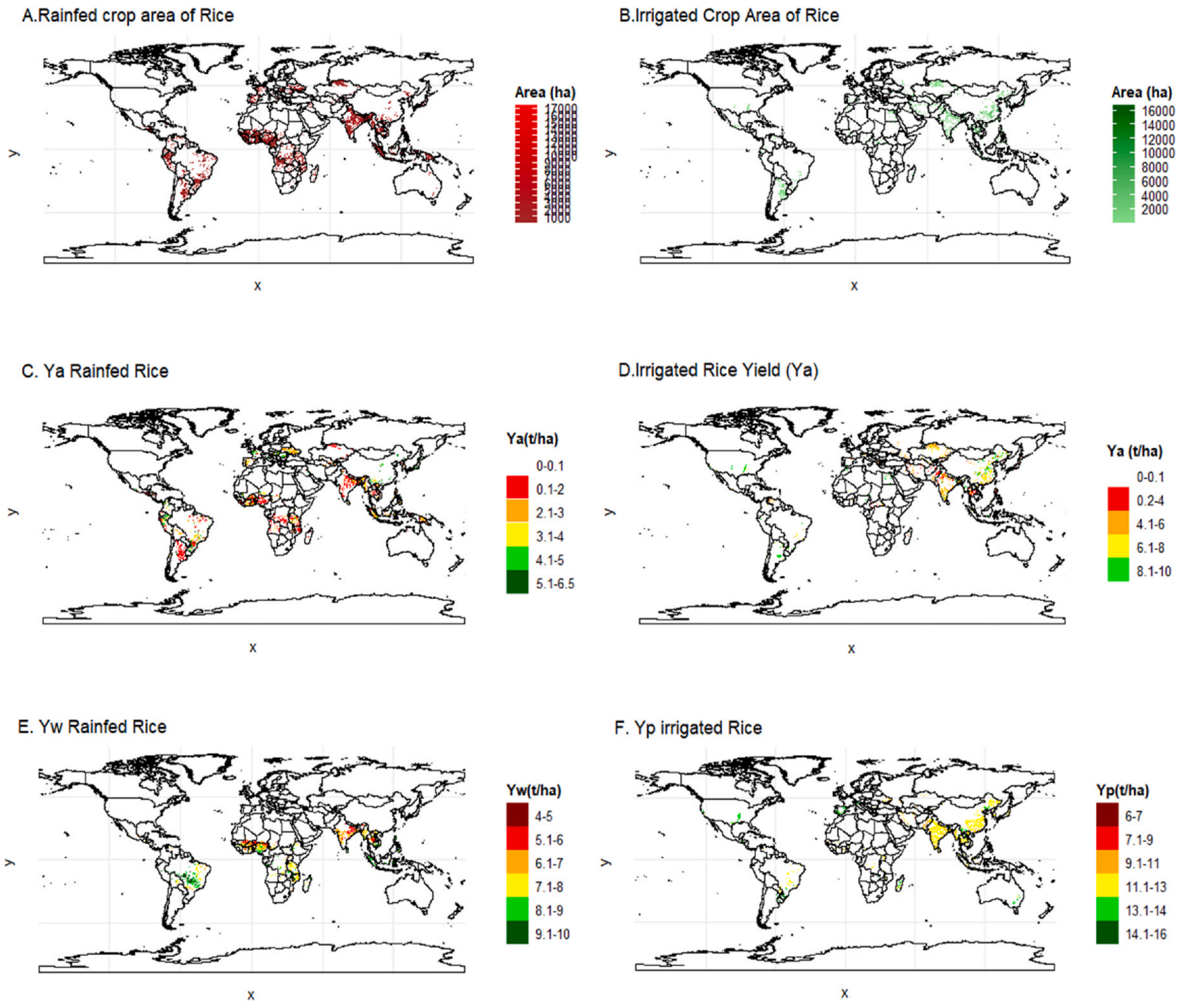

Fig. 2. Map of irrigated and rainfed rice crop area, actual and potential yield in global scale (Ya: is Actual yield, Yp; potential yield in irrigated condition, Yw: water limited potential yield in rainfed condition).

change. Fig. 3C and D illustrate the impact of early sowing as an adaptation to SSP245 and SSP585, respectively. The implementation of early sowing techniques offers a modest enhancement in suitability, particularly in South America and Central Asia. However, this does not entirely compensate for the reduction in the quantity of highly suitable land in pivotal rice-producing regions, such as South and Southeast Asia. Fig. 3 E and F illustrate the impact of a late sowing adaptation strategy on SSP245 and SSP585. The implementation of a late sowing strategy demonstrates a more pronounced enhancement in suitability than that observed with an early sowing approach. This is particularly evident in North and South America, as well as in specific regions of Asia, including China, Iran, and parts of Central Asia (e.g., Kazakhstan). This strategy serves to sustain or expand suitable areas, thereby mitigating some negative effects of climate change. Ultimately, Fig. 3 H elucidates the optimal adaptation strategy under disparate scenarios for irrigated rice, demonstrating that late sowing is especially efficacious in maintaining or enhancing land suitability across a multitude of regions. In light of these findings, late sowing emerges as the most efficacious strategy for maintaining rice suitability in North and South America, as well as in regions of Asia such as China and Central Asia, in the context of projected climate change. This highlights the importance of targeted adaptation strategies, with late sowing being especially beneficial for optimizing land suitability for irrigated rice cultivation on a global scale.

The analysis of irrigated rice land suitability across 19 sub-regions reveals significant variations in response to climate change scenarios (SSP245 and SSP585) and adaptation strategies (early sowing (ES), and late sowing (LS)), with late sowing emerging as a critical strategy for mitigating declines in suitability. In Eastern Asia, which hosts the largest irrigated rice area at 32.58 million hectares (Mha) under current conditions, suitability undergoes substantial shifts. Very suitable land, initially 0.19 Mha, nearly doubles to 0.37 Mha under SSP245 but surges to 5.25 Mha with late sowing in this scenario and 7.15 Mha with late sowing under SSP585, indicating that late sowing significantly enhances high-quality rice-growing areas by aligning with cooler periods. However, weakly suitable land increases from 9.14 Mha to 12.07 Mha (SSP245, ES), reflecting heat stress in marginal zones. Southern Asia, with 36.51 Mha, shows stable total area but a decline in very suitable land from 3.23 Mha to 3.00 Mha (SSP245, ES), though late sowing boosts it to 3.99 Mha under SSP585, underscoring its effectiveness in countering temperature rises. Marginally suitable land in Southern Asia remains relatively stable, fluctuating between 8.68 and 9.42 Mha across scenarios (Fig. 4).

South-Eastern Asia, a major rice-producing region with 25.12 million hectares (Mha), is projected to see a decrease in highly suitable land from 9.59 Mha to 6.72 Mha under the SSP2-4.5 scenario without adaptation. However, early and late sowing strategies can restore suitability to 11.46 Mha and 11.37 Mha, respectively, under the same scenario. Under SSP5-8.5, the region maintains a high level of suitability both with and without adaptation, highlighting the resilience of monsoon-dependent systems. The area classified as weakly suitable increases slightly from 5.21 Mha to 5.95 Mha under SSP2-4.5, with only marginal changes observed under sowing adaptations. In South

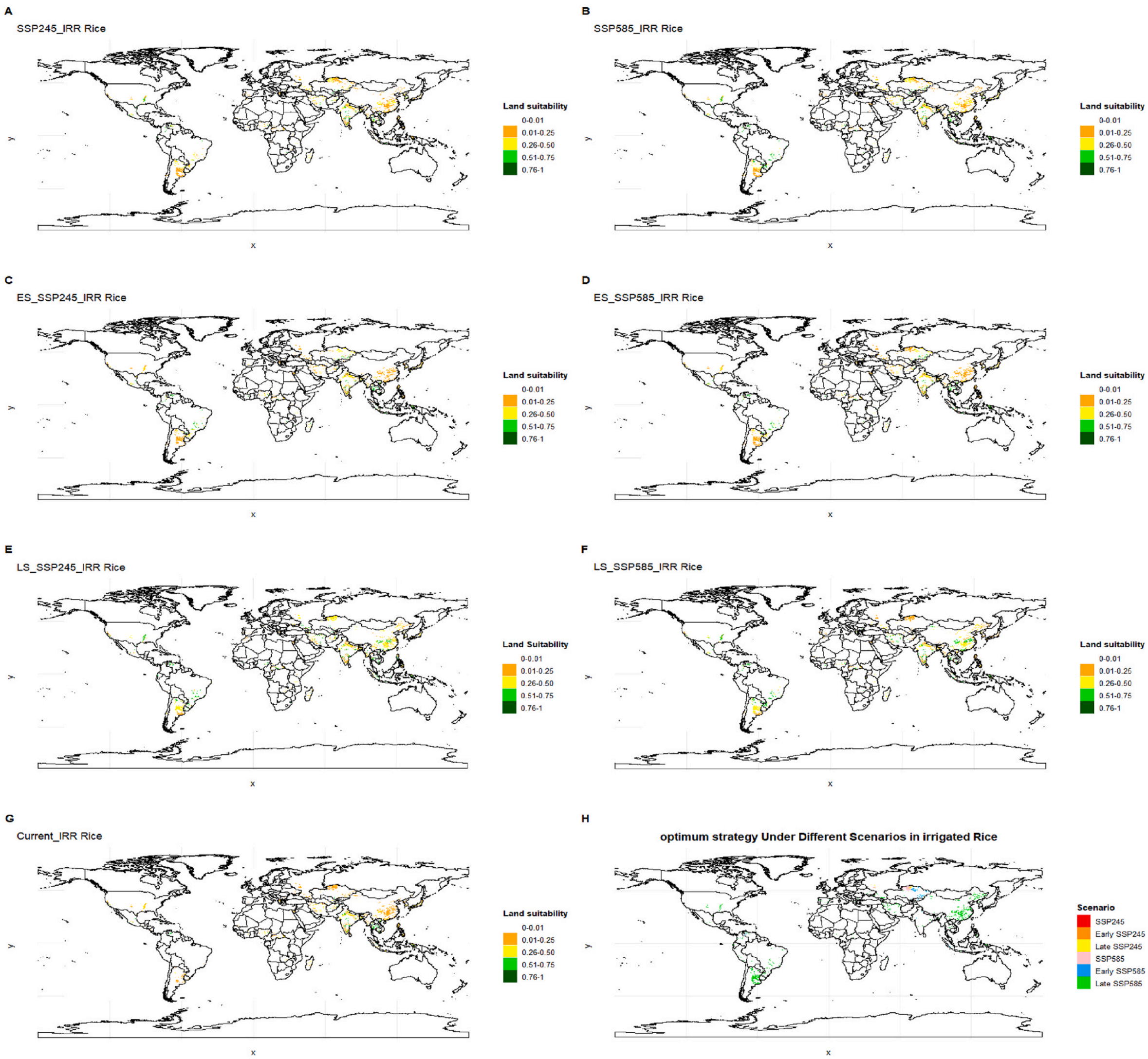

Fig. 3. Land suitability for irrigated rice under current and projected future climate conditions, based on two scenarios (SSP245 and SSP585) and two adaptation strategies (early and late sowing dates) in this chart ES and LS stand for early and late sowing date and optimum strategies under different scenarios in rainfed rice area in global scale.

America, total irrigated area expands dramatically from 2.12 Mha to 10.01 Mha across scenarios, driven by a surge in very suitable land from 0.27 Mha to 4.74 Mha (SSP245, LS) and 4.61 Mha (SSP585, LS), highlighting late sowing's role in unlocking new cultivation potential. Weakly suitable land also rises from 1.03 Mha to 3.84 Mha (SSP245), suggesting challenges in marginal areas. Central America sees a modest increase in total area from 0.14 Mha to 0.20 Mha, with very suitable land nearly doubling from 0.06 Mha to 0.10 Mha under both ES and LS in SSP245 and SSP585, indicating adaptation benefits in tropical climates (Fig. 4).

In the Caribbean, total suitability increases from 0.28 Mha to 0.34 Mha across scenarios, with very suitable land growing from 0.13 Mha to 0.16 Mha under both sowing strategies, showing consistent gains. Eastern Africa's irrigated area of 1.68 Mha expands to 1.91 Mha, with very suitable land increasing from 0.18 Mha to 0.44 Mha (SSP245, LS) and 0.47 Mha (SSP585, ES), though weakly suitable land rises from 0.21 Mha to 0.32 Mha, reflecting mixed impacts. Western Africa's 1.35 Mha area grows to 1.76 Mha, with very suitable land slightly increasing from 0.41 Mha to 0.50 Mha (SSP585, LS), supported by late sowing's alignment with rainfall peaks. Middle Africa's smaller area (0.25 Mha) sees very suitable land rise from 0.02 Mha to 0.09 Mha (SSP585, LS), indicating potential for expansion with adaptation (Fig. 4).

Northern Africa's suitability remains stable at 0.51 Mha, with negligible changes in very suitable land (0.001 Mha), constrained by aridity. Central Asia's 0.16 Mha area shows a dramatic increase in very suitable land from 0.001 Mha to 0.06 Mha (SSP245, LS) and 0.05 Mha (SSP585, LS), driven by late sowing's mitigation of heat stress. Eastern Europe's limited 0.21 Mha area sees very suitable land rise from 0.001 Mha to 0.12 Mha (SSP245, LS), suggesting new opportunities in cooler climates. Southern Europe's 0.33 Mha area maintains stability, with very suitable land marginally increasing to 0.002 Mha (SSP245, LS). Northern America's 1.07 Mha area benefits significantly from late sowing, with very suitable land rising from 0.0004 Mha to 0.47 Mha (SSP585, LS), despite a decline in suitable land from 0.58 Mha to 0.16 Mha. Oceania's minimal 0.02 Mha area remains weakly suitable, with no notable adaptation gains. Southern Africa and Western Asia have negligible areas (0.0003 Mha and 0.05 Mha), with limited suitability improvements. Northern and Western Europe show no suitability, reflecting climatic constraints (Fig. 4).

Late sowing consistently enhances very suitable land across most sub-regions, particularly in Eastern Asia (7.15 Mha gain), South America (4.61 Mha gain), and Central Asia (0.06 Mha gain), by optimizing temperature and rainfall alignment. Early sowing offers smaller benefits, with gains in Eastern Africa (0.47 Mha) and Northern America (0.47

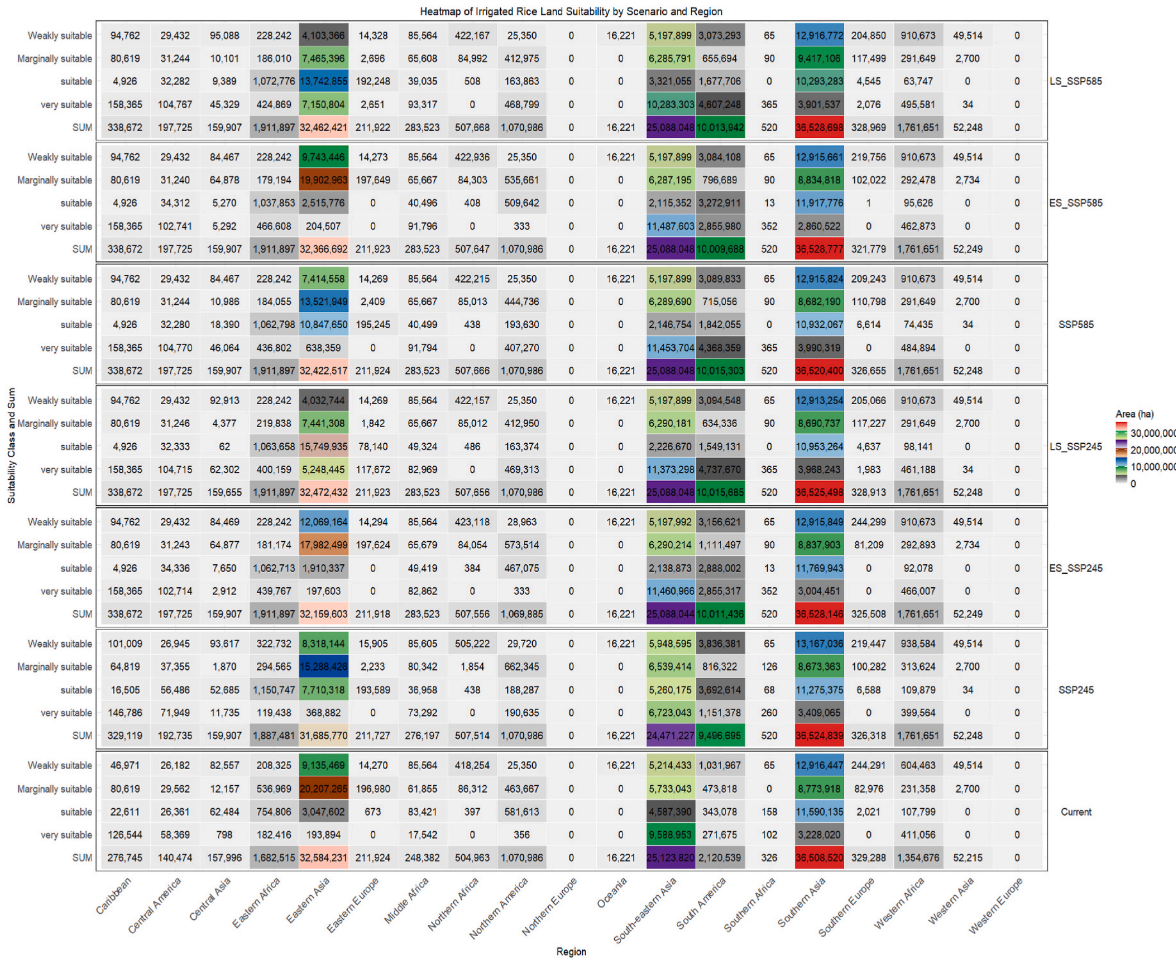

Fig. 4. Land Suitability (ha) for Irrigated Rice Across 19 agroecological region (based on FAO classification) Under Current and Projected Climate Change Conditions, and Cropland Area Under Different Adaptation Strategies (Early and Late Sowing Dates, ES and LS), Based on Two Climate Scenarios (SSP245, SSP585) Through 2050. Projections Represent the Mean of 10 GCMs.

Mha). These findings underscore the importance of tailored sowing adjustments to preserve and expand rice cultivation zones under climate change, with late sowing proving most effective in high-production regions facing heat and water stress (Fig. 4).

3.3. Land suitability of rainfed rice under climate change condition

The results of the land suitability analysis for rainfed rice indicate that the total global area of this crop is 62.28 million hectares (Mha). Of this total area, 29.45 Mha are located in areas that are weakly suitable for rainfed rice cultivation, while 13.56, 13.70 and 5.57 Mha are located in marginally suitable, suitable and very suitable areas, respectively (Figs. 5G and 6). The maps (Fig. 5A–F) illustrate the SSP245 and SSP585 scenarios with early (ES) and late (LS) sowing adaptations. Map Fig. 5G depicts the current baseline, while map Fig. 5H represents an optimum strategy that synthesises the most favourable outcomes. In the current conditions depicted in Fig. 5G, the areas of high suitability are concentrated in Southeast Asia, sub-Saharan Africa, and parts of South America. In contrast, Europe, North America, and northern Africa are predominantly classified as low suitability or unsuitable. The baseline map illustrates the regions with the strongest potential for rainfed rice production. In comparison to the current baseline (Fig. 5G), the SSP245 scenario (Fig. 5A) indicates a slight decline in suitability across Africa and Southeast Asia. Additionally, highly suitable areas become increasingly fragmented. The early sowing adaptation (Fig. 5C) in SSP245 results in minor improvements in Southeast Asia and parts of South America, whereas the late sowing adaptation (Fig. 5E) demonstrates a more pronounced increase in suitability, particularly in Southeast Asia and some areas in South America. This suggests that late sowing may be a more effective strategy for counteracting moderate climate changes. In the SSP585 scenario (Fig. 5B), which represents a high-emission future, the suitability of the land is further reduced in comparison to current conditions. This reduction is most significant in areas of high suitability in Africa and South America. The implementation of early sowing (Fig. 5D) under SSP585 yields only marginal improvements, whereas the utilisation of late sowing (Fig. 5F) facilitates a discernible enhancement in suitability, particularly in Southeast Asia, which retains a considerable proportion of highly suitable regions. The optimum strategy map (Fig. 5H) synthesises the highest suitability outcomes across all scenarios and adaptations, thereby demonstrating the potential to optimize land suitability through the implementation of adaptive sowing strategies. The expansion of high-suitability areas in Southeast Asia, South America, and Africa relative to both SSP scenarios and current conditions suggests that the strategic timing of sowing practices can significantly enhance the potential for rainfed rice production in the context of future climate scenarios. These findings indicate that late sowing is an effective adaptation for both moderate (SSP245) and high-emission (SSP585) scenarios, particularly in regions such as Asia and South America, where it preserves or enhances land suitability for rainfed rice (Fig. 5). The optimum strategy map highlights the necessity of adaptive management in order to maintain productive rice-growing areas in the context of projected climate change.

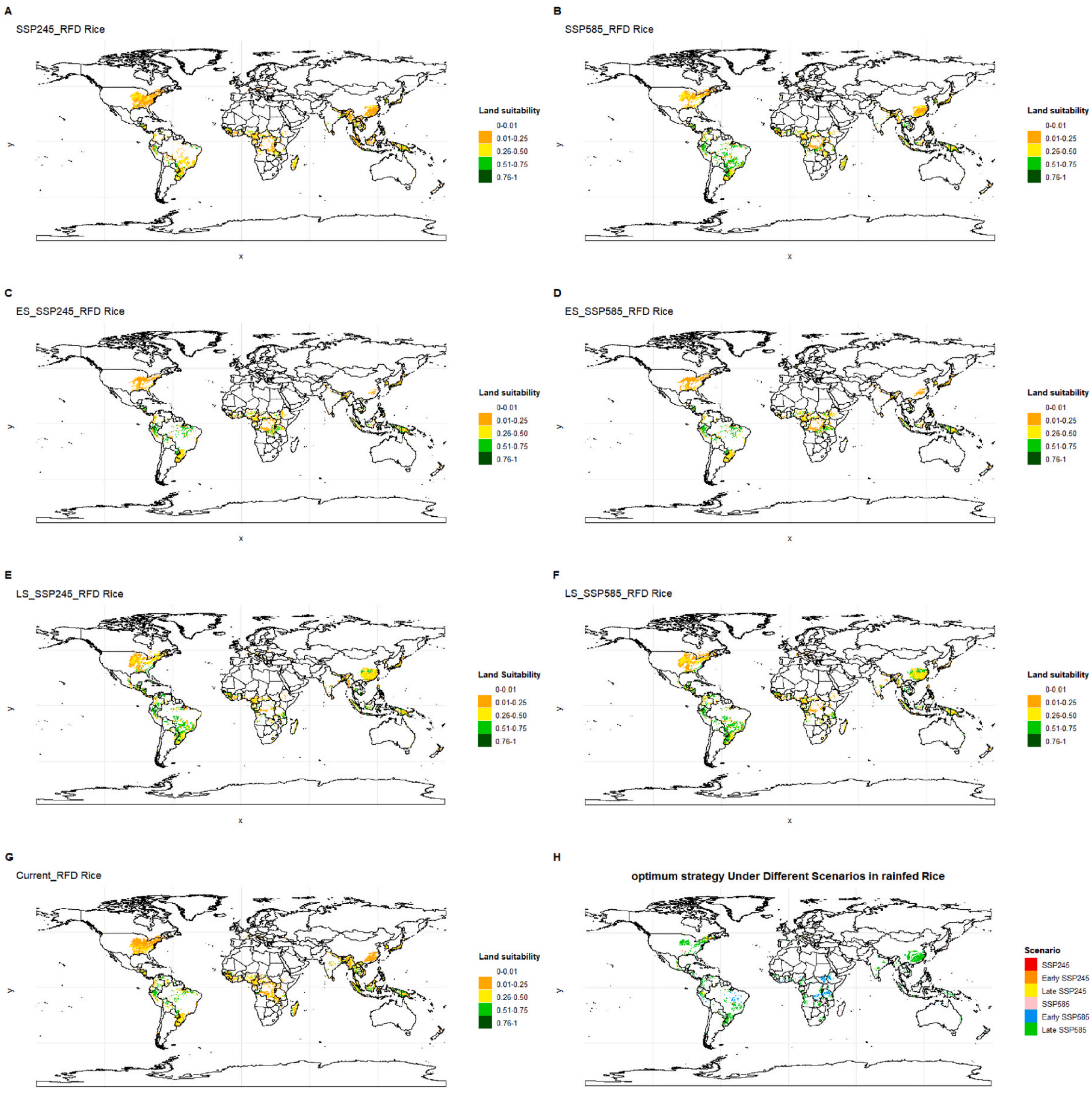

Fig. 5. Land suitability for rainfed rice under current and projected future climate conditions, based on two scenarios (SSP245) and two adaptation strategies (early and late sowing dates) in this chart ES and LS stand for early and late sowing date and optimum strategies under different scenarios in rainfed rice area in global scale.

The analysis of rainfed rice land suitability across 19 sub-regions, as depicted in Fig. 6, highlights diverse regional responses to climate change scenarios (SSP245 and SSP585) and adaptation strategies (early sowing (ES), and late sowing (LS)), with late sowing consistently enhancing suitability in several key regions. South-eastern Asia, with the largest rainfed rice area at 20.07 million hectares (Mha) under current conditions, experiences a decline in very suitable land from 2.77 Mha to 1.27 Mha under SSP245 without adaptation, but late sowing boosts this to 2.45 Mha under SSP585, aligning planting with optimal rainfall. Weakly suitable land increases from 6.14 Mha to 7.66 Mha (SSP245, ES), indicating challenges in marginal areas. Southern Asia, with 27.49 Mha, sees very suitable land drop from 1.84 Mha to 0.59 Mha under SSP245, but late sowing mitigates this to 0.35 Mha under SSP585, though weakly suitable land rises from 15.81 Mha to 18.90 Mha, reflecting heat and water stress. Eastern Africa's 1.61 Mha area expands to 2.03 Mha (SSP585, ES), with very suitable land increasing from 0.15 Mha to 0.44 Mha (SSP245, LS) and 0.44 Mha (SSP585, LS), driven by late sowing's alignment with wet seasons, though weakly suitable land grows from 0.91 Mha to 1.33 Mha (Fig. 6).

South America's 1.90 Mha area shows very suitable land rising from 0.35 Mha to 0.48 Mha (SSP245, LS) and 0.49 Mha (SSP585, LS), with total area peaking at 2.05 Mha under SSP245, supported by late sowing's mitigation of drought risks. Weakly suitable land increases from 0.97 Mha to 1.21 Mha (SSP245), highlighting marginal land challenges. Western Africa's 8.40 Mha area sees very suitable land rise from 0.48 Mha to 0.75 Mha (SSP585, LS), but early sowing reduces total suitability to 6.34 Mha (SSP245, ES), suggesting sensitivity to sowing date. Middle Africa's 1.63 Mha area benefits significantly from late sowing, with very suitable land increasing from 0.06 Mha to 0.23 Mha (SSP245, ES) and 0.29 Mha (SSP585, ES), though total area fluctuates, dropping to 1.35 Mha (SSP245, LS). Eastern Asia's 0.78 Mha area sees a modest increase in very suitable land from 0 Mha to 0.02 Mha (SSP585, LS), with weakly suitable land rising from 0.42 Mha to 0.61 Mha (SSP585, ES), indicating limited adaptation gains (Fig. 6).

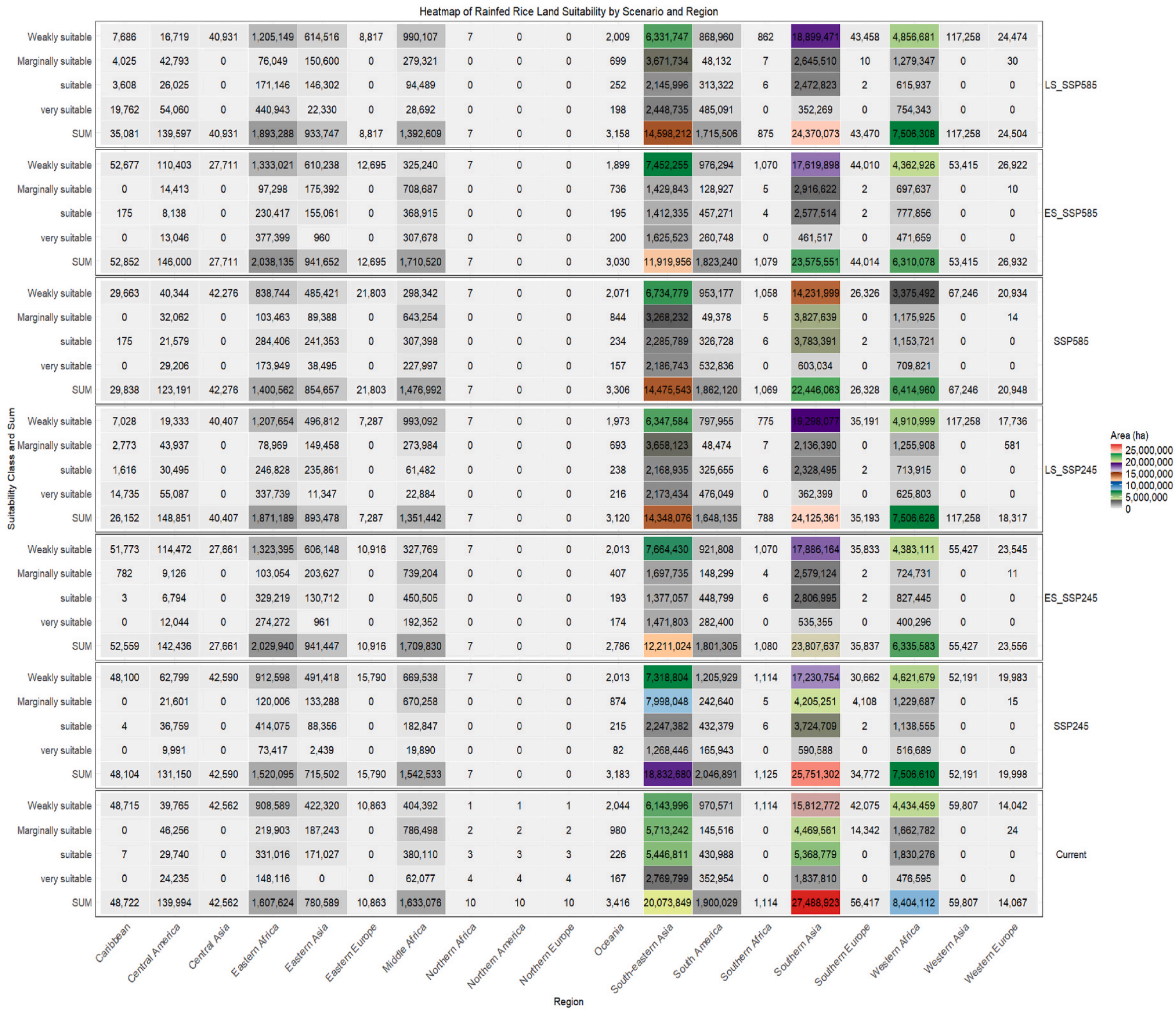

Fig. 6. Land Suitability (ha) for rainfed Rice Across 19 agroecological region (based on FAO classification) Under Current and Projected Climate Change Conditions, and Cropland Area Under Different Adaptation Strategies (Early and Late Sowing Dates, ES and LS), Based on Two Climate Scenarios (SSP245, SSP585) Through 2050. Projections Represent the Mean of 10 GCMs.

Central America's 0.14 Mha area experiences a surge in very suitable land from 0.02 Mha to 0.06 Mha (SSP245, LS) and 0.05 Mha (SSP585, LS), with total area stable at 0.14 Mha, reflecting adaptation benefits in rain-dependent systems. The Caribbean's small 0.05 Mha area sees very suitable land emerge at 0.02 Mha (SSP585, LS) from 0 Mha, with total suitability peaking at 0.05 Mha (SSP245, ES). Central Asia's 0.04 Mha area remains weakly suitable, with no very suitable land across scenarios, constrained by aridity. Eastern Europe's 0.01 Mha area shows minimal suitability, with weakly suitable land peaking at 0.02 Mha (SSP585). Southern Europe's 0.06 Mha area declines to 0.03 Mha (SSP245, LS), with no very suitable land. Western Europe's 0.01 Mha area sees weakly suitable land rise to 0.02 Mha (SSP585, ES), with no significant adaptation gains. Oceania's minimal 0.003 Mha area shows stable suitability, with very suitable land at 0.0002 Mha (SSP245, LS). Southern Africa, Western Asia, Northern Africa, Northern America, and Northern Europe have negligible or no suitability, limited by climatic constraints (Fig. 6).

Late sowing significantly enhances very suitable land in South-eastern Asia (2.45 Mha gain), South America (0.49 Mha gain), Eastern Africa (0.44 Mha gain), and Western Africa (0.75 Mha gain), by optimizing planting with rainfall patterns. Early sowing yields smaller benefits, notably in Middle Africa (0.29 Mha) and Eastern Africa (0.38 Mha). These results emphasize the critical role of late sowing in sustaining rainfed rice production under climate change, particularly in monsoon-dependent and drought-prone regions (Fig. 6).

4. Discussion

4.1. Climate and soil parameter effects on land suitability

The present study evaluates the impacts of climate change on the suitability of land for rice cultivation across 19 sub-regions under the SSP245 and SSP585 scenarios. This is achieved by employing early and late sowing adaptations driven by region-specific changes in temperature and precipitation (SFigs. 3–9). In South-Eastern Asia, the area suitable for irrigated systems decreases from 9.58 million hectares (Mha) to 6.72 Mha, and for rainfed systems, it declines from 2.76 Mha to 1.26 Mha under SSP245, as monthly rainfall decreases by 10–20 mm and temperatures rise by 1–2 °C (SFig. 4), with Tave Mean increasing from 26 °C to 27.5 °C (SFig. 4). The reduced rainfall has been shown to limit water availability for rainfed systems (Jagadish et al., 2015), while higher temperatures have been found to cause heat stress, with a consequent negative effect on spikelet fertility. The findings of Wassmann et al. (2009) demonstrate that late sowing under SSP585 (SFig. 9) improves suitability by aligning rainfall with key growth stages and reducing Tmax by 0.3 °C, thereby aligning flowering with wetter periods and supporting crop adaptation to future climate conditions. In Southern Asia, a major rice-producing region, irrigated land constitutes 36.50 Mha, while rainfed land covers 27.48 Mha. The impact of climate change on irrigated areas is minimal, whilst rainfed systems are significantly affected.

The effectiveness of irrigation in reducing heat stress varies significantly from region to region, highlighting the need for region-specific adaptation (Chakraborty et al., 2025). Research consistently demonstrates that irrigation in arid and semi-arid regions, such as Central Asia and Northwest China, produces a significant cooling effect on land surface temperature, primarily due to enhanced evapotranspiration under low humidity conditions. Satellite observations show that in these regions, irrigation can lower daytime land surface temperatures by more than 6 °C during the growing season, with the cooling effect being much stronger in arid zones compared to humid ones (Siebert et al., 2014; Chen and Dirmeyer, 2019). In humid monsoon regions such as South-East Asia, however, irrigation plays a more supportive role, preventing drought-induced amplification of heat stress. Nevertheless, its cooling effect is less pronounced here and may even contribute to humid heat stress under extreme conditions (Mishra et al., 2020). While most studies focus on general croplands, research in semi-arid regions like Pakistan's Punjab and Burkina Faso demonstrates that irrigation in rice systems can help mitigate heat stress and maintain yields, though the effectiveness may be limited under extreme heat or water scarcity (Johnson et al., 2024). Additionally, heat stress reduces photosynthesis and increases pollen sterility. In rainfed systems, T_(can) can exceed T_(air) by more than 10 °C during drought events, leading to severe yield losses (Siebert and Ewert, 2014). Irrigation counteracts this effect by lowering T_(can) below T_(air) through evapotranspiration cooling, particularly in arid zones where vapour pressure deficit magnifies this process (Kimball et al., 2015). Consequently, reductions in canopy heat stress of over 5 °C have been observed in irrigated systems (Pinto and Reynolds, 2015), whereas rainfed systems experience elevated canopy temperatures and greater yield penalties (Lobell and Bonfils, 2008).

The implementation of SSP585 has resulted in a contraction of the suitable rainfed rice area, which has decreased from 27.48 million hectares (Mha) to 22.44 Mha. However, the adoption of late sowing practices has led to an augmentation of this area to 24.37 Mha. Boxplots in the supplementary materials (S Figs. 3–9) demonstrate an increase in precipitation and temperature, with elevated temperatures during the rice-growing season proving more damaging to rainfed systems due to their sensitivity to temperature fluctuations. In Eastern Asia, the 32.58 Mha of irrigated and 0.78 Mha of rainfed rice land are particularly vulnerable to the impacts of climate change on irrigated rice. The implementation of late sowing has been demonstrated to result in a substantial augmentation of areas deemed to be highly suitable, a phenomenon attributable to a reduction in mean temperatures of approximately 1 °C in comparison with prevailing contemporary conditions. However, without adaptations, the temperature increases of 1–2 °C during rice growth stages exceed the optimal range (S Figs. 3, 7, and 9). Nonetheless, adjusting sowing dates can enhance suitability and boost yields. The present study employs region-specific climate parameters (SFigs. 3–9) and Liebig's Law to identify limiting factors temperature in Asia, water in Africa refining rice suitability mapping, with soil parameters (SFig. 2) further shaping these trends (Dadrasi et al., 2024).

In the context of rainfed rice cultivation in Western Africa, a region of particular significance, climate change has been shown to reduce the area deemed suitable for cultivation by approximately 2 Mha in the absence of adaptation measures (Myers et al., 2022). The timing of sowing, that is to say, the decision of when to initiate the process of plant cultivation, has been shown to mitigate the impacts of climatic shifts, such as those precipitated by alterations in precipitation and temperature patterns. As demonstrated in Sections 3–9 of the SSI, under the SSP245 and SSP585 scenarios, precipitation and temperature increase by approximately 20 mm and 2 °C, respectively, during the rice-growing season. It is evident that early and late sowing reduce precipitation by approximately 20 mm in the fourth month of the growing cycle, potentially enhancing suitability by aligning drier conditions with anthesis and grain-filling stages, which benefit from less rainfall. As demonstrated in Fig. 4, South America possesses the potential to emerge as a significant irrigated rice-producing region under the projected conditions of future climate change, particularly in the context of early and late sowing adaptations. The shift is driven by rising temperatures, which alleviate current low-temperature constraints in regions such as Rio Grande do Sul, Brazil. In this region, suboptimal temperatures during flowering reduce yields (Guimarães et al., 2018). The potential for future warming to mitigate this issue has been demonstrated in various studies (Lobell and Field, 2007; Peng et al., 2004). These studies suggest that an increase of up to 8 Mha in suitable irrigated rice area may be possible, provided that sufficient irrigation water is available (Wassmann et al., 2009). In Eastern Africa, climate change has been shown to reduce precipitation and increase temperatures by 10–20 mm and 1–2 °C, respectively. Early sowing has been demonstrated to enhance precipitation and lower temperatures, thereby improving land suitability and expanding suitable areas (Challinor et al., 2014). The boxplots for SSP585 (SFigs 3, 7, and 8) demonstrate that Taver1 increases from 15.1 °C to 16.9 °C, but early sowing reduces it to 13.7 °C; Taver2 rises from 15 °C to 16.7 °C, decreasing to 12.9 °C with early sowing; Tmax4th increases from 18 °C to 20.5 °C, falling to 17.1 °C with early sowing; and Tmin5th rises from 12.9 °C to 13.1 °C, decreasing to 11.8 °C with early sowing. These changes have been shown to enhance the suitability of rice cultivation by reducing heat stress during the reproductive phase, a critical consideration in Eastern Africa where temperatures often exceed the optimal 25–30 °C for flowering and grain filling (Jagadish et al., 2007). It has been demonstrated that lower temperatures from early sowing improve spikelet fertility, reduce sterility, and enhance panicle development, increasing yield potential and suitable areas (Rurinda et al., 2015). A similar improvement in land suitability under early sowing compared to late sowing or no adaptation is demonstrated in Middle Africa. The results and supplementary figures present other regions, but due to their lower contribution to global rice production, these are less detailed here. It is imperative to acknowledge a salient point concerning these results. Liebig's Law postulates a unifying principle, namely that crop productivity is governed by a single limiting factor. In reality, however, biophysical factors are frequently interdependent, resulting in a phenomenon known as co-limitation, as opposed to isolated constraints. This assertion is further substantiated by contemporary agricultural research (Chandio et al., 2021). This interdependence is evident in arid regions like Central Asia, where low precipitation and high temperatures co-occur, amplifying heat stress and reducing suitability scores by 20–30 % as water scarcity exacerbates thermal effects (Habib-Ur-Rahman et al., 2022). Conversely, in humid monsoon regions such as South-Eastern Asia, substantial precipitation is often accompanied by cooler temperatures and more fertile soils. Consequently, variations in one factor (a delayed monsoon leading to a drought) seldom result in a single limiting factor (Urfels et al., 2022). In favourable conditions, suboptimal performance in one factor such as a slight water deficit can constrain growth. This phenomenon is exemplified in rainfed systems, where the simultaneous occurrence of heat and drought leads to a decline in photosynthesis and spikelet fertility, potentially resulting in a yield reduction of up to 30 % (Costa et al., 2021). In order to incorporate these dynamics, future suitability models should account for interactive effects, adjusting scores by 15–25 % to reflect real-world synergies, ensuring more accurate climate impact assessments for rice systems (Wu et al., 2020).

4.2. Socioeconomic barriers to adaptation

Socioeconomic constraints have been identified as a significant hindrance to the adaptation of smallholders to climate change across 19 sub-regions, with limitations imposed on early and late sowing under SSP245/SSP585. In Western Africa, 80 % of smallholders (i.e. those with less than 2 ha of land) lack access to quality seeds, irrigation, and extension services, resulting in reduced early sowing yields of 20–30 % and food insecurity for millions (Atube et al., 2022a). The inadequate subsidies and weak advisory systems characteristic of Southern Asia have been identified as factors that hinder the adoption of late sowing, thereby exacerbating livelihood vulnerabilities and poverty (Hertel et al., 2010). The volatility of the South-East Asian market, as evidenced by fluctuations in rice prices, has been identified as a factor discouraging investments in late sowing, thereby posing a threat to regional stability (Mottaleb et al., 2016). The limited institutional capacity in Eastern Africa has been identified as a key factor hindering the adoption of irrigation for early sowing, thereby impeding the potential for yield gains (Tadesse et al., 2019). As Nkonya et al. (2015) demonstrate, financial constraints in middle Africa serve to diminish the efficacy of rainfed systems, thereby reducing the advantages offered by early sowing. The adoption of strategic crop cultivation is further hindered by credit constraints and labour shortages, which are prevalent among smallholders in Central America and the Caribbean (Harvey et al., 2018). These challenges contribute to the exacerbation of rural poverty. It is evident that water governance disputes in Central Asia, in conjunction with land tenure conflicts in Northern Africa, Southern Africa, Western Asia and Oceania, have a detrimental effect on the implementation of costly irrigation infrastructure, thereby limiting its suitability to a negligible degree (Rosegrant et al., 2014; Deininger and Byerlee, 2011). As stated in the research by Pretty et al. (2018), there is a requirement for enhanced extension services in order to assist small-scale farmers in Northern America, Western Europe, Eastern Europe and Southern Europe to scale up their sowing, whether late or normal. Solutions to this problem have been proposed, including microfinance, cooperatives, public-private partnerships (World Bank, 2020), digital extension apps in Southern Asia (FAO, 2019), climate insurance in Eastern Africa (Greatrex et al., 2015), and seed banks in Middle Africa (McGuire and Sperling, 2016). It is imperative that these barriers are addressed in order to ensure food security, as the failure to do so will have repercussions for sustainable rice production and global supply.

4.3. Adaptation strategies: feasibility, trade-offs, and complementary measures

The practice of late sowing has been demonstrated to be a viable option in South-Eastern Asia, Eastern Asia, Southern Asia, and South America, with a reported enhancement in suitability by 10–15 %. However, the implementation of this strategy necessitates the utilisation of short-duration varieties, a measure adopted to mitigate the risks posed by pests and to ensure the maintenance of yields (Saud et al., 2022). Nevertheless, the assertion that late sowing is 'most effective' requires careful nuance, particularly in these area (Wassmann et al., 2009). This practice has the capacity to influence several factors, including climate conditions (the timing of monsoon rains), soil moisture, pest dynamics, labor availability, and crop rotation. The advantages of this include improved resilience to early-season drought and heat stress, increased suitability in regions with delayed monsoon onset, and potential yield stability with short-duration varieties, which can boost productivity by 10–15 % under optimal conditions (Saud et al., 2022). However, it should be noted that significant trade-offs exist. These arise from extended labour, water, and input needs, which potentially reduce efficiency by 10–20 % due to resource constraints (McDonald et al., 2022b). The potential risks associated with this practice include the possibility of delayed harvests, which can expose crops to late-season pests such as rice stem borers. Additionally, erratic rainfall may result in yield losses of up to 15 % in vulnerable years (Baruah and Dutta, 2020). Furthermore, the practice of late sowing has been demonstrated to disrupt crop rotation cycles, thereby reducing overall farm income by 10–15 % in multi-cropping systems (Fu et al., 2023). In the context of humid South-Eastern Asia, this practice may also serve to exacerbate humid heat stress, further complicating the management of pests and diseases in the region (Fu et al., 2023). Consequently, while the practice of late sowing can offer certain adaptive benefits, its effectiveness is contingent on the specific context in which it is employed. A balanced evaluation of these trade-offs is therefore essential to avoid overstating its advantages. In order to address these challenges, the implementation of targeted solutions has the potential to enhance the project's viability. The adoption of efficient irrigation techniques, such as Alternate Wetting and Drying (AWD), has been shown to result in a reduction in water and labour costs of up to 30 % (Tian et al., 2024) The implementation of Integrated Pest Management (IPM) with resistant short-duration varieties and biocontrol has been shown to minimise pest-related yield losses (McDonald et al., 2022a). The precise scheduling of crops with digital tools has been demonstrated to align late sowing with subsequent crop cycles, thereby preserving multi-cropping income (McDonald et al., 2022b). Furthermore, the application of precision irrigation in conjunction with heat-tolerant varieties has been shown to alleviate humid heat stress in South-Eastern Asia (Khan et al., 2019). These strategies collectively address the trade-offs, making late sowing a justifiable adaptation when tailored to local conditions. Also, Early sowing has been demonstrated to be effective in Eastern Africa, Central America, and Middle Africa, thereby enhancing the suitability of the environment for cultivation (Ding et al., 2020). However, in order to mitigate water stress, the cultivation of drought-tolerant varieties is imperative. The prevailing climatic conditions in Northern America, Western Europe, Eastern Europe, and Southern Europe are conducive to the successful cultivation of this crop, requiring minimal adjustments due to the stability of the conditions. It is evident that Central Asia, Northern Africa, Southern Africa, Western Asia, and Oceania necessitate crop diversification (e.g., millet) or large-scale irrigation due to their low suitability (Godfray et al., 2010). Trade-offs are significant: late sowing in Southern Asia disrupts rice-wheat systems, resulting in a 10–20 % reduction in farm income (McDonald et al., 2022b); early sowing in Western Africa strains labour, leading to a 25 % reduction in the capacity of smallholders (van Oort and Zwart, 2018). The rainfed systems of South America are confronted with water shortages, which impose limitations on the scalability of late sowing. Complementary measures have been identified, including the cultivation of heat-tolerant varieties in Eastern Asia (Koide et al., 2021a), the implementation of small-scale irrigation systems, such as ponds, in Middle Africa (Li et al., 2020), the adoption of precision agriculture in Northern America (Schimmelpfennig, 2016), and the provision of agroecological training in South-Eastern Asia (Settle et al., 2014). It is evident that Central Asia and Northern Africa are in need of government-funded irrigation systems, while Eastern Africa stands to benefit from the implementation of climate insurance measures (Greatrex et al., 2015). These bespoke strategies are aligned with regional constraints, thereby ensuring optimal suitability and food security.

4.4. Risks of extreme climate events

To account for the risks posed by extreme climate events, this study utilized monthly climate data over a five-month rice-growing period—determined by region-specific sowing and harvest dates—at the global scale. While this approach supports the analysis of climate suitability, it is important to acknowledge the influence of extremes that may not be fully captured by monthly averages. In South Asia and South-Eastern Asia, heatwaves during the flowering period have been shown to result in 8–18 % reductions in the suitability of rainfed systems, thereby disrupting the effectiveness of late sowing (Wassmann et al., 2019). The recurrent droughts that are characteristic of Eastern Africa have been shown to have a detrimental effect on early sowing yields, with a reduction of 15–25 % being observed (Rowhani et al., 2011). This has the effect of undermining any gains that have been made in terms of suitability. The floods that occur in South America have been shown to decrease rainfed suitability by 10–20 %, thereby limiting the scalability of late sowing (Zaveri and Lobell, 2019). In regions such as Middle Africa, Central America, and the Caribbean, erratic rainfall patterns have been observed to adversely impact the reliability of early and late sowing, with studies indicating a reduction of 10–15 % in yield (Knox et al., 2012). Central Asia, Northern Africa, Southern Africa, Western Asia, and Oceania are enduring prolonged droughts, which are constraining their minimal suitability (Turral et al., 2011). The regions of Northern America, Western Europe, Eastern Europe, and Southern Europe have experienced a surge in heat, resulting in yield losses ranging from 5 to 10 % (Olesen et al., 2011). Mitigation strategies encompass the implementation of flood-tolerant infrastructure, such as elevated fields, in South America, drought-resistant varieties in Eastern Africa, and heat-tolerant cultivars in South Asia (IPCC et al., 2021). Early-warning systems in South-Eastern Asia (Rao et al., 2019) and climate-resilient seed systems in Middle Africa (McGuire and Sperling, 2016) have been shown to enhance resilience. The incorporation of extreme event forecasts into adaptation planning is imperative for the safeguarding of suitability and the assurance of food security.

4.5. Policy recommendations for resilience

Region-specific policy interventions are essential for operationalizing rice adaptation strategies, overcoming socioeconomic barriers, and managing extreme weather risks under scenarios like SSP245 and SSP585. Research highlights that adaptation measures such as reservoir-based irrigation systems can significantly mitigate the impact of floods and erratic rainfall, with studies in Southeast Asia and South America showing that improved irrigation can increase rice yields by 8–43 % and enhance suitability for late sowing, especially in flood-prone areas (Ojo et al., 2020; Boonwichai et al., 2019), Targeted investments—such as a $500 million phased program with 40 % subsidies for smallholders—are supported by evidence that financial and institutional support is crucial for adoption, particularly among vulnerable groups (Ojo and Baiyegunhi, 2020). Subsidizing drought-tolerant and short-duration rice seeds by 25–30 % and providing targeted training can significantly boost late sowing adoption and help smallholder farmers in Vietnam and Thailand mitigate the effects of heatwaves and market volatility. Research indicates that government subsidies for drought-tolerant seed production and dissemination, combined with extension services and training, are effective in overcoming adoption barriers and increasing the use of climate-resilient varieties in Asia (Pray et al., 2011; Rahman et al., 2022). In order to ensure the security of early sowing yields in the face of droughts (defined as a sum of rainfall less than 600 mm), the implementation of policies promoting drought-tolerant varieties (NERICA strains) with a 20 % seed subsidy and extension services for 1 million hectares in Eastern Africa, Central America, and Middle Africa by 2028, enhancing resilience by 15–20 % is essential (Sum rain <600 mm) (Rowhani et al., 2011). This approach is predicted to increase resilience by 15 %. It is recommended that South Asia consider the expansion of crop insurance, such as India's Pradhan Mantri Fasal Bima Yojana, in order to protect late sowing transitions and thereby reduce income losses of 10–20 % from multi-cropping disruptions across 2.5 million hectares, with a 15 % premium subsidy for farmers to stabilize revenues amid erratic monsoons (McDonald et al., 2022b). Early-warning systems, as evidenced by the Maharashtra, India, example, have been demonstrated to optimize sowing in Eastern Africa, South Asia, Middle Africa, and Central America, thereby reducing extreme event losses by 10–15 % across 3 million hectares with a rollout target of 2027 (Rao et al., 2019). In order to address the challenges faced by small-scale farmers in Western and Middle Africa, it is essential to establish public-private partnerships offering 50 % subsidies on drip irrigation and seed access for 5 million smallholders (60 % of the 80 % affected population) by 2030, boosting yields by 20–30 % (Atube et al., 2022b). In regions such as Central Asia, Northern Africa, Southern Africa, Western Asia, and Oceania, the implementation of subsidised drip irrigation has been identified as a crucial strategy to mitigate the impact of droughts, characterised by annual rainfall amounts of less than 300 mm (Turral et al., 2011). It is recommended that Northern America, Western Europe, Eastern Europe and Southern Europe enhance their precision agriculture policies with a view to boosting normal sowing efficiency (Schimmelpfennig, 2016). Localized climate models address the limitations of 2.41-min resolution, thereby refining forecasts (IPCC et al., 2021). The implementation of these policies has been demonstrated to facilitate the reduction of socioeconomic disparities, the mitigation of extreme risks, and the assurance of food security through the promotion of resilient rice production methods. To guide governments in prioritizing between irrigation investments and sowing-date adjustments, a decision-making framework is proposed. In regions like South America and Central Asia, where water availability is a primary constraint due to floods or droughts, irrigation infrastructure should be prioritized to ensure stable water supply, enabling the scalability of late sowing adaptations. Conversely, in high-production areas like Eastern Asia and South-Eastern Asia, where temperature stress is the dominant limiting factor, governments should prioritize sowing-date adjustments, supported by seed subsidies and training, as these offer immediate suitability gains with lower investment costs. A cost-benefit analysis, considering regional water resources, temperature trends, and socioeconomic capacity, can further refine this prioritization, ensuring efficient resource allocation for resilient rice production (Lobell and Field, 2007).

5. Conclusion

This study sheds light on the profound and varied impacts of climate change on rice land suitability across 19 sub-regions. Tropical areas such as South-Eastern Asia, Southern Asia, and Eastern Africa face significant declines in suitable land due to heat stress and erratic rainfall. In contrast, temperate regions such as Eastern Asia, South America, and Eastern Europe experience gains from extended growing seasons. The most effective adaptation strategy is late sowing, particularly in major rice-producing regions such as Eastern Asia and South-Eastern Asia, where it enhances suitability by aligning planting with optimal climatic conditions. Conversely, early sowing is beneficial in Eastern Africa and Middle Africa, where it mitigates temperature extremes. Socioeconomic barriers, including restricted access to seeds, irrigation, and extension services, impede the adoption of agricultural practices by smallholders, thereby exacerbating vulnerabilities in the regions of Western Africa and Southern Asia. The implementation of these practices is further complicated by market volatility and institutional constraints. Trade-offs, such as income losses from disrupted cropping systems in Southern Asia and labour strains in Western Africa, necessitate complementary measures such as heat-tolerant varieties and small-scale irrigation. It is evident that extreme climate events, including heatwaves, droughts and floods, pose additional risks and reduce the suitability of rainfed systems across South Asia and South-Eastern Asia. This emphasises the necessity for flood-tolerant infrastructure and drought-resistant cultivars.

CRediT authorship contribution statement

Amir Dadrasi: Writing – review & editing, Writing – original draft, Visualization, Software, Formal analysis, Data curation. **Davina Vačkářová:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Fatemeh Salmani:** Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Can Trong Nguyen:** Writing – review & editing, Software, Data curation. **Jan Weinzettel:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.127630.

Data availability

Global climatic data are available on WorldClim (https://www.worldclim.org/), Global crop calendar data are available on SAGE, UW-Madison (https://sage.nelson.wisc.edu/data-and-models/datasets/crop-calendar-dataset/), Global gridded soil data are available on ISRIC (https://data.isric.org/), Crop distribution maps are available on SPAM (https://mapspam.info).

References

Aramburu-Merlos, F., van Loon, M.P., van Ittersum, M.K., Grassini, P., 2024. High-resolution global maps of yield potential with local relevance for targeted crop production improvement. Nat. Food 1–6. https://doi.org/10.1038/s43016-024-01029-3.

Arunrat, N., Pumijumnong, N., Sereenonchai, S., Chareonwong, U., Wang, C., 2020. Assessment of climate change impact on rice yield and water footprint of large-scale and individual farming in Thailand. Sci. Total Environ. 726, 137864. https://doi.org/10.1016/j.scitotenv.2020.137864.

Atube, F., Malinga, G.M., Nyeko, M., Okello, D.M., Alarakol, S.P., Okello-Uma, I., 2022a. Determinants of smallholder farmers' adaptation strategies to the effects of climate change: evidence from northern Uganda. Agric. Food Secur. 10 (1), 6. https://doi.org/10.1186/s40066-020-00279-1.

Atube, F., Okello, D., Malinga, G., Nyeko, M., Okello-Uma, I., 2022b. Farmers' adaptation to climate change and crop yield: a case of Amuru and Apac districts of Northern Uganda. Int. J. Agric. Sustain. 20, 967–981. https://doi.org/10.1080/14735903.2022.2028400.

Baruah, M., Dutta, B., 2020. Effect of planting dates on stem borer incidence and its natural enemies in relation to weather variables in rice ecosystem. Journal of Entomology and Zoology Studies. https://doi.org/10.22271/j.ento.2020.v8.i5t.7703.

Bassu, S., Asseng, S., Motzo, R., Giunta, F., 2009. Optimising sowing date of durum wheat in a variable Mediterranean environment. Field Crops Res. 111, 109–118. https://doi.org/10.1016/j.fcr.2008.11.002.

Boonwichai, S., Shrestha, S., Babel, M., Weesakul, S., Datta, A., 2019. Evaluation of climate change impacts and adaptation strategies on rainfed rice production in Songkhram River Basin, Thailand. The Science of the total environment 652, 189–201. https://doi.org/10.1016/j.scitotenv.2018.10.201.

Chakraborty, T., Qian, Y., Li, J., Leung, L., Sarangi, C., 2025. Daytime urban heat stress in North America reduced by irrigation. Nat. Geosci. https://doi.org/10.1038/s41561-024-01613-z.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4 (4), 287–291. https://doi.org/10.1038/nclimate2153.

Chandio, A., Gokmenoglu, K., Ahmad, M., Jiang, Y., 2021. Towards sustainable rice production in Asia: the role of climatic factors. Earth Systems and Environment 6, 1–14. https://doi.org/10.1007/s41748-021-00210-z.

Chen, L., Dirmeyer, P., 2019. Global observed and modelled impacts of irrigation on surface temperature. Int. J. Climatol. 39, 2587–2600. https://doi.org/10.1002/joc.5973.

Costa, M., Ramegowda, Y., Ramegowda, V., Karaba, N., Sreeman, S., Udayakumar, M., 2021. Combined drought and heat stress in rice: responses, phenotyping and strategies to improve tolerance. Rice Sci. 28, 233–242. https://doi.org/10.1016/J.RSCI.2021.04.003.

Dadrasi, A., Soltani, E., Makowski, D., Lamichhane, J.R., 2024. Does shifting from normal to early or late sowing dates provide yield benefits? A global meta-analysis. Field Crops Res. 318, 109600. https://doi.org/10.1016/j.fcr.2024.109600.

Deininger, K., Byerlee, D., 2011. Rising Global Interest in Farmland: Can it Yield Sustainable and Equitable Benefits? World Bank. https://doi.org/10.1596/978-0-8213-8591-3.

Ding, Y., Wang, W., Zhuang, Q., Luo, Y., 2020. Advances in molecular breeding of drought-tolerant rice. Field Crops Res. 245, 107662. https://doi.org/10.1016/j.fcr.2019.107662.

FAO, 2019. Digital Agriculture Transformation: the Role of Mobile Apps and Big Data in Sustainable Farming. Food and Agriculture Organization. http://www.fao.org/3/ca4887en/ca4887en.pdf.

Fischer, G., Nachtergaele, F.O., Van Velthuizen, H.T., Chiozza, F., Franceschini, G., Henry, M., Muchoney, D., Tramberend, S., 2021. Global Agro-Ecological Zones v4 – Model Documentation. Food and Agriculture Organization of the United Nations, Rome.

Fu, Z., Zhang, K., Zhang, J., Cao, Q., Tian, Y., Zhu, Y., Cao, W., Liu, X., 2023. Optimizing nitrogen application and sowing date can improve environmental sustainability and economic benefit in wheat-rice rotation. Agric. Syst. https://doi.org/10.1016/j.agsy.2022.103536.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327 (5967), 812–818. https://doi.org/10.1126/science.1185383.

Greatrex, H., Hansen, J.W., Garvin, S., Diro, R., Blakeley, S., Le Guen, M., Rao, K.N., Osgood, D.E., 2015. Scaling up Index Insurance for Smallholder Farmers: Recent Evidence and Insights. CGIAR Research Program on Climate Change, Agriculture and Food Security Report No. 14. https://hdl.handle.net/10568/53101.

Guimarães, E.P., Stone, L.F., Confalonieri, R., 2018. Climate change impacts on rice production in Brazil: a review. Agric. Syst. 164, 148–159. https://doi.org/10.1016/j.agsy.2018.04.001.

Habib-Ur-Rahman, M., Ahmad, A., Raza, A., Hasnain, M., Alharby, H., Alzahrani, Y., Bamagoos, A., Hakeem, K., Ahmad, S., Nasim, W., Ali, S., Mansour, F., Sabagh, E., 2022. Impact of climate change on agricultural production; issues, challenges, and opportunities in Asia. Front. Plant Sci. 13. https://doi.org/10.3389/fpls.2022.925548.

Harvey, C.A., Saborio-Rodríguez, M., Martinez-Rodríguez, M.R., Viguera, B., Chain-Guadarrama, A., Vignola, R., Alpizar, F., 2018. Climate change impacts and adaptation among smallholder farmers in Central America. Agric. Food Secur. 7 (1), 57. https://doi.org/10.1186/s40066-018-0209-x.

Hertel, T.W., Burke, M.B., Lobell, D.B., 2010. The poverty implications of climate-induced crop yield changes by 2030. Glob. Environ. Change 20 (4), 577–585. https://doi.org/10.1016/j.gloenvcha.2010.07.001.

IPCC, 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Zhou, B. (Eds.), Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157896.

IPCC, 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Jagadish, S.V.K., Craufurd, P.Q., Wheeler, T.R., 2007. High temperature stress and spikelet fertility in rice (Oryza sativa L.). J. Exp. Bot. 58 (7), 1627–1635. https://doi.org/10.1093/jxb/erm003.

Jagadish, S.V.K., Murty, M.V.R., Quick, W.P., 2015. Rice responses to rising temperatures–challenges, perspectives and future directions. Plant Cell Environ. 38 (9), 1686–1698. https://doi.org/10.1111/pce.12430.

Johnson, J., Becker, M., Kaboré, J., Dossou-Yovo, E., Saito, K., 2024. Alternate wetting and drying: a water-saving technology for sustainable rice production in Burkina Faso? Nutrient Cycl. Agroecosyst. https://doi.org/10.1007/s10705-024-10360-x.

Khan, S., Anwar, S., Anwar, S., Ashraf, M., Khaliq, B., Sun, M., Hussain, S., Gao, Z., Noor, H., Alam, S., 2019. Mechanisms and adaptation strategies to improve heat tolerance in rice. A review. Plants 8. https://doi.org/10.3390/plants8110508.

Kimball, B.A., White, J.W., Ottman, M.J., Wall, G.W., Bernacchi, C.J., Morgan, J., Smith, D.P., 2015. Predicting canopy temperatures and infrared heater energy requirements for warming field plots. Agron. J. 107 (1), 129–141.

Knox, J., Hess, T., Daccache, A., Wheeler, T., 2012. Climate change impacts on crop productivity in Africa and South Asia. Environ. Res. Lett. 7 (3), 034032. https://doi.org/10.1088/1748-9326/7/3/034032.

Koide, J., Kawasaki, Y., Yonemura, S., Sakai, T., 2021a. Development of heat-tolerant rice varieties to address global warming. Plant Breed. 140 (4), 589–599. https://doi.org/10.1111/pbr.12921.

Koide, J., Yokoyama, S., Hirouchi, S., Hirose, C., Oka, N., Oda, M., Yanagihara, S., 2021b. Exploring climate-resilient and risk-efficient cropping strategies using a new pond irrigation system: an experimental study in northern Ghana. Agric. Syst. 191, 103149. https://doi.org/10.1016/j.agsy.2021.103149.

Landa, B.B., Navas-Cortés, J.A., Jiménez-Díaz, R.M., 2004. Integrated management of Fusarium wilt of chickpea with sowing date, host resistance, and biological control. Phytopathology 94, 946–960. https://doi.org/10.1094/PHYTO.2004.94.9.946.

Li, T., Angeles, O., Marcaida, M., Manalo, E., Manalili, M.P., Radanielson, A., Mohanty, S., 2020. From ORYZA2000 to ORYZA (v3): an improved simulation model for rice in drought and nitrogen-deficient environments. Agric. Syst. 178, 102727. https://doi.org/10.1016/j.agsy.2019.102727.

Lobell, D.B., Bonfils, C., 2008. The effect of irrigation on regional temperatures: a spatial and temporal analysis of trends in California, 1934–2002. J. Clim. 21 (10), 2063–2071.

Lobell, D.B., Field, C.B., 2007. Global scale climate-crop yield relationships and the impacts of recent warming. Environ. Res. Lett. 2 (1), 014002. https://doi.org/10.1088/1748-9326/2/1/014002.

McDonald, A.J., Keil, A., Jat, M.L., Sharma, P., Craufurd, P., 2022b. Trade-offs in rice-wheat system adaptation to climate change in the Indo-Gangetic plains. Agric. Syst. 201, 103463. https://doi.org/10.1016/j.agsy.2022.103463.

McDonald, A.J., Keil, A., Srivastava, A., Craufurd, P., Kishore, A., Kumar, V., Paudel, G., Singh, S., Singh, A.K., Sohane, R.K., Malik, R.K., 2022a. Time management governs climate resilience and productivity in the coupled rice–wheat cropping systems of eastern India. Nat. Food 3, 542–551. https://doi.org/10.1038/s43016-022-00549-0.
McGuire, S., Sperling, L., 2016. Seed systems smallholder farmers use. Food Secur. 8 (1), 179–195. https://doi.org/10.1007/s12571-015-0528-8.
Mishra, V., Ambika, A., Asoka, A., Aadhar, S., Buzan, J., Kumar, R., Huber, M., 2020. Moist heat stress extremes in India enhanced by irrigation. Nat. Geosci. 13, 722–728. https://doi.org/10.1038/s41561-020-00650-8.
Mottaleb, K.A., Mohanty, S., Nelson, A., 2016. Benefits of the development and dissemination of climate-smart rice: ex ante impact assessment of drought-tolerant rice in South Asia. Mitig. Adapt. Strategies Glob. Change 21 (6), 879–901. https://doi.org/10.1007/s11027-015-9637-7.
Mourtzinis, S., Specht, J.E., Conley, S.P., 2019. Defining optimal soybean sowing dates across the US. Sci. Rep. 9, 2800. https://doi.org/10.1038/s41598-019-38971-3.
Muthayya, S., Sugimoto, J.D., Montgomery, S., Maberly, G.F., 2014. An overview of global rice production, supply, trade, and consumption. Ann. N. Y. Acad. Sci. 1324, 7–14. https://doi.org/10.1111/nyas.12540.
Myers, S., Fanzo, J., Wiebe, K., Huybers, P., Smith, M., 2022. Current guidance underestimates risk of global environmental change to food security. BMJ 378.
Naidu, L.G.K., 2006. Manual, Soil-Site Suitability Criteria for Major Crops, vol.129. National Bureau of Soil Survey and Land Use Planning, ICAR, Nagpur.
Nkonya, E., Place, F., Kato, E., Mwanjololo, M., 2015. Economics of land degradation and improvement in Sub-Saharan Africa. In: Nkonya, E., Mirzabaev, A., von Braun, J. (Eds.), Economics of Land Degradation and Improvement – a Global Assessment for Sustainable Development. Springer, pp. 215–259. https://doi.org/10.1007/978-3-319-19168-3.
Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34 (2), 96–112. https://doi.org/10.1016/j.eja.2010.11.003.
Ojo, T., Ojo, T., Baiyegunhi, L., 2020. Determinants of credit constraints and its impact on the adoption of climate change adaptation strategies among rice farmers in South-West Nigeria. Journal of Economic Structures 9, 1–15. https://doi.org/10.1186/s40008-020-00204-6.
Ojo, T., Baiyegunhi, L., 2020. Impact of climate change adaptation strategies on rice productivity in South-west, Nigeria: an endogeneity corrected stochastic frontier model. The Science of the total environment 745, 141151. https://doi.org/10.1016/j.scitotenv.2020.141151.
Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Cassman, K.G., 2004. Rice yields decline with higher night temperature from global warming. Proc. Natl. Acad. Sci. 101 (27), 9971–9975. https://doi.org/10.1073/pnas.0403720101.
Pinto, R.S., Reynolds, M.P., 2015. Common genetic basis for canopy temperature depression under heat and drought stress associated with optimized root distribution in bread wheat. Theoretical and Applied Genetics 128 (4), 575–585.
Prasad, R., Shivay, Y., Kumar, D., 2017. Current status, challenges, and opportunities in rice production. In: Rice Production Worldwide. Springer, Cham, pp. 1–32. https://doi.org/10.1007/978-3-319-47516-5_1.
Pretty, J., Benton, T.G., Bharucha, Z.P., Dicks, L.V., Flora, C.B., Godfray, H.C.J., Wratten, S.D., 2018. Global assessment of agricultural system redesign for sustainable intensification. Nat. Sustain. 1 (8), 441–446. https://doi.org/10.2018/s41893-018-0114-0.
Pray, C., Nagarajan, L., Li, L., Huang, J., Hu, R., Selvaraj, K., Napasintuwong, O., Babu, R., 2011. Potential impact of biotechnology on adaption of agriculture to climate change: the case of drought tolerant rice breeding in Asia. Sustainability 3, 1723–1741. https://doi.org/10.3390/SU3101723.
Rahman, M., Sujan, M., Acharjee, D., Rasha, R., Rahman, M., 2022. Intensity of adoption and welfare impacts of drought-tolerant rice varieties cultivation in Bangladesh. Heliyon 8, e09490. https://doi.org/10.1016/j.heliyon.2022.e09490.
Rao, K.P.C., Ndegwa, W.G., Kizito, K., Oyoo, A., 2019. Climate information and early warning systems for agriculture in Sub-Saharan Africa. Clim. Dev. 11 (6), 496–507. https://doi.org/10.1080/17565529.2018.1476362.
Rezvi, H.U.A., Tahjib-Ul-Arif, M., Azim, M.A., Tumpa, T.A., Tipu, M.M.H., Najnine, F., Dawood, M.F.A., Skalicky, M., Brestič, M., 2023. Rice and Food Security: Climate Change Implications and the Future Prospects for Nutritional Security, vol. 12. Food and Energy Security, e430. https://doi.org/10.1002/fes3.430.
Rosegrant, M.W., Koo, J., Cenacchi, N., Ringler, C., Robertson, R., Fisher, M., Sabbagh, P., 2014. Food Security in a World of Natural Resource Scarcity: the Role of Agricultural Technologies. International Food Policy Research Institute. https://doi.org/10.2499/9780896298477.
Rowhani, P., Lobell, D.B., Linderman, M., Ramankutty, N., 2011. Climate variability and crop production in Tanzania. Agric. For. Meteorol. 151 (4), 449–460. https://doi.org/10.1016/j.agrformet.2010.12.002.
Rurinda, J., van Wijk, M.T., Mapfumo, P., Descheemaeker, K., Supit, I., Giller, K.E., 2015. Climate change and maize yield in southern Africa: what can farm management do? Glob. Change Biol. 21 (12), 4588–4601. https://doi.org/10.1111/gcb.13062.
Santiago-Arenas, R., Soe, H.N., Ullah, H., Agarwal, A., Datta, A., 2022. Optimum sowing date and nitrogen rate ensure sustainable production of wet direct-seeded rice under water-saving irrigation technique. J. Soil Sci. Plant Nutr. 22, 2805–2820. https://doi.org/10.1007/s42729-022-00847-3.
Saud, S., Wang, D., Fahad, S., Alharby, H.F., Bamagoos, A.A., Mjrashi, A., Alabdallah, N. M., AlZahrani, S.S., AbdElgawad, H., Adnan, M., 2022. Comprehensive impacts of climate change on rice production and adaptive strategies in China. Front. Microbiol. 13, 926567. https://doi.org/10.3389/fmicb.2022.926567.
Schimmelpfennig, D., 2016. Farm profits and adoption of precision agriculture. USDA Economic Research Service Economic Research. Report No. ERR-217.1-46. https://www.ers.usda.gov/publications/pub-details/?pubid=80325.
Seck, P.A., Diagne, A., Mohanty, S., Wopereis, M.C.S., 2012. Crops that feed the world 7: rice. Food Secur. 4, 7–24. https://doi.org/10.1007/s12571-012-0168-1.
Settle, W., Soumare, M., Sarr, M., Garba, M.H., Poisot, A.S., 2014. Reducing pesticide risks to farming communities: evidence from an agroecological intervention in Indonesia. Agric. Ecosyst. Environ. 183, 1–10. https://doi.org/10.1016/j.agee.2013.10.017.
Siebert, S., Ewert, F., 2014. Future crop production threatened by extreme heat. Environ. Res. Lett. 9 (4), 041001.
Siebert, S., Ewert, F., Rezaei, E.E., Kage, H., Graß, R., 2014. Impact of heat stress on crop yield—on the importance of considering canopy temperature. Environ. Res. Lett. 9 (4), 044012.
Silalertruksa, T., Gheewala, S.H., Mungkung, R., Nilsalab, P., Lecksiwilai, N., Sawaengsak, W., 2017. Implications of water use and water scarcity footprint for sustainable rice cultivation. Sustainability 9, 2283. https://doi.org/10.3390/su9122283.
Sys, C., Van Ranst, E., Debaveye, J., Beenaert, F., 1993. Land Evaluation Part III: Crop Requirements. General Administration for Development Cooperation, Brussels.
Tadesse, G., Zewdie, T., Shiferaw, B., 2019. Institutional and governance issues in irrigation management in Sub-Saharan Africa. Irrig. Drain. 68 (2), 202–212. https://doi.org/10.1002/ird.2298.
Tang, L., Wu, A., Li, S., Tuerdimaimaiti, M., Zhang, G., 2023. Impacts of climate change on rice grain: a literature review on what is happening, and how should we proceed? Foods 12, 536. https://doi.org/10.3390/foods12030536.
Tian, Z., Yin, Y., Li, B., Zhong, K., Liu, X., Jiang, D., Cao, W., Dai, T., 2024. Optimizing planting density and nitrogen application to mitigate yield loss and improve grain quality of late-sown wheat under rice-wheat rotation. J. Integr. Agric. https://doi.org/10.1016/j.jia.2024.01.032.
Turner, N.C., 2004. Agronomic options for improving rainfall-use efficiency of crops in dryland farming systems. J. Exp. Bot. 55, 2413–2425. https://doi.org/10.1093/jxb/erh154.
Turral, H., Burke, J., Faurès, J.M., 2011. Climate change, water and food security. FAO Water Reports 36. http://www.fao.org/3/i2096e/i2096e.pdf.
Urfels, A., Montes, C.B., Van Halsema, G., Struik, P., Krupnik, T., Mcdonald, A., 2022. Climate adaptive rice planting strategies diverge across environmental gradients in the Indo-Gangetic plains. Environ. Res. Lett. 17. https://doi.org/10.1088/1748-9326/aca5a2.
van Oort, P.A.J., Zwart, S.J., 2018. Impacts of climate change on rice production in Africa and causes of simulated yield changes. Glob. Change Biol. 24 (3), 1029–1045. https://doi.org/10.1111/gcb.13967.
Vollset, S.E., Goren, E., Yuan, C.W., Cao, J., Smith, A.E., Hsiao, T., Bisignano, C., Azhar, G.S., Castro, E., Chalek, J., Dolgert, A.J., 2020. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the global burden of disease study. Lancet 396 (10258), 1285–1306. https://doi.org/10.1016/S0140-6736(20)30677-2.
Waha, K., Müller, C., Bondeau, A., Dietrich, J.P., Kurukulasuriya, P., Heinke, J., Lotze-Campen, H., 2013. Adaptation to climate change through the choice of cropping system and sowing date in Sub-Saharan Africa. Glob. Environ. Change 23, 130–143. https://doi.org/10.1016/j.gloenvcha.2012.11.001.
Wassmann, R., Jagadish, S.V.K., Heuer, S., Ismail, A., Redona, E., Serraj, R., Bouman, B., 2009. Climate change affecting rice production: the physiological and agronomic basis for possible adaptation strategies. Adv. Agron. 101, 59–122. https://doi.org/10.1016/S0065-2113(08)00802-X.
Wassmann, R., Jagadish, S.V.K., Sumfleth, K., Pathak, H., Howell, G., Ismail, A., Serraj, R., Redoña, E., Singh, R.K., Heuer, S., 2019. Regional vulnerability of rice production in Asia to climate change impacts and adaptation options. Adv. Agron. 102, 91–133. https://doi.org/10.1016/S0065-2113(09)01003-7.
World Bank, 2020. Transforming Agriculture for Climate Resilience: a Framework for Systemic Change. World Bank. https://openknowledge.worldbank.org/handle/10986/34729.
Wu, F., Wang, Y., Liu, Y., Liu, Y., Zhang, Y., 2020. Simulated responses of global rice trade to variations in yield under climate change: evidence from main rice-producing countries. J. Clean. Prod., 124690 https://doi.org/10.1016/j.jclepro.2020.124690.
Zaveri, E., Lobell, D.B., 2019. The role of irrigation in changing wheat yields and heat sensitivity in India. Nat. Commun. 10, 4144. https://doi.org/10.1038/s41467-019-12183-9.