

EFFECTS OF PROJECTED CLIMATE CHANGE ON SPRING MAIZE IN RAIN-FED AGRICULTURE SYSTEM OF THE LOESS PLATEAU

CHENGUANG MA^{1,2,3,4}, LONGFEI XIA^{1,2,3,4}, YANG WEI^{1,2,3,4}, JIAN LI^{1,2,3,4},
ZHEZHE MU^{1,2,3,4}, ZHAORONG ZHANG^{1,2,3,4}, HAILAN SHI^{1,2,3,4} AND YAN XU^{1,2,3,4*}

Shaanxi Provincial Land Engineering Construction Group Co. Ltd., Xi'an Shaanxi, China 710075

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Abstract

To bolster food security in the Loess Plateau, the Chinese government initiated a land expansion program (2013-2017) targeting a 337.80 km² increase in cultivated area through integrated ditch management and reclamation. Given the region's reliance on rain-fed agriculture, optimizing production under climate change is critical for evidence-based policymaking. This study evaluates climate and fertilization impacts on spring maize yields using the APSIM model under two Shared Socioeconomic Pathways SSP1-2.6 (sustainable low-emission development) and SSP5-8.5 (fossil-fueled high-emission development). Baseline simulations (1980-2014) revealed substantial yield gains with elevated nitrogen application: compared to the 90 kg N/ha control, treatments of 150 kg N/ha and 200 kg N/ha increased yields by 1,263 kg/ha and 1,326 kg/ha, respectively, during the 2030-2100 projection period. Climate-driven yield variability exhibited marked spatiotemporal heterogeneity, with annual mean increases under 90 kg N/ha fertilization reaching 1,111 kg/ha (SSP1-2.6) and 1,018 kg/ha (SSP5-8.5) relative to baseline conditions. These findings highlight the dual role of adaptive nitrogen management and climate-resilient land-use planning, providing actionable insights to maximize the ecological and agricultural returns of soil-water conservation initiatives while safeguarding long-term food security in this vulnerable agroecosystem.

Introduction

Spanning approximately 640,000 km², China's Loess Plateau hosts the world's largest loess deposits (Li *et al.* 2019) and remains one of Earth's most erosion-prone regions, with gully systems occupying nearly 50% of its terrain (Wen *et al.* 2020, Guo *et al.* 2024). To combat ecological degradation, the Chinese government implemented the Grain for Green Program (1999-2013) (Bai *et al.* 2019, Deng *et al.* 2020), restoring 17.92 km² of vegetation through farmland-to-forest (4.83 km²) and pasture-to-grassland conversions, significantly enhancing regional ecosystem services (Jin 2014). However, these conservation efforts exacerbated tensions between agricultural productivity and environmental protection due to reduced cropland availability. In response, a dual-strategy initiative was launched: (i) a 51.72-billion-yuan (≈7.72-billion-USD) gully rehabilitation and land reclamation program targeting the plateau's central erosion corridors, and (ii) planned creation of 337.8 km² of machine-arable cropland (2013-2017) via engineered terracing. This innovative approach involves backfilling gullies with stabilized slope soils, followed by mechanical compaction to form productive terraces—a method proven to convert degraded landscapes into high-fertility farmland (Kang *et al.* 2021). By synergistically

*Author for correspondence: <1213349323@qq.com>. ¹Shaanxi Provincial Land Engineering Construction Group Co. Ltd., Xi'an Shaanxi, China 710075. ²Land Engineering Technology Transformation Center, Shaanxi Provincial Land Engineering Construction Group Co. Ltd. Xianyang, Shaanxi, China 712000. ³Institute of Land Engineering and Technology, Shaanxi Provincial Land Engineering Construction Group Co. Ltd. Xi'an Shaanxi, China 710021. ⁴Shaanxi Engineering Research Center of Land Consolidation, Xi'an Shaanxi, China 710075.

addressing ecological restoration and agricultural expansion, these measures aim to reconcile socioeconomic development with sustainable land management across this fragile yet vital region. The Loess Plateau serves as northern China's primary grain-producing region, where over 60% of croplands rely on rain-fed agriculture (Wang *et al.* 2015). Spring maize, the dominant crop, occupies more than 27% of the cultivated area (Jiquan *et al.* 2008), with its productivity constrained by two critical variables: precipitation and nitrogen availability (Li *et al.* 2009, Liu *et al.* 2010a). Notably, nitrogen application rates in some localities exceed 330 kg/ha far surpassing agronomic requirements for maize (Liu *et al.* 2015). Such overapplication under soil moisture-limited conditions reduces nitrogen use efficiency and intensifies crop water stress (Zhang *et al.* 2021), ultimately suppressing growth (Liu *et al.* 2010b). Conversely, synergistic optimization of soil moisture and nitrogen enhances productivity (Wang *et al.* 2019): balanced nitrogen supplementation strengthens root development and vigor (Jia *et al.* 2018), elevates crop water use efficiency, and mitigates drought impacts. These findings underscore that calibrated management of water and nitrogen regimes can simultaneously improve resource-use efficiency and sustain rain-fed spring maize production across the Loess Plateau's fragile agroecosystems.

Water availability, solar radiation, and thermal conditions form the foundational triad governing crop growth, with global climate change altering these variables and posing significant risks to agricultural systems-particularly in ecologically vulnerable regions like China's Loess Plateau, where balancing food security and environmental preservation remains a critical challenge (Piao *et al.* 2010, Lobell *et al.* 2012). While the global scientific community has extensively examined climate change impacts on crop yields (Liu *et al.* 2010b, Tao *et al.* 2016, Zhai *et al.* 2017), findings remain contentious: some models project yield declines (Zhao *et al.* 2017), whereas others utilizing tools like the Agricultural Production System Simulator (APSIM) suggest adaptive opportunities, such as northward shifts in China's maize cultivation boundaries and extended growing seasons that may enhance productivity (Liu *et al.* 2013, Tao *et al.* 2014). However, these spatially and temporally heterogeneous impacts (Wang *et al.* 2020) have been predominantly studied in China's agriculturally stable regions-including the Guanzhong Plain (Xu *et al.* 2020, Zhang *et al.* 2024) and North China Plain (Li *et al.* 2021, Wang *et al.* 2023) with limited quantitative assessments addressing the unique interplay of climate variability, farming practices, and ecological fragility characteristic of the Loess Plateau's rain-fed agroecosystems.

This study employs region-specific agronomic and climatic data from the Loess Plateau to rigorously calibrate and validate the APSIM-Maize model, ensuring its applicability to local edaphic and climatic conditions. Following robust model verification, we implemented scenario-based simulations to quantify spring maize yield responses under contrasting climate futures: the sustainable development pathway (SSP1-2.6, representing low radiative forcing of 2.6 W/m² by 2100) and fossil-fueled development pathway (SSP5-8.5, 8.5 W/m² radiative forcing). Historical climate data (1980-2014) served as the baseline for comparative analysis of nitrogen management regimes. The dual objectives of this investigation are to (i) characterize spatiotemporal patterns of agroclimatic variability across the Loess Plateau under divergent emission trajectories, and (ii) identify nitrogen optimization thresholds that balance yield maximization with environmental sustainability in reclaimed gully systems. By integrating climate projection ensembles with process-based crop modeling, this work establishes a decision-support framework for adaptive land management, directly informing strategies to enhance the ecological resilience and agricultural productivity of large-scale soil-water conservation initiatives.

Materials and Methods

The Loess Plateau (33°~41°N, 100°~114°E), spanning 45 municipal jurisdictions across seven provinces and autonomous regions in northern China, encompasses approximately 640,000

km² of topographically complex terrain characterized by northwest-to-southeast elevational gradients (Fig. 1). This ecotone straddles China's semi-humid and semi-arid climatic zones, featuring a temperate continental monsoon regime with pronounced seasonality: summer months experience concentrated convective precipitation (> 60% of annual rainfall), while winters are marked by cold, arid conditions with frequent aeolian dust events. Agroclimatic analysis of the 1961-2015 period reveals a mean annual temperature range of 3.7-14.3°C, cumulative $\geq 10^{\circ}\text{C}$ growing degree days of 2,300-3,200°C·d, and photothermal resources comprising 1,900-3,200 annual sunshine hours. Regional precipitation averages 447 mm yr⁻¹, exhibiting strong interannual variability ($\pm 19\%$ CV) and spatial heterogeneity driven by orographic effects (Wang *et al.* 2022). These biophysical parameters define a marginal cropping environment where water availability—rather than thermal or radiative constraints—predominantly limits agricultural productivity.

Future climate projections were derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6) ensemble within the World Climate Research Programme's (WCRP) Global Climate Models (GCMs), accessible via the Earth System Grid Federation portal (<https://esgf-node.llnl.gov/search/cmip6>). Two representative Shared Socioeconomic Pathways (SSPs) were selected: SSP1-2.6, representing a sustainable development trajectory with radiative forcing stabilization at 2.6 W/m² by 2100, and SSP5-8.5, reflecting fossil fuel-intensive development culminating in 8.5 W/m² radiative forcing. These scenarios were chosen to bracket the spectrum of plausible climate futures for assessing spring maize yield responses in the Loess Plateau. Meteorological inputs for model calibration and validation were obtained from a high-resolution gridded dataset (1980-2014) curated by the National Tibetan Plateau Data Center, which synthesizes multi-source observational records through a hybrid assimilation approach. This dataset integrates conventional ground station measurements from the China Meteorological Administration with globally validated reanalysis products, including Princeton atmospheric forcing, GLDAS land surface data, GEWEX-SRB radiative fluxes, and TRMM satellite precipitation retrievals, employing Bayesian reconciliation to minimize spatial biases (Yang *et al.* 2010, He *et al.* 2020). The rigorous quality control and multi-scale fusion techniques applied ensure robust representation of the region's hydroclimatic variability, providing a critical foundation for process-based crop modeling under climate uncertainty.

The Agricultural Production Systems sIMulator (APSIM), developed by the Australian Agricultural Systems Research Institute (Holzworth *et al.* 2014), represents a robust crop growth simulation framework with demonstrated efficacy in modeling critical agricultural parameters. Peer-reviewed studies, including those by Dixit *et al.* (2018), have validated its simulation accuracy for crop yield projections, biomass accumulation dynamics, and the complex interactions within soil water-nitrogen cycles. This process-based model has emerged as a valuable tool for assessing climate change impacts (Chisanga *et al.* 2020) and evaluating agricultural management strategies through empirical validation. Notably, its application has been extensively documented across the Loess Plateau region, with Yang *et al.* (2020, 2023) demonstrating its adaptability to local pedoclimatic conditions through multiple longitudinal studies examining crop-environment interactions under varying management scenarios.

This investigation employed the APSIM-Maize model (version 7.10) to systematically quantify the combined effects of climate variability and nitrogen fertilization regimes on spring maize (*Zea mays* L.) productivity within the Loess Plateau agroecosystem. The simulation framework utilized high-resolution daily meteorological inputs encompassing maximum/minimum temperatures, precipitation patterns, solar radiation flux, and atmospheric parameters to drive process-based representations of crop phenological development, biomass accumulation, and yield formation mechanisms. Through this computational approach, the study mechanistically evaluated spring maize responses to divergent climatic projections and agronomic management strategies,

establishing quantitative relationships between environmental drivers, nutrient application levels, and final grain yield outcomes under scenario-based analyses.

This study implemented a multi-stage validation protocol for the APSIM-Maize model using observational datasets derived from peer-reviewed literature. Given the geographical heterogeneity of the Loess Plateau and spatial variability in spring maize (*Z. mays*) cultivars, three widely cultivated genotypes demonstrating broad agroecological adaptability were selected as representative cultivars through systematic screening. Model performance was systematically evaluated using a triad of statistical metrics: the coefficient of determination (R^2) to quantify variance explanation capacity, root mean square error (RMSE) to measure prediction accuracy, and Willmott's agreement index (d) to assess model-prediction concordance. This multidimensional validation framework simultaneously addressed climate data reliability and model simulation fidelity, ensuring robust evaluation of both input datasets and biophysical process representations within the APSIM architecture.

$$R^2 = \left(\frac{\sum_{i=1}^n (o_i - \bar{o})(s_i - \bar{s})}{\sqrt{\sum_{i=1}^n (o_i - \bar{o})^2 \sum_{i=1}^n (s_i - \bar{s})^2}} \right)^2$$

Where, o_i is the observed value, s_i is the simulated value, $\bar{o}$ is the mean value of observations, $\bar{s}$ is the mean value of simulations, and n is the number of observations.

$$d = 1 - \frac{\sum_{i=1}^n (s_i - o_i)^2}{\sum_{i=1}^n (|s_i - \bar{o}| + |o_i - \bar{o}|)^2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (o_i - s_i)^2}{n}}$$

Lower RMSE and higher R^2 and d indicate good agreement between simulated and observed values.

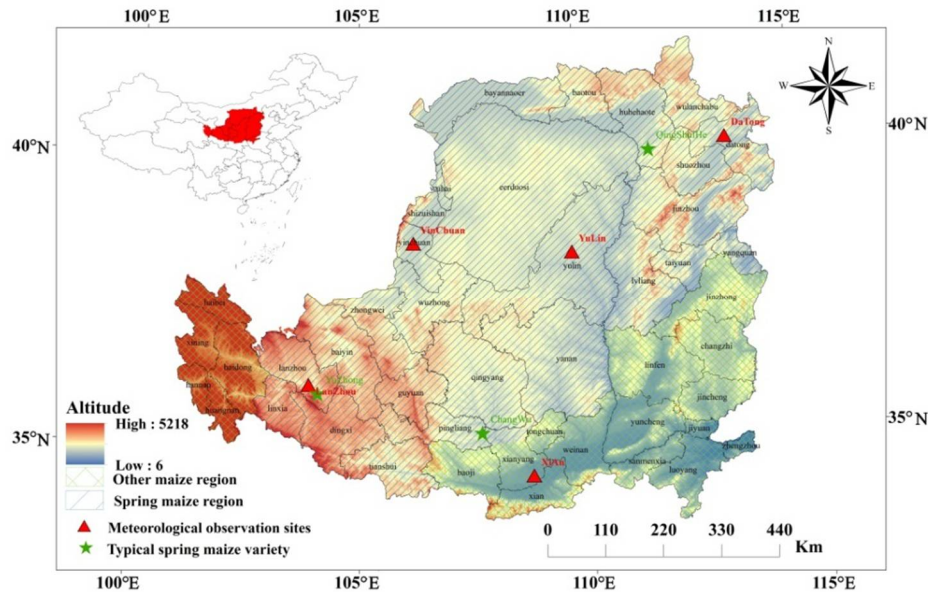


Fig. 1. Altitude, maize growing areas, typical maize variety growth observation points and meteorological observatories on the Loess Plateau.

This study employed spatially aggregated CMIP6 climate datasets at municipal grid resolution, with historical climate averages (1980-2014) serving as the climatic baseline for detecting future anomalies. The dataset's fidelity was verified through comparative analysis with observed meteorological records from five representative stations (Fig. 1) spanning the baseline period. The research domain encompasses the entire Loess Plateau, justified by the region's predominant spring maize cultivation pattern and the existence of intercropped spring maize in adjacent summer maize zones as illustrated in Fig. 1. Under controlled experimental assumptions maintaining static soil parameters and agronomic practices, the investigation isolated climate-nutrient interactions by implementing a multi-factorial simulation framework. The calibrated APSIM-Maize model executed scenario analyses across three nitrogen application gradients (90, 150, and 200 kg/ha) under contrasting climate pathways (SSP126 and SSP585), projecting spring maize yield responses through 21st-century climate projections (2030-2100). This experimental design enables quantitative disaggregation of climate change impacts from nitrogen management effects on crop productivity in semi-arid cropping systems.

Results and Discussion

The calibration outcomes presented in Table 1 and Fig. 2 demonstrate robust agreement between modeled and observed parameters across five representative climate stations and three dominant spring maize cultivars in the Loess Plateau. For meteorological variables, the model

Table 1. Comparison of CMIP6 historical climate data and actual observation data from 5 meteorological observation stations and comparison of APSIM-maize yield simulation values and measured yield values of 3 typical maize variety growth observation points.

Parameters	$T_{\max}$ (°C)	$T_{\min}$ (°C)	Pre (mm)	Rec (MJ/m ²)	Yield (Kg/ha)
RMSE	4.58	3.81	80	2.68	900
R ²	0.92	0.93	0.82	0.87	0.85
d	0.96	0.97	0.95	0.94	0.94

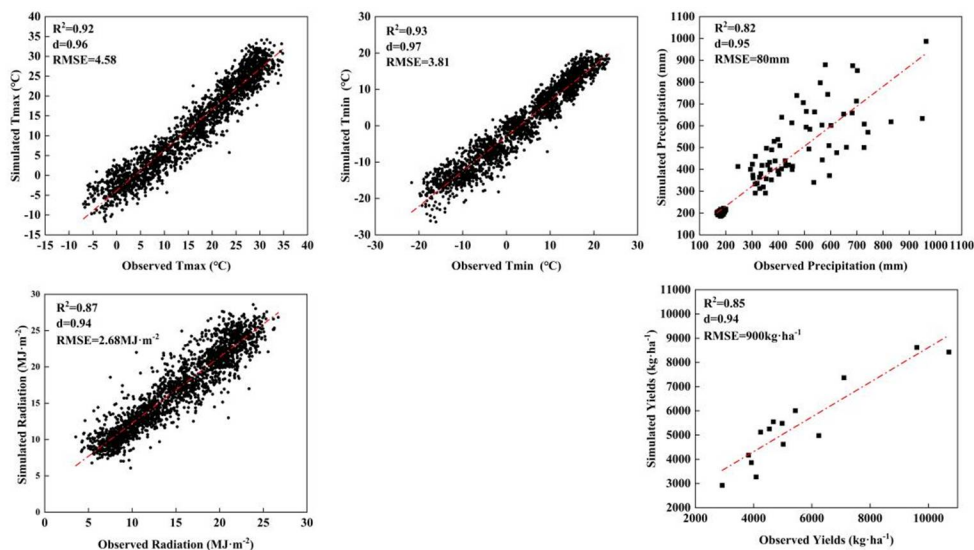


Fig. 2. Comparison of CMIP6 historical climate data and actual observation data from 5 meteorological observation stations and comparison of APSIM-maize yield simulation values and measured yield values of 3 typical maize variety growth observation points. (The dashed red line is the linear regression line).

exhibited root mean square errors (RMSE) of 4.58°C (maximum temperature), 3.81°C (minimum temperature), 80.22 mm (precipitation), and 2.68 MJ m⁻² (solar radiation), with corresponding coefficients of determination (R²) of 0.92, 0.93, 0.82, and 0.87, alongside Willmott agreement indices (d) of 0.96, 0.97, 0.95, and 0.94. Crop yield simulations achieved an RMSE of 900 kg/ha, R² of 0.85, and d-index of 0.94, confirming strong predictive capacity for agroclimatic interactions. These validation metrics collectively demonstrate the CMIP6 dataset's fidelity in replicating historical climate patterns and the APSIM-Maize model's competence in simulating yield responses under baseline conditions, thereby justifying their combined application for projecting climate change impacts. The statistical coherence across both climatic and agronomic variables supports the reliability of employing CMIP6 future climate projections (SSP126, SSP585) with the calibrated model to assess long-term yield dynamics under varying nitrogen regimes. Critical cultivar-specific parameters governing phenological development and resource use efficiency are detailed in Table 2, providing full transparency for model reproducibility.

Table 2. APSIM model parameter.

Position	Parameter	Value
QingShuiHe	tt_emerg_to_endjuv/(°C·d)	210
	photoperiod_crit/h	12
	photoperiod_slope/(°C·d)	22
	tt flower to _maturity/(°C·d)	650
	Head_grain_no_max	620
	Grain_gth_rate/ (mg· kernel ⁻¹)	12
ChangWu	tt_emerg_to_endjuv/(°C·d)	240
	photoperiod_crit/h	12
	photoperiod_slope/(°C·d)	22
	tt flower to _maturity/(°C·d)	700
	Head_grain_no_max	620
	Grain_gth_rate/(mg· kernel ⁻¹)	12
YuZhong	tt_emerg_to_endjuv/(°C·d)	240
	photoperiod_crit/h	12
	photoperiod_slope/(°C·d)	22
	tt flower to _maturity/(°C·d)	650
	Head_grain_no_max	620
	Grain_gth_rate/ (mg· kernel ⁻¹)	12

Fig. 3 illustrates projected climate anomalies relative to the 1980-2014 baseline for key meteorological drivers (maximum temperature, minimum temperature, precipitation, and solar radiation) under SSP126 and SSP585 scenarios, as implemented in the APSIM-Maize simulations. Both scenarios exhibit multi-decadal warming trends, with SSP126 showing moderate increases compared to its high-emissions counterpart. Under SSP126, mean maximum temperatures rise by 2.89°C (2030s) and 2.99°C (2080s), while minimum temperatures increase by 3.54°C (2030s) and 3.45°C (2080s), indicating stable nocturnal warming patterns. Precipitation demonstrates temporal divergence, increasing by 88.75 mm (2030s) and 59.19 mm (2080s), with the latter period showing reduced hydrological intensification. Radiation intensity rises incrementally by 0.3 MJ m⁻² (2030s) and 0.6 MJ m⁻² (2080s).

The SSP585 pathway reveals accelerated thermal accumulation, with maximum temperature increases of 3.62°C (2030s) and 6.17°C (2080s), and minimum temperature elevations of 3.80°C (2030s) and 6.82°C (2080s), reflecting enhanced diurnal warming later in the century.

Precipitation exhibits non-linear intensification, rising by 66.83 mm (2030s) and 176.21 mm (2080s), while radiation remains statistically comparable to baseline levels ($\Delta \leq 0.1 \text{ MJ m}^{-2}$). Temporal analysis highlights greater magnitude shifts in the 2080s across both scenarios, particularly under SSP585 where late-century maximum temperature, minimum temperature, and precipitation anomalies exceed SSP126 projections by 3.18°C, 3.37°C, and 117.02 mm, respectively. These differential trajectories underscore scenario-dependent climate forcings, with SSP585 manifesting pronounced thermal and hydrological extremes by century's end, critical for evaluating crop response thresholds in semi-arid agroecosystems.

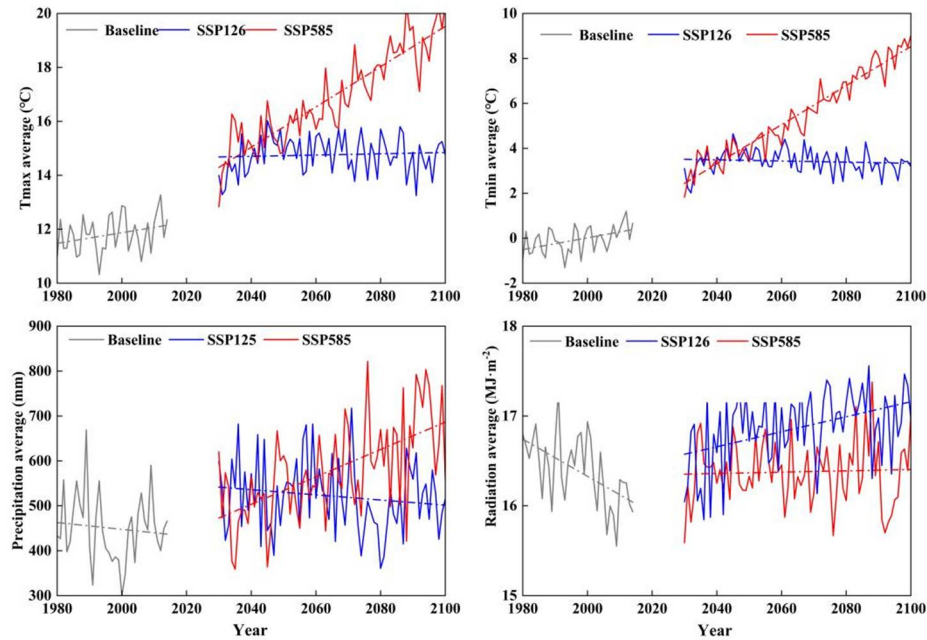


Fig. 3. Anomalies in annual maximum temperature, minimum temperature, precipitation, and radiation under SSP126 and SSP585 scenarios in Loess Plateau relative to the baseline.

At the city level, the maximum temperature showed an increasing trend under both the SSP126 and SSP585 scenario models (Fig. 4b~e). There is little difference in the warming trends among regions under the SSP126 scenario, and the warming range is between 2.27°C~3.00°C (2030S), 2.45°C~2.91°C (2080S); under the SSP585 scenario, the maximum temperature increasing trend in the 2080s is particularly obvious, with the temperature increase ranging is between 2.91°C~6.38°C. The minimum temperature increase trend in the north is more obvious under the SSP126 and SSP585 scenarios (Fig. 4g~j). Under the SSP126 and SSP585 scenarios, precipitation in various regions shows an increasing trend (Fig. 4l~o). which is particularly pronounced at 2080S for SSP585, where regional precipitation can increase by up to 343 mm (Fig. 4o). However, under the SSP585 scenario, precipitation in parts of the northeast and southwest will show a downward trend in 2030S, with the maximum regional decrease reaching 137 mm (Fig. 4n). The radiation changes trends under the SSP126 and SSP585 scenarios are quite different in space and time. Under the SSP126 scenario, the radiation in the northwest region shows a downward trend, with a change range of $-0.17 \text{ MJ} \cdot \text{m}^{-2} \sim 0.00 \text{ MJ} \cdot \text{m}^{-2}$ (2030S), and the southeast region shows an upward trend, with a change range of $0.00 \text{ MJ} \cdot \text{m}^{-2} \sim 0.49 \text{ MJ} \cdot \text{m}^{-2}$

(2030S), the rising range of radiation in 2080S is $0.04 \text{ MJ}\cdot\text{m}^{-2}\sim 0.091 \text{ MJ}\cdot\text{m}^{-2}$; under the SSP585 scenario, the radiation in 2030S and 2080S basically shows a downward trend, but the maximum decrease does not exceed $1 \text{ MJ}\cdot\text{m}^{-2}$.

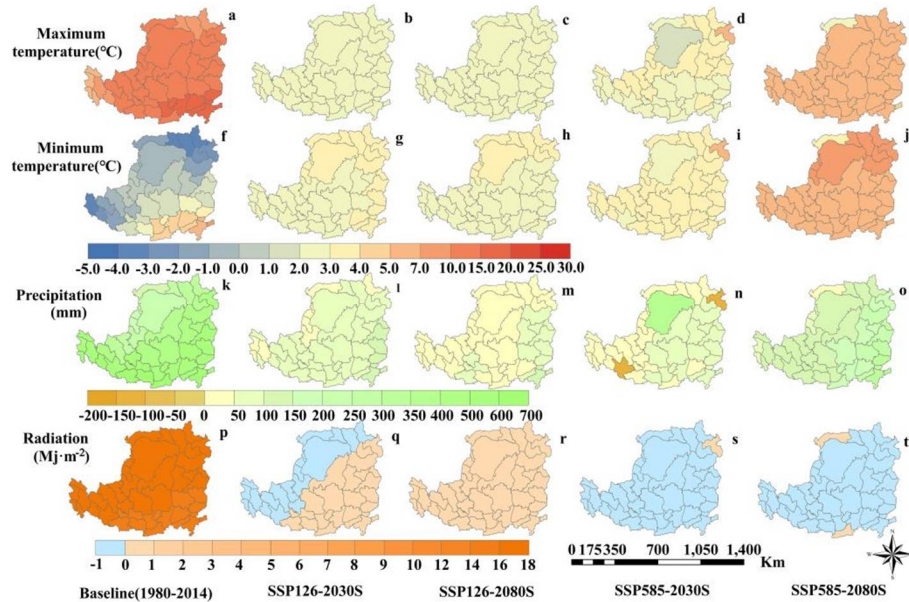


Fig. 4. The baseline is the historical simulation value from 1980 to 2014, SSP126-2030S, SSP126-2080S, SSP585-2030S and SSP585-2080S is the difference between each indicator and the baseline under the future climate scenario.

Fig. 5. shows that when the nitrogen application rate is $90 \text{ kg}\cdot\text{ha}^{-1}$, the spring maize yield under the SSP126 and SSP585 scenarios increased slightly compared with the baseline (Fig. 5a). There is no major difference in yield under the two future climate scenarios. When the nitrogen application rate is $150 \text{ kg}/\text{ha}$ and $200 \text{ kg}/\text{ha}$, the yield of the baseline and two future climate scenarios increased compared with that of $90 \text{ kg}/\text{ha}$. The yield of spring maize under the two future climate changes increased slightly compared with the baseline, but the difference is small; There are also no significant difference in spring maize yield between the two nitrogen application levels of $150 \text{ kg}/\text{ha}$ and $200 \text{ kg}/\text{ha}$ (Fig. 5b,c).

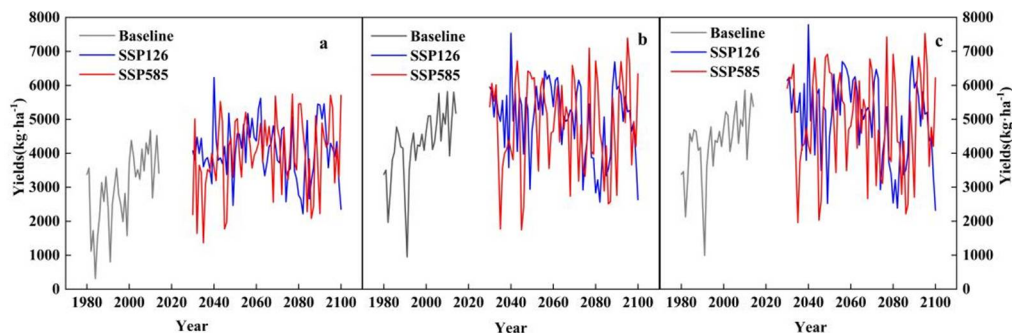


Fig. 5. Average APSIM-maize simulated yield under historical climate, SSP126 and SSP585 climate data of the Loess Plateau.

Fig. 6. shows that at the city level, the spring maize yield in the southeastern part of the Loess Plateau was higher than when nitrogen application rate is 150 kg/ha and 200 kg/ha than when the nitrogen application rate was 90 kg/ha (Fig. 6a, f, k). There is no significant difference in yield between 150 kg/ha and 200 kg/ha (Fig. 6f, k). Fig. 6a~o show that under the same nitrogen application level, the spring maize yield change trends in the Loess Plateau under the SSP126 and SSP585 scenarios are basically the same. The yield in the northeast and southwest regions shows an upward trend, while the yield in the central and southeast regions shows a downward trend. Under SSP585 scenario, the effects of increasing production in the southwest region and decreasing production in the southeastern region in 2080S are more obvious (Fig. 6o).

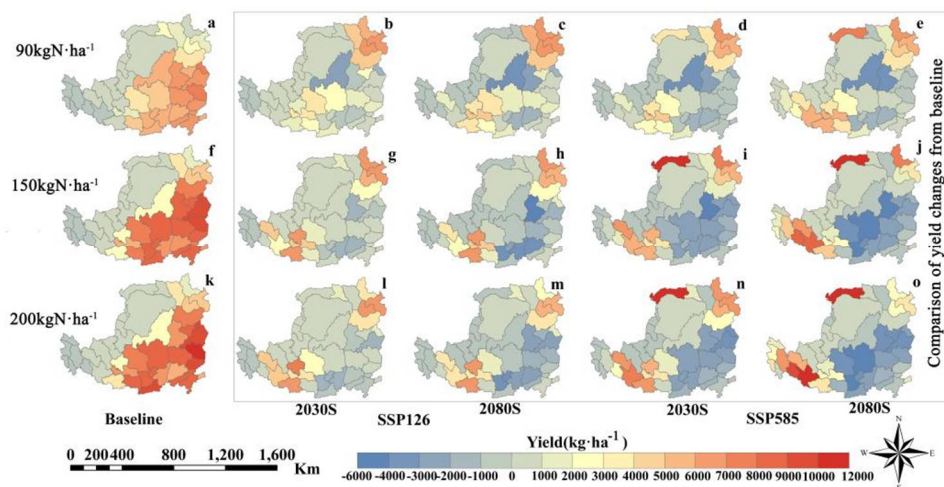


Fig. 6. The baseline is the simulated production value from 1980 to 2014, SSP126-2030S, SSP126-2080S, SSP585-2030S and SSP585-2080S is the difference between production and baseline under future climate scenario.

The accelerating process of global industrialization has profoundly transformed land use patterns while exacerbating climate change (Abubakari *et al.* 2016), necessitating rigorous assessment of climate change impacts on agricultural systems. This study addresses this imperative through a dual methodological approach: First, meteorological station observations were systematically validated against daily climate projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) Scenario Model Intercomparison Program (ScenarioMIP), demonstrating strong agreement through statistical metrics ($R^2 = 0.82-0.93$; Willmott's index $d = 0.94-0.97$). This robust validation establishes the CMIP6 projections as reliable predictors for climate pattern evolution in the Loess Plateau region. Building upon this climatic foundation, the research subsequently employs the APSIM-Maize model - a recognized analytical tool for climate-agriculture interactions (Jiang *et al.* 2023) - to quantify nitrogen management impacts on spring maize productivity under future climate scenarios. Following comprehensive calibration, the model exhibited enhanced predictive capability, achieving a root mean square error (RMSE) of 900 kg ha^{-1} alongside strong correlation metrics ($R^2=0.85$; $d=0.94$), thereby providing a validated framework for assessing sustainable intensification strategies in this critical agro-ecological zone.

The CMIP6 daily climate projections reveal distinct regional climate trajectories across the Loess Plateau under contrasting emission scenarios. Comparative analysis with baseline conditions (1980-2014) demonstrates projected increases in maximum temperature, minimum

temperature, and precipitation for most regions under both SSP126 and SSP585 scenarios, with radiation exhibiting downward trends except in northwestern sectors during the 2030s and 2080s under SSP126 (Fig. 4e, j, t). Notably, the historically productive southeastern Loess Plateau (Fig. 6a, f, k), characterized by baseline climate optimality for crop cultivation, shows progressive yield reductions under future scenarios-particularly pronounced under SSP585-2080s (Fig. 6o). This decline correlates strongly with the emerging thermal-radiation imbalance, where temperature elevation (1°C increase corresponding to 150 kg/ha yield reduction) coupled with radiation diminution creates suboptimal phenological conditions, consistent with documented maize vegetative phase shortening under thermal stress (Chen *et al.* 2017a, b). Conversely, yield enhancement emerges in two distinct ecotopes: the high-latitude northeastern plateau and the high-altitude southwestern zone (Fig. 6), where synergistic temperature-precipitation increases appear to mitigate climate constraints. Significantly, spatial analysis identifies the northeastern high-latitude region as a future maize production hotspot under evolving climate regimes (Wang *et al.* 2023), suggesting strategic agricultural adaptation potential through regional cultivation redistribution. These differential responses underscore the necessity for spatially explicit climate-resilient farming strategies across the plateau's heterogeneous agroecological zones.

Comparative analysis of nitrogen application strategies reveals distinct optimization thresholds across the Loess Plateau's agroecological zones. While both 150 and 200 kg/ha nitrogen inputs demonstrate significantly greater yield enhancement than the 90 kg/ha baseline (Fig. 6a, f, k), these two higher application levels exhibit marginal differentiation in productivity outcomes (Fig. 6f, k), aligning with established optimal nitrogen thresholds (150-200 kg/ha) for this region (Zhang *et al.* 2022). However, spatial heterogeneity emerges in the high-latitude northeastern plateau, where the 200 kg/ha application level demonstrates diminishing returns compared to 150 kg/ha under equivalent climate scenarios (Fig. 6j, o). This counterintuitive response likely stems from two interacting mechanisms: (i) transient dry matter accumulation from nitrogen enrichment initially boosts growth, and (ii) subsequent exacerbation of soil moisture depletion in this rainfed agricultural system induces cumulative drought stress during critical reproductive phases. The resulting yield depression under elevated nitrogen inputs reflects a classic trade-off between nutrient-driven productivity and water balance sustainability, consistent with documented moisture-nitrogen interactions in semi-arid cropping systems (Zhang *et al.* 2021). These findings underscore the necessity for spatially differentiated nitrogen management strategies that account for both immediate agronomic responses and long-term hydrological consequences across the plateau's diverse microclimates.

This study employed the APSIM-Maize model to systematically evaluate the spatiotemporal impacts of climate change and nitrogen management on spring maize (*Z. mays*) productivity across the Loess Plateau, integrating historical climate data (baseline period: 2000~2014) with two CMIP6 future climate scenarios (SSP126 and SSP585, 2030~2100). Climate projections revealed statistically significant increases ($p < 0.05$) in daily maximum temperature, minimum temperature, and precipitation under both scenarios compared to baseline, while solar radiation exhibited a marginal decline. Model simulations demonstrated distinct spatiotemporal heterogeneity in yield responses, with city-level analysis showing annual yield increments ranging from 754 to 1111 kg/ha under SSP126 and 628 to 1018 kg/ha under SSP585 across nitrogen application regimes. Notably, geospatial differentiation analysis identified the northeastern and southwestern subregions as priority zones for gully stabilization and land reclamation project. These findings offer empirical evidence for optimizing coupled agroecological management strategies, emphasizing the critical role of spatially explicit nitrogen use efficiency optimization in climate-resilient intensification within this ecologically fragile region.

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