Multi-Model Ensemble Simulation of Climate Change Impacts on Maize Yield (Postprint)

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Abstract

Climate model-driven crop modeling constitutes the primary approach for climate change impact assessment. However, uncertainties in research findings arise from structural disparities between single climate model outputs and crop models. Multi-model ensemble probabilistic projections can effectively mitigate such uncertainties. Accordingly, this study utilized historical meteorological data and maize crop data from agrometeorological stations in three regions of Northeast China—Hailun, Changling, and Benxi—covering 1981-2009 to establish crop statistical models and validate the applicability of the APSIM mechanistic model within the study region. Building upon this foundation, in conjunction with eight global models from CMIP5 under the RCP4.5 scenario, we attempted to evaluate the potential impacts of climate change on maize yields for the future periods 2010-2039 and 2040-2069 (relative to the 1976-2005 baseline period) through multi-model ensemble assessment. The results demonstrate that the APSIM model exhibits robust simulation capability for maize growth, development, and yield formation. The simulation error (RMSE) for maize growth period ranges from 3 to 4 days, while yield RMSE ranges from 0.6 to 0.8 t • hm ^{2}. The established yield statistical model indicates that temperature increases during the maize emergence stage (mid-May) positively influence yield, whereas increased temperature and precipitation coupled with insufficient solar radiation during the flowering to maturity stage (mid-July to early September) adversely affect yield. Compared with the 1976-2005 baseline period, climate-driven yield reductions are projected at 3.8% (Hailun) to 7.4% (Benxi) for 2010-2039, with probabilities of yield reduction ranging from 64% (Changling) to 73% (Benxi); for 2040-2069, yield reductions of 6.4% (Hailun) to 10.5% (Benxi) are anticipated, with probabilities from 74% (Hailun) to 83% (Benxi). For the future periods 2010-2039 and 2040-2069, mechanistic model-simulated yield reductions are 6.6% (Hailun) to 8.9% (Benxi) and 9.7% (Hailun) to 13.7% (Benxi), respectively, both exceeding the corresponding yield reduction results derived from the statistical model: 0.9% (Hailun) to 6.0% (Benxi) and 2.0% (Changling) to 7.3% (Benxi).

Full Text

Multi-model ensemble for simulation of the impact of climate change on maize yield*

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Abstract: Climate projections through process-based statistical crop models are important in studying the impacts of climate change on agricultural production. However, extensive assessments have generally relied on single climate with single crop models which have shown large discrepancies in predicted crop yields and estimations uncertainty hardly assessed. The proper understanding of uncertainties associated with such models is essential for effective use of projected results in devising adaptation strategies. Assessing crop yield response to future climate conditions based on an ensemble of possible outcomes from multiple climate projections and crop models could be more reliable than using a single model outcome. To estimate uncertainties associated with the study of the impacts of climate change on crop yield, we used 8 climate projections by GCMs under RCP4.5 in the CMIP5 (which represented the uncertainties in the projected climate change) and a statistical process-based crop model (which represented the uncertainties in the different structures or different formulations of physiological processes of crop models). Historical data of crop and meteorological data during 1981-2009 from agro-meteorological stations of China Meteorological Administration in Hailun, Changling and Benxi in Northeast China were used to establish and evaluate statistical and process-based APSIM (Agricultural Production Systems sIMulator) models, respectively. Then the two crop models were linked with 8 climate projections to evaluate the impact of climate change on maize yield during 2010–2039 and 2040–2069, using 1976–2005 as the baseline period. In total, 2 crop models under 8 climate projections for a period of 30 years (a total of 480 simulations) were generated for both the baseline and two future climate periods. The results showed that APSIM model well simulated the growth and yield of maize. The root mean square error (RMSE) for the growth progress (flowering and maturity) simulation was 3–4 days and that for the yield simulation was 0.6–0.8 t • hm ^{2}. The established statistical model suggested that temperature during emergence (mid May) had a positive effect on maize yield. However, the increase of temperature and rainfall, and lack of solar radiation during flowering and grain-filling periods (mid July to early September) had negative impact on increase of maize yield. Compared with 1976-2005, the resulting probability distributions indicated that due to climate change, maize yield in 2010–2039 decreased on average by 3.8% (Hailun) -7.4% (Benxi), at a probability of 64% (Changling) -73% (Benxi). During 2040–2069, maize yield increased by 6.4% (Hailun) -10.5% (Benxi), at a probability of 74% (Hailun) -83% (Benxi). The simulated yield decrease by the APSIM model was 6.6% (Hailun) -8.9% (Benxi) during 2010-2039 and 9.7% (Hailun) - 13.7% (Benxi) during 2040-2069. These were higher relative to those simulated by the statistical model, which were 0.9% (Hailun) -6.0% (Benxi) during 2010-2039 and then 2.0% (Changling) -7.3% (Benxi) during 2040-2069.

Keywords: Climate change; Statistical model; APSIM model; Ensemble simulation; Maize; Growth progress; Yield

Introduction

Crop models are primary tools for evaluating the impacts of future climate change on crop yield. Among them, mechanistic models are most commonly used in climate change impact studies due to their strong theoretical foundation, such as APSIM [?], DSSAT [?], WOFOST [?], and ORYZA [?]. However, these complex process-based models require extensive detailed initial data on crop growth, management, and soil conditions for calibration [?, ?], and inaccuracies in these data increase simulation uncertainty [?, ?]. In contrast, statistical models do not require field production and management data for calibration and can potentially capture the effects of relatively poorly understood processes (such as pest and disease dynamics) with limited data, thereby effectively reducing the uncertainty associated with numerous parameters in mechanistic models [?, ?]. While mechanistic models have been widely applied in climate change impact studies, the role of statistical models has gradually gained attention. For example, Lobell et al. [?] developed statistical models linking historical meteorological factors to yields of four crops—maize (*Zea mays*), wheat (*Triticum aestivum*), rice (*Oryza sativa*), and soybean (*Glycine max*)—at the national scale to quantify climate change impacts on global food crops from 1980-2008. Tao et al. [?] used statistical models to analyze the effects of meteorological conditions and cultivation management practices on rice yields in China from 1981-2009, effectively compensating for mechanistic models' limitations in quantifying the contribution of management practices to yields under historical climate conditions.

Current climate change impact studies predominantly rely on results from single climate models driving single crop models. However, structural differences between climate and crop models can lead to substantially different or even contradictory assessments. For example, Zhang et al. [?] applied the WOFOST model with different climate scenario data to simulate maize yields in Northeast China, finding that the multi-scenario weighted average based on RegCM3 output (REA scenario) projected an approximate 8% yield reduction during 2011-2050, while scenarios based on PRECIS output (A2 and B2) projected yield increases of 20% and 7%, respectively. Conversely, Yuan et al. [?] used PRECIS B2 scenario data with an improved Northeast China maize growth simulation model [?] and projected predominantly yield reductions during 2011-2050. Similarly, Guo et al. [?] used HadCM3 with the CERES model (without CO fertilization effects) to project increased wheat yields in North China, whereas

Zhang et al. [?] used PRECIS output to drive the APSIM model and projected wheat yield reductions in the same region. These discrepancies highlight the importance of accounting for uncertainties arising from structural differences in climate and crop models when conducting climate change assessments [?, ?]. To address this issue, this study examined spring maize in Hailun (Heilongjiang Province), Changling (Jilin Province), and Benxi (Liaoning Province) in Northeast China [Figure 1: see original paper], using both mechanistic and statistical crop models driven by eight GCMs to conduct multi-model ensemble simulations of potential climate change impacts on maize yields during 2010–2039 and 2040–2069, aiming to reduce uncertainties associated with single-model approaches.

1. Materials and Methods

1.1 Study Area and Data Sources

Northeast China primarily includes Heilongjiang, Jilin, and Liaoning provinces, characterized by a cold temperate humid to semi-humid climate zone with cold, dry winters and warm, humid summers. The annual mean temperature ranges from -3 to 10 °C, and annual precipitation ranges from 400 to 1,000 mm, with 80% concentrated between May and September. The fertile land contains organic matter at 12.4–34.2 g·kg ^{1}. Spring maize in this region is primarily single-cropped, accounting for approximately 30% of the national maize planting area and serving as a crucial commercial grain production base.

Based on the principles of representing major maize production levels and having relatively complete long-term datasets, this study selected three China Meteorological Administration agro-meteorological experimental stations: Hailun (47.4°N, 127.0°E), Changling (44.2°N, 124.0°E), and Benxi (41.3°N, 123.8°E) [Figure 1: see original paper]. Crop data for the study sites, including maize growth periods and yields from 1981–2009, were obtained from the National Meteorological Information Center. Historical meteorological observations from the China Meteorological Administration Science Data Sharing Service Network included daily maximum temperature, daily minimum temperature, sunshine hours, and precipitation. Sunshine hours were converted to total radiation using the Angström-Prescott formula [?]. Based on the typical maize growth and development periods, ten-day averages of maximum temperature, minimum temperature, cumulative precipitation, and cumulative radiation were calculated for each growth stage. Climate scenario data were obtained from the National Climate Center, selecting eight global models from CMIP5 under the RCP4.5 scenario: BCC-CSM1-1 (China) and NorESM1-M (Norway), which generated daily data for future climate periods (2010–2039 and 2040–2069) and the baseline period (1976–2005), including daily maximum temperature, minimum temperature, and precipitation. All models had a resolution of 1°×1°. Radiation data were substituted with historical observations. Climate model data were downscaled to the study sites using inverse distance weighting interpolation.

1.2 Research Methods

Based on collected crop and meteorological data, this study established a crop statistical model and validated a mechanistic crop model. By driving different crop models with outputs from different climate models, ensemble probability methods were used to quantify potential climate change impacts on maize yield. The specific technical workflow is shown in [Figure 2: see original paper].

1.2.1 Crop Mechanistic Model Since its introduction to China, the APSIM (Agricultural Production Systems sIMulator) model has been widely applied to evaluate the impacts of climate variability and environmental change on crop growth [**?**, **?**]. This study was conducted at the site scale, using a single ecotype cultivar as representative for each climate zone. Data from 1981-1995 were used to calibrate cultivar parameters through a "trial-and-error" approach, enabling simulated flowering dates, maturity dates, and yields to match observed values as closely as possible. Data from 1996-2009 were then used to validate the calibrated model. The following statistical indicators were selected to evaluate model performance: the coefficient of determination R^2 (1:1) of the fitted equation y = x between simulated and observed values, reflecting true deviations; the slope , indicating overall overestimation or underestimation; and the root mean square error (RMSE), reflecting absolute errors. When simulating yields of representative cultivars under climate change using the APSIM model, fixed sowing dates were adopted as the average of 1981-2009 dates from the agro-meteorological experimental stations, with harvest at physiological maturity. Other management practices such as irrigation and fertilization were set to optimal conditions (i.e., without stress effects).

1.2.2 Crop Statistical Model Maize yield data from 1981-2009 were used to develop a crop statistical model. The model included trend yield (primarily influenced by agricultural technological progress) and meteorological yield (primarily influenced by climate factors) to ensure comparable magnitude with mechanistic model outputs. Trend yield was obtained using polynomial fitting:

For Hailun: MATH_HAILUN
For Changling: MATH_CHANGLING
For Benxi: MATH_BENXI

Where Y is trend yield and t is the year sequence (ranging from 1 to 29, representing 1981 to 2009). Due to limitations in extrapolating trend yield, this study did not consider contributions from updated cultivars and cultivation techniques under climate change, instead using the average trend yield level from the most recent period (2005-2009). Meteorological yield was obtained by subtracting trend yield from actual yield. It was then fitted using stepwise regression with 64 ten-day meteorological factors during the maize growth period. Stepwise selection criteria used F-distribution probabilities, with factors entered at A = 0.05 and removed at A = 0.1.

1.2.3 Yield Analysis This study used eight climate model datasets to drive two crop models, generating 480 sets of yield simulation data for the baseline period (1976-2005) and two future periods (2010-2039 and 2040-2069). Considering potential impacts and uncertainties from using different climate and crop models in climate change studies, multi-model ensemble approaches were employed to quantify potential climate change impacts on maize yield using probability density functions (PDFs) and cumulative distribution functions (CDFs).

2. Results

2.1 APSIM Model Validation

[Figure 3: see original paper] shows validation results for simulated maize flowering dates, maturity dates, and yields against observed values. The slope was close to 1.0, indicating that simulated values closely matched observations. R^2 values for growth stages and yield exceeded 0.6, indicating that the model explained over 60% of observed variations. The RMSE for growth stages was 3-4 days, with average errors less than 3%. The RMSE for yield was 0.6-0.8 t · hm ^{2}, with average errors less than 11%. Overall, RMSE for different growth stages increased with developmental progress, primarily because simulated phenology depends on accumulated previous stages, and errors in phenology simulation affect yield simulation. Additionally, considering potential observation errors such as sampling heterogeneity, the APSIM model demonstrated good capability in simulating maize growth at the study sites.

2.2 Statistical Model Development

Parameters and coefficients in the yield statistical models are shown in . The regression models indicate that temperature during the flowering and grain-filling stage (mid-July to early September) was negatively correlated with yield. Increased temperature during this stage accelerated developmental progress, reducing biomass accumulation and affecting yield formation. Conversely, temperature during the emergence stage (mid-May) was positively correlated with meteorological yield, as moderate temperature increases during this period benefit crop emergence and seedling establishment. Heavy rainfall or insufficient sunlight during flowering and grain-filling can affect pollination and fertilization, induce kernel abortion, and ultimately reduce yield.

2.3 Simulated Maize Yield Changes from Different Models

shows that simulated maize yields based on different crop models all decreased under future climate change, with greater yield reductions in 2040-2069 than in 2010-2039. As climate change intensified, yield reduction rates increased. Yield reductions simulated by the mechanistic model were higher than those from the statistical model. During 2010-2039, the most pronounced difference occurred in Changling, where the APSIM mechanistic model projected an 8.4% yield reduction while the statistical model projected only 1.4%. During 2040-

2069, Changling again showed the largest discrepancy, with APSIM projecting a 12.6% reduction versus only 2.0% from the statistical model. Averaged across all sites, mechanistic model simulations projected yield reductions of 6.6% (Hailun) to 8.9% (Benxi) during 2010–2039 and 9.7% (Hailun) to 13.7% (Benxi) during 2040–2069. In contrast, statistical model simulations showed smaller yield reductions of 0.9% (Hailun) to 6.0% (Benxi) and 2.0% (Changling) to 7.3% (Benxi) for the respective periods. No significant differences in bias or dispersion were observed between yield changes simulated by different models.

2.4 Probabilistic Analysis of Climate Change Impacts on Maize Yield

Based on multi-model ensembles, probability density and cumulative probability results for maize yield changes relative to the baseline period during 2010–2039 and 2040–2069 [Figure 4: see original paper] show that yield change probability densities follow a normal distribution, but peak positions shift further left as climate change intensifies, with increased negative area indicating higher probability of yield reduction. The probability of yield reduction during 2010–2039 was approximately 64% (Changling) to 73% (Benxi), increasing to 74% (Hailun) to 83% (Benxi) during 2040–2069. Compared with the baseline period, average yield reductions during 2010–2039 were 3.8% (Hailun) to 7.4% (Benxi), with continued reductions of 6.4% (Hailun) to 10.5% (Benxi) during 2040–2069. Overall, data dispersion for climate change impacts on maize yield was relatively high, averaging approximately 11%.

3. Discussion and Conclusion

Results from different crop model structures indicate that maize yield changes simulated by mechanistic models were greater than those from statistical models, consistent with current research findings. Most mechanistic model assessments project yield changes of -11% to 20% [?, ?], while statistical model results show changes of less than 10%. For example, Ma et al. [?] used integral regression to develop correlation models between meteorological factors and maize yields across different Chinese provinces, projecting national maize yield reductions within 7% under future climate change. Zhang et al. [?] and Zhou et al. [?] used multiple CMIP5 GCMs with different statistical crop model parameters and projected Northeast China maize yield changes of less than 5%. Additionally, Roudier et al. [?] synthesized 16 studies on climate change impacts on crop yields in West Africa and obtained similar results. This may occur because mechanistic models better capture complex non-linear relationships among climate factors (such as extreme temperatures, precipitation, and average temperature) that affect yield.

This assessment of future maize yields only considered climate factors and did not account for adjustments in crop cultivation practices or increasing CO concentrations under climate change. Previous studies have shown that adaptation measures such as cultivar replacement [?] and sowing date adjustment [?] can enhance crop yields under climate change. Furthermore, elevated CO concentrations can mitigate or offset negative effects of temperature increases, thereby improving crop yields.

Multi-model ensemble is an effective method for reducing uncertainty in climate change impact assessments. This study addressed uncertainties arising from climate model structures and crop model structural differences through multi-model ensemble evaluation, reflecting the possible range of maize yield changes in Northeast China. The results indicate yield reductions of 3.8%-7.4% during 2010-2039 and 6.4%-10.5% during 2040-2069, similar to Tao et al.' s [?] findings based on multiple climate scenarios and mechanistic crop models. Notably, Zhou et al. [?] projected increasing trends for Northeast China maize yields by considering uncertainties from both climate models and internal crop model parameters. These differences demonstrate the sensitivity of crop model selection and highlight the importance of considering internal model parameters. Therefore, integrating previous research findings and comprehensively considering uncertainties from climate model structure, crop model structure, and internal model parameters should be the focus of future research.

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Note: Figure translations are in progress. See original paper for figures.