博 士 論 文 の 要 約

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学 位 論 文 題 名

生理生態学的作物モデル(MATCRO-Soy)による気候変動下における
グローバルなダイズ収量の将来予測

Future prediction of global soybean yield under climate change using the eco-physiological crop growth model (MATCRO-Soy)

1. Introduction

Soybean is a key crop in the global food resource as a major source of protein and vegetable oil. It plays a critical role in both human and animal food production. Soybeans also provide additional nitrogen to the soil, making the agricultural system more advantageous for farmers in terms of intercropping. The global demand for soybeans is expected to increase due to population growth and the expansion of livestock industries. Consequently, accurate projections of future soybean production are essential for effective agricultural planning and policy development.

Recent studies report a 10–20% decline in global soybean yields associated with rising temperatures and increased climate variability, whereas climate change represents a critical challenge for global agricultural systems. Rising temperatures, changing precipitation patterns, and changing climate variability affect crop yield stability. These environmental changes threaten global food security, especially for soybean that is vital to human nutrition and agricultural economies.

Crop simulation models are widely employed to assess the potential impacts of climate change on agricultural productivity. There are many kinds of models that have been developed from theories and observational studies. Those models have been simplified from the real world using many different approaches. Each model has been using a different approach based on its aim. There are key mechanisms that have been considered in developing crop models: biomass assimilation, biomass allocation, phenological development, and water and nutrient stress. One kind of model is process-based crop models, which are particularly valuable because they represent physiological processes across different environmental conditions. These models offer a framework to analyze how environmental variables, including temperature, solar radiation, and soil moisture, influence crop productivity.

Despite these advances, projections of crop yields under climate change remain highly uncertain. One major source of uncertainty arises from climate projections produced by general circulation models (GCMs). Different climate models produce different projections of temperature and precipitation, leading to large differences in simulated crop yields. As a result, projections based on a single climate model may not adequately represent the range of possible future outcomes. Although previous studies have attempted to address this issue by employing multi-model ensembles of climate and crop models. Soybean yield projections continue to exhibit considerable variability due to differences in climate inputs, model structures, and parameterization. Additionally, some crop models simplify plant physiological processes, which may limit its capacity to accurately represent crop responses to environmental stress.

This thesis investigates soybean yield responses to climate change using an eco-physiological crop modeling framework to address the challenges in climate change studies for soybean. The MATCRO crop model (Masutomi et al. 2016), which integrates plant physiological processes with land surface modeling, is applied in this study. A soybean-specific version of the model, designated as MATCRO-Soy, is used to simulate soybean growth and yield across various spatial and temporal scales. This approach aims to enhance understanding of soybean yield dynamics under climate change and to quantify uncertainties associated with climate projections. This thesis consist of 4 chapters including: 1) General Introduction, 2) An ecophysiological process-based crop growth model (MATCRO-Soy): Model description and evaluation, 3) Future simulation on soybean yield using multiple General Circulation Models (GCMs), and 4) General Conclusions.

2. Research Problem and Objectives

Despite growing research on the impacts of climate change on agriculture, several challenges remain in accurately projecting soybean productivity under future climate conditions. Specifically, the combined influence of crop physiological processes and climate model uncertainty has not been sufficiently examined within a unified modeling framework. This thesis investigates the soybean growth response to environmental factors using an eco-physiological process-based model framework. It specifically applies the eco-physiological crop growth model of MATCRO that has been apply to soybean (MATCRO-Soy).

To address this problem, the thesis aims to achieve the following objectives:

(a) How does the model reproduce spatial and temporal patterns of soybean yields at global, national, and grid-cell scales compared with observation data from the reference dataset? **(Reliability of the model**, explained in Chapter 2**)**

(b) How large are future soybean yield changes under CMIP6 scenarios (SSP126, SSP245, SSP370, and SSP585) using an ensemble of more than 30 GCMs and the uncertainty? **(Soybean future yield predictions**, explained in Chapter 3**)**

(c) What is key climate factors affect the uncertainty in future soybean yield projections? **(Source of uncertainty**, explained in Chapter 3**)**

The main contributions of this thesis can be summarized as follows: (a) This study employs an eco-physiological crop modeling framework that integrates plant physiological processes with land surface modeling, thereby offering a mechanistic representation of crop growth compared to simplified empirical approaches. (b) The study evaluates soybean yield projections using a large ensemble of climate models, allowing systematic analysis of uncertainty from climate projections. (c) The study demonstrates that representative subsets of climate models can reproduce the statistical characteristics of full climate model ensembles. These results will offer a practical approach for reducing computational costs in large-scale crop simulations. Through these contributions, the thesis provides new insights into the mechanisms and uncertainties associated with global soybean yield responses to climate change.

3. Methodology

Crop Model Description (Chapter 2)

MATCRO quantifies leaf-level photosynthesis from a land surface model with the ability to simulate the crop physiology, hence it will give the understanding the soybean mechanism and is not common in crop model. The model represents crop growth as a series of physiological processes influenced by environmental conditions during the growing season. Soybean-specific physiological parameters were incorporated into the model. Key processes simulated in the model include phenological development, photosynthetic carbon assimilation, plant respiration, biomass accumulation, and yield formation. Crop yield is represented as the output of carbon assimilation and biomass allocation from the soybean pod during the growing season. Environmental variables such as temperature, solar radiation, precipitation, nitrogen fertilizer, and soil moisture influence crop growth estimation. This eco-physiological modeling framework enables simulation of crop responses to environmental variability while maintaining a mechanistic representation of plant growth processes.

The model simulates soybean yield using input data as described in Table 4. It uses the following global input data: crop calendar from the Global Gridded Crop Model Intercomparison (GGCMI), which separates rainfed and irrigated systems; atmospheric CO2 and climate data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), which provides bias-adjusted climate input data for historical data (GSWP3-W5E5 v2.0); soil classifications from the Harmonized World Soil Database (HWSD v1.2); and nitrogen fertilization for C3 fixing crops of the ISIMIP, which is derived from the land use dataset (Hurt et al., 2020). ISIMIP bias-adjusted data are used to maintain uniformity in the climate impact data across sectors and scales in the framework. This dataset, which is provided by ISIMIP, has a spatial resolution of 0.5° × 0.5°. To determine the growing degree days for maturity, we considered the phenological maturity time from the GGCMI crop calendar for harvest time and global ISIMIP climate data over 10 years

(2000–2010) to capture the shifts in variability across the current evaluation years.

Model Calibration and Evaluation (Chapter 2)
MATCRO-Soy model was calibrated to ensure reliable simulation results. It used observational and experimental datasets reported in previous studies: Frederico Westphalen and Piracicaba (Brazil), Ya'an (China), Champaign (United States of America, US), Morioka and Tsukubamirai (Japan) for year 2002, 2004–2007, and 2007–2016. Calibration focused on parameters controlling crop growth dynamics using one unified global parameters that can represent the average of soybean productivity, including carbon allocation and phenological development. Moreover, model performance was evaluated using soybean yield data from multiple spatial scales. Observed yield datasets were obtained from FAOSTAT (Food and Agriculture Organization's global statistical database) and another global agricultural databases for grid-cell level (Global Dataset of Historical Yield, established by Iizumi and Sakai 2020). Model evaluation included comparisons between simulated and observed yields at global, national, and grid-cell levels for 30-year (average and interannual variability) during 1980–2014. These analyses assessed the model ability to reproduce spatial patterns of yield distribution as well as temporal variability in crop yield.

Future Climate Data (Chapter 3)
Future climate conditions were sourced from the Coupled Model Intercomparison Project Phase 6 (CMIP6) using general circulation models (GCMs). Climate variables of temperature (maximum, minimum, and average), precipitation, wind speed, specific humidity, surface air pressure, and solar radiation served as inputs to the crop model. Simulations were conducted from 2015 to 2100 at a spatial resolution of 0.5° × 0.5°, enabling global analysis of soybean yield responses. Simulations were performed under four Shared Socioeconomic Pathway (SSP) scenarios of SSP1-2.6 (low emission scenario), SSP2-4.5 (intermediate emission scenario), SSP3-7.0 (high emission scenario), and SSP5-8.5 (very high emission scenario). These scenarios represent distinct greenhouse gas emission pathways and corresponding climate futures. The yield changes simulations focus on two scenarios: 1) yield under constant CO_2 at year 2010 condition, 2) yield changes under varied CO_2 conditions with uncertainty across GCMs and SSPs. We used bias-corrected climate datasets from Shiogama et al. (2025) as inputs for the crop model simulations: SSP1-2.6 (32 GCMs), SSP-2.45 (30 GCMs), SSP-3.70 (28 GCMs), SSP-5.85 (33 GCMs), resulting in about 103×2 simulations by the model (GCMs × SSPs × CO_2 setting).

Ensemble Modeling Approach (Chapter 3)
An ensemble of 28 to 33 bias-corrected from all existing climate models (GCMs) was employed as inputs in simulating yield change to address uncertainty in climate projections. The yield change is a relative value in percentage where the baseline period (2000–2014) in each GCM is paired with its future scenario (2015–2100). The statistical metric used to represent the uncertainty of the ensemble is the mean, median, standard deviation, coefficient of variation, and interquartile range.

In addition to the full ensemble, representative subsets were analyzed to determine whether smaller ensembles could reproduce the principal characteristics of the full ensemble (all existing GCMs with the number 28-33 GCMs which is available for the model in term of climate variables). This approach enables the assessment of both the magnitude of yield changes and the uncertainty inherent in climate projections. The subset ensemble approach is designed to identify smaller groups of climate models that reproduce the statistical characteristics of the full ensemble while reducing computational complexity. The selection criteria for representative subsets included: similarity of projected yield changes to the full ensemble and representation of variability among climate models.

4. Experimental Analysis and Results

Evaluation of Model Performance (Chapter 2)
The yield simulation during 1981–2014 has been tested in point-scale simulation prior to regional-scale simulation in term of phenological (sowing, flowering, seed filling, and harvest time) and biomass using 1:1 line comparison. While point-scale simulations employed the unified global parameters, the results demonstrated reasonable agreement with $p < 0.01$ and bias of 30–63 % for harvested yield, seasonal LAI, aboveground biomass, and pod biomass.

The regional-scale simulation demonstrates that the global mean yields revealed a statistical correlation of 0.81 ($p < 0.001$) between the simulated yields and yields reported by FAOSTAT without subtracting the long-term yield trend. The correlation value was lower between simulated yields and detrended yield data.

On the basis of comparisons of modelled and observed yields over a 34-year period (1981–2014), the correlation coefficients were 0.45 ($p < 0.050$) on the global scale and 0.52 ($p < 0.001$) for the top 10 soybean-producing countries. At the grid-cell level, the correlation between modelled and observed yields were significant in 66% of grid cells.

Projections of Future Soybean Yields using an Ensemble (Chapter 3)
Future simulations indicate that global soybean yield may experience modest changes under climate change scenarios. MATCRO-Soy with the ensemble of full GCMs for future soybean projections highlighted the complex relationship between emission scenarios and variations in global scale. The uncertainty of yield changes ensemble for decadal global mean during 2015–2100 using full GCMs range from 8.83 – 21% across four scenarios under climate change and CO_2 fertilization effect. Higher-emission scenarios result in increased uncertainty, primarily due to greater variability in projected temperature and precipitation patterns. Meanwhile, yield losses under climate change only (without considering the CO_2 fertilization effect) becoming larger and more consistent as warming more pronounced from SSP126 to SSP585, indicating an increasing sensitivity of yield to temperature under higher-emission pathways.

Future yield change demonstrated significant regional variations. The degree of agreement among GCMs further highlights the robustness of these patterns, where high agreement on yield decreases was evident in several temperate regions for late-century (2070–2100) climate conditions under SSP126. Yield losses were observed across parts of East Asia, Europe, and North America, while yield gain were more frequent in South America, Africa, and Southeast Asia. The main factor of these yield changes is the extended growing time in near tropical areas (latitude of 0–20°), and elevated maturity time in higher latitudes.

The number of models in the ensemble was evaluated using root mean square error (RMSE) of yield change between historical data (1980–2014) for each GCM and FAOSTAT global yield data. The best fit using the ensemble of 35 GCM in historical data can produce an error of 373 kg ha^{-1} for detrended yield data and is saturated after using 20 models. Meanwhile, for using future climate scenarios, results show that using 5 GCMs with random combinations and 50,000 repetitions of bootstrap method results in an RMSE of about 148 kg ha^{-1}, while an ensemble of 10 GCMs yields an RMSE of about 118 kg ha^{-1}, compared with the full GCM ensemble across SSPs.

Climate Drivers of Yield Variability (Chapter 3)
The uncertainty in GCMs is affecting yield changes through the climate variables used as inputs. The study identifies key climate variables influencing soybean yield variability by reporting the square of Pearson correlations between inter-model uncertainty in yield change under climate change and increased CO_2 and the corresponding uncertainties in future decadal changes (2015–2100) of temperature, precipitation, and radiation relative to historical (1981–2014). The correlation varies across SSP emission scenarios, with temperature showing the highest correlation, followed by precipitation and radiation. In SSP126, variation in temperature and radiation explained about 17–21% of the uncertainty in yield change, with significance ($p < 0.01$). Greater uncertainty in future temperature changes (relative to the baseline) indicates higher uncertainty in yield changes due to higher greenhouse gas emissions (SSP-2.45, SSP-3.70, SSP-5.85).

In this study, we then compared the ensemble combinations using a smaller number of models (10 GCMs) with the closest uncertainty metrics (mean and standard deviation) to the full ensemble (28-33 GCMs). The result shows that the relative mean yield changes (decadal average from 2015–2100) of best fit (lowest difference of mean and standard deviation using 10 GCMs and full GCMs) underestimated the interquartile range of all existing GCMs. We also compared the decadal climate variables pattern that can produce the best fit in this study. The study shows that representative GCMs perform better when model combinations accurately represent mean temperature and preserve the full range of precipitation variability.

5. Discussion

Model strength and limitation (Chapter 2)
The model evaluation shows moderate correlation for global yield mean during 1981–2014 where MATCRO-Soy model effectively captures the linear trend in soybean yields, with higher accuracy for long-term trends (pearson correlation of 0.812) than for detrended yields (pearson correlation of 0.446). This result for the global detrended yield improves upon that of the benchmark of previous study. MATCRO-Soy was able to capture the trend of increased atmospheric CO_2 and nitrogen fertilizer inputs,

despite the interannual variability in climate conditions. Factors such as changes in sowing date, land use, pest management, cultivar maturity group, and planting density may contribute to discrepancies in simulation with observed soybean yield. Moreover, the strength of MATCRO-Soy lies in its ability to simulate key physiological processes of soybean growth (e.g., photosynthesis, phenology, and biomass partitioning) under varying climatic conditions and the integrated framework related to climatic factors, soil, and nitrogen fertilization to capture biophysical processes involved in soybean growth and yield formation.

Uncertainty in MATCRO-Soy is reflected in challenges in evaluating the model at a global scale, particularly due to its assumption of globally homogeneous crop cultivars and the upscaling processes required by limited observed data. While MATCRO-Soy presents a valuable framework for understanding the impacts of climate change on global soybean production, many localized factors that influence soybean yield resulting from shifts in climate (e.g., pests and diseases) can lead to discrepancies in yield prediction. Despite some discrepancies between simulated and observed yields due to simplification of nitrogen mechanism in the soil, variety difference, and local climate factors, the overall model performance indicates that the eco-physiological framework provides an effective representation of soybean growth processes.

GCMs uncertainty in the crop model (Chapter 3)

MATCRO-Soy model provides a mechanistic framework for simulating crop responses to environmental conditions. However, the study also demonstrates that uncertainty in climate projections (GCMs) remains a major challenge in predicting future agricultural productivity. Multiple climate factors have been significantly found to influence soybean growth. Increased CO_2 concentration will enhance photosynthesis and water use efficiency, while warming temperatures can accelerate phenological development and increase water stress under altered precipitation. These findings suggest that the positive effects of elevated atmospheric CO_2 concentrations on photosynthesis could partially offset the negative impacts of temperature stress. However, regional yield responses vary considerably due to differences in local climate conditions.

The ensemble modeling approach used in this study provides a robust framework for quantifying model uncertainties from climate projections. This study reveals that increased greenhouse gas emissions under SSP scenarios correlate with greater yield variability, with projections under SSP370 and SSP585 showing yield changes ranging from -25% to +30% relative to the historical baseline. Analyzing large ensembles of climate models captures a wide range of possible future outcomes and provides insights into the reliability of yield projections. Differences among climate models lead to significant variability in projected temperature and precipitation patterns, which in turn propagate into crop yield simulations.

The results further indicate that representative subsets of climate models can reproduce the central tendencies of the full ensemble. This finding suggests that smaller ensembles may be sufficient for efficient yield projections with cautious selection of reliable temperature range prediction and precipitation. Temperature is a major stress factor, as high temperatures can reduce photosynthetic efficiency and shorten the growing period. Meanwhile, precipitation variability affects soil moisture and significantly contributes to yield variability. Moreover, the length of the growing period also determines the time for biomass accumulation and seed development.

The present framework incorporates the effect of elevated CO_2 and utilizes a comprehensive multi-GCM CMIP6 ensemble, without implementing extensive local adaptations such as widespread irrigation or cultivar shifts. Adaptation strategies may be necessary to mitigate the potential negative impacts of climate change on soybean production. These strategies may include adjusting planting dates, developing heat-tolerant cultivars, and improving agricultural management practices.

6. Conclusions

Global soybean yield responses to climate change were investigated using the eco-physiological crop model MATCRO-Soy. The model combines mathematical simulation with empirical data and accounts for key factors such as climate, soil type, and nitrogen fertilization. Model evaluation during 1981–2014 using reference data showed that MATCRO-Soy can reproduce long-term yield trends and interannual variability while accurately representing physiological processes such as photosynthesis. These findings indicate that the model offers a reliable framework for simulating soybean responses to environmental conditions. However, discrepancies between simulated and observed yields persist due to localized factors such as genotype variation, pest damage, and disease. These limitations highlight the need for further model refinement, especially in representing temperature extremes, soil water dynamics, and nitrogen uptake.

Future soybean projections using MATCRO-Soy model combined with the bias-corrected of all existing climate projections from CMIP6 scenarios (SSP-1.26, SSP-2.45, SSP-3.70, and SSP-5.85) suggest modest global soybean yield increases of about 2–6% under climate change and CO_2 fertilization, though regional variability is large. This increase is modest compared to historical yield gains, indicating that climate variability and diminishing returns from current practices may limit future productivity. Ensemble simulations reveal considerable uncertainty in yield projections, underscoring the need to use multiple climate models to assess future crop productivity. The analysis also found that a representative subset of 10 GCMs can reproduce the mean results of the full ensemble, with considerable error.

The study identified key climate variables contributing to uncertainty in future soybean yield projections. Temperature was the most significant stress factor, whereas precipitation showed a lower correlation with yield changes due to its effects on photosynthesis and biomass accumulation. These results underscore the complex interactions between climate factors and crop productivity. The findings suggest that adaptation strategies could include adjusting sowing dates to avoid extreme temperature stress. Integrating MATCRO-Soy with multiple climate projections ensembles provides a robust framework for evaluating soybean yield responses to climate change and offers valuable insights for improving projections, guiding management, and supporting adaptation strategies.

7. References

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