学位論文内容の要旨

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学位論文題名

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

（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）

Understanding the complex relationships between crop-soil-climate interactions will help improve the reliability of yield projections. The underlying physiological processes of crop growth at the ecosystem level can be explored using an eco-physiological process-based model, which integrates plant growth mechanisms (e.g., photosynthesis and respiration) with environmental factors (e.g., temperature, radiation, and CO_2 concentration). Rising temperatures pose a serious challenge for soybean production by potentially shortening the grain-filling period while at the same time increasing heat stress that can damage leaves. In contrast, elevated CO_2 can enhance photosynthesis and biomass, but these gains are often reduced over time by acclimation and other environmental stresses. Understanding these interactions requires a mechanistic crop model that links physiological processes with environmental drivers.

The impact of climate change on major crops grown on agricultural land (rice, wheat, soybean, and maize) has been thoroughly studied, but less studied for soybean (Glycine max), especially on a global scale. Soybean is one of the major crops that widely consumed for human and livestock due to its high protein, oil content and its unique ability to fix atmospheric nitrogen. The newly developed model in this study (namely: MATCRO-Soy) integrates photosynthetic regulation, carbon allocation, and growth dynamics within a unified framework. The model assumed a globally homogenous crop cultivars by averaging the experimental data from four major soybean-producing countries for model calibration, then the result is compared with FAOSTAT data at the global, country, and grid-cell scales to represent a wide range of environmental conditions for model evaluation. The results of modelled and observed yields over 34 years historically (1981–2014) show Pearson correlation coefficients of 0.45 ($p < 0.050$) at the global scale, and 0.52 ($p < 0.001$) at the top 10 soybean-producing countries for the interannual variability (after removing the long-term trend). At the grid-cell level, modelled and observed yields showed significant correlations in 66% of grid cells. However, the use of globally uniform parameters, simplified nitrogen fixation, and limited calibration data for detailed important mechanism means that the model is intended for global to regional analyses. These limitations restrict the model's applicability at the local site level.

There are few studies that have integrated eco-physiological process-based approaches with multiple global climate model (GCM) ensembles to project future soybean yields. It presents a significant gap in fully understanding how C_3 crops, like soybean, will respond to changes in climate variables. The interaction between elevated CO_2, temperature changes, and altered precipitation patterns will affect yield, and these patterns could be captured by bias-corrected GCM ensembles. We performed future projections using a bias-corrected GCM ensemble (28–33 GCMs) to examine the impact of climate change on global soybean yield. The ensemble of yield change projections using model for 2015 – 2100 based on full GCMs underscores the substantial uncertainty in future crop productivity at $0.5° \times 0.5°$ resolution, with yield changes ranging from a 25% decrease to a 30% increase across the four GCM scenarios (shared socioeconomic pathways, e.g. SSP126, SSP245, SSP370, SSP585). The results compared the use of a representative 10 GCMs ensemble and the full GCMs ensemble with a difference of less than 10% in median yield change. It indicates that a representative subset adequately captures the central tendency of the full ensemble, while the full GCM ensemble describes the full uncertainty range across climate models.

Coupling physiological mechanisms with large-scale applicability provides a mechanistic yet scalable framework for evaluating the impacts of climate change on soybean production. Sensitivity analysis of the model identified the key physiological parameters influencing yield, revealing that temperature and growing period have a strong influence on the yield variability. The model framework enables the estimation of essential processes, such as photosynthesis and transpiration, which are crucial for tuning the model using experimental data. It opens the opportunity for model development and broader assessment of crop response under diverse conditions for global food security assessment.