IMPROVEMENTS IN CLIMATE CHANGE RISK ASSESSMENT FOR GLOBAL CROP PRODUCTION

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ABSTRACT

Accumulated evidence indicates that agricultural production is being affected by climate change. Between 1981 and 2010, the global average annual production loss caused by climate change, relative to that caused by the non-warming counterfactual climatic conditions, accounted for 22.3, 13.6, 6.5, 0.8 billion US dollars for maize, wheat, soybean and rice, respectively. These findings confirm that climate change has resulted in food production losses, and till date, food production has not been sufficiently adapted to offset the negative impacts of climate change, particularly at lower latitudes. Adaptation technology, in addition to crop yield-increasing technology, is therefore necessary to maintain yield growth at rates necessary to meet the increasing demand for food. Climate change risk assessments are a basis of national adaptation policy making and planning. As consumers in many countries are becoming more dependent on food imports than before, national governments and commercial entities in import-dependent countries are paying close attention to variations in food production and export prices in major food-exporting countries, as well as to their own domestic production. For this reason, both global assessments and detailed country-based assessments are vital for national food agencies. However, global assessments often suffer from a lack of data, imperfect modeling, and uncertainties associated with various sources. This chapter describes the recent efforts made by the National Agriculture and Food Research Organization, with the help of research collaborators, to address some of these issues. The topics discussed in this article include improvements to global gridded crop modeling, spatially explicit global and historical crop datasets, and climate change risk assessments for changes in yield growth and variability with respect to major crops at the global scale.

Keywords: Climate change, global assessment, yield growth, yield variability

INTRODUCTION

Global demand for food has been anticipated to increase two-fold in 2050 compared with that in 2005 (Ray *et al*., 2013). In other words, the anticipated food demand in the middle of this century will be 1.6 times higher than that in 2016. Although a 2.4% annual yield growth is required to meet this supply goal without further land clearing, the actual yield growth rates of major crops in the past decades (1989−2008; 0.9%–1.6%) were lower than the target rate (Ray *et al*., 2013). More importantly, yield stagnation has been observed for some crop–country combinations (Ray *et al*., 2012, Grassini *et al*., 2013, Iizumi *et al*., 2014). These findings indicate that global agriculture is already under pressure to meet the increasing demand for food even without being affected by climate change.

Recent climate change has proved to be an additional burden for crop production systems worldwide. A report by the Japan Meteorological Agency (JMA) revealed that, as of February 2019, all of five warmest years regarding global annual mean surface temperature, relative to 1981–2010, occurred in the 2010s, namely, 2016 (+0.45°C), 2015 (+0.42°C), 2017 (+0.38°C), 2018 (+0.31°C) and 2014 (+0.27°C) (JMA, 2018). This warming is attributed to a main climatic factor leading to 5.5% and 3.8% decline in global production for wheat and maize, respectively, compared with what would have been achieved without the effect of warming during 1980–2008 (Lobell *et al*., 2011). These production losses are not negligible considering the global food demand–supply balance if these losses are considered to be approximately equal to the annual production of wheat in France (33 Mt) and maize in Mexico (23 Mt) (Lobell *et al*., 2011).

Recently, temperature and precipitation changes have been identified to contribute in some degree to the recent yield stagnation of wheat and barley in Europe (Moore and Lobell, 2015); however, it is very likely that changes in environmental policy and economy contributed more to the reported yield stagnation (Brisson *et al*., 2010). This poses a question that needs to be addressed by research: how will future yield growth be affected by projected climate change? Process-based crop models are essential tools in climate change risk assessment, but it is not easy to answer this question because assumptions regarding future agronomic technologies are necessary.

Improvements to global crop modeling to simulate yield growth

To address the aforementioned question, a global gridded crop model Crop Yield Growth Model with Assumption on climate and socioeconomy (CYGMA; Iizumi *et al*., 2017) has been developed. The model globally operates at the 0.5° resolution with a daily time step. Yields under rainfed and irrigated conditions are separately simulated and then combined when calculating the average yield over a given spatial domain (e.g., country).

In the model, crop development is modeled as a fraction of the accumulated growing degree-days relative to the crop's thermal requirements. Leaf growth and senescence are determined according to the fraction of the growing season using the prescribed shape of the leaf area index curve. Yields are computed from the photosynthetically active radiation intercepted by the crop canopy, radiation-use efficiency (RUE), effects of CO_2 fertilization on RUE, and fraction of total biomass increments allocated to the harvestable component. The soil water balance submodel, which is coupled with the snow cover submodel, is used to calculate the actual evapotranspiration. Five different stress types, nitrogen (N) deficit, heat, cold, water deficit, and water excess, are taken into account. The most dominant stress type for each day reduces the daily potential increase in the leaf area and yield. All the stress types, except N deficit, are the functions of daily weather, and the tolerance of each crop to these stresses increases as the knowledge stock increases. Knowledge stock is an economic indicator that is calculated as the sum of the annual agricultural research and development expenditures for each country since the 1961, with a certain obsolescence rate, and it represents the average level of technology and management used by farmers in the country in question.

The N application rates in the model increase and level according to the changes in a country's annual per capita gross domestic product and per capita agricultural area. Sowing dates in the model are updated annually in response to changes in temperature and moisture regimes. Crop thermal requirements are also updated annually based on long-term mean temperature conditions, which represent the use of longer-season varieties to prevent shortened crop durations and associated yield decreases. Additional modeling details and validation results have been reported in the study by Iizumi *et al*. (2017).

Production losses associated with historical climate change

By using the historical and non-warming counterfactual climate conditions derived from the atmospheric general circulation model simulation as the inputs to the CYGMA model, Iizumi *et al*. (2018b) demonstrated that climate change has decreased the global mean yields of maize, wheat, and soybeans by 4.1%, 1.8%, and 4.5%, respectively, relative to the non-warming counterfactual, even when CO_2 fertilization and agronomic adjustments are considered. For rice, no significant yield impacts (+0.9%) were detected at the global scale. The estimates are comparable to those derived from statistical regression reported by Lobell *et al*. (2011) (−3.8%, +2.9%, and

−2.5% for maize, rice, and wheat, respectively), with a discrepancy for soybean (+1.3%). The estimates of yield impacts between 1981 and 2010 indicate average annual production losses over the globe as a result of climate change, relative to the non-warming counterfactual, valued at 22.3, 13.6, 6.5, 0.8 billion US dollars for maize, wheat, soybean and rice, respectively. These findings are based on the process-based climate and crop modeling, and underpin the ideas that global crop production is being affected by climate change and that net production losses have occurred. The similarities between statistical and process-based approaches improve our confidence in the impacts of historical climate change on global crop production. More details on the simulated historical and non-warming counterfactual climate data are available from Shiogama *et al*. (2016), Imada *et al.* (2017), and Mizuta *et al*. (2017), as well as from Iizumi *et al*. (2018b).

Anticipated yield growth under future climate change

Using the CYGMA model and bias-corrected atmosphere–ocean coupled general circulation model daily outputs generated in phase 5 of the Coupled Model Intercomparison Project (CMIP5), Iizumi *et al*. (2017) revealed that the global mean maize yield for a temperature increase of 1.8°C would stagnate slightly, compared to the no-climate-change case (it assumes that future climate change is fixed to be the level of the 1981−2010 period). The yield stagnation of maize would be more severe under warming conditions (1.11 with a 2.7°C increase and 1.02 with a 3.2°C increase when average yield in the base period 2001−2010 is scaled to be 1.00) and would eventually result in a net decrease in yield at a temperature increase of 4.9°C (0.61) (Fig. 1). A net decrease in the global mean yield was also found for soybean, while yield stagnation under extreme warming (4.9°C) was found for both rice and wheat even though CO_2 fertilization and agronomic adjustments had been taken into account. Although rice and wheat on a global mean basis are found to be relatively less sensitive to warming than maize and soybean, note that yield stagnation of rice and wheat with a 1.8°C temperature increase is projected at lower latitudes (Iizumi *et al*., 2017). These outlooks suggest that adoption of more advanced adaptation technology beyond simple agronomic adjustments (such as changing sowing date and using long-season cultivars) is unavoidable if we are to maintain yield growth in coming decades under anticipated conditions of climate warming.

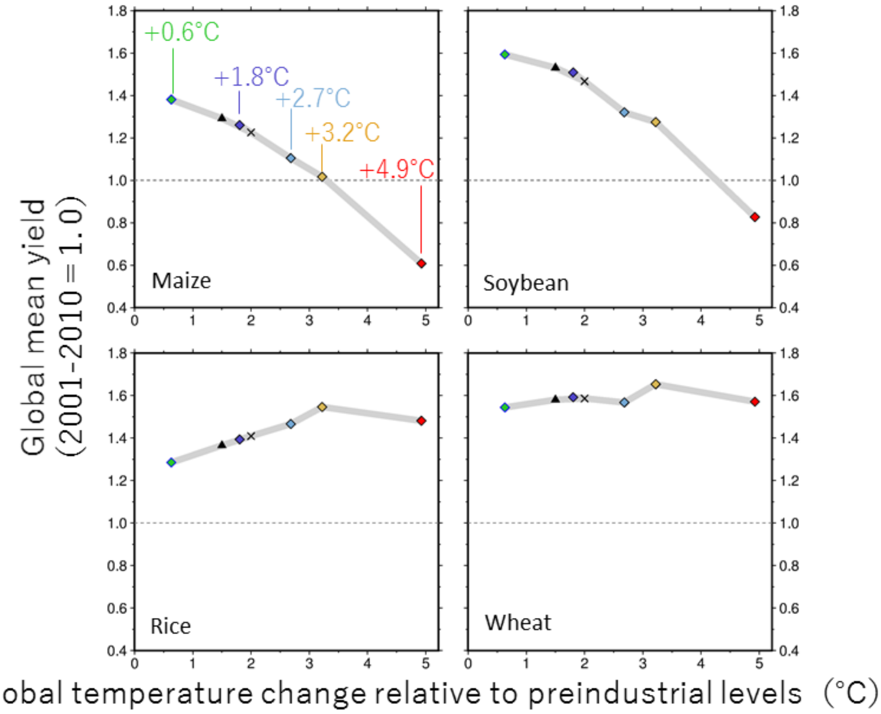

Fig. 1. Responses of global decadal mean yield at the end of this century (2091–2100) to warming relative to preindustrial levels. The global decadal mean surface temperature changes, relative to 1850–1900, have been used as the indicators of warming. Decadal mean yields are scaled so that the average yield in 2001–2010 is 1.00. The middle-of-road socioeconomic development pathways [known as the Shared Socioeconomic Pathways (SSP) 2; O'Neill *et al.* (2014)] has been used to derive future agronomic technologies and management scenarios. The data shown here are sourced from those presented in the study by Iizumi *et al.* (2017).

Improvements to global crop datasets

Climate change risk assessments are the basis of adaptation policy making and planning. Continual improvements to basic tools, such as crop models and datasets, are therefore necessary to enable researchers conducting such an assessment to aim to address questions related to more recent political agendas, including the United Nations Sustainable Development Goals (SDGs) (the United Nations (UN), 2018). As already shown, the climate change impacts on recent and future yield growth are one example of such questions related to the food security target in SDGs 2 and the climate change target in SDGs 13.

Another example of such a question is: have recent changes in weather extremes had a measurable influence on yield variability? To address this question, annual time series data of crop yields are required. At this moment in time, only two different global historical yield datasets are available. One was compiled by Ray *et al.* (2012), which is a crop yield and area harvested database covering ~2.5 million statistics in ~13,500 political units globally for the period 1961−2008. The other is described by Iizumi *et al.* (2014) and is a hybrid of national yield statistics reported by the Food and Agriculture Organization of the United Nations (FAO) and a satellite-derived crop-specific vegetation index. Our dataset (Iizumi *et al*., 2014) initially covered the period 1982−2006 with the grid size of 1.125° (version 1; Table 1) but was extended to cover the period 1981−2011 (Iizumi and Ramankutty, 2016) (version 1.1). Furthermore, the latest version 1.2 of our dataset was improved to have a spatial resolution of 0.5°, while the year coverage was the same as the earlier version (1981−2011) (Iizumi *et al*., 2018a).

To the best of our knowledge, Iizumi *et al*. (2018a) was the first study to explore uncertainties in the estimated areas with yield variability changes associated with different yield datasets and spatial resolutions. They found that the conclusion of Iizumi and Ramankutty (2016) (that a decrease in yield variability is the main trend worldwide across crops, though yields in some regions of the world have become more unstable) was robust, especially for maize and soybean (Fig. 2). For rice and wheat, however, the conclusion on yield variability changes was relatively sensitive to the choice of dataset and resolution. Nevertheless, in most cases across the possible combinations of datasets and resolutions, for rice and wheat, the extent of areas with increased yield variability were comparable to that with decreased yield variability. Importantly, on a global scale, over 21% of the yield variability change could be explained by climate change (Iizumi and Ramankutty, 2016). It is evidence showing that recent changes in daily temperature and precipitation extremes have affected yield variability in many parts of the world. Given the projection that yield variability would increase in a warmer climate (Tigchelaar *et al*., 2018), these findings have implications for national governments and commercial entities in import-dependent countries to have greater preparedness in terms of response to production and price shocks in food-exporting countries as a result of climate extremes.

Table 1. Improvements to global datasets of historical yields

	Version 1.0	Version 1.1	Version 1.2
Reference	Iizumi *et al.* (2014)	Iizumi and Ramankutty (2016)	Iizumi *et al.* (2018a)
Period	1982–2006	1981–2011	
Resolution	1.125°		0.5°
Crops	Maize (major/secondary), soybean, rice (major/secondary), wheat (winter/spring)		
Yield statistics	FAO national yield statistics (FAO, 2018)		
Satellite products	Second generation GIMMS 0.073° 15-day NDVI (Pinzon *et al.*, 2005, Tucker *et al.*, 2005)	Third generation GIMMS 0.083° 15-day LAI and FPAR (Zhu *et al.*, 2013)	
Radiation	JRA-25 reanalysis (Onogi *et al.*, 2007)		
Harvested area	M3-Crops (Monfreda *et al.*, 2008)		
Calendar	SAGE (Sacks *et al.*, 2010)		
Production share by season	Major world crop areas and climatic profiles (U.S. Department of Agriculture, 1994)		

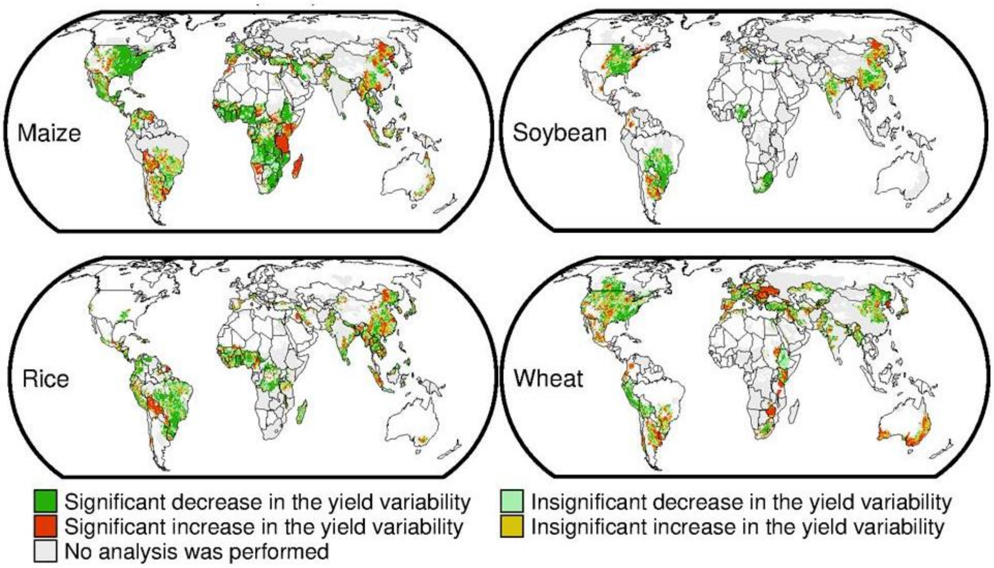

Fig. 2. Yield variability changes of maize, soybean, rice, and wheat during 1981–2008 calculated using the global dataset of historical yields version 1.2 (see Table 1 for details). The data are classified into the four categories of yield variability change. The data shown here are sourced from those presented in the study by Iizumi *et al.* (2018a). The similar but colored figure is found in Figure G in Supporting Information of Iizumi *et al.* (2018a).

CONCLUSION

This article describes the recent efforts achieved at NARO with collaborating researchers to improve climate change risk assessments for global crop production. The improvements to the global gridded crop model and the global crop dataset described earlier lead to insights on what has occurred in global crop production systems over the past decades and what can be anticipated in terms of global food security in coming decades because of climate and socioeconomic change. Our assessment results highlight the importance of advanced adaptation technology to maintain yield growth at rates necessary to meet increasing global food demand. At the same time, efforts to make production systems more resilient to climate variability and extremes are important in the face of climate change.

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