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Climate Change Effects on Long–term World–crop Production: Incorporating a Crop Model into Long–term Yield Estimates

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Abstract

Annual crop yield forecasts are necessary for analysis because evaluating climate–change impacts on world food markets requires supply–response functions, including output prices of the prior year. This research was undertaken to develop yield–response functions of the world food model to evaluate climate–change effects by incorporating a crop model into the yield–trend function. Yield–trend functions of rice, wheat, maize, and soybeans were obtained by estimating logistic functions or linear functions with a logarithmic time–trend term and climate variables. Furthermore, temperature and solar–radiation elasticities of yields were calculated using a crop model of the FAO and IIASA. The functions of the maximum rate of gross biomass production and the maximum net rate of CO_2 exchange of leaves in the crop model were modified by introducing cubic spline interpolation and logistic functions. Smoothing these two functions alleviates drastic changes, but reveals small changes in the elasticities of crop yields compared to the kinked functions and these more realistic elasticities can improve the evaluation accuracy of climate–change impacts on crop supply and demand. These variable elasticities of temperature and solar–radiation were inserted into the yield–trend functions, whereupon the global effects of changes in climate variables, including rainfall, were analyzed. The changes in yields obtained using climate variables of two of the four RCP scenarios were compared with the baseline, for which climate variables were fixed. Results of trend analyses show that yields of rice, wheat, maize, and soybeans under RCP8.5 are lower than those under RCP2.6, except for wheat in China. Results of geographical analysis show that climate change can be expected to affect wheat and maize productions in low–latitude countries. Furthermore, results suggest that climate change will depress rice production in sub–Saharan African countries in the 2040s.

Discipline: Agricultural economics and Crop production
Additional key words: CMIP5, CO_2 exchange rate, Cubic-spline, Logistic function, RCP

Introduction

Analyzing climate–change effects on crop production is crucial for developing food–security countermeasures because a widespread decline in crop production will trigger a sharp rise in food prices. Such a price hike constitutes a threat to human entitlement to food, as asserted by Sen (1981).

To evaluate climate–change effects on agricultural product markets, supply and demand models of agricultural products have been incorporated into crop models. Parry *et al*. (1999) estimated the yield functions for which the dependent variable is the potential yield of crop models such as CERES-Wheat and for which independent variables include temperature, rainfall, and CO_2 concentration. The yield functions are used in a supply and demand model: the Basic Linked System of International Institute for Applied Systems Analysis (IIASA).

Furuya & Koyama (2005) developed a world food model with yield functions, including terms of climate variables as independent variables and used it to evaluate the

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effects of global warming on agricultural markets. The model was then extended by Furuya & Kobayashi (2009) to a stochastic world food model considering variations in climate variables. These functions are specified as linear functions, for which explanatory variables are the time trend, temperature, and rainfall. An important shortcoming of the linear yield–function approach is the inability of the function to follow the inverse–u shaped relation between yield and temperature. However, it is difficult to estimate quadratic– or parameter–variable yield functions when time–series data are lacking.

To analyze climate–change effects on crop production and agricultural markets, the parameter–variable yield function, which has an inverse–u shaped relation between the yield and temperature, is necessary for long-term forecasting. Furthermore, this yield function follows a diminishing rate of increase of technological progress. Introducing crop models to the world food model is one means of improving it and Rosenzweig *et al*. (2013) organized a group comprising climate, crop modeling, and economic teams to improve the model accuracy, but connecting crop models and the economic sector remains difficult to evaluate. Equilibrium prices and quantities in the supply and demand model sector will not be obtained if gaps exist between the estimated yield from a crop model and actual yield in statistics. To fill that gap, as shown earlier, Parry *et al*. (1999) estimated the quadratic functions for which the yield was calculated, using a crop model explained by temperature, rainfall, and CO_2 concentration using cross–section data.

Most crop models incorporate a system such as a Decision–Support System for Agrotechnology Transfer (DSSAT), which help analyze climate–change effects on crop production such as the analysis reported by Jones & Thornton (2003). However, it is difficult to apply such systems to economic models because the system parameters are obscure.

In contrast to these packaging models, the crop–model parameters of the Global Agro-ecological Zones (GAEZ) of the Food and Agriculture Organization of the United Nations (FAO) and the IIASA are presented in a report by Fischer *et al*. (2002), although not shown in Fischer *et al*. (2012). The parameters cover 34 crops in four climate zones worldwide. The biomass production and yield calculation method of the GAEZ (Doorenbos & Kassam 1979) is applied to estimate climate–variable elasticities of yields in this study. These parameters are incorporated into yield functions for long–term forecasting and the long–term trend and annual changes in global crop yields under RCP scenarios will be obtained using the yield functions.

The target crops in this study are rice, wheat, maize, and soybeans. Changes in the yields of four simulations using climate variables under the Representative Concentration Pathway (RCP) scenarios of the Coupled–Model Intercomparison Project Phase 5 (CMIP5) of the Intergovernmental Panel on Climate Change (IPCC) are compared with the baseline, for which climate variables are fixed on those in the base year of 2008.

This study was conducted to develop yield–response functions of the world food model to evaluate climate–change effects by incorporating the crop model into the yield–trend function. Another purpose is ascertaining the climate–change impacts on crop yield in the long term in the world by these yield–response functions, using climate–forecast data of the RCP scenarios of the CMIP5.

Model

The relation between temperature and crop yield is inverse–u shaped, resembling that presented by Horie *et al*. (1995). However, since it is difficult to estimate the quadratic functions using crop yield and climatic–variable data due to the limited duration of available data, many studies instead evaluate climate–change impacts on crop production using sophisticated crop models based on plant physiology. However, the parameters and functions of most such models remain undisclosed. Moreover, these packaging models are unsuitable for research if the research purpose is to analyze annual changes in crop yields under climate change. A method of incorporating the climatic parameters of a crop model to the yield–trend functions is investigated in this section.

First, the trends of the yield, as a proxy of the technological progresses of the four crops for each country, are estimated considering past climate change. Second, the parameters of changes in yield to temperature and solar–radiation calculated from the crop–model parameters, are introduced into the yield–trend functions. The first stage involves estimating the yield–trend function using the time trend and climate variables before the base year for exclusion of the climate–change effects from the trend.

The general form of the yield–trend function before the base year is $Y = f_{YH}$ (T, TP_H, RG_H, PT_H), where T is the time trend and where TP_H, RG_H, and PT_H respectively represent the historical temperature, solar–radiation, and rainfall. After the base year, the yield–trend function responds only to the time trend: the general form of the function is $Y = f_{YB}$ (T). Results estimated using this function are used as the baseline.

The general form of the yield function with the climate parameters of the crop model is $Y = f_{YF}$ [T, $g_{TP}(TP_F, RG_F)$, $g_{RG}(TP_F, RG_F)$, PT_F], where TP_F, RG_F, and PT_F respectively denote the forecast temperature, solar–radiation, and rainfall. Results estimated using this function are used as simulation results in the RCP scenarios.

The potential yield, Yp, is used in the crop model and determined by climate conditions such as changes in temperature and solar–radiation. The difference in the potential yield *Yp* and the actual or forecast yield *Y* corresponds to the differences in technological and institutional circumstances in each country.

1. Yield–trend function

Crop yields increased dramatically during the 1960s–1980s in economically developing countries because of the green revolution, i.e., dissemination of modern plant varieties and chemical fertilizers and construction of irrigation facilities. Recently however, rates of increase in yields have slumped (Ray *et al.* 2012). Considering crop yield–trends, the yield functions of the four crops are specified as the four parameter logistic function. These logistic functions are used mainly to analyze nutritional input–output responses such as those presented by Vedenov & Pesti (2008). Moreover, 1–5 parameter logistic models exist (Harris 1989, Gottschalk & Dunn 2005). Considering the lack of data in economically developing countries and the future uncertainty related to yield changes, the results of a five-parameter logistic model, which assumes an asymmetric slope, will depend heavily on the few most recent data. Therefore, the following four–parameter logistic models are estimated with climate variables as crop–yield functions. The climate–change effects are included in these yield–trends because atmospheric CO_2 concentrations have been increasing since the mid–twentieth century. To eliminate climate–change effects from yield trend, climate variables are introduced into the yield function.

$$Y_{lk} = a_{lk} + \frac{b_{lk} - a_{lk}}{1 + \exp[-c_{lk}(T - d_{lk})]} + \beta_{TPlk}TP_{lk} + \beta_{RGlk}RG_{lk} + \beta_{PTlk}PT_{lk} \quad (1)$$

Therein, l stands for crop index, k is the country index, Y_{lk} signifies the crop yield, a_{lk} denotes the minimum yield (1st parameter), b_{lk} represents the maximum yield (2nd parameter), c_{lk} is the slope (3rd parameter), and d_{lk} is the inflection point (4th parameter). In addition, T is the time trend where 1961=1, TP_{lk} is temperature, RG_{lk} is solar–radiation, and PT_{lk} is rainfall. Figure 1 exhibits an estimation result of the logistic rice yield function in Bangladesh as an example.

In some economically developing countries, such as many in Africa, technological progress in crop production started only recently. The logistic function does not fit well in these cases. The following linear function with the logarithmic time trend as a variable is used as yield functions in this case.

$$Y_{lk} = a_{0lk} + b_{Tlk}\ln T_L + \beta_{TPlk}TP_{lk} + \beta_{RGlk}RG_{lk} + \beta_{PTlk}PT_{lk} \quad (2)$$

Therein, T_L stands for the time trend where 1951=1. As in the previously introduced equation, TP_{lk} signifies temperature, RG_{lk} denotes solar–radiation, and PT_{lk} represents rainfall. Figure 2 presents an estimation result of a linear–yield function with the logarithmic trend of soybeans in Argentina as an example.

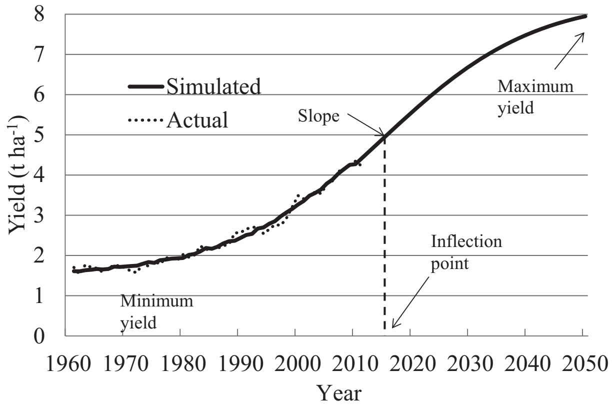


Fig. 1. Rice yield in Bangladesh

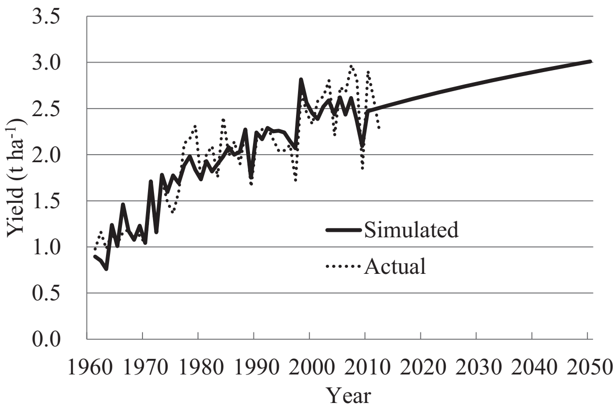


Fig. 2. Soybeans yield in Argentina

2. Yield function with climate parameters based on a crop model

The crop model used for this study was developed by Doorenbos & Kassam (1979) and summarized by Fischer *et al*. (2002). The model incorporates 34 crops produced worldwide, including rice, wheat, maize, and soybeans. All functions of the crop model are presented in the Appendix 4-5 (PP. 141-142) of Fischer *et al.* (2012). The functions of the maximum rate of gross biomass production and the maximum net rates of CO_2 exchange of leaves have been modified for smoothing in this study because kinks of functions engender drastic changes in the elasticities and yields of crops. Furthermore, these smoothed functions can capture the effects of small changes in climate variables on the elasticities. These more realistic elasticities will improve the accuracy of evaluations of the climate–change impacts on the supply and demand of crops.

(1) Maximum rate of gross biomass production

The maximum rate of gross biomass production (b_{gm}) (kg ha^{-1} day^{-1}) changes dramatically at 20 kg ha^{-1} h^{-1} of the maximum net CO_2 exchange rate (P_m) (kg ha^{-1} h^{-1}) in the original model as follows.

If $P_m < 20$, then,

$$b_{gm} = F(0.5 + 0.025P_m)b_o + (1 - F)(0.05P_m)b_c. \qquad (3)$$

If $P_m \geq 20$, then,

$$b_{gm} = F(0.8 + 0.01P_m)b_o + (1 - F)(0.5 + 0.025P_m)b_c. \qquad (4)$$

Therein, F stands for the fraction of the daytime for which the sky is cloudy, as determined using the following function: $F = (A_c - 0.5RG) / (0.8A_c)$, and A_c signifies the maximum solar–radiation on clear days (cal cm^{-2} day^{-1}). RG denotes the solar–radiation for a given location and year (cal cm^{-2} day^{-1}). b_o represents the gross dry matter production rate of a standard crop for a given location and year on a completely overcast day (kg ha^{-1} day^{-1}). b_c is the gross dry matter production rate of a standard crop for a given location and year on a perfectly clear day (kg ha^{-1} day^{-1}).

The kink of the function engenders sharp declines in crop yields, while the four parameters of the functions of b_{gm} vary according to logistic curves from 15 to 25 kg ha^{-1} h^{-1} of P_m, as follows to alleviate drastic changes in this study.

If $P_m < 15$, then, function (3).

If $15 \leq P_m < 25$, then,

$$b_{gm} = F\left[\left(0.5 + \frac{0.3}{1+e^{20-pm}}\right) + \left(0.01 + \frac{0.015}{1+e^{pm-20}}\right)P_m\right]b_0$$

$$+ (1 - F)\left[\left(\frac{0.5}{1+e^{20-pm}}\right) + \left(0.025 + \frac{0.025}{1+e^{pm-20}}\right)P_m\right]b_c. \qquad (5)$$

If $P_m \geq 25$, then, function (4).

Figure 3 depicts the relation between P_m and b_{gm} of the modified function.

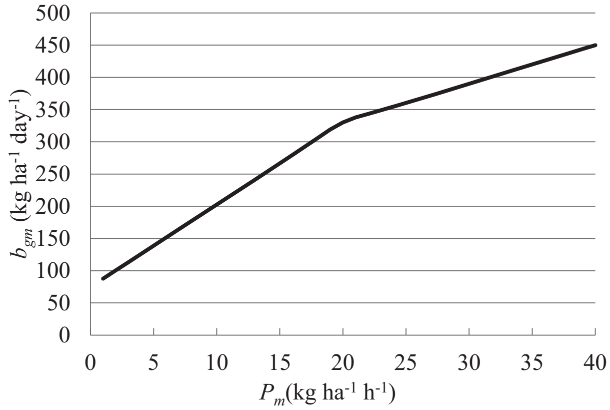


Fig. 3. Relation between maximum net CO_2 exchange rate (P_m) and maximum gross biomass production rate (b_{gm})

F=0.6, bo=250, bc=450

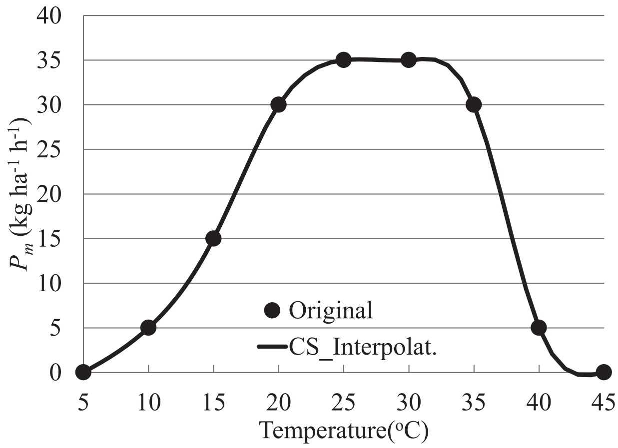


Fig. 4. Relation between temperature and maximum net CO_2 exchange rate (P_m) of rice, Japonica, wetland

(2) Maximum net CO_2 exchange rate of leaves

The maximum net CO_2 exchange rates of crop leaves according to temperatures are provided in the tables of appendix VII of an earlier report (Fischer *et al*. 2002). Those are point data in 5°C increments. First, linear interpolations are applied to the data. However, the estimated yields change dramatically over the point data, such as 25°C. Alleviating the drastic changes in thresholds, cubic–spline (CS) interpolations are applied to the data. If points of data are $(x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)$ for $(a \leq x_1 \leq x_2 \leq \cdots \leq x_n \leq b)$, then the CS function of $[x_i, x_{i+1}]$ is defined as

$$s_i(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3, \quad (i = 1, 2, \cdots n-1). \qquad (6)$$

Using conditions of interpolation and continuity of the first and second derivatives on the tangent points, parameters c_i are obtained by solving the tri-diagonal matrix function, while other parameters are obtained from the conditions of continuities (Shimoda & Tabe 1990). The CS functions are estimated for four crops with two or three types and Figure 4 presents the relation between temperature and P_m of Japonica rice in a wetland area.

(3) Temperature and solar–radiation elasticities of the potential yield

The temperature elasticity of the potential yield is calculated using the following equation.

$$\frac{\partial \ln YP}{\partial \ln TP} = \frac{\partial Yp}{\partial TP}\frac{TP}{Yp} = \frac{\partial B_n}{\partial TP}\frac{TP}{B_n}$$

$$= \frac{\partial b_{gm}}{\partial TP}\frac{TP}{b_{gm}} + \frac{\partial (1/N + 0.25c_t)^{-1}}{\partial TP} TP(1/N + 0.25c_t). \qquad (7)$$

In that equation, Yp signifies the potential yield (kg ha^{-1}), TP

denotes the temperature (°C), B_n represents the rate of net biomass production (kg ha^{-1}), b_{gm} stands for the maximum rate of gross biomass production (kg ha^{-1} day^{-1}), N denotes the total growing days (day), and c_t stands for a constant proportion of maintenance respiration (g g^{-1} day^{-1}). The potential yield is that calculated from the crop model of Doorenbos & Kassam (1979). The gap separating the actual yield and the potential yield is explained by evapotranspiration in the GAEZ. The total growing days (N) are estimated from cropping calendars of the United States Department of Agriculture (World Agricultural Outlook Board 1994).

Substituting $\partial b_{gm} / \partial TP$, i.e., the marginal propensity of the maximum rate of gross biomass production to temperature, and $c_t = c_{30}(0.0044 + 0.0019TP + 0.0010TP^2)$, which is shown in equation (8) of Appendix 4-5 of a report by Fischer *et al.* (2012), into the equation, the temperature elasticities of potential yield were obtained as presented below.

If $P_m < 15$, then,

$$\frac{\partial \ln Yp}{\partial \ln TP} = \frac{[0.025Fb_o + 0.05(1-F)b_c]TP}{b_{gm}} \frac{\partial P_m}{\partial TP} - \frac{0.25(0.0019 + 0.0020TP)c_{30}TP}{1/N + 0.25c_t}. \tag{8}$$

If $15 \le P_m < 25$, then,

$$\frac{\partial \ln Yp}{\partial \ln TP} = \left[\frac{0.3Fb_0 + 0.5(1-F)b_c}{(1+e^{20-Pm})^2} e^{20-Pm} + \left\{ 0.01Fb_0 + 0.025(1-F)b_c + \frac{0.015Fb_0 + 0.025(1-F)b_c}{1+e^{Pm-20}} \right\} - \frac{0.015Fb_0 + 0.025(1-F)b_c}{(1+e^{Pm-20})^2} e^{Pm-20} P_m \right] \frac{\partial P_m}{\partial t} \frac{TP}{b_{gm}} - \frac{0.25(0.0019 + 0.0020TP)c_{30}TP}{1/N + 0.25c_t}. \tag{9}$$

If $P_m \ge 25$, then,

$$\frac{\partial \ln Yp}{\partial \ln TP} = \frac{[0.01Fb_o + 0.025(1-F)b_c]TP}{b_{gm}} \frac{\partial P_m}{\partial TP} - \frac{0.25(0.0019 + 0.0020TP)c_{30}TP}{1/N + 0.25c_t}. \tag{10}$$

In those equations, $c_{30} = 0.0283$ for legume crops and $c_{30} = 0.0108$ for other crops.

The potential yield is calculated as

$$Yp = \frac{0.36HI \cdot b_{gm} \cdot LAI/5}{1/N + 0.25c_t}, \tag{11}$$

where HI stands for the harvest index and LAI represents the leaf area index. Figure 5 presents relations between the

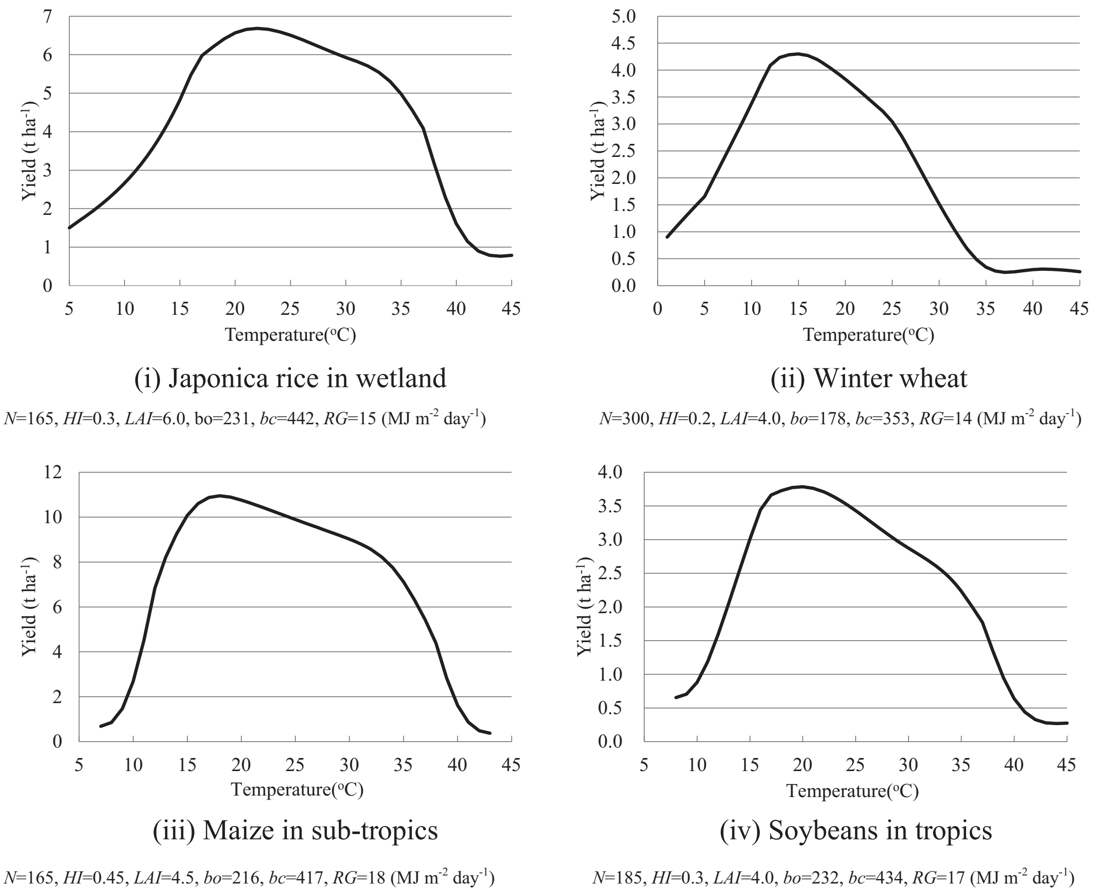


Fig. 5. Relation between temperature and potential yield

temperature and potential yield of Japonica rice in wetland, winter wheat, maize in sub-tropics, and soybeans in the tropics of the crop model of the GAEZ. These graphs indicate smoothing loci based on the modified functions of the maximum rate of gross biomass production and the maximum net rates of CO_2 exchange of leaves as shown in Figure 3 and 4. Total growing days (N) (day), harvest index (HI) (dimensionless number), leaf area index (LAI) (dimensionless number), the gross dry–matter production rate on a completely overcast day and a perfectly clear day (b_o, b_c) (kg ha^{-1} day^{-1}), and solar–radiation (RG) (MJ m^{-2} day^{-1}) are shown in the graph notations. The unit of solar–radiation is changed from cal cm^{-2} day^{-1} to MJ m^{-2} day^{-1} in these graphs of Figure 5 (1 MJ m^{-2} day^{-1} = 23.89 cal cm^{-2} day^{-1}).

The solar–radiation elasticity of potential yield is calculated using the following equation:

$$\frac{\partial \ln Yp}{\partial \ln RG} = \frac{\partial Yp}{\partial RG}\frac{RG}{Yp} = \frac{\partial B_n}{\partial RG}\frac{RG}{B_n} = \frac{\partial b_{gm}}{\partial RG}\frac{RG}{b_{gm}} = \frac{\partial b_{gm}}{\partial F}\frac{\partial F}{\partial RG}\frac{RG}{b_{gm}}. \qquad (12)$$

The marginal propensity of F to RG is shown below.

$$F = \frac{A_c - 0.5RG}{0.8A_c}, \ \frac{\partial F}{\partial RG} = -\frac{0.625}{A_c}. \qquad (13)$$

Substituting the marginal propensity of b_{gm} to F and that of F to RG into the equation, the solar–radiation elasticities of the potential yield are obtained as presented below.

If $P_m < 15$, then

$$\frac{\partial \ln Yp}{\partial \ln RG} = -\frac{0.625}{A_c}[(0.5+0.025P_m)b_o - 0.05P_m b_c]\frac{RG}{b_{gm}}. \qquad (14)$$

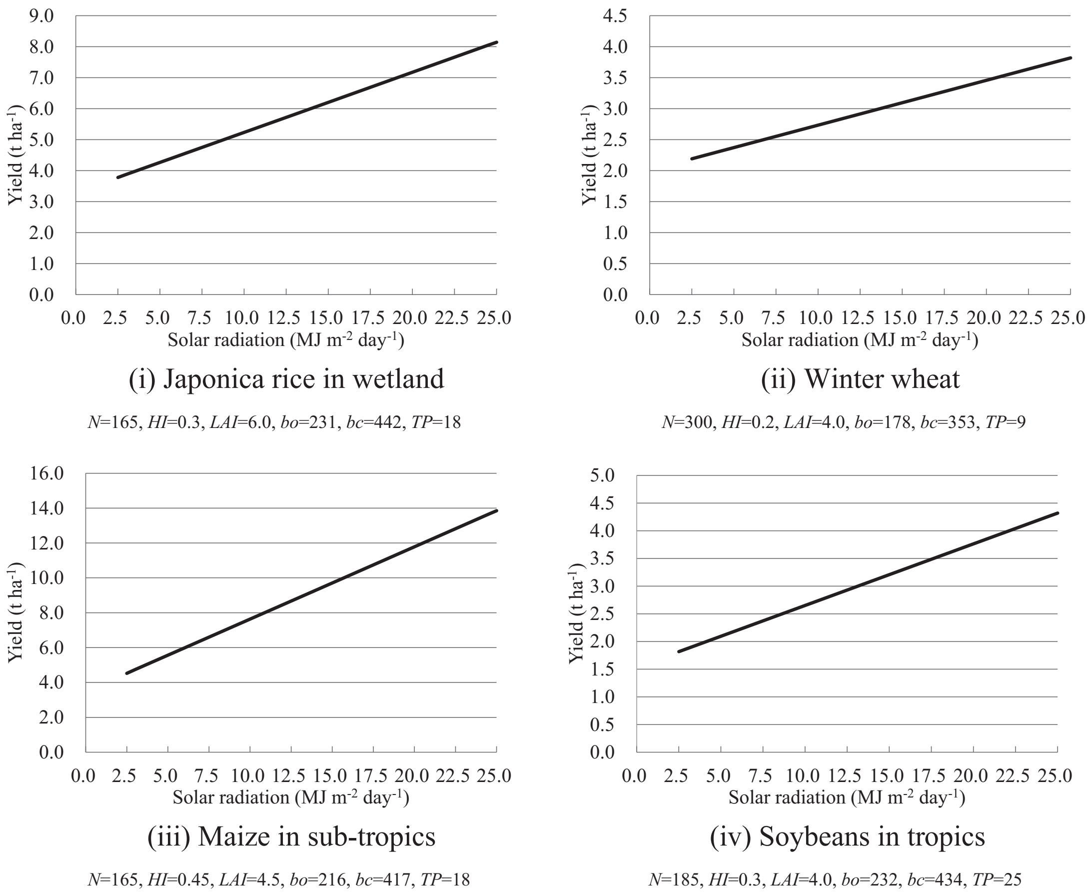
If $15 \le P_m < 25$, then

$$\frac{\partial \ln Yp}{\partial \ln RG} = -\frac{0.625}{A_c}[0.05b_0 + 0.75b_c + (0.0775b_0 - 0.1375b_c)P_m - (0.0015b_0 - 0.0025b_c)P_m^2]\frac{RG}{b_{gm}}. \qquad (15)$$

If $P_m \ge 25$, then

$$\frac{\partial \ln Yp}{\partial \ln RG} = -\frac{0.625}{A_c}[(0.8+0.01P_m)b_o - (0.5+0.025P_m)b_c]\frac{RG}{b_{gm}}. \qquad (16)$$

Figure 6 shows the relations between solar–radiation and



(i) Japonica rice in wetland

N=165, HI=0.3, LAI=6.0, bo=231, bc=442, TP=18

(ii) Winter wheat

N=300, HI=0.2, LAI=4.0, bo=178, bc=353, TP=9

(iii) Maize in sub-tropics

N=165, HI=0.45, LAI=4.5, bo=216, bc=417, TP=18

(iv) Soybeans in tropics

N=185, HI=0.3, LAI=4.0, bo=232, bc=434, TP=25

Fig. 6. Relation between solar–radiation and potential yield

the potential yield of the crop model of the GAEZ for given conditions. N, HI, LAI, b_o, b_c, and TP are shown in the graph notation.

(4) Incorporating temperature and solar–radiation elasticities into the yield functions

Yield functions specified as logistic functions with marginal propensity to temperature, solar–radiation, and rainfall in the base year 2008 and the 2009 are

$$Y_{lk2008} = a_{lk} + \frac{b_{lk} - a_{lk}}{1+\exp[-c_{lk}(T_{2008} - d_{lk})]} + \frac{\partial Yp_{lk2008}}{\partial TP_{lk2008}} TP_{lk2008} + \frac{\partial Yp_{lk2008}}{\partial RG_{lk2008}} RG_{lk2008} + \frac{\partial Yp_{lk}}{\partial PT_{lk}} PT_{lk2008}, \quad (17)$$

$$\begin{aligned} Y_{lk2009} = a_{lk} &+ \frac{b_{lk} - a_{lk}}{1+\exp[-c_{lk}(T_{2009} - d_{lk})]} + \frac{\partial Yp_{lk2008}}{\partial TP_{lk2008}} TP_{lk2008} + \frac{\partial Yp_{lk2008}}{\partial RG_{lk2008}} RG_{lk2008} + \frac{\partial Yp_{lk}}{\partial PT_{lk}} PT_{lk2008} \\ &+ \frac{1}{2}\left(\frac{\partial Yp_{lk2009}}{\partial TP_{lk2009}} + \frac{\partial Yp_{lk2008}}{\partial TP_{lk2008}}\right)(TP_{lk2009} - TP_{lk2008}) \\ &+ \frac{1}{2}\left(\frac{\partial Yp_{lk2009}}{\partial RG_{lk2009}} + \frac{\partial Yp_{lk2008}}{\partial RG_{lk2008}}\right)(RG_{lk2009} - RG_{lk2008}) \\ &+ \frac{\partial Yp_{lk}}{\partial PT_{lk}}(PT_{lk2009} - PT_{lk2008}) \ . \end{aligned} \quad (18)$$

where T stands for the time trend where 1961=1, Yp_{lk} denotes the potential yield, l stands for the index of crop, k represents the index of country, and t signifies the year. Parameters a_{lk}, b_{lk}, c_{lk}, and d_{lk} of function (17) are the same as those in function (1). The yield function in year t can be written as follows.

$$\begin{aligned} Y_{lkt} = Y_{lkt-1} &+ \frac{b_{lk} - a_{lk}}{1+\exp[-c_{lk}(T_t - d_{lk})]} - \frac{b_{lk} - a_{lk}}{1+\exp[-c_{lk}(T_{t-1} - d_{lk})]} \\ &+ \frac{1}{2}\left(\frac{\partial Yp_{lkt}}{\partial TP_{lkt}} + \frac{\partial Yp_{lkt-1}}{\partial TP_{lkt-1}}\right)(TP_{lkt} - TP_{lkt-1}) \\ &+ \frac{1}{2}\left(\frac{\partial Yp_{lkt}}{\partial RG_{lkt}} + \frac{\partial Yp_{lkt-1}}{\partial RG_{lkt-1}}\right)(RG_{lkt} - RG_{lkt-1}) \\ &+ \frac{\partial Yp_{lk}}{\partial PT_{lk}}(PT_{lkt} - PT_{lkt-1}) \end{aligned} \quad (19)$$

In a similar fashion, the yield function that is specified as the linear function with the logarithmic time trend is

$$\begin{aligned} Y_{lkt} = Y_{lkt-1} &+ b_{Tlk}(\ln T_{Lt} - \ln T_{Lt-1}) \\ &+ \frac{1}{2}\left(\frac{\partial Yp_{lkt}}{\partial TP_{lkt}} + \frac{\partial Yp_{lkt-1}}{\partial TP_{lkt-1}}\right)(TP_{lkt} - TP_{lkt-1}) \\ &+ \frac{1}{2}\left(\frac{\partial Yp_{lkt}}{\partial RG_{lkt}} + \frac{\partial Yp_{lkt-1}}{\partial RG_{lkt-1}}\right)(RG_{lkt} - RG_{lkt-1}) \\ &+ \frac{\partial Yp_{lk}}{\partial PT_{lk}}(PT_{lkt} - PT_{lkt-1}) \ , \end{aligned} \quad (20)$$

where T_L is the time trend where 1951=1. Parameter b_{Tlk} of function (20) is the same as that in function (2). The marginal propensities are replaced by elasticities multiplied by the yield by temperature in the base year 2008.

$$\begin{aligned} Y_{lkt} = Y_{lkt-1} &+ \frac{b_{lk} - a_{lk}}{1+\exp[-c_{lk}(T_t - d_{lk})]} - \frac{b_{lk} - a_{lk}}{1+\exp[-c_{lk}(T_{t-1} - d_{lk})]} \\ &+ \frac{1}{2}\left(\frac{\partial \ln Yp_{lkt}}{\partial \ln TP_{lkt}} + \frac{\partial \ln Yp_{lkt-1}}{\partial \ln TP_{lkt-1}}\right)\frac{Y_{lk2008}}{TP_{lk2008}}(TP_{lkt} - TP_{lkt-1}) \\ &+ \frac{1}{2}\left(\frac{\partial \ln Yp_{lkt}}{\partial \ln RG_{lkt}} + \frac{\partial \ln Yp_{lkt-1}}{\partial \ln RG_{lkt-1}}\right)\frac{Y_{lk2008}}{RG_{lk2008}}(RG_{lkt} - RG_{lkt-1}) \\ &+ \beta_{PTlk}(PT_{lkt} - PT_{lkt-1}) \end{aligned} \quad (21)$$

$$\begin{aligned} Y_{lkt} = Y_{lkt-1} &+ b_{Tlk}(\ln T_{Lt} - \ln T_{Lt-1}) \\ &+ \frac{1}{2}\left(\frac{\partial \ln Yp_{lkt}}{\partial \ln TP_{lkt}} + \frac{\partial \ln Yp_{lkt-1}}{\partial \ln TP_{lkt-1}}\right)\frac{Y_{lk2008}}{TP_{lk2008}}(TP_{lkt} - TP_{lkt-1}) \\ &+ \frac{1}{2}\left(\frac{\partial \ln Yp_{lkt}}{\partial \ln RG_{lkt}} + \frac{\partial \ln Yp_{lkt-1}}{\partial \ln RG_{kt-1}}\right)\frac{Y_{lk2008}}{RG_{lk2008}}(RG_{lkt} - RG_{lkt-1}) \\ &+ \beta_{PTlk}(PT_{lkt} - PT_{lkt-1}) \ . \end{aligned} \quad (22)$$

In those equations, the β_{PTlk} values of functions (21) and (22) are respectively equivalent to those in functions (1) and (2). Y_{lk2008} is the average yield of crop l and country k during 2007–2009. TP_{lk2008}, RG_{lk2008}, and PT_{lk2008} respectively denote the average temperature, solar–radiation, and rainfall of crop l and country k during 2007–2009. The historical climate data are available by 2009. The temperature and solar–radiation elasticities of yield of the four crops in each country are comparable among different years and countries. The yield rate of change to these climate variables is calculated using yield and climate variables in the base year. Accordingly, the risk of overestimating climate–change impacts on yields in lower productivity countries is eliminated. The temperature and solar–radiation elasticities are varied by changes in these climate variables in these yield functions.

Data

Yields of rice, wheat, maize, and soybeans from 1961 or the earliest available year to 2011 were gathered from FAO–STAT for 129 countries. The selected countries depend on those of the database of GTAP 8 (Narayanan *et al*. 2012). Hong Kong, Singapore, and the rest of the world including Greenland were omitted because no yield data for them are included in the FAO–STAT.

Data of the forecast temperature and solar–radiation from 2006–2050 are the values of a high-resolution Model for Interdisciplinary Research on Climate (MIROC5) of the Center for Climate System Research, The University of Tokyo (CCSR), National Institute for Environmental Studies (NIES), and the Japan Agency for Marine–Earth Science and Technology (JAMSTEC). Four outputs depend on the representative concentration pathways (RCP) (van Vuuren *et al*. 2011: RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios of the CMIP5 of the IPCC). Average temperature, solar–radiation, and rainfall of the four scenarios are used for the simulations.

These GCM forecast climate data were interpolated to the 0.5° grid using the method described by Yokozawa *et al*. (2003). These grid data are averaged for each country. If the country is large, such as the U.S.A. or mainland China, these data are averaged for crop–cultivation regions according to Furuya & Koyama (2005).

Results

1. Trend analyses of major production countries

Table 1–4 presents the estimation results of yield functions specified as logistic functions or linear functions with terms of logarithmic time trends. Columns of a_{lk}, b_{lk}, c_{lk}, and d_{lk} show the parameters of logistic function, i.e., minimum yield, maximum yield, slope, and inflection point, where l is the index of crops and k is the index of countries. In addition, β_{TPlk}, β_{RGlk}, and β_{PTlk} respectively represent the estimated parameters of temperature, solar–radiation, and rainfall of the yield functions. Accordingly, the minimum and maximum yields are shifted by these climate terms. If the convergence results of the logistic function were not obtained, then the linear–yield functions that have terms of logarithmic time trends were estimated using OLS, AR1, or AR2. The logarithmic time trend parameters are shown in these tables in column b_{Tlk}.

In addition to the climate variables, soil moisture and CO_2 concentration are important factors underlying yield changes under climate–change. This study includes the effects of changes in soil moisture in the parameter of rainfall. Moreover, the effects of increased CO_2 concentration are included in the time–trend parameter because the rate of increase in CO_2 concentration has remained almost constant over the past 50 years.

The three simulations are selected to ascertain climate–change effects on crop production: 1) Baseline, 2) RCP2.6, and 3) RCP8.5. The baseline scenario includes an assumption of unchanged temperature, solar–radiation, and rainfall during the simulation term of 2009–2050. Simulations of RCP2.6 and RCP8.5 include assumptions that temperature, solar–radiation, and rainfall will match those of RCP2.6 and RCP8.5 scenarios of the CMIP5.

Some loci of trend and simulation results showing yields of main production countries are investigated using graphs. Figures 7(i) and 7(ii), respectively present rice yields in Japan and India. As one might expect, Japonica and Indica rice are respectively cultivated in Japan and India. The rice yield in Japan faces a downtrend phase because farmers select high eating–quality but low–yield varieties when confronted with declining demand situation. Climate change increases the yield. Average yields under RCP8.5 and RCP2.6 scenarios are expected to be 5.98 and 6.00 t ha^{-1}, respectively, during 2041–2050, whereas the baseline yield is expected to be 5.72 t ha^{-1} in those years. The rice yield in India will increase steadily, but the rate of increase is expected to slow. Yields under RCP8.5 and RCP2.6 scenarios are expected to fall respectively to 4.01 and 4.06 t ha^{-1} from the baseline yield in 4.09 t ha^{-1}, on average during 2041–2050.

Figures 7(iii) and 7(iv) respectively portray wheat yields in mainland China and India. The baseline results show a steady increase in wheat in mainland China. Climate change puts upward pressure on the yield. The respective yields of RCP8.5 and RCP2.6 are expected to become 6.29 and 6.17 t ha^{-1}, whereas the baseline yield will be 5.73 t ha^{-1} in the 2040s. The simulation results in mainland China of the climate change show substantial fluctuations during the simulation term in both RCP8.5 and RCP2.6 scenarios. The peak of the locus between yield and temperature of wheat is sharper than those of other crops such as those presented in Figure 5(ii). The yield of wheat in mainland China will fall dramatically in the crop model if temperatures exceed 12°C. The coefficients of variation, which represent the ratio of standard deviations to averages, of yield of wheat in mainland China during the simulation term of RCP8.5 and RCP2.6 are, respectively, 7.9 and 6.4% respectively. The yield of wheat in India is decreased by climate change under the RCP8.5 scenario. The average yields under RCP8.5 scenario during 2041–2050, are expected to be 3.00 t ha^{-1}, whereas the baseline yield is expected to be 3.06 t ha^{-1} that same years.

Maize differs physiologically from the other three crops: it is a C4 crop, whereas rice, wheat, and soybeans are C3 crops. The C4 plants have thrived at higher temperatures and in drier environments than the C3 plants have, while C4 plants can adapt to a low-CO_2 atmosphere (Rötter & van de Geijn 1999, Hatch 2002). Figures 7(v) and 7(vi) respectively present maize yields in the U.S.A. and mainland China. The graph of the U.S.A. shows that higher temperatures will push up the yields of this crop in either scenario. Maize yields in the U.S.A. in the baseline will increase over the next 40 years. The respective yields of RCP8.5 and RCP2.6 are expected to become 12.33 and 12.55 t ha^{-1}, whereas the baseline yield will be 11.93 t ha^{-1} in the 2040s.

Table 1. Parameters of rice yield functions

k	Country	$a1k$	$b1k$	$c1k$	$d1k$	$bT1k$	$\beta TP1k$	$\beta RG1k$	$\beta PT1k$
1	AUS	-8.812	-6.661	2.941	28.473		0.627	-0.001	0.002
2	NZL								
3	XOC	3.494	4.752	0.010	5.015		0.102	-0.012	0.001
4	CHN	5.105	9.262	0.146	20.476		-0.108	-0.001	0.000
5	HKG								
6	JPN					0.889	0.142	0.001	-0.007
7	KOR	1.937	5.327	0.382	15.527		0.147	-0.001	-0.001
8	MNG								
9	TWN	2.632	6.218	0.078	19.348		-0.072	0.004	0.000
10	XEA					-0.444	-0.126	0.005	0.008
11	KHM	5.585	8.062	0.155	45.133		-0.072	-0.007	0.000
12	IDN	1.528	4.637	0.157	17.791		0.049	-0.003	0.000
13	LAO	0.944	8.078	0.051	48.198		-0.064	0.001	0.002
14	MYS					0.905	-0.123	0.001	0.000
15	PHL	-0.582	2.917	0.077	24.005		0.077	-0.002	0.000
16	SGP								
17	THA	1.215	2.793	0.136	38.958		0.003	0.001	0.000
18	VNM	3.711	7.988	0.118	37.167		-0.080	0.001	-0.001
19	XSE					1.411	-0.133	0.002	0.000
20	BGD	1.128	8.168	0.075	54.652		-0.005	0.001	0.000
21	IND					2.434	0.123	0.003	0.000
22	NPL	3.619	4.773	0.215	34.443		-0.087	-0.001	0.003
23	PAK					1.082	0.053	-0.008	-0.001
24	LKA	3.100	5.066	0.120	24.654		0.016	-0.004	-0.001
25	XSA	0.206	1.619	0.539	42.941		0.003	0.005	-0.001
26	CAN								
27	USA	7.296	12.879	0.072	40.302		-0.061	-0.003	0.002
28	MEX	-0.128	2.784	0.110	20.231		-0.005	0.005	0.000
29	XNA								
30	ARG	-6.741	-2.238	0.118	40.937		-0.028	0.022	0.000
31	BOL	-0.391	0.425	0.233	31.406		0.018	0.003	0.000
32	BRA	-1.147	2.732	0.139	42.377		-0.018	0.008	0.000
33	CHL	-19.279	-16.112	0.107	21.984		-0.032	0.040	0.000
34	COL					2.048	0.033	-0.002	0.003
35	ECU					1.246	-0.239	0.011	0.002
36	PRY	-4.735	-2.705	0.314	36.179		0.153	0.005	0.004
37	PER	7.164	10.774	0.139	35.598		-0.148	-0.002	0.003
38	URY					2.343	0.354	0.017	-0.003
39	VEN	-2.299	1.841	0.098	19.884		0.221	-0.004	-0.002
40	XSM	1.280	3.369	0.155	18.343		0.018	0.001	-0.001
41	CRI	-5.009	-2.181	0.151	17.866		0.224	0.000	0.003
42	GTM					0.939	-0.179	-0.023	0.000
43	HND					1.769	0.112	0.017	0.000
44	NIC					1.172	0.038	0.007	0.001
45	PAN	2.111	3.514	0.170	14.639		-0.057	0.001	-0.001
46	SLV					2.866	-0.433	-0.025	0.002
47	XCA					8.992	-0.469	0.003	0.001
48	XCB	7.311	9.023	0.383	15.404		-0.272	0.003	0.000
49	AUT								
50	BEL								
51	CYP								
52	CZE								
53	DNK								
54	EST								
55	FIN								
56	FRA	7.545	9.295	0.727	22.107		0.000	-0.005	-0.028
57	DEU								
58	GRC	5.322	9.215	0.121	26.158		-0.122	0.003	-0.003
59	HUN	-9.649	-7.840	0.108	9.559		0.644	0.000	-0.003
60	IRL								
61	ITA					0.666	0.283	0.016	-0.003
62	LVA								
63	LTU								
64	LUX								
65	MLT								

k	Country	$a1k$	$b1k$	$c1k$	$d1k$	$bT1k$	$\beta TP1k$	$\beta RG1k$	$\beta PT1k$
66	NLD								
67	POL								
68	PRT	3.041	4.479	0.932	31.708		0.163	-0.004	0.004
69	SVK								
70	SVN								
71	ESP	3.511	4.635	0.997	36.542		0.074	0.002	0.012
72	SWE								
73	GBR								
74	CHE								
75	NOR								
76	XEF								
77	ALB					1.576	-0.014	-0.013	-0.007
78	BGR					0.775	0.262	-0.001	0.009
79	BLR								
80	HRV								
81	ROU	-6.832	-1.755	0.610	49.093		0.066	0.018	0.005
82	RUS					6.299	0.045	0.037	0.028
83	UKR					4.724	0.381	0.008	0.012
84	XEE								
85	XER					3.955	-0.179	0.005	0.012
86	KAZ					2.148	0.057	0.012	0.004
87	KGZ					5.825	-0.050	0.013	0.007
88	XSU					3.929	-0.365	0.023	0.025
89	ARM								
90	AZE					14.265	0.616	-0.045	0.002
91	GEO								
92	BHR								
93	IRN	6.528	9.425	0.069	24.931		-0.118	-0.003	0.050
94	ISR								
95	KWT								
96	OMN								
97	QAT								
98	SAU								
99	TUR					1.807	-0.146	-0.019	-0.021
100	ARE								
101	XWS					0.024	-0.063	-0.046	-0.013
102	EGY	-0.019	4.743	0.228	32.787		0.029	0.008	-0.091
103	MAR	-33.078	-30.251	0.245	38.240		0.296	0.058	0.020
104	TUN								
105	XNF					-1.055	0.115	-0.002	0.153
106	CMR					2.115	0.087	0.001	0.008
107	CIV					0.599	-0.127	0.001	0.002
108	GHA	-0.639	0.448	0.488	30.435		0.068	-0.002	0.003
109	NGA					0.831	0.077	0.003	0.002
110	SEN	-2.923	-1.378	0.185	21.740		0.130	-0.002	0.011
111	XWF					0.543	-0.030	-0.001	0.002
112	XCF					0.309	0.135	0.015	0.012
113	XAC					-0.093	0.014	0.000	0.000
114	ETH								
115	KEN					1.058	0.137	0.015	0.011
116	MDG	-2.558	-0.231	0.139	48.336		-0.042	0.012	0.000
117	MWI	1.585	2.594	0.230	20.787		-0.101	0.003	0.003
118	MUS								
119	MOZ					0.264	-0.037	-0.007	0.000
120	TZA					0.437	0.030	0.003	0.003
121	UGA					0.235	0.033	-0.004	-0.002
122	ZMB								
123	ZWE					0.661	-0.039	0.003	0.001
124	XEC								
125	BWA								
126	NAM								
127	ZAF					0.612	0.213	0.010	0.009
128	XSC					1.956	0.263	-0.025	-0.003
129	XTW								

Note: Trend in India, log(*year*-1920); otherwise, log(*year*-1950)

Table 2. Parameters of wheat yield functions

k	Country	a2k	b2k	c2k	d2k	bT2k	βTP2k	βRG2k	βPT2k	k	Country	a2k	b2k	c2k	d2k	bT2k	βTP2k	βRG2k	βPT2k
1	AUS	-0.519	0.372	0.174	30.639		-0.128	0.006	0.030	66	NLD	1.443	6.178	0.168	19.972		-0.187	0.018	0.001
2	NZL	1.036	6.793	0.146	37.143		-0.179	0.018	-0.008	67	POL	-0.037	2.277	0.118	11.601		0.067	0.004	-0.003
3	XOC					1.260	-0.203	0.007	-0.006	68	PRT	3.561	4.821	0.193	26.992		-0.188	0.000	-0.003
4	CHN	1.726	7.074	0.080	26.836		-0.003	-0.003	-0.009	69	SVK					-0.885	0.121	0.002	0.043
5	HKG									70	SVN					1.086	0.139	-0.005	0.011
6	JPN	-4.266	-2.698	0.122	21.657		-0.008	0.021	0.005	71	ESP	-1.664	0.977	0.103	23.629		-0.094	0.008	0.012
7	KOR	-3.167	-1.708	0.190	19.964		0.134	0.012	0.000	72	SWE	0.668	8.990	0.064	-6.959		0.251	-0.015	-0.001
8	MNG					0.391	-0.037	-0.005	0.017	73	GBR	5.531	10.351	0.155	22.226		-0.226	0.003	-0.008
9	TWN	1.135	4.941	0.062	36.497		0.033	0.000	-0.001	74	CHE	3.100	5.810	0.206	18.880		0.034	0.004	-0.008
10	XEA					1.088	0.056	0.001	0.000	75	NOR	12.487	16.063	0.134	6.083		-0.079	-0.068	0.009
11	KHM									76	XEF								
12	IDN									77	ALB					1.817	0.013	0.009	-0.003
13	LAO									78	BGR					2.051	-0.063	0.011	0.020
14	MYS									79	BLR					2.407	0.103	0.037	0.038
15	PHL									80	HRV					3.635	-0.012	0.014	-0.011
16	SGP									81	ROU	3.968	5.553	0.221	11.476		-0.037	-0.008	0.002
17	THA									82	RUS					3.157	-0.320	-0.005	-0.007
18	VNM									83	UKR					1.254	0.011	-0.028	-0.041
19	XSE	-5.987	-4.936	0.542	20.940		0.218	0.004	0.003	84	XEE					-6.251	0.518	-0.051	0.087
20	BGD	-4.666	-3.186	0.548	16.379		-0.003	0.014	0.002	85	XER					2.897	-0.206	0.019	0.017
21	IND	-4.571	-1.832	0.091	23.822		-0.061	0.015	-0.002	86	KAZ					2.010	-0.298	-0.005	-0.017
22	NPL	2.802	3.929	0.215	39.403		-0.003	-0.004	-0.002	87	KGZ					1.460	-0.238	0.006	-0.010
23	PAK					1.084	0.001	0.008	0.010	88	XSU					8.442	0.008	0.023	0.046
24	LKA									89	ARM					0.725	0.030	-0.010	0.028
25	XSA	2.012	3.011	0.407	44.241		-0.064	-0.001	-0.002	90	AZE					3.027	-0.148	-0.001	-0.001
26	CAN					0.751	-0.002	0.012	0.008	91	GEO					1.320	-0.104	-0.002	0.009
27	USA					0.793	0.009	0.011	0.010	92	BHR					0.000	0.000	0.000	0.000
28	MEX	1.241	4.916	0.109	13.628		-0.140	0.007	-0.014	93	IRN					0.000	0.000	0.000	0.000
29	XNA									94	ISR					0.580	-0.312	0.026	0.030
30	ARG	3.648	5.595	0.085	34.570		-0.126	-0.004	0.002	95	KWT					-0.111	-0.263	-0.082	-0.011
31	BOL					0.292	0.058	0.001	-0.005	96	OMN	5.690	8.187	0.185	33.763		-0.664	0.026	0.070
32	BRA	0.773	3.040	0.089	33.910		-0.123	0.008	-0.003	97	QAT					1.057	-0.008	0.004	-0.007
33	CHL	-1.864	1.192	0.197	30.090		0.103	0.010	0.000	98	SAU	5.979	9.866	0.385	24.149		-0.071	-0.003	-0.207
34	COL	1.811	2.693	0.260	25.059		0.033	-0.005	0.001	99	TUR	4.692	5.970	0.196	13.865		-0.017	-0.011	0.001
35	ECU					0.144	0.004	0.001	0.000	100	ARE					0.741	-0.086	-0.059	-0.159
36	PRY	-4.704	-3.571	0.191	21.133		-0.004	0.017	-0.005	101	XWS	6.243	8.043	0.109	34.412		-0.019	-0.013	0.013
37	PER	-2.357	-1.983	0.680	24.305		0.039	0.006	0.002	102	EGY	-5.633	-1.300	0.158	29.350		-0.130	0.024	0.035
38	URY	-2.982	-0.653	0.119	32.514		-0.156	0.021	0.000	103	MAR	10.366	11.079	0.473	22.455		-0.230	-0.018	0.012
39	VEN	0.715	0.481	0.371	8.485		0.010	-0.001	0.000	104	TUN	-0.575	1.001	0.087	36.721		0.001	0.002	0.020
40	XSM									105	XNF	0.087	1.864	0.099	48.079		-0.038	0.001	0.113
41	CRI									106	CMR					1.030	-0.076	0.003	-0.007
42	GTM	7.135	8.114	0.273	20.241		0.044	-0.015	-0.002	107	CIV								
43	HND					0.061	0.002	0.006	0.000	108	GHA								
44	NIC									109	NGA					-0.276	-0.209	-0.009	0.028
45	PAN									110	SEN								
46	SLV									111	XWF					0.541	0.186	-0.001	-0.020
47	XCA									112	XCF					0.139	0.039	-0.010	-0.015
48	XCB									113	XAC					0.992	0.043	0.002	0.001
49	AUT	7.966	10.902	0.140	15.543		0.048	-0.015	-0.014	114	ETH								
50	BEL					3.480	-0.748	0.029	0.027	115	KEN					0.666	-0.008	0.004	0.009
51	CYP	4.902	6.198	0.455	25.709		-0.158	-0.005	0.013	116	MDG								
52	CZE					6.921	-0.107	-0.035	0.008	117	MWI					0.601	-0.163	-0.005	0.008
53	DNK	2.001	4.809	0.226	20.456		0.218	0.003	-0.002	118	MUS								
54	EST					3.508	0.046	-0.005	0.018	119	MOZ					0.318	-0.144	-0.008	-0.005
55	FIN	8.651	14.607	0.051	31.953		0.009	-0.042	-0.009	120	TZA					0.344	0.178	0.005	0.010
56	FRA	6.473	11.901	0.116	17.412		-0.149	-0.007	-0.015	121	UGA								
57	DEU	6.863	12.320	0.103	23.126		-0.048	-0.012	-0.013	122	ZMB	30.325	38.066	0.095	26.153		-0.791	-0.034	0.150
58	GRC	-2.857	-1.558	0.267	10.585		-0.039	0.012	0.012	123	ZWE	-12.675	-8.252	0.172	10.506		0.103	0.028	0.033
59	HUN	4.307	7.199	0.285	12.130		-0.087	-0.006	-0.006	124	XEC					0.338	0.305	0.000	0.003
60	IRL	-4.590	0.670	0.184	22.831		0.091	0.032	0.002	125	BWA					0.012	-0.442	-0.017	-0.045
61	ITA	5.917	7.985	0.121	26.605		-0.266	-0.002	-0.002	126	NAM	7.474	11.970	0.175	25.745		-0.318	-0.003	0.155
62	LVA					4.208	0.150	0.003	0.006	127	ZAF					1.391	-0.276	-0.023	-0.015
63	LTU					5.688	0.075	0.001	-0.006	128	XSC					0.041	0.032	0.001	0.016
64	LUX					1.296	-1.264	0.067	0.079	129	XTW								
65	MLT	-4.945	-2.385	0.331	15.732		0.292	0.007	0.007										

Table 3. Parameters of maize yield functions

k	Country	*a3k*	*b3k*	*c3k*	*d3k*	*bT3k*	*βTP3k*	*βRG3k*	*βPT3k*
1	AUS	1.113	4.693	0.172	27.483		-0.138	0.008	0.006
2	NZL					3.947	0.388	-0.002	-0.007
3	XOC	-2.652	-1.069	0.595	34.406		0.126	0.003	-0.002
4	CHN	2.805	7.734	0.107	20.619		-0.190	0.000	0.011
5	HKG								
6	JPN					-0.104	-0.020	0.005	0.000
7	KOR	2.963	6.457	0.570	16.434		-0.248	0.006	0.002
8	MNG								
9	TWN	3.230	8.317	0.122	27.167		-0.037	-0.001	-0.001
10	XEA	5.032	12.065	0.114	29.278		-0.065	-0.005	0.003
11	KHM					9.809	-3.028	0.016	0.003
12	IDN					2.806	-0.015	0.001	0.000
13	LAO	-2.924	2.122	0.251	45.821		0.133	0.002	0.001
14	MYS					4.059	0.065	-0.005	-0.002
15	PHL					0.837	-0.037	0.000	0.000
16	SGP								
17	THA	6.580	8.545	0.204	33.702		-0.174	-0.002	0.004
18	VNM	1.487	4.585	0.197	38.457		0.016	-0.001	-0.001
19	XSE					3.263	-0.018	0.002	0.002
20	BGD					23.925	-0.205	0.005	0.006
21	IND	2.347	7.062	0.073	56.801		-0.136	0.004	0.002
22	NPL					1.661	-0.012	-0.001	-0.001
23	PAK					5.135	0.054	0.012	-0.003
24	LKA					2.768	-0.014	-0.004	0.003
25	XSA					0.156	0.342	-0.003	-0.009
26	CAN	0.986	6.817	0.076	37.412		0.239	-0.002	0.007
27	USA					5.688	-0.091	-0.058	-0.018
28	MEX					1.128	-0.017	0.002	0.000
29	XNA								
30	ARG					2.796	-0.273	-0.007	0.011
31	BOL					0.718	-0.060	-0.002	-0.003
32	BRA	13.068	16.814	0.118	40.848		-0.190	-0.017	-0.001
33	CHL	-19.328	-11.559	0.226	26.599		-0.109	0.042	0.025
34	COL					0.700	0.057	-0.002	0.000
35	ECU					0.751	-0.096	0.001	-0.001
36	PRY	-0.122	1.241	0.140	29.017		0.014	0.001	0.003
37	PER					0.823	-0.036	0.001	0.002
38	URY	10.320	18.902	0.157	43.899		-0.095	-0.015	-0.005
39	VEN	4.934	7.372	0.191	30.785		-0.090	-0.003	-0.002
40	XSM					-0.094	-0.332	-0.047	0.000
41	CRI					0.540	0.013	0.000	-0.001
42	GTM					0.786	-0.080	0.001	0.000
43	HND					0.277	0.012	-0.004	0.000
44	NIC					0.410	-0.027	0.001	0.000
45	PAN	0.205	1.026	0.247	28.888		0.038	-0.001	0.000
46	SLV					1.284	-0.336	-0.017	0.001
47	XCA					1.430	-0.084	0.006	-0.002
48	XCB					0.135	-0.082	0.000	0.000
49	AUT					3.913	0.358	-0.007	0.000
50	BEL					5.377	-0.927	0.035	0.099
51	CYP								
52	CZE					10.856	-0.879	0.027	0.018
53	DNK								
54	EST								
55	FIN								
56	FRA					3.789	0.523	-0.054	-0.013
57	DEU	0.791	12.700	0.047	40.408		0.225	-0.003	0.000
58	GRC	0.538	8.813	0.313	18.670		-0.189	0.010	0.008
59	HUN					2.391	-0.144	-0.009	0.023
60	IRL								
61	ITA					4.452	-0.049	-0.030	-0.009
62	LVA								
63	LTU								
64	LUX					0.974	-0.859	-0.023	0.010
65	MLT								
66	NLD	9.712	20.170	0.110	33.482		-0.176	-0.005	-0.030
67	POL					2.445	0.193	-0.005	0.003
68	PRT	5.341	10.885	0.203	33.208		-0.046	-0.007	-0.006
69	SVK					6.741	-0.406	0.005	0.067
70	SVN								
71	ESP					4.288	0.048	-0.023	-0.012
72	SWE								
73	GBR								
74	CHE					2.905	0.364	-0.002	0.009
75	NOR								
76	XEF								
77	ALB					2.317	-0.065	0.008	0.007
78	BGR					0.659	-0.618	0.021	0.040
79	BLR					8.549	0.324	0.022	0.024
80	HRV					7.905	-0.352	-0.021	0.000
81	ROU					1.088	-0.229	0.003	0.017
82	RUS					3.262	0.062	0.015	0.106
83	UKR					7.168	-0.326	0.021	0.016
84	XEE					1.496	-0.824	-0.013	-0.004
85	XER					4.208	-0.343	-0.003	0.010
86	KAZ					7.436	-0.233	0.053	0.106
87	KGZ					8.049	-0.233	0.006	-0.027
88	XSU					13.701	-1.446	-0.024	-0.092
89	ARM					8.224	-0.522	-0.004	0.090
90	AZE					12.685	0.020	0.018	0.093
91	GEO					-2.368	0.014	-0.013	0.009
92	BHR								
93	IRN	23.043	30.545	0.141	32.314		-0.286	-0.026	-0.096
94	ISR					9.207	0.073	-0.178	0.957
95	KWT					19.716	0.393	-0.030	0.447
96	OMN								
97	QAT					7.462	0.210	0.113	-0.038
98	SAU	12.189	19.352	0.126	42.119		0.042	-0.022	-0.083
99	TUR					2.782	-0.050	0.004	0.014
100	ARE								
101	XWS	-14.436	-11.834	0.153	26.095		-0.027	0.027	0.054
102	EGY	12.520	17.693	0.175	32.800		-0.078	-0.010	-0.427
103	MAR					0.000	-0.067	-0.008	0.014
104	TUN								
105	XNF					0.560	0.231	0.014	0.077
106	CMR					0.928	-0.052	-0.001	0.001
107	CIV	4.433	5.902	0.353	33.721		-0.077	-0.004	0.000
108	GHA					0.377	0.015	-0.001	0.002
109	NGA					0.602	0.002	0.002	0.004
110	SEN					0.555	-0.036	-0.020	0.004
111	XWF					0.524	-0.026	-0.004	0.001
112	XCF					0.175	0.054	-0.001	-0.002
113	XAC					-0.062	0.046	-0.001	-0.002
114	ETH								
115	KEN					0.371	-0.031	0.002	0.006
116	MDG					-0.049	0.107	-0.006	0.000
117	MWI					4.527	-0.486	-0.042	-0.019
118	MUS	-1.170	7.252	0.127	38.800		-0.018	0.010	0.001
119	MOZ					1.049	0.196	-0.011	0.005
120	TZA					0.731	-0.021	-0.009	-0.001
121	UGA					0.377	0.136	0.006	0.002
122	ZMB					0.682	0.083	0.015	0.015
123	ZWE					-0.249	-0.179	0.009	0.016
124	XEC					0.114	-0.127	0.000	0.002
125	BWA					-0.145	-0.095	0.002	0.002
126	NAM					0.145	0.075	0.010	0.012
127	ZAF					1.141	-0.275	0.019	0.033
128	XSC					0.133	0.045	-0.009	-0.001
129	XTW								

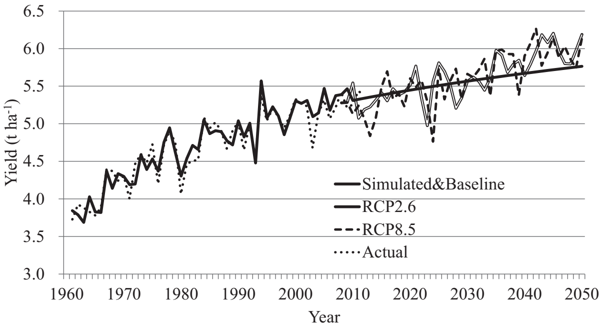
Note: Trend in U.S., log(*year*-1930); otherwise, log(*year*-1950)

Table 4. Parameters of soybeans yield functions

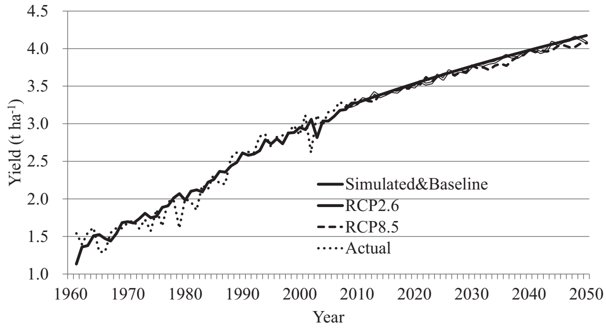
k	Country	*a4k*	*b4k*	*c4k*	*d4k*	*bT4k*	*βTP4k*	*βRG4k*	*βPT4k*
1	AUS					0.994	-0.214	0.006	0.009
2	NZL								
3	XOC								
4	CHN					0.674	0.057	-0.002	0.001
5	HKG								
6	JPN					0.322	-0.061	0.003	-0.002
7	KOR					0.797	-0.050	0.001	-0.001
8	MNG								
9	TWN					0.734	-0.097	-0.004	-0.001
10	XEA					0.493	-0.001	0.000	0.000
11	KHM					0.453	-0.073	-0.002	0.000
12	IDN	1.483	2.236	0.116	26.194		-0.014	-0.001	0.000
13	LAO					3.470	0.192	-0.003	0.001
14	MYS					1.367	-0.135	-0.004	-0.004
15	PHL					0.301	0.031	0.000	0.000
16	SGP								
17	THA					0.429	-0.025	0.001	0.001
18	VNM	1.448	2.881	0.096	37.039		-0.022	-0.001	0.000
19	XSE					0.492	0.034	0.001	0.000
20	BGD					1.580	0.000	0.000	0.000
21	IND					0.432	-0.016	-0.003	0.001
22	NPL	0.406	0.862	0.231	37.579		0.008	0.000	0.000
23	PAK					0.390	-0.003	-0.001	-0.001
24	LKA					2.227	0.063	0.006	0.001
25	XSA					0.555	-0.122	-0.001	-0.001
26	CAN	0.249	1.010	0.169	26.387		0.124	-0.002	0.005
27	USA					1.506	0.019	-0.018	-0.005
28	MEX					-0.139	-0.046	0.008	0.001
29	XNA								
30	ARG					1.054	-0.242	-0.003	0.003
31	BOL					0.696	0.232	0.000	0.000
32	BRA	6.161	9.745	0.057	43.052		-0.097	-0.008	0.002
33	CHL					0.207	-0.222	0.007	0.010
34	COL					0.350	-0.106	-0.001	-0.002
35	ECU					0.372	0.044	-0.006	-0.003
36	PRY					0.478	-0.136	-0.001	0.002
37	PER					0.347	-0.146	-0.003	-0.002
38	URY					0.670	-0.086	0.012	0.008
39	VEN					3.005	0.504	0.011	0.011
40	XSM					0.038	0.099	0.000	0.000
41	CRI					0.000	0.000	0.000	0.000
42	GTM					1.987	0.400	-0.002	0.000
43	HND					1.520	-0.222	-0.004	0.002
44	NIC					1.106	-0.201	0.006	-0.001
45	PAN					-1.244	-0.071	0.001	0.000
46	SLV					1.023	-0.073	-0.001	0.000
47	XCA					0.967	-0.663	-0.001	0.001
48	XCB								
49	AUT					2.125	-0.067	-0.002	0.003
50	BEL								
51	CYP								
52	CZE					3.175	0.140	0.003	0.029
53	DNK								
54	EST								
55	FIN								
56	FRA					0.661	0.228	-0.020	-0.006
57	DEU					-0.854	0.138	0.001	-0.020
58	GRC					-1.381	-0.188	0.020	0.005
59	HUN					0.929	0.004	-0.001	0.008
60	IRL								
61	ITA	6.564	8.467	0.178	16.168		-0.054	-0.009	0.000
62	LVA								
63	LTU								
64	LUX								
65	MLT								

k	Country	*a4k*	*b4k*	*c4k*	*d4k*	*bT4k*	*βTP4k*	*βRG4k*	*βPT4k*
66	NLD								
67	POL					3.038	0.014	-0.034	0.013
68	PRT								
69	SVK					1.500	-0.253	0.000	0.019
70	SVN					3.282	-0.016	-0.025	0.002
71	ESP					0.971	0.029	-0.006	-0.003
72	SWE								
73	GBR								
74	CHE					0.265	0.287	-0.013	0.004
75	NOR								
76	XEF								
77	ALB					2.798	-0.018	-0.016	-0.009
78	BGR					0.337	-0.208	0.003	0.014
79	BLR								
80	HRV					1.693	-0.214	-0.010	-0.002
81	ROU					0.636	0.078	-0.004	0.017
82	RUS					1.886	-0.153	0.001	0.000
83	UKR					1.854	-0.071	0.005	0.012
84	XEE					3.131	-0.278	-0.001	0.003
85	XER					2.903	-0.303	0.007	0.012
86	KAZ					2.013	0.015	0.024	0.024
87	KGZ					2.792	-0.557	0.018	-0.052
88	XSU					0.658	-0.080	-0.003	-0.011
89	ARM								
90	AZE					-2.250	0.274	-0.001	0.051
91	GEO					10.272	-0.371	-0.037	-0.023
92	BHR								
93	IRN					0.651	0.237	0.015	0.077
94	ISR								
95	KWT								
96	OMN								
97	QAT								
98	SAU								
99	TUR					2.281	-0.057	0.018	0.011
100	ARE								
101	XWS					0.440	0.011	0.019	0.028
102	EGY					1.971	-0.033	-0.010	0.286
103	MAR					-0.091	0.042	-0.008	0.026
104	TUN								
105	XNF								
106	CMR					0.562	-0.038	0.001	-0.001
107	CIV					0.851	-0.095	0.007	0.001
108	GHA								
109	NGA	0.258	0.813	0.809	36.478		0.002	-0.001	0.002
110	SEN								
111	XWF	-0.051	0.548	0.156	27.861		0.022	-0.001	0.001
112	XCF					-0.921	-0.062	0.012	0.006
113	XAC					0.119	0.052	0.000	0.001
114	ETH					13.555	-0.213	-0.007	-0.010
115	KEN					1.114	-0.190	-0.004	0.001
116	MDG					-1.229	-0.091	-0.001	0.000
117	MWI					2.283	-0.090	-0.001	0.001
118	MUS								
119	MOZ								
120	TZA					0.365	0.034	0.001	0.001
121	UGA					0.448	0.025	-0.004	0.000
122	ZMB					0.705	0.171	-0.012	-0.001
123	ZWE					0.879	-0.305	-0.012	-0.004
124	XEC					-0.166	-0.114	0.011	0.004
125	BWA								
126	NAM								
127	ZAF					0.896	-0.059	-0.021	-0.006
128	XSC								
129	XTW								

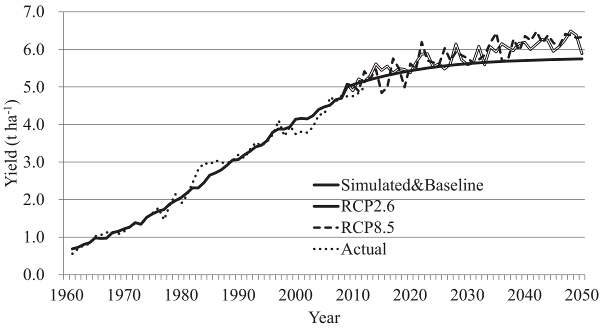
Note: Trend in U.S, log(*year*-1920); otherwise, log(*year*-1950)



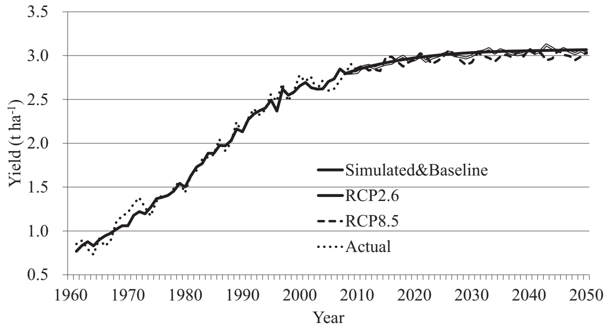
(i) Rice in Japan



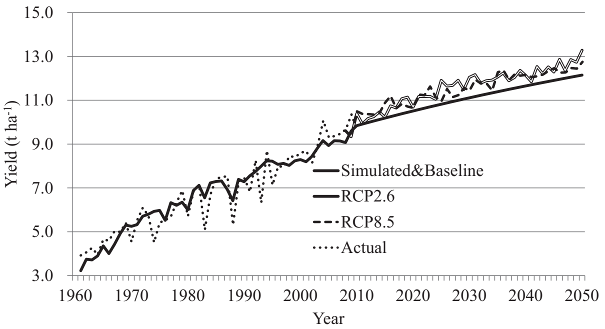
(ii) Rice in India



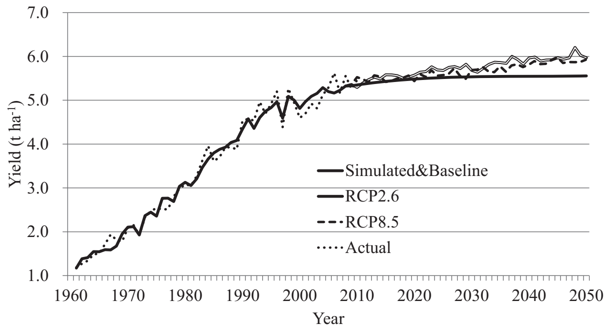
(iii) Wheat in mainland China



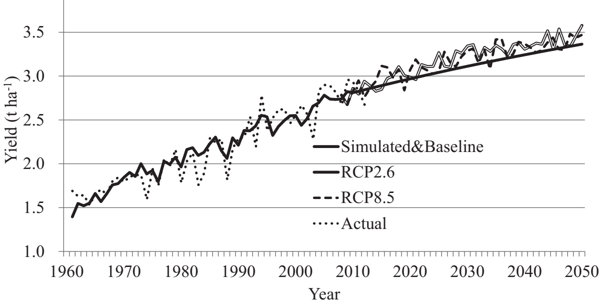
(iv) Wheat in India



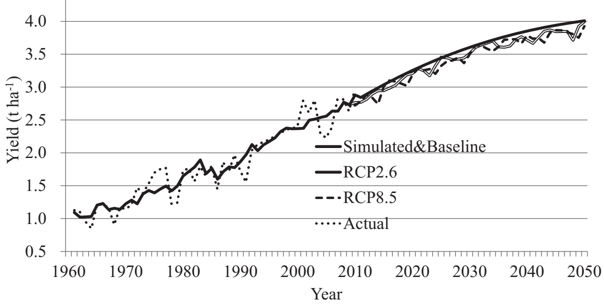
(v) Maize in the U.S.A.



(vi) Maize in mainland China



(vii) Soybeans in the U.S.A.



(viii) Soybeans in Brazil

Fig. 7. Forecast crop yields of main production countries

The maize yields in mainland China are expected to be 5.89 t ha^{-1} in RCP8.5 and 5.98 t ha^{-1} in RCP2.6 scenarios, respectively, at the average of the 2040s. Those are 0.33 and 0.43 t ha^{-1} higher than the yield of the baseline.

Figures 7(vii) and 7(viii) respectively depict soybeans yields in the U.S.A. and Brazil. Yields of soybeans in the U.S.A. are expected to increase steadily from 2.83 t ha^{-1} in 2011 to 3.36 t ha^{-1} in 2050 in the baseline. Climate change will push up soybeans yields in the U.S.A. Those under the climate scenario are expected to be 3.37 and 3.42 t ha^{-1} in the 2040s, respectively, under RCP8.5 and RCP2.6 scenarios. However, it is anticipated that climate change will affect soybeans yields in the Brazil. Soybeans yields are expected to be 3.80 and 3.83 t ha^{-1} respectively under RCP8.5 and RCP2.6 scenarios at the average of the 2040s, although that of the baseline is expected to be 3.94 t ha^{-1} during those years.

2. Geographical analysis

By analyzing climate–change effects on crop yields geographically, differences in average yields for the four crops between RCP6.0 scenario and baseline during the periods 2021–2030 and 2041–2050 can be investigated. Figures 8(i) and 8(ii) respectively portray differences in rice yields between the baseline and RCP6.0 scenarios about the two periods. These figures suggest that yields of rice in low–latitude countries except sub–Saharan African (SSA) countries will be affected by climate change in the 2020s. However, the benefits of higher temperatures will cease to exist by the 2040s in SSA countries.

Figures 8(iii) and 8(iv) respectively present differences in wheat yields between the baseline and RCP6.0 scenario for the two periods. Figure 8(iii) shows that wheat yields in Eastern Europe are expected to be decreased by low temperatures in the 2020s. Climate change will probably affect wheat yields severely in these low-latitude countries. These figures suggest that wheat yields in southern Asian and SSA countries will decrease under the scenario.

Figures 8(v) and 8(vi) respectively depict differences in the yield of maize between the baseline and RCP6.0 scenario for the two periods. Figure 8(vi) shows that maize yields in southern Asia, Southeast Asia, Australia, the Middle East, Africa, and Latin America are expected to be affected by climate change under the RCP scenario in the 2040s. However, both figures show that maize yields in high–latitude countries are expected to be increased by climate change under the scenario.

Figures 8(vii) and 8(viii) respectively portray differences in soybeans yields between the baseline and RCP6.0 scenarios for the two periods. Figure 8(vii) shows that yields in Russia will be decreased by low temperatures and yields in low-latitude countries will be decreased by high temperatures in the 2020s. Figure 8(viii) shows that the higher temperatures decrease the soybeans yield in China.

Parry *et al*. (2004) demonstrated that cereal yields in Russia and European region will be decreased by climate change under several scenarios. However, the results of our research suggest that yields of the four crops in the region will be increase by climate change. Their model, as described by Parry *et al*. (1999), consists of two–stage yield estimation. First, the potential yields are obtained from crop models and are aggregated in each region. Second, the potential yields are estimated by linear or quadratic functions, the explanatory variables for which are temperature, rainfall, and CO_2 concentration. Yield functions incorporating a crop model are used for this study. The difference in structure of the models used for yield estimation engenders the difference in results. Furthermore, as Rosenzweig *et al*. (2014) have reported, the differences in estimated crop–model yields affect the differences in the results of this study from those of other studies.

Conclusion

Yield functions of rice, wheat, maize, and soybeans were obtained by estimating logistic functions or linear functions with a term of logarithmic time trend. These yield functions include climate factors as explanatory variables. Furthermore, the temperature and solar–radiation elasticities of yields were calculated using a crop model developed by Doorenbos & Kassam (1979) and the crop model was modified by introducing cubic spline interpolation and logistic functions. The results of productions will exhibit large oscillations if no such smoothing procedures are used. These elasticities of climate variables are inserted into yield functions, whereupon the worldwide effects of changes in temperature and solar–radiation to yield were analyzed.

Results of the trend analysis show that yields of the four crops under RCP8.5 are lower than those under RCP2.6, except for wheat in China. Higher temperatures lead to higher wheat yields in China. Specifically addressing the variance future yields, the magnitude of fluctuation of yields of some crops in some countries is expected to be greater than in others, as for wheat in China. The magnitude of yield fluctuation will increase if the relation between yield and temperature is kinked sharply at around the optimal temperature, as shown in Figure 5(ii), and if temperature varies in the band that is lower than the optimal temperature.

Results of the geographical analysis indicate that wheat and maize production in low-latitude countries are affected by climate change because the peak of yield to temperature is skewed to lower temperatures than those of other crops. The results suggest that yields in some countries are expected to be decreased by further rising temperatures. Production of rice in some countries, especially SSA coun-

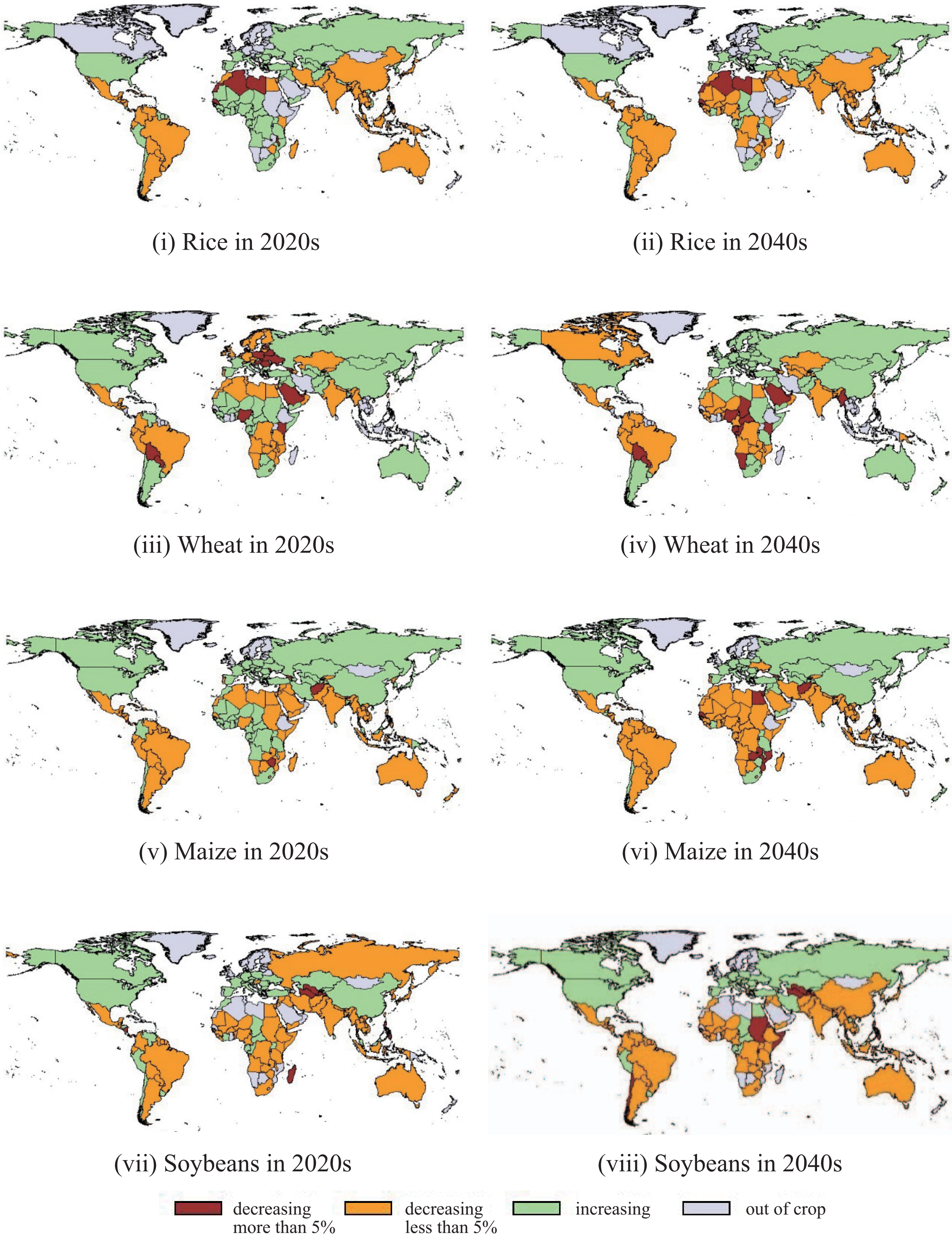


Fig. 8. Difference in crop yields between baseline and RCP6.0

tries, is also expected to be affected by climate change.

These results were obtained assuming the lack of any adaptation technologies. Progress in bio-technologies is expected to shift the loci shown in Figure 5 to the higher temperature side. Changes in CO_2 concentration and evapotranspiration must also be considered for additional analyses. The yield estimates obtained from simulations shall be applied to the world food model.

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