Impacts of Climate Change on Rice Yield and Irrigation Water Requirement in Paddy Field Simulated with Crop Model

Kenichi Tatsumi
Tokyo University of Agriculture and Technology
ktatsumi@cc.tuat.ac.jp

ABSTRACT

A daily climate dataset was developed (1961–2100) for scenarios SRES A1B and A2 using a statistical downscaling model and data that included the CGCM3 model outputs, NCEP reanalysis data, and SDP observation data. The climate data obtained were used as inputs for a crop yield model in order to estimate the present (2007–2011) and future (2071–2100) rice yield, transpiration, and irrigation requirements of a paddy field in Matsuyama city, Ehime prefecture, and to also assess the climate change impact on its rice yield and water balance. The results show that the yield increased by over 30% in both scenarios under high CO_2 concentrations, while the transpiration rate from the rice plants decreased by 12%. The future irrigation water requirement increased by 28% for A1B and by 36% for A2, indicating a need to significantly increase water intake from rivers.

Keywords: CO_2 fertilization effect, irrigation, GCM, statistical downscaling, rice yield, crop model, Japan

1. INTRODUCTION

Changes in the global temperature and precipitation have become noticeable in the recent years, and many studies have assessed the effect of global warming on agricultural production around the world (Masutomi *et al.*, 2009; Tan *et al.*, 2003). In this context, there is a need to make a detailed assessment of the effect of climate change on food production, and to review current plans for adaptation to those changes, in order to secure the sustainability of domestic agriculture.

Using SDSM (Statistical Downscaling Model) (Wilby *et al.*, 2002), this study calculates the daily weather dataset for each day from 1961 to 2100 using NCEP (National Centers for Environmental Prediction) reanalysis data, CGCM3 (the third version of the coupled Canadian Global Climate Model) output data, and data collected from the Matsuyama observation point (33.84°N, 132.78°E) of the SDP (Surface Daily Observation Point) data network. This study also used the obtained values as inputs for a crop yield model, estimated the present (2007–2011) and future (2071–2100) paddy yields in Matsuyama city, Ehime prefecture, and clarified the effect of climate change on paddy yields. The study also aims to make a trial calculation of future changes in irrigation water requirements, and analyzes the plans for adaptation to these changes.

2. MATERIALS AND METHODS

2.1 Study area

The present work is a study on a paddy field (area 12.37a) in Daima, Masaki-cho, Iyo District, Matsuyama city, Ehime prefecture (33.79°N, 132.73°E). The crop planted was Koshihikari (row space, 21cm; planting space, 30cm), and the soil was of the sandy clay type. Samples from the soil have been collected every year since 2005 at 3-5 locations, and soil data such as moisture content, organic matter content, electric conductivity, total carbon, total nitrogen yield, and soil hardness have been recorded. The aim of this paddy field is twofold: (1) to realize localized management in order to mitigate the environmental load while improving productivity, and (2) to determine the fertilizer inputs based on soil analysis and past growth and yield data. Operations for sustainable precision agriculture based on the data obtained are conducted by the Agricultural Production Cooperative Agri. Table 1 partially lists the crop calendar of the paddy field and enumerates its soil components and yield.

Table 1. Crop calendar of studied paddy field and its soil components and yield

Year	Transplanting day	Harvesting day	Yield ($t\ ha^{-1}$)	EC (ms)	Total N (%)	Total C (%)
2007	6/17	9/24	0.393	0.37	0.17	1.63
2008	–	–	0.393	0.10	0.14	1.17
2009	6/13	9/21	0.415	0.96	0.15	1.08
2010	6/18	9/20	0.360	0.93	0.2	1.65
2011	6/20	9/28	0.371	0.66	0.14	1.27

2.2 Statistical downscaling

Using GCM (Global Circulation Model) data to perform an impact assessment at a regional level without spatial treatment is not appropriate, in terms of its resolution. For this reason, SDSM, which is able to develop point-scale data with high reliability from GCM output (large-scale field data), is applied for the development of input data for the crop yield model. This method assumes a nonlinear relationship among objective variables, or among climate data at a regional level, and explanatory variables (large-scale weather data), determines the optimal explanatory variables for the model and selects a regression equation, and obtains a dataset for the target location. SDSM is poor in physical justification for obtaining local field data from GCM outputs because statistical

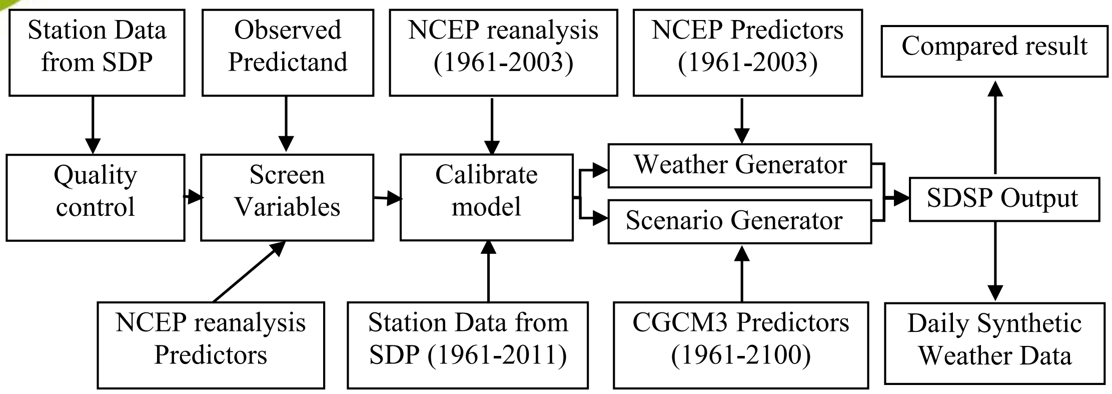

Figure 1. Data processing flow using SDSM

relational expressions are used, but the bias is small and the calculation efficiency is high. On the other hand, it is known that the reproducibility of variation components reproduced by observed data is not very high for precipitation. The technical information for SDSM and its usage are available in Wilby *et al*. (2007). Figure 1 shows the data processing flow using SDSM.

2.2.1 Explanatory variables

NCEP reanalysis data (1961–2003) was used to develop a regression equation, while 20C3M (20th Century Climate in Coupled Models), A1B (a society with high economic growth with a balancing of all energy sources), and A2 (low economic growth, high population growth rate, and coexisting local societies via low technology development) scenario data from CGCM3 (1961–2100) were used to generate scenarios. Data can be obtained from the CCCSN (Canadian Climate Change Scenarios Network) website. NCEP reanalysis data (2.5° × 2.5° lat–long) is interpolated with respect to the CGCM3 grid size (3.75° × 3.75° lat–long), and it is possible to use both data to obtain only the portion needed for the scope of this study. This study uses the nearest grid point dataset (35.26°N, 131.25°E) for the paddy fields. The explanatory variable candidate datasets include the ground surface; an altitude of 850hPa; and the temperature, humidity, and wind velocity of an altitude of 500hPa, with a total of 26 available variables.

2.2.2 Objective variables

The eight factors that were used as the crop yield model inputs – daily precipitation; daily minimum, average, and maximum temperature; daily minimum and average relative humidity; daily average vapor pressure, and daylight hours –were determined as objective variables for SDSM. The data was taken from the Matsuyama observation point of SDP.

Using the explanatory and objective variables detailed above, present and future daily weather data was developed by the following procedure: 1) development of a nonlinear regression model by means of a statistical transfer function, using NCEP reanalysis data and the observed values; 2) verification of the simulation precision of the model by comparing its results with the observed data; and 3) development of a daily weather dataset for 1961–2100 for scenarios A1B and A2 of CGCM3 using the regression model, weather generator, and scenario generator. By using the developed daily dataset at the nearest paddy fields as the model inputs for the crop yield calculations, the yield was calculated and a preliminary calculation was performed for the amount of water required for irrigation.

2.2.3 Crop yield model

The crop yield model iGAEZ (improved Global Agro-Ecological Zones model), which was developed by Tatsumi *et al.* (2011) was used as a basis for the yield calculations. This model uses soil, water balance, climate data, crop characteristics (cover rate, root depth, water productivity, harvest index, etc.) and field management (irrigation, soil texture) as inputs, and is able to calculate the evapotranspiration, biomass, yield, water requirements per day. The basic equation for yield is

$$Y = f_{hi}\, HI\, Ks\, WP\, \Sigma(Tr/ET_0) \quad (1)$$

where Y : yield (ton ha^{-1}) , f_{hi} : adjustment factor, HI : harvest index (%), Ks: heat and soil stress coefficient, WP : water productivity (ton ha^{-1}), Tr : crop transpiration (mm), ET_0 : reference crop transpiration (mm). The adjustment factor is determined by the water and temperature stresses before and after germination, and the stress is determined by the pollination efficiency. The yield coefficient is adjusted according to the variations in the cover rate due to water and heat stress. The heat and soil stress coefficients and crop transpiration are all adjusted to account for factors such as plant density, temperature during growth period, water and soil stresses, and the aging of cells. In addition, WP is adjusted based upon the CO_2 concentration given in the following equations:

$$WP^* = f_{co_2} WP \quad (2)$$

$$f_{co_2} = \frac{(C_{a,i} - C_{a,o})}{1 + (C_{a,i} - C_{a,o})[(1-w)b_{base} + w\,(f_{sink} b_{Sted} + (1 - f_{sink}) b_{FACE})]} \quad (3)$$

where $C_{a,o}$: reference CO_2 concentration (= 369.41 ppm), $C_{a,i}$: CO_2 concentration in the i th year (ppm), b_{base}= 0.000138, b_{FACE}= = 0.001165 (Free-Air CO_2 Enrichment, from FACE experiment), $w = (1 - (550 - C_{a,i})/(550 - C_{a,o}))$ and f_{sink} : crop sink strength coefficient (= 0.5). The irrigation requirement was calculated per day based on the water balance in the soil as derived from climate conditions, the soil moisture content of the previous day, and the growth of the crop. This study assumed that minimal irrigation takes place, given that the insufficiency of moisture in the soil does not fall below 50% of RAW in equation (4):

$$RAW = 1000(0.2 + 0.04(5 - ET_a))SW\ Z_r \quad (4)$$

where: readily available water (mm), SW: soil water content (-), ET_a: evapotranspiration (mm), and Z_r: root depth (m). Observation data from 2007–2008 was used for the model calibration, and data from 2009–2011 was used for the model validation in calculating the yield. Table 2 shows the initial parameters of the model (excluding the stress coefficients). Here, the transplanting day and the number of days of the cultivation period were assumed to remain the same in the future as they are today.

Table 2. Initial parameters used in the model

Variable	Value
Initial coverage	0.37 %
Rate of coverage development	21.7 % day^{-1}
Maximum coverage	90 %
Water productivity（WP）	0.170 t ha^{-1}
Yield coefficient (no stress)	37 %
Maximum root depth	0.3 m

3. RESULTS AND DISCUSSION

3.1 Reproducibility of climate data and future change

The data for R^2 and the climate reproducibility per month and per season were high enough to be used as inputs for the agricultural models, and the reproducibility was favorable overall. The change in the maximum daily temperature from the present to the projected future climate was +4.3°C for fall and +3.6°C for winter in A1B, and +5.2°C in fall and +4.4°C in winter in A2, showing a greater degree of increase in the maximum temperature than in the spring and summer. A similar tendency was also observed for the minimum and average daily temperatures. Compared to the present climate, the number of extremely hot days in which the temperature exceeded 35°C increased greatly, especially in the summer, in scenario A2. Compared to the present period, the average daily precipitation decreased by over 50% in both future scenarios, particularly in the summer, indicating that water and temperature management are key factors in establishing sustainable crop production in the experimental field in the future. As regards other climate levels, the actual vapor pressure was shown to increase by 3–20% every month in the future. Details were omitted in a limited number of pages.

3.2 Yield reproducibility and future change

Table 3 shows the precipitation, estimated growing degree-days, irrigation water requirements, yield, and water productivity for the present climate and A1B and A2 under projected future climate conditions during the growth period. The yield from the model tends to be greater than the observed data except for the year 2009 (Table 1, Table 3), but the mean absolute error was 0.24 t ha^{-1} and the adjusted R^2 was 0.83, and given that there were no events such as extreme weather or pest outbreaks, which significantly affect crop production, the reproducibility of the yield was favorable.

The yield under projected future climates showed a 33% and 39% increase over the present data in scenarios A1B and A2, respectively (Table 1, Table 3). Because the yield barely changed in a simulation in which the CO_2 concentration did not change, despite a slight increase in heat stress, the large increase in the yield is the result of a rise in the atmospheric CO_2 concentration, which was caused by an increase in *WP* from equation (2). On the other hand, the transpiration of rice decreased by about 12% in both scenarios. This was observed particularly in the initial stages of the growth period (Table 3, Figure 2). These results reflect an accelerating aging process due to water and heat stress under the projected future climate, as well as the closure of stomatas. A decrease in transpiration caused by various stresses decreases photosynthesis activity, leading to a lower yield. In other words, there is a large impact on yield from the balance between the increased yield caused by the photosynthesis that is promoted increased CO_2 concentrations, and factors that decrease, such as stomatal closure. The degree of yield increase calculated in this study was slightly greater than the 33% increase reported by Kimball (1983), as well as the meta analysis of the FACE experiment with C3 plants (an average increase of 24%, Long *et al.,* 2004); it was consistent, though, with results in the past literature, in terms of

Table 3. Simulation results for present and future scenarios

Year	Precipipitation. (mm)	GDD (°C-day)	Irrigation (mm)	Biomass (t ha^{-1})	Yield (t ha^{-1})	WPet (kg/m^3)
2007	527	1856	284	11.08	4.10	0.85
2008	322	1832	332	11.11	4.11	0.83
2009	634	1785	227	11.14	4.12	0.89
2010	429	1873	369	10.97	4.06	0.80
2011	688	1837	276	11.03	4.09	0.85
2080s(A1B)	307	1902	382	14.86	5.50	1.25
2080s(A2)	283	1954	405	15.45	5.72	1.28

*WPet = yield / evapotranspired water

its great effect on biomass and yield due to the rise in atmospheric CO_2. There is great uncertainty regarding the degree of stomatal closure and its quantitative impact on

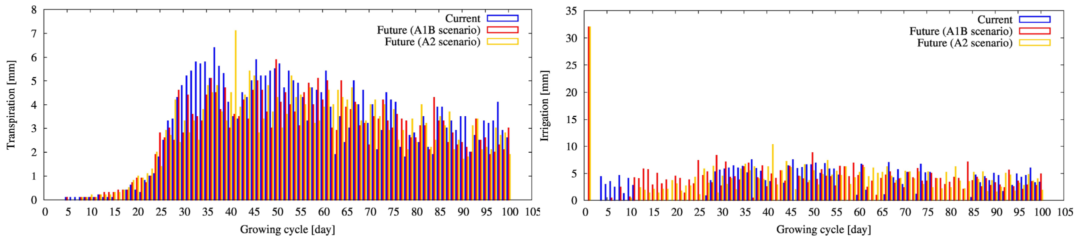

Figure 2. Transpiration from leaf surface (left), and irrigation water requirement (right) during cultivation period.

transpiration from leaves, since they depend not only on the temperature and water environment, but also on other environmental factors such as solar radiation, humidity, and wind velocity. Therefore, there is a need to conduct a detailed paddy experiment that includes observation, along with reciprocal communication between models, in order to analyze the effect of high-temperature stress and the carbon cycle on yields.

The irrigation water requirement increased by 28% and 36% in scenarios A1B and A2, respectively, due to a decrease in future precipitation during the cultivation period, while water productivity was expected to increase by 49% and 52% in A1B and A2, respectively (Table 3). Evapotranspiration from irrigation and leaf surfaces increased, but evaporation from the soil displayed little change. This indicates that a rise in the average temperature and increased yield due to the CO_2 fertilization effect greatly increases the efficiency of water use. However, the paddy in the present study takes water from the Shigenobu River for irrigation, and a future decrease in precipitation means that cultivation in a ponded state will be difficult without a large increase in water intake from the river. Therefore, there is a need to evaluate appropriate measures for promoting sustainable agriculture by considering a river flow simulation and changes in water resources under projected future climates. Despite the fact that there are many uncertainties, there is also a need to understand the mechanism of a change in yield due to global warming and an increased CO_2 concentration.

4. CONCLUSIONS

In this study, we predicted local-scale climate values using a statistical downscaling model, and data from a CGCM3 climate model under SRES A1B, A2 scenarios and observed data. The predicted values were used as the input values for the yield calculation model in order to estimate the future yield (2071–2100), and to evaluate the effect of climate change on rice yields. The results show that the yield increased by over 30% in both scenarios due to high CO_2 concentrations, while the transpiration of rice decreased by 12% in both scenarios. It was also found that the water intake from rivers needs to be increased significantly, assuming that there are no improvements in irrigation and/or water-saving cultivation technologies, because there is a possibility that the factors that inhibit rice growth that are associated water stress cannot be countered if the irrigation water requirement is increased by at least by 28% and 36% in scenarios A1B and A2, respectively, due to the decrease in precipitation that is projected in future climates during the growth period. There are many uncertainties that affect the prediction of rice yields, such as changes in water resources in projected future climates, the movement of pests, extreme weather, and the mechanism of transpiration. Plans to adapt to such uncertainties need to be evaluated in order to realize sustainable food production from a global point of view. This can be done by precisely identifying the factors responsible for an increase/decrease of crops due to global warming, and by extrapolating the future yield from a paddy level to a global level. Finally, this study used singular GCM data, but estimations using multiple GCM data are needed in order to mitigate the uncertainty of the results.

5. REFERENCES

Agricultural Production Cooperative Agri. Available at: http://aguri.jp (in Japanease).

Kimball, B.A., Kobayashi, K. and Bindi, M. 1983. Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. *Agronomy Journal* 75: 293-368.

Long, S.P., Ainsworth, E.A., Rogers, A. and Ort D.R. 2004. Rising atmospheric carbon dioxide: plants FACE the future. *Annual Review of Plant Biology* 55: 591-628.

Masutomi, Y., Takahashi, K., Harasawa, H. and Matsuoka Y. 2009. Impact assessment of climate change on rice production in Asia in comprehensive consideration of process/parameter uncertainty in general circulation models. *Agriculture, Ecosystems and Environment* 131: 281-291.

Tan, G. and Shibasaki, R. 2003. Global estimation of crop productivity and the impacts of global warming by GIS and EPIC integration. *Ecological Modelling*, 168: 357-370.

Tatsumi, K., Yamashiki, Y., Roverto, V.S., Takara, K., Matsuoka, Y., Takahashi, K., Maruyama, K. and Kawahara N. 2011. Estimation of potential changes in cereals production under climate change scenarios. *Hydrological Processes* 25: 2715-2725.

Wilby R.L., Dawson, C.W. and Barrow, E.M. 2002. SDSM: A decision support tool for the assessment of regional climate change impacts. *Environmental Modelling & Software* 17: 145-157.

Wilby, R.L. and Dwason, C.W. 2007. Using SDSM Version 4.1 SDSM 4.2.2- a decision support tool for the assessment of regional climate change impacts. User Manual, Leicestershire, UK.
