Vol. 64: 275–290, 2015
doi: 10.3354/cr01320

CLIMATE RESEARCH
Clim Res

Published August 31

FREE ACCESS

Adaptation of rice to climate change through a cultivar-based simulation: a possible cultivar shift in eastern Japan

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ABSTRACT: As surface warming threatens rice production in temperate climates, the importance of cool regions is increasing. Cultivar choice is an important adaptation option for coping with climate change but is generally evaluated with a single metric for a few hypothetical cultivars. Here, we evaluate adaptation to climate change based on multiple metrics and cultivars in presently cool climates in Japan. We applied the outputs of a global climate model (MIROC5) with a Representative Concentration Pathways 4.5 scenario, dynamically downscaled to a 10 km mesh for the present (1981–2000) and future (2081–2099) climate conditions. The data were input into a rice-growth model, and the performances of 10 major cultivars were compared in each mesh. With the present-day leading cultivars, the model predicted reduced low-temperature stress, a regional average yield increase of 17%, and several occurrences of high-temperature stress. The most suitable cultivars in each grid cell changed dramatically because of climate change when a single metric was used as a criterion, and the yield advantage increased to 26%. When yield, cold, and heat stress were taken into account, however, the currently leading cultivars maintained superiority in 64% of the grid cells, with an average regional yield gain of 22%, suggesting a requirement for developing new cultivars by pyramiding useful traits. A trait such as low sensitivity to temperature for phenology helps in ensuring stable growth under variable temperatures. Increasing photoperiod sensitivity can be an option under future climates in relatively warmer regions.

KEY WORDS: Rice cultivar · Yield · High-temperature stress · Low-temperature stress · Climate change

1. INTRODUCTION

Recent and projected surface warming has the potential to negatively affect crop growth (Porter et al. 2014); therefore, climate change related impact assessments are required for ensuing food security. Climate change scenarios from global climate models are widely used as input in crop-growth models, and global impact assessments have been conducted for major crops, such as wheat, maize, and rice (Parry et al. 2004, Lobell & Field 2007, Deryng et al. 2011, 2014, Rosenzweig et al. 2014). Regional impact assessments for major crop species have also been reported in various regions (reviewed by Porter et al. 2014) considering their respective agro-ecosystems and projected climatic changes. In Asia, rice is the most important food crop and impact assessments for rice have been carried out in various regions (e.g.

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Tao et al. 2008, Iizumi et al. 2011, Kim et al. 2013, Soora et al. 2013, Yu et al. 2014).

Rice production is sensitive to considerable variation in various climatic factors, including atmospheric CO_2 concentrations, precipitation, solar radiation, and temperatures, all of which are projected to change in the future. Among these factors, high- and low-temperature extremes in the reproductive growth phases are serious concerns (Wassmann et al. 2009) because they cause floret sterility, which reduces grain yield (Satake 1976, Satake & Yoshida 1978). In temperate rice-growing countries such as Japan, cool-summer damages have been a major yield constraint for many years (Satake 1976), but heat-induced sterility is also emerging as a result of recent hot-summer events (Hasegawa et al. 2011) and will become a serious threat to rice production in Japan (Nakagawa et al. 2003).

The effects arising from predicted changes in climate will differ, even within Japan. According to Iizumi et al. (2011), the probability of a decrease in rice yield in the 2090s relative to the 1990s is >20% for western Japan, whereas it is <10% in eastern Japan, where current temperatures are lower. Rice quality is currently deteriorating in western Japan because of high temperatures, and this is projected to continue under future climate conditions (Okada et al. 2011). While high-temperature stress is not presently evident in eastern Japan, climate change would bring this stress to presently cool regions as well (Nemoto et al. 2012). In eastern Japan, cold damage caused by a local northeasterly wind known as Yamase is a more serious threat to crop growth than heat damage (Shimono 2011). The frequency of Yamase airflows is projected to decrease in the future, but the event will still occur (Kanno et al. 2013) and cool-summer damages to rice are projected to persist under future climate conditions (Kanda et al. 2014). However, because surface warming caused by climate change has the potential to negatively affect rice growth in currently warm regions, such as in low-latitude or western Japan (e.g. Iizumi et al. 2007), rice production in presently cool regions (e.g. eastern Japan) is becoming more significant for a stable food supply (Nakagawa et al. 2003, Easterling et al. 2007, Shimono 2011).

Climatic conditions at each site affect farmers' choice of cultivars, which is one of the most important options for agricultural management. The choice of cultivars will become even more important in the future because they are considered to be the most effective adaptation measures against climate change (Porter et al. 2014). For this reason, a number of simulations were conducted to examine the impact of climate change on currently planted cultivars and cultivars adapted to projected climate change conditions based on a single metric, namely grain yield (reviewed by Porter et al. 2014). These simulations most commonly use one or a few hypothetical cultivars that match growth duration in new climates based on the altered thermal time requirements, assuming a linear response of developmental rate to temperature (e.g. Challinor et al. 2009, Yu et al. 2014, Kassie et al. 2015). Because most crop models predict shorter growth duration due to warmer climate, which leads to less biomass accumulation, and thus reduction in yield, varieties with longer thermal time requirements (i.e. late maturation) than the current varieties are expected to be more productive in warmer climates. However, rice is a short-day crop, and phenological traits of cultivars are determined by a combination of different degrees of photoperiod and temperature sensitivities. Replacement of the currently planted cultivars with those planted in warmer climates is tempting, but whether this simple solution is an alternative should be examined based on the realistic representation of the phenological traits of the cultivars. Previously, we evaluated phenological traits of various major cultivars, which cover more than 80% of the current rice harvest area in Japan (Fukui et al. 2015). By incorporating these parameters into a rice growth model, we can evaluate the adaptability of major rice cultivars to new environments.

In this study, we aimed to determine the suitability of the response of rice cultivars to climate change in the presently cool regions in Japan. To objectively determine the spatial distribution of the most suitable cultivar, we simulated grain yields of 10 major rice cultivars for 10 km gridded cells under current and projected future climatic conditions. Because both low and high temperatures are concerns in the current and future climates, we introduce these metrics as criteria for cultivar rankings in addition to grain yield. A consideration of multiple metrics together, such as yield and stress, for a multiple-cultivar choice would offer useful information on the efficacy of cultivar replacement and traits of cultivars conferring adaptability to climate change.

2. METHODS

2.1. Downscaling of the climate change scenario

We used the outputs of the global climate model (GCM) Model for Interdisciplinary Research on Climate (MIROC5; Watanabe et al. 2010) using the Representative Concentration Pathways (RCP) 4.5, because the climate data for Asia have focused on the Yamase airflow (Kanno et al. 2013). The original 150 km grid mesh resolution is insufficient for resolving regional differences in the meteorological elements of eastern Japan; therefore, we used the 20 km mesh MIROC5 output dataset for Japan based on the method of Ishizaki et al. (2012; Fig. 1). We downscaled the data to a 10 km mesh for eastern Japan in the JMA-NHM regional climate model (RCM; Saito et al. 2007). The JMA-NHM model utilizes the Kain-Fritsch scheme for convective parameterization (Kain 2004) and the improved Mellor-Yamada Level 3 scheme for turbulent parameterization (Nakanishi & Niino 2004). The downscaling was conducted for the key growing period, from May 28 to August 31, for 1981–2000 (present climate) and 2081–2099 (future climate), and the first 4 d were used as a spin-up period and excluded from the analysis.

Outputs from GCMs and RCMs are generally biased by the observed values (e.g. Yoshida et al. 2012a). To avoid biases, we used changes in the climatological mean (20 yr mean for present climate and 19 yr mean for future climate), rather than the original, downscaled climate data. Based on previous studies (Kimura & Kitoh 2007, Iizumi et al. 2010, Yoshida et al. 2012b), the following procedures were conducted to compose the climate datasets. First, the gridded, observed dataset from the Automated Meteorological Data Acquisition System (Mesh-AMeDAS; Seino 1993) for 1981–2000 was defined as the present climate. Then, the future climate was calculated from climate differences derived from the downscaled data and the Mesh-AMeDAS data. Here, differences (i.e. difference = future – present) were calculated for the daily maximum, mean, and minimum temperatures, and the multiplying ratios (ratio = future/present) were calculated for downward shortwave radiation, relative humidity, and wind speed. This method was used to account for the impacts of summer climate change on rice production.

2.2. Rice yield simulation

To account for cultivar-based rice production, we modified the Hasegawa/Horie rice-growth model (H/H model; Hasegawa & Horie 1997, Nakagawa et al. 2005, Fukui et al. 2015) to incorporate responses to extreme temperatures and CO_2 based on climate change studies, which are outlined below.

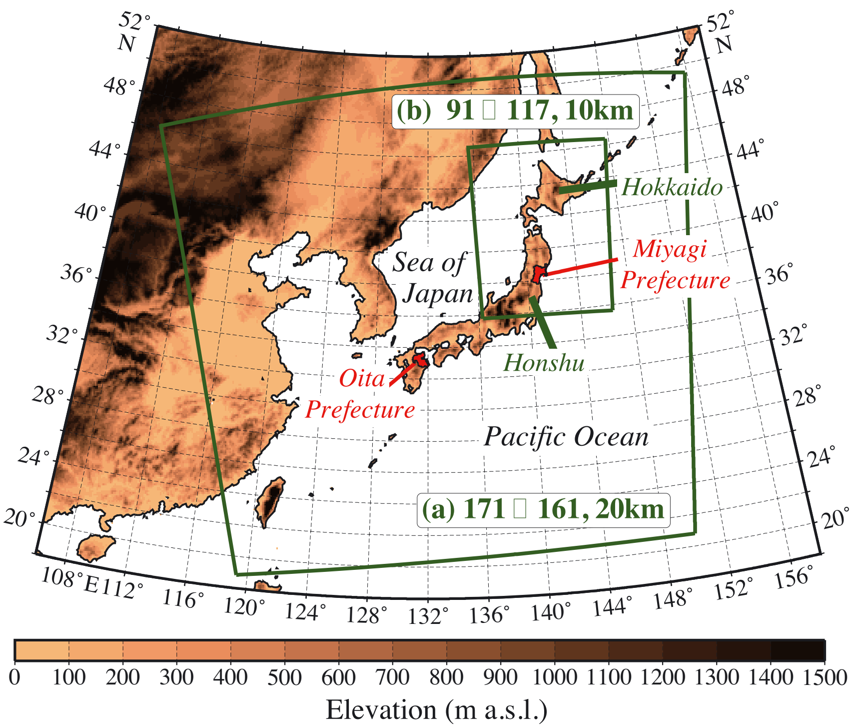

Fig. 1. Calculation domain used for the Japan Meteorological Agency nonhydrostatic model (JMA-NHM) simulations. (a) Outer domain: 171 × 161 grids with 20 km spacing for the dataset based on the method in Ishizaki et al. (2012). (b) Inner domain: 91 × 117 grids with 10 km spacing for the JMA-NHM model simulation

2.2.1. Stomatal conductance

Rising atmospheric CO_2 concentrations will enhance photosynthesis and reduce stomatal conductance. In this model, we used a combination of the Farquhar-von Caemmerer-Berry (FvCB) photosynthesis model (Farquhar et al. 1980) and the Ball-Berry (BB) stomatal conductance model (Collatz et al. 1991) to account for the CO_2 response. Two key parameters in the FvCB model, the maximum rate of Rubisco activity (V_{cmax}, µmol m^{-2} s^{-1}) and potential rate of electron transport (J_{max}, µmol m^{-2} s^{-1}), were expressed as linear functions of specific leaf nitrogen (SLN, g m^{-2}) derived from leaf-level gas exchange measurements in controlled chamber experiments (data presented in Hasegawa et al. 2015):

$$V_{cmax} = \max[86 \times (\mathrm{SLN} - 0.5), 0] \quad (1)$$

$$J_{max} = \min\{\max[138 \times (\mathrm{SLN} - 0.4), 0], 210\} \quad (2)$$

The other parameters for the FvCB model were from Medlyn et al. (1999). Stomatal conductance (g_c, mol m^{-2} s^{-1}) was then given by the BB model:

$$g_c = \frac{b_1 \times A_f \times \text{RH}}{C_a} + b_0 \tag{3}$$

where A_f is the assimilation rate obtained from the FvCB model, RH is the relative humidity (dimensionless), C_a is the atmospheric CO_2 concentration, and b_0 and b_1 are empirical parameters (0.00001 and 5.9; Katul et al. 2000).

2.2.2. Phenology

Rice phenology is simulated by a development index (DVI; 0 = seeding emergence, 1 = panicle initiation, 2 = heading, and 3 = maturity). The DVI value increases daily, and its development rate (DVR) is controlled by the air temperature and photoperiod (Nakagawa et al. 2005) as follows:

$$\text{DVR} = \begin{cases} \dfrac{f_1(T)\,g(L)}{G_1}, & (0 \le \text{DVI} < 2) \\ f_2(T), & (2 \le \text{DVI} \le 3) \end{cases} \tag{4}$$

where T indicates the average temperature between the daily maximum and minimum temperatures, L denotes the photoperiod, G_1 is the parameter. Each respective development function was expressed as follows:

$$f_1(T) = \begin{cases} \left\{\left(\dfrac{T - T_{\min}}{T_o - T_{\min}}\right)\left(\dfrac{T_{\max} - T}{T_{\max} - T_o}\right)^{\frac{T_{\max}-T_o}{T_o-T_{\min}}}\right\}^{\alpha}, & (T_{\min} < T < T_{\max}) \\ 0, & (T < T_{\min} \text{ or } T_{\max} < T) \end{cases} \tag{5}$$

$$g(L) = \begin{cases} \left\{\left(\dfrac{L}{L_{\min}}\right)\left(\dfrac{L_{\max} - L}{L_{\max} - L_{\min}}\right)^{\frac{L_{\max}-L_{\min}}{L_{\min}}}\right\}^{\beta}, & (L_{\min} < L < L_{\max}) \\ 1, & (L < L_{\min}) \end{cases} \tag{6}$$

$$f_2(T) = \begin{cases} \dfrac{1}{G_2}[1.0 - e^{-A(T-T_c)}], & (T_c < T) \\ 0, & (T \le T_c) \end{cases} \tag{7}$$

where $T_{\max}$ and $T_{\min}$ are the maximum and minimum temperatures in terms of the growth thresholds (fixed at 42 and 8°C) (Yin et al. 1997). $L_{\max}$ and $L_{\min}$ are maximum and minimum photoperiods (24 and 10 h), and α, β, A, G_2, T_o and T_c are cultivar-dependent parameters. We analyzed 10 Japanese cultivars developed in the cool-temperate and temperate climates (Table 1).

2.2.3. Yield and temperature stress

Rice growth is sensitive to the daily maximum and minimum temperatures after initiation of the panicle (Horie et al. 1999):

$$Y = \frac{H_v}{0.85}\{M_a \times [1 - f(\text{HDD})] \times [1 - f(\text{CDD})]\} \tag{8}$$

where Y is the yield (unhulled grain weight expressed at the 15% moisture content, g m^{-2}), H_v is the potential harvest index (0.5), M_a is the mass above the ground (g m^{-2}), and f(HDD) and f(CDD) are the high- and low-temperature stress functions (i.e. fertility under the high-temperature stress and sterility under the low-temperature stress; value range: 0 = free to 1 = stress). Each stress function was calculated according to Horie et al. (1999):

$$f(\text{HDD}) = (1 + e^{k1 \times \text{HDD}})^{-1} \tag{9}$$

$$\text{HDD} = 36.6 - \frac{1}{n}\sum_{\text{DVI}=1.6}^{2.2} T_x \tag{10}$$

$$f(\text{CDD}) = \frac{\max[100 - (\gamma_0 + k_2 \times \text{CDD}^y), 0]}{100 \times [1 + e^{-6.2\times(\text{DVI}-2.29)}]} \tag{11}$$

$$\text{CDD} = \sum_{\text{DVI}=1.5}^{2.2} \max(22 - T, 0) \tag{12}$$

where HDD is the heating degree-days (°C), n is the number of days during the flowering period (d), T_x is the daily maximum temperature (°C), CDD is the cooling degree-days (°C), and k_1, γ_0, k_2, and y are the empirical parameters (8.53, 4.6, 0.054, and 1.56, respectively). Although this scheme excludes cultivar differences, the simulated stress values differed for each cultivar, because the growth rate was cultivar-dependent, as shown in the parameters in Table 1 and Eqs. (4–7). We defined the yield attained in the absence of stress as the potential yield.

2.2.4. Yield and temperature stress simulation

Using the climate data and the H/H model, we conducted the following analyses:

(1) climate change scenarios for eastern Japan were analyzed for the meteorological elements that were used in the H/H model.

(2) The reproducibility of the H/H model was evaluated by simulating rice yields using the Mesh-AMeDAS data for the present climate (1981–2000). In this simulation, we used the current leading cultivar of each prefecture (Japanese administrative dis-

Table 1. Cultivars and parameters used in the H/H phenology scheme (Fukui et al. 2015). G_1 = minimum number of days required from emergence to heading under optimum conditions; G_2 = insensitiveness to temperature after heading; α and β = sensitiveness to temperature and photoperiod before heading; A = multiplying factor of temperature impact on growth after heading; T_o = optimum temperature before heading; T_c = minimum temperature required for growth. These parameters were estimated based on the days to heading observed in the nationwide variety trials (Fukui et al. 2015). Because dates for panicle initiation were not recorded in the database, development index (DVI) was assigned as 1 at heading and 2 at maturity. To conform to the Hasegawa/Horie (H/H) rice-growth model, which assumes DVI = 1 at panicle initiation, 2 at heading and 3 at maturity, the estimated DVI values using the above parameters were corrected to the 0–3 system scale assuming that panicle initiation occurs at DVI = 0.64 in the 0–2 system

ID	Cultivar	G_1 (d)	G_2 (d)	α	β	A (×10^{-2})	T_o (°C)	T_c (°C)
1	Hitomebore	56.7	23.3	0.93	0.95	3.5	32.9	0.4
2	Kirara397	45.3	22.0	1.25	0.07	3.3	32.1	1.9
3	Hinohikari	30.9	38.0	1.25	7.34	15.9	30.6	9.9
4	Asahinoyume	30.9	35.8	1.07	6.70	9.9	31.3	4.3
5	Akitakomachi	54.6	24.7	1.24	0.13	5.8	34.3	7.4
6	Aichinokaori	30.7	29.9	1.48	7.90	6.2	28.3	4.9
7	Haenuki	55.1	24.0	1.68	1.12	3.7	30.0	1.5
8	Koshiibuki	59.0	23.6	1.20	0.45	6.1	32.3	10.0
9	Koshihikari	36.6	29.1	1.11	3.42	5.3	34.6	0.2
10	Kinuhikari	30.2	26.5	1.50	4.32	6.7	33.3	9.2

trict) obtained from Crop Statistics of the Ministry of Agriculture, Forestry, and Fisheries (MAFF, data as of 2009, www.maff.go.jp/j/tokei/kouhyou/kensaku/bunya2.html) for simulating yields in the grid cells for the 1981–2000 period. For all grid cells, the current leading cultivar corresponds to 1 of the 10 cultivars listed in Table 1. The amount of nitrogen fertilizer each year was given as follows. We obtained consumption of nitrogenous fertilizers for rice production from the Rice and Wheat Production Cost Statistics (MAFF 1981–2000, www.e-stat.go.jp/SG1/estat/List.do?bid=000001014632&cycode=0) and calculated the elemental weight of N applied, which was then divided by the rice-planted area. Because this statistic provides only aggregated data for the regions covering several prefectures, N supply in the simulation was almost homogenous over the entire study area, as was the soil fertility. The time of transplanting by prefecture was fixed for each grid cell based on the Crop Statistics (MAFF, data as of 2000) for each prefecture. Nitrogen fertilizer was spilt-applied thrice during the growing season; 58% of the total N was applied immediately before planting and the remaining 42% in 2 equal splits during the panicle development (21% each at about the spikelet differentiation stage and reduction division stage of the pollen mother cell), as commonly practiced by farmers in the study regions. The H/H model simulates rice growth under no water limitation, and the paddy was assumed to be maintained in flooded condition, which is supported by the fact that >99% of the rice-growing areas are fully irrigated. We compared the simulated yields with those obtained from the crop data on a sub-prefectural scale, as summarized by MAFF. Because the crop statistics by MAFF provided the hulled grain yield, we converted the yield to unhulled data multiplying it by 1.25 as reported by Yoshida (1981).

(3) Climate change impacts on rice yields and temperature stresses for the current cultivars were estimated using the projected future climate data. Planting times and N fertilizer amount were kept constant at the year 2000 values. The timing of the split-application of N fertilizer was determined according to the predicted phenology.

(4) Potential yield and temperature stresses under climate change conditions in all the grid cells were also examined for all 10 cultivars listed in Table 1. On the basis of simulated yields, we selected a 'top cultivar' for each grid cell that provided the maximum yield among the 10 cultivars. We also counted the total number of top grid cells by cultivars, which was divided by the total number of analyzed grid cells (i.e. 1307). This ratio was defined as the share of each cultivar. For all crop simulations, grid cells with paddy-field ratios of <1% in the National Land Numerical Information database (MLITT 2012) were defined as non-paddy areas and excluded from the analysis. The geographical distribution of paddy fields in 2006 (the latest available year) was applied and fixed throughout the analysis period.

3. RESULTS

3.1. Effects of climate change on meteorological elements

We estimated the present and future meteorological elements required for the H/H model (Fig. 2). Temperature variables (daily mean, maximum, and minimum temperatures) showed similar geographical distributions, and surface warming was more evident in the northern area on the Pacific Ocean side (Fig. 2a–i). A regional average of ~3°C of surface

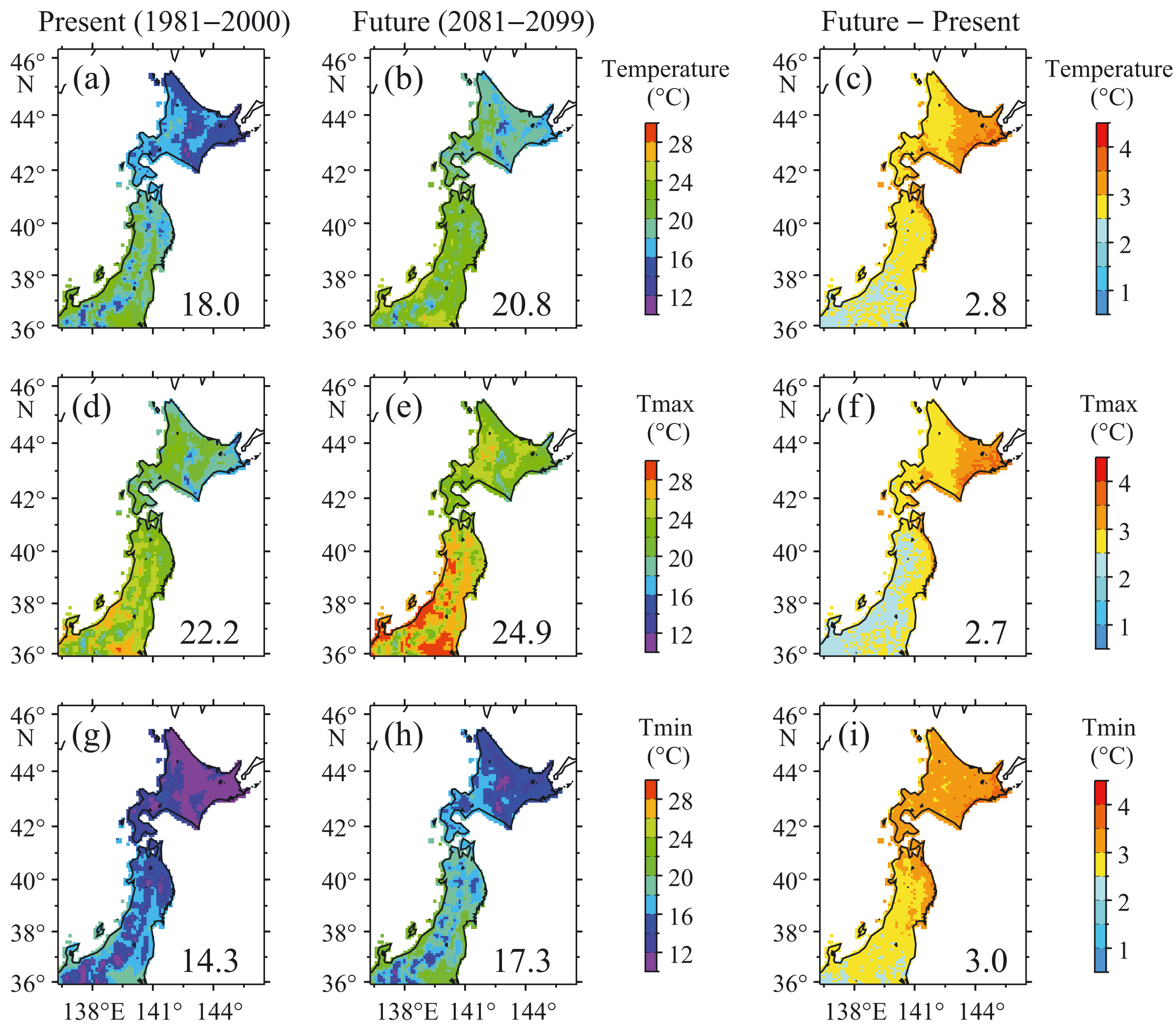

Fig. 2. (cont. on next page). Geographical distributions of the downscaled summer meteorological factors in the present and future climates, and their differences. Daily (a–c) mean, (d–f) maximum and (g–i) minimum temperatures

warming was obtained across the land surface, which fell within the 5 to 95% ranges for the global land-surface warming projected by the global climate models in the Coordinated Modeling Intercomparison Project Phase 5 (1.3 to 3.4°C) (Collins et al. 2013). Similar east–west geographical patterns were indicated for downward shortwave radiation in both present and future climates (Fig. 2j,k). A small increase (<1% of the regional average) occurs over most of the area, and a relatively large increase (~10%) occurs in eastern Hokkaido (the northern island in the 10 km mesh domain, see Fig. 1) and the southern part of the analyzed area (Fig. 2l). Relative humidity also showed similar geographical patterns but decreased slightly with climate change (Fig. 2m,n). The decrease appeared in most grid cells (80.0% of the total land grid cells), but a small increase (<1%) was also estimated for a part of the northern area (Fig. 2o). Future changes in wind speed were estimated to be the smallest among the elements analyzed. Although intensified wind speed was found in the western part of Hokkaido, its contribution was negligible compared with changes at the regional scale (Fig. 2p–r). These meteorological elements were utilized in the H/H model to simulate the yield and temperature stresses.

3.2. Reproducibility of the rice growth model

We first examined the performances of the H/H model by comparing the simulated yields with historical yield records between 1981 and 2000. Fig. 3 depicts the inter-annual variation of the observed

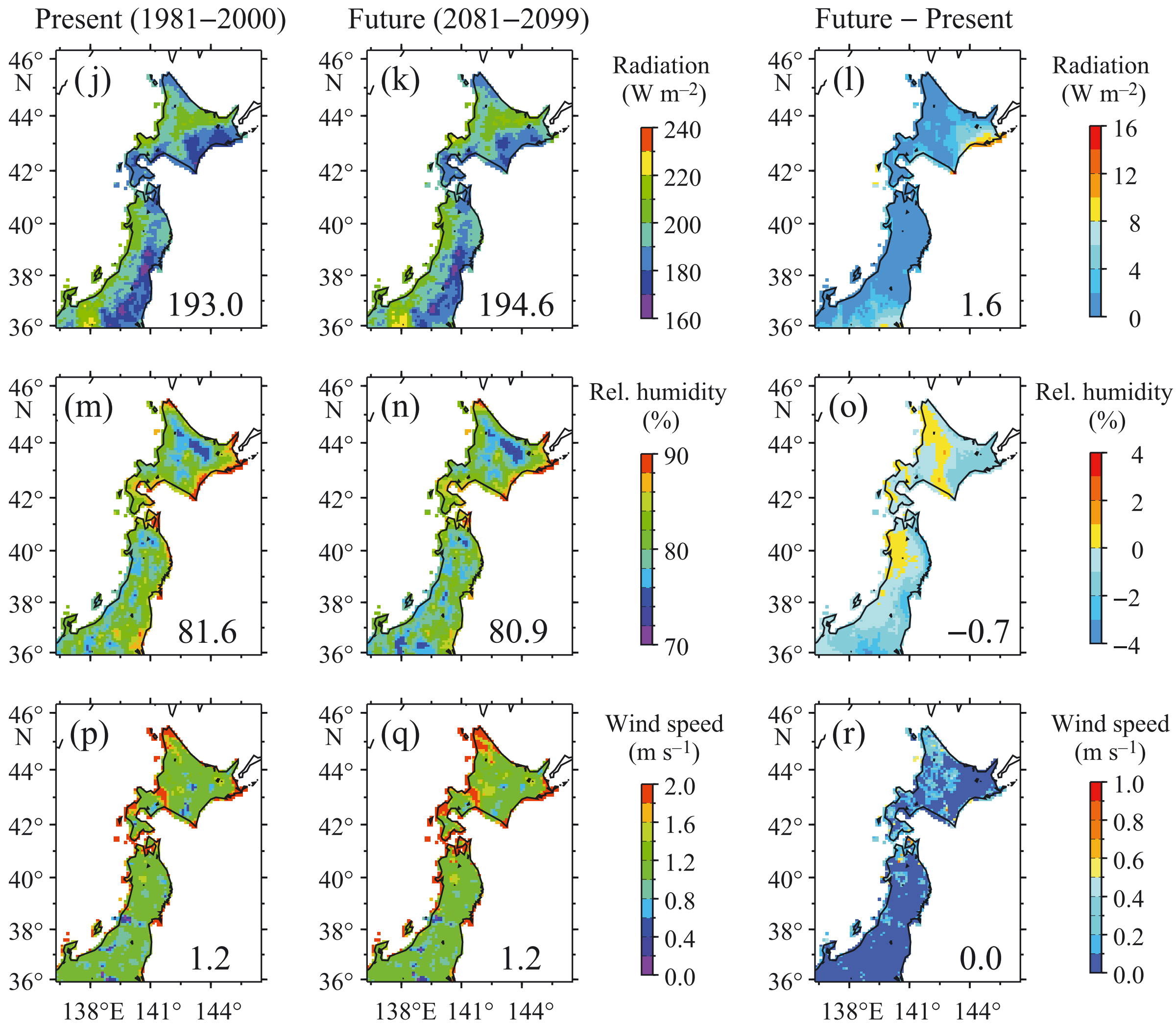

Fig. 2. (cont.). (j–l) Downward shortwave radiation at the surface; (m–o) relative humidity; and (p–r) wind speed. Bottom right value in each figure: regional average

and simulated yields for the period as an average over the grid cells with paddy fields ≥1%. The H/H model reasonably reproduced the inter-annual variation in the observed yield (Fig. 3a). The correlation coefficient (r) was 0.80 and the average bias −1.8%. The yield dropped sharply in 1993 because of a strong Yamase airflow, which resulted in severe cold damage to rice. The model simulated the large 1993 reduction in yield, reflecting a high f(CDD) value (Fig. 3b). The simulation also predicted relatively low yields in other years, such as 1981, 1983, 1995, 1996, and 1997, when f(CDD) exceeded 0.3, although the predicted yield reduction tended to be larger than the observed yield reduction.

The geographical distribution (Fig. 4) of the observed yield showed a small regional difference (mean ± SD: 628.5 ± 67.9 g m^{-2}) because of the coarse

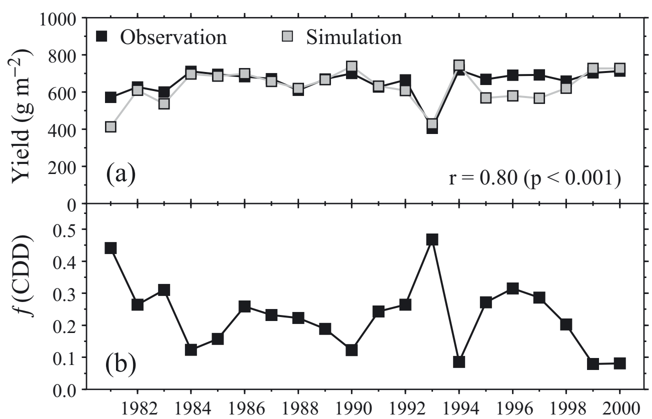

Fig. 3. (a) Interannual variation of observed and simulated yields from 1981 to 2000 averaged over the analyzed area. r: Pearson's correlation coefficient. (b) Same as (a) but for f(CDD), the simulated low-temperature stress value

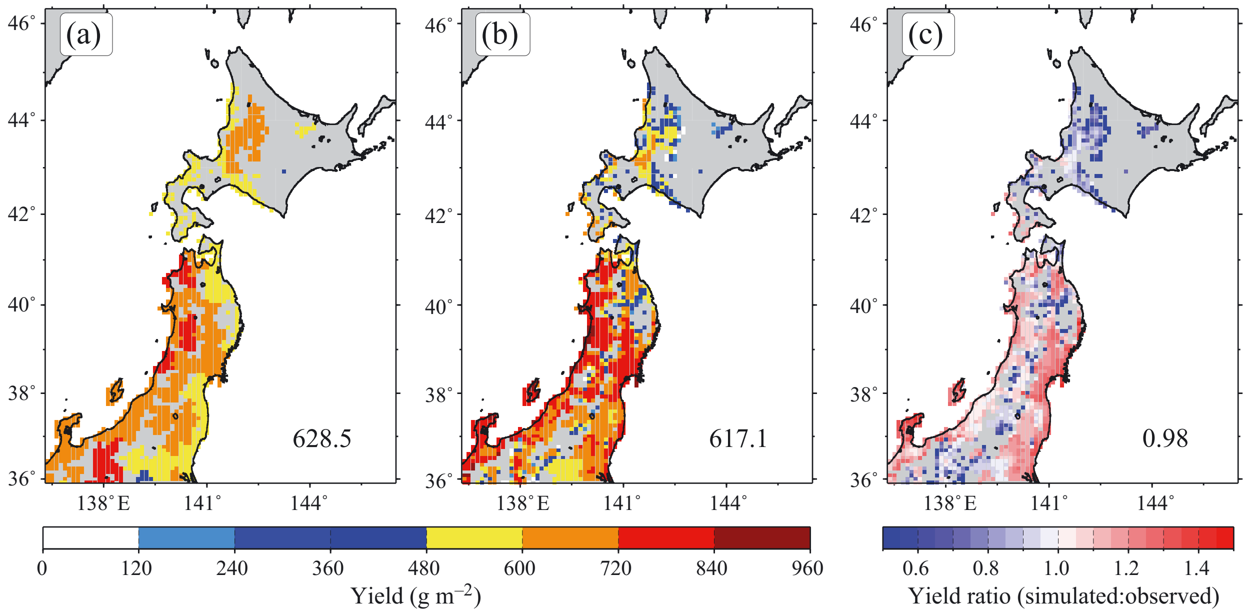

Fig. 4. Geographical distribution of the 20 yr (1981–2000) averaged yield. (a) Observation, (b) simulation, and (c) simulated: observed yield ratio. Gray: areas with <1% paddy fields in the 10 km grid cells. Bottom right values: regional average

spatial resolution. The Crop Statistics reports yield data by several regional divisions in each prefecture. Although the horizontal resolutions differ because of the non-uniformity of the areas of the prefectures, all of the regional divisions are larger than the 10 km mesh used for downscaling. Because of the detailed meteorological elements derived from the downscaling, the simulated yield had larger geographical variations (617.1 ± 187.8 g m^{-2}) than the observations.

3.3. Impact of climate change on rice yield

By fixing the cropped cultivar as the current leading one, we estimated the climate change impacts on rice yield and temperature stresses. For the present climate, high yield (720 to 840 g m^{-2}) in the analyzed area was found in the plains on the Japan Sea side (Fig. 5a). In most of Honshu (see Fig.1), this high yield was simulated for the future climate (Fig. 5b). The in-

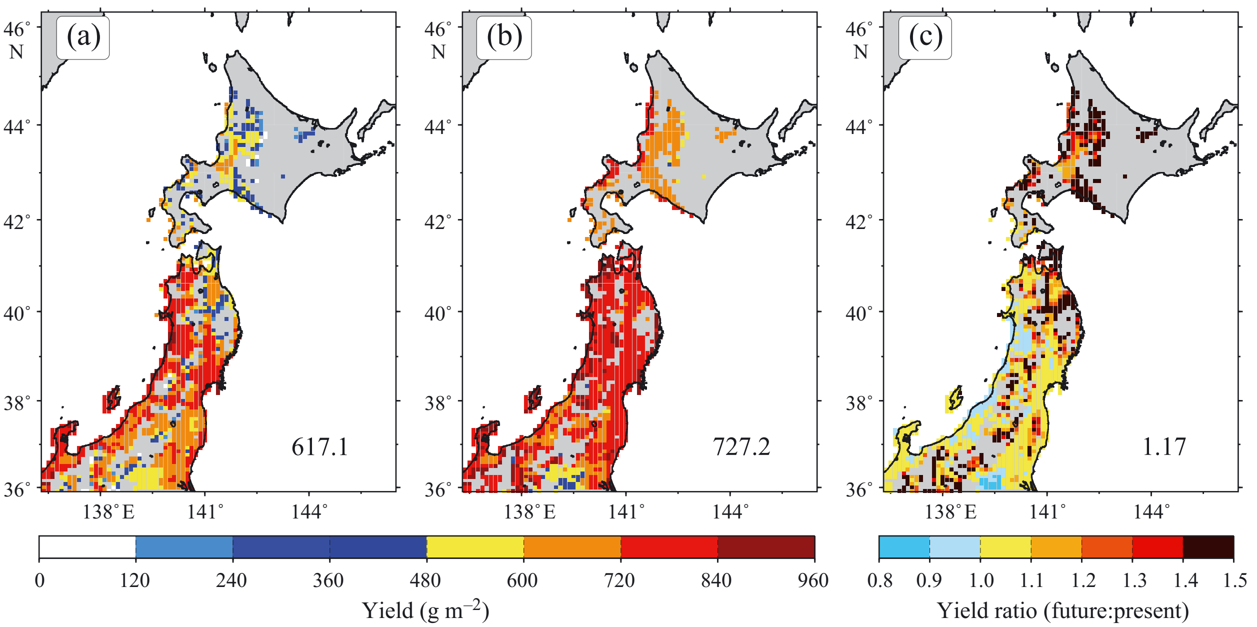

Fig. 5. Simulated yield for (a) present (1981–2000) and (b) future (2081–2099) climates, and (c) future:present yield ratio with the current leading cultivar. Bottom right values: regional average. Gray shading as in Fig. 4

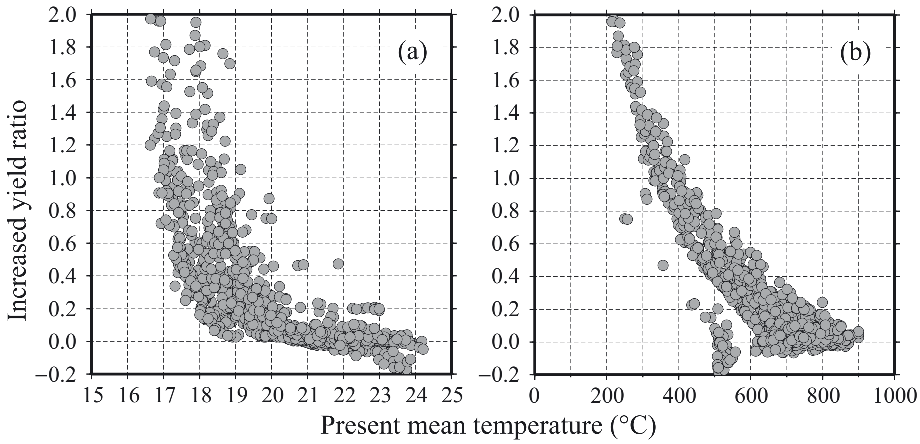

Fig. 6. Relationship between daily (a) mean temperature and (b) rice yield in the present climate and the increased yield ratio from the present to the future climate

creased-yield ratio (i.e. future yield/present yield) averaged 17%, but differed between regions. It was ~10% in the plains and >40% in the mountainous areas and on Hokkaido (Fig. 5c), whereas a negative impact was found in several areas of the Japan Sea side and in a southern area with a higher estimated surface temperature (Fig. 2e). A high increased-yield ratio was found in the northern and high-elevation areas, so we focused on the relation between the increased-yield ratio and the present mean temperature. The negative correlation ($r = -0.71$) illustrated the high increased-yield ratio for low temperature (Fig. 6a). Present yield was more strongly related to the ratio ($r = -0.85$), whereas a high ratio was estimated for the lower-yield area (Fig. 6b).

In the present climate, the rice crop was not exposed to high-temperature stress in eastern Japan (Fig. 7a), but the high-temperature stress became obvious in the future climate (Fig. 7b). In particular, the increase was more evident in the southern plains (Fig. 7c). The increased ratio of the future high-temperature stress normalized by the present stress (i.e. [future – present]/present) was 551% on average regionally. The ratio is large because of the small value in the present climate. On the other hand, the geographical distribution of low-temperature stress in the present climate followed the north–south gradient (Fig. 7d). Climate change had positive effects from the perspective of reducing cold damage, as the regional average of low-temperature stress in the future climate decreased to 36% of the present climate (Fig. 7e). In contrast to the situation for high-temperature stress, low-temperature stress was reduced in the northern or mountainous area (Fig. 7f). When we focused on the balance between high and low-temperature stresses, high-temperature stress was negligibly small in the present climate [f(HDD):f(CDD) = 1:71]. However, the intensity of the high-temperature stress increased a quarter of the value of the low-temperature stress under the future climate [f(HDD):f(CDD) = 1:3.9]. High-temperature stress was projected to increase in southern Japan and low-temperature stress was projected to decrease in the northern area.

3.4. Potential cultivar shift due to climate change

Fig. 8 shows a meridional distribution of the cultivar with the higher yield. More than one top cultivar is occasionally presented within the same latitudinal zones, because the best cultivars vary, depending on the variation in climatic conditions between east and west. The location of the top cultivar generally shifted northward in the future climate (Fig. 8a). In particular, Kirara397 (cultivar ID: 2), which was widely distributed as the top cultivar in the present climate, shifted and became limited to high latitudes or high altitudes in the future climate (corresponding to a sparse distribution in the south). A similar shift was found for Akitakomachi (ID: 5).

Hitomebore (ID: 1) was predominant in both climates (Fig. 8b). One of the northward-shifting cultivars, Kirara397 (ID: 2), occupied the highest share in the present climate (37.6%), but decreased to 11.3% in the future climate. The decreased-share cultivars, such as Kirara397 or Akitakomachi, are sensitive to changes in the daily surface air temperature. This characteristic is expressed as the smaller value of G_2 and the larger value of α (Table 1). In contrast, the photoperiod-sensitive cultivars (larger β value), such as Asahinoyume (ID: 4) or Aichinokaori (ID: 6), increased their share by ~20%.

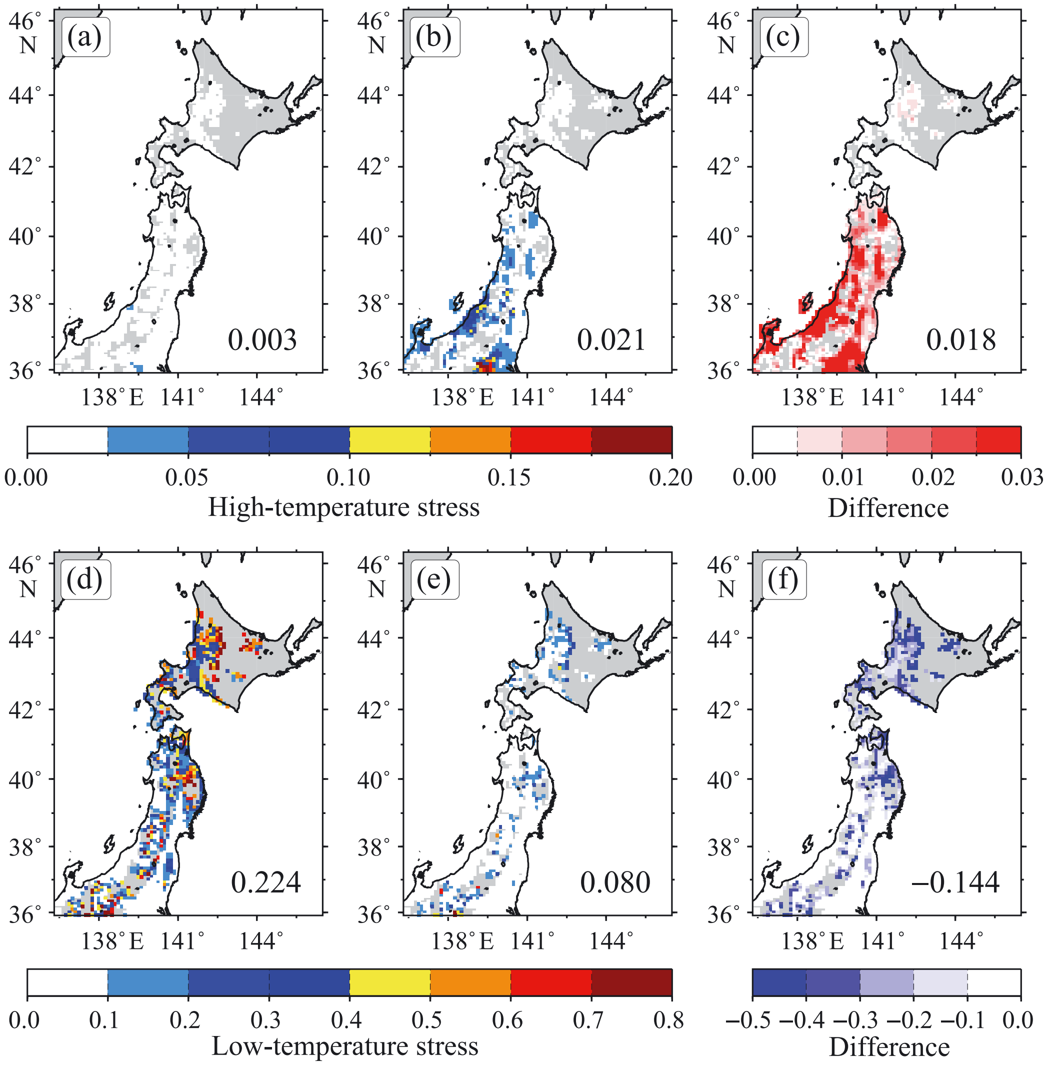

Fig. 7. Distribution of simulated temperature stress for the (a,d) present climate (1981–2000), (b,e) future climate (2081–2099), and (c,f) their difference (future climate – present climate): Function values of (a–c) high-temperature stress and (d–f) low-temperature stress. Gray shading: areas with <1% paddy fields in 10 km grid cells. Bottom right values: regional average

For the 3 major cultivars in the future climate (i.e. Hitomebore, Asahinoyume, and Aichinokaori), their distribution is shown for the present and future in Fig. 9. The Hitomebore grid cells are distributed throughout the study area except Hokkaido in the present climate, and they shift toward the north or the mountainous areas in the future climate. Asahinoyume and Aichinokaori, the photoperiod-sensitive cultivars, barely exist in the present climate, but become dominant in the southern plains in the future climate.

Yields averaged for the top cultivars in future climates were 26% higher than in the current climate. High yields were recorded for Asahinoyume and Aichinokaori, which are more photoperiod-sensitive than Hitomebore (Table 2). Growth duration, in days from transplanting to maturity, of these top cultivars were close to the current growth duration (MAFF, data as of 2009, www.maff.go.jp/j/study/suito_sakugara/h2204/pdf/ref_data3-3.pdf), suggesting that these phenological traits match well to local future climates.

Based on the projected yield and temperature stress of the current leading cultivars (Figs. 5 & 7), we analyzed the cultivars that provided more favorable outcomes (i.e. higher potential yield or lower temperature stress) than the current leading cultivars (Fig. 10). Additionally, we extracted the grid cells for which the current leading cultivar was ranked 6 or lower (i.e. 6 of the current non-leading cultivars surpassed the leading one) and designated them as reversed grid cells. For example, 53.9% of the paddy grid cells were selected as reversed grid cells when

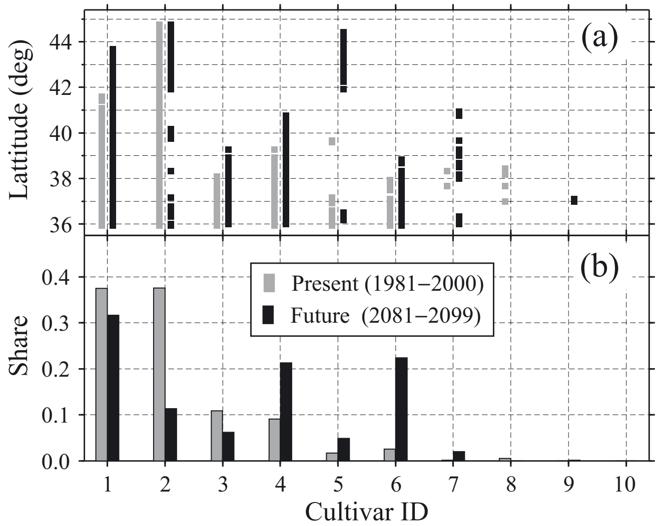

Fig. 8. (a) Meridional distribution of cultivars that provide the maximum yield among the 10 cultivars and (b) their share of the entire analyzed area. Gray/black = present/future climate, respectively. Cultivar names for each ID are presented in Table 1

we focused on a potential yield (Fig. 10a). This tendency was more evident in the high-temperature stress case, with 86.8% of the total paddy grid cells (Fig. 10b). However, the ratio dropped to 10.4% for the low-temperature stress case (Fig. 10c).

Next, we performed the multi-condition assessment. Multi-condition assessment means that two or three conditions are considered concurrently for judgment of reversed grid cells. For the case of higher potential yield and less high-temperature stress, the southern area was expected to have a large proportion of reversed grid cells (Fig. 10d; 29.2%), whereas the northern area had fewer because of difficulties in maintaining higher yield. As the decrease in low-temperature stress was more difficult for the current non-leading cultivars compared to high-temperature stress (Fig. 10b,c), the reversed grid cells under the condition of higher potential yield and less low-temperature stress were rarely found in eastern Japan (Fig. 10e; 5.2%). Therefore, good performance under all 3 conditions (higher potential yield, less high-temperature, and less low-temperature stresses, Fig. 10f) was limited to only a few grids and cultivars. In approximately 64% of the grid cells, the current leading cultivar was the top cultivar.

Table 2. Future yield and growing period averaged over the grid cells for the 3 major simulated cultivars (i.e. maximum yield value among 10 cultivars)

	Yield (g m^{-2})	Growing duration (d)
Hitomebore (ID: 1)	828	127
Asahinoyume (ID:4)	886	144
Aichinokaori (ID: 6)	937	154

4. DISCUSSION

When the current leading cultivars were maintained in the future (2081–2099) climate, rice yield was projected to increase by an average of 17% compared with the baseline climate (1981–2000). The positive effect was mainly for 2 reasons: (1) increases in atmospheric CO_2 concentrations (C_a) and (2) rise in temperatures from sub-optimal levels. In the simulation, mean C_a for the baseline period was 354 µmol mol^{-1}, but in the future period it reached 534 µmol mol^{-1} under RCP 4.5 (Meinshausen et al. 2011). A meta-analysis of the previous free-air CO_2 enrichment (FACE) studies showed a 12% increase in grain yield under the C_a range of 500 to 599 µmol mol^{-1} (Ainsworth 2008). A recent rice model intercomparison study demonstrated that current rice models also predict a yield increase of ~14 to 15%, with an increase in C_a by 180 µmol mol^{-1} (Li et al. 2015). These findings support that rising C_a is an important factor for the increase in rice yields.

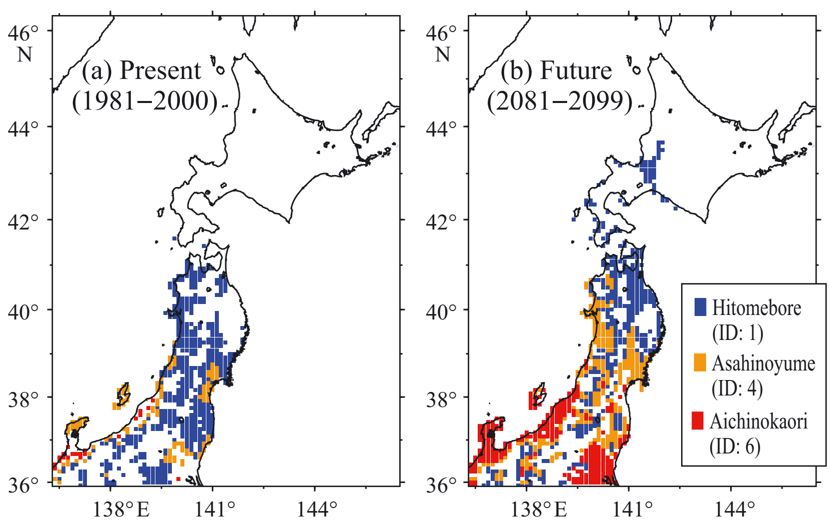

Fig. 9. Geographical distribution of the top cultivar for Hitomebore (blue), Asahinoyume (orange), and Aichinokaori (red) in (a) present and (b) future climates. Non-paddy area is unmasked to clarify the figure

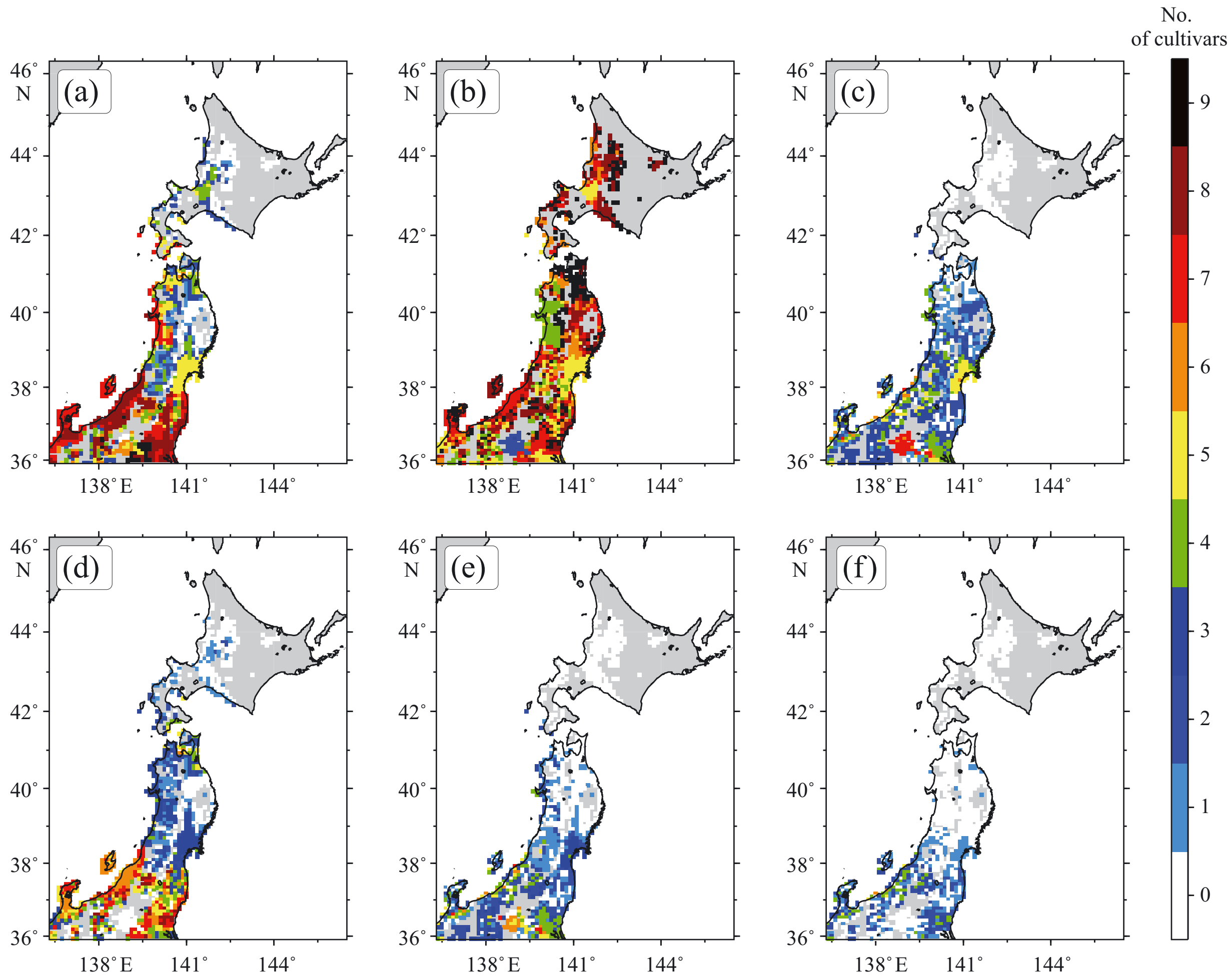

Fig. 10. Number of cultivars that provide more favorable rice production in the future climate than the current leading cultivar (i.e. higher potential yield, less high-temperature stress, and less low-temperature stress): (a) higher yield, (b) less high-temperature stress, (c) less low-temperature stress, (d) higher yield + less high-temperature stress, (e) higher yield + less low-temperature stress, and (f) higher yield + less high-temperature stress + less low-temperature stress. Gray shading: non-rice-cropped areas with <1% paddy fields in the 10 km grid cells

Summer air temperature of 18.0°C averaged for the baseline period (Fig. 2a) is apparently cooler than the optimum, even for temperate japonica cultivars, whose optimal temperature range for the ripening process is 20 to 22°C (Yoshida 1981). The projected surface warming in this study was ~3°C (Figs. 2c,f,i), and thus provided favorable conditions for rice growth. Our results for yields are consistent with the previous studies that demonstrated how a warming of 1 to 3°C brings favorable rice growth in the mid-latitudes in contrast to the negative impact projected in the low latitudes (Nakagawa et al. 2003, Easterling et al. 2007). An observational study found that yields are currently increasing in northern Japan (Shimono 2008).

Several concerns remain despite these optimistic projections for the impacts of climate change. Our projections and other studies suggest that the risk of cold damage will persist in the future (Fig. 7e; Kanda et al. 2014), so precautions for low-temperature stress are continuously required (Kanno 2004). High-temperature stress was estimated to become more apparent in the future, and therefore, both stresses deserve attention. CO_2 fertilization effects in rice are decreased under both low and high temperatures (Shimono 2008, Hasegawa et al. 2015), but the present model does not account for this interaction. Interaction between CO_2 and temperature, in fact, is pointed out as the major source of uncertainties in the rice-yield predictions (Li et al. 2015), and the CO_2 fertilization may be smaller than expected. Future model evaluation must account for the CO_2 and temperature interaction.

The present study is unique in that it examines whether cultivar shifts occur as a result of climate change among the widely planted cultivars in Japan at present based on 3 metrics: (1) potential yield, (2) cold stress, and (3) heat stress. A major decline was predicted for Kirara397 (ID: 2), an early maturing cultivar widely planted in Hokkaido at present. This cultivar was replaced with longer, but weakly photoperiod-sensitive cultivars, such as Hitomebore (ID: 1) and Akitakomachi (ID: 5) (Fig. 8a). Hitomebore (ID: 1) maintained its high share values in terms of yield under climate change conditions (Fig. 8b) by becoming the leading cultivar in the future climate (i.e. it was selected in most grid cells; Fig. 10a), while giving away several current 'winning' grid cells. This cultivar was developed in Miyagi Prefecture (38° N, 140° E on the Pacific Ocean side, Fig. 1) in 1991 as a highly cold tolerant cultivar with a high eating quality. It is currently the second most popular cultivar in Japan and is widely planted across different regions, including southern prefectures such as Okinawa (24°–27° N) and Oita prefecture (33° N, Fig. 1), with 13.7% of the total paddy area in 2009 (MAFF 2014). This wide adaptability could in part be attributed to a low temperature sensitivity of phenology, as evidenced by the smallest α value (Table 1), i.e. growth duration is relatively unaffected by the temperature change. This could be one of the key traits for stable rice production in the future climate. Two longer-duration cultivars, Asahinoyume (ID: 4) and Aichinokaori (ID: 6) (Fig. 8b), gained share in the future climates. These cultivars are currently not major winners but are projected to become dominant in the southern plains (Fig. 9), suggesting that photoperiod sensitivity helps to ensure growth duration in relatively warmer regions.

When we consider all of the higher potential yields and reduced high- and low-temperature stresses, cultivar replacement was projected to occur in 35.6% of the paddy grid cells, whereas the current leading cultivars kept their superiority in the remaining 64.4% grid cells (Fig. 10f). The regional yield average for the top cultivars, based on the multiple metrics, was 22% higher than the baseline. Of the new cultivars, those selected in each grid cell were developed in the more southern areas. When they are grown in the current climate, they take too long to mature, but under warmer conditions, they grow sufficiently long to ensure higher yield but without temperature stress. Thus, introducing the 'southern cultivars' would be an effective way to adapt to the future climate in approximately 36% of the study area. An observational study also suggested the introduction of a southern cultivar to mitigate the high-temperature damage projected for the current leading cultivars (Nemoto et al. 2011).

In approximately 64% of the grid cells, however, presently leading cultivars remained the winners if the 3 metrics are taken into account (Fig. 9f). This finding suggests that cultivar replacement is not an 'easy' option. Southern cultivars often failed to win despite many reverse grid cells based on a single metric (Figs. 9a–c). A trait such as low sensitivity to temperature for phenology observed for Hitomebore also helps current winners under climate change conditions because of its smaller variation in growth duration. This trait could also be a valuable trait under variable weather conditions. The results also suggest that breeding new cultivars for the future by utilizing or pyramiding higher yield potentials and stress tolerances is essential. Phenology is the first trait that needs to be considered for climate change adaptation, but keeping growth duration long is not the only way to improve productivity. In the context of climate change, enhancing the CO_2 fertilization effect is an option for the future (Ziska et al. 2012). A previous FACE study demonstrated a large genotypic variability in the grain-yield response to elevated C_a, ranging from 3 to 36% (Hasegawa et al. 2013).

The current study is an initial attempt to account for multiple metrics to visualize a possible cultivar shift under climate change conditions. In reality, farmers' cultivar choices are more complex, with many more metrics taken into account. Marketability, eating, and appearance quality, in addition to pest, diseases, and lodging resistance, all count when choosing cultivars, all of which can be potentially influenced by climate change. Future work is required to link these metrics, as they directly affect the profitability of farmers.

5. CONCLUSION

This study evaluated adaptation to climate change for crop production based on multiple metrics and multiple choices of existing cultivars, taking the presently cool climate as an example for rice production in Japan. Projection based on the MIROC5 global climate model under RCP4.5 and a rice model (H/H) demonstrated that climate change in the 2081–2099 period would increase grain yield by a regional average of 17% compared with the baseline climate (1981–2000), even without any cultivar shift. The simulation also predicted that low-temperature stresses would be reduced but that high-temperature stresses would become apparent, suggesting that countermeasures against both heat and cold damages will be required in the future climate.

Comparisons of simulations among 10 major Japanese cultivars demonstrated that top cultivars change dramatically with climate change if only a single metric, such as yield, is accounted for. The predicted yield averaged for the yield 'winners' was 26% higher than the baseline yield. When all 3 metrics (yield, cold and heat stress) are taken into account, however, cultivar replacement is projected to occur in ~36% of the grid cells, and the current leading cultivars maintained their superiority in ~64% of the total grid cells. The resultant yield advantage compared with the baseline was 22%. This finding suggests a requirement for developing new cultivars by pyramiding useful traits for the future climates. A trait such as low sensitivity to temperature for phenology helps in ensuring growth duration under variable temperatures. Increasing photoperiod sensitivity can be an option in the future climates in relatively warmer regions.

Future studies must include other important metrics, such as quality and profitability, in combination with management practices, including crop calendar and fertilizer managements. Uncertainties from climate projections and crop models should also be combined with the benchmark testing of these adaptation measures.

Acknowledgements. This study was supported by JSPS KAKENHI (Grant No.: 25892004), Asahi Group Foundation, the Research Program on Climate Change Adaptation (RECCA) of the Ministry of Education, Culture, Sports, Science, and Technology of Japan, the Environment Research and Technology Development Fund (S-8-1) of the Ministry of the Environment, Japan, and the Cross-ministerial Strategic Innovation Promotion Program of the Cabinet Office, Government of Japan. The H/H model improvement was conducted through a research project entitled 'Development of technologies for mitigation and adaptation to climate change in agriculture, forestry and fisheries,' funded by the Ministry of Agriculture, Forestry and Fisheries, Japan. We thank Dr. Shinji Sawano for providing N fertilizer input data converted from the Production Cost Statistics.

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Editorial responsibility: Gerrit Hoogenboom, Prosser, Washington, USA

Submitted: August 25, 2014; Accepted: June 3, 2015
Proofs received from author(s): August 25, 2015