Probabilistic Risk Assessment of the Rice Cropping Schedule for Central Hokkaido, Japan

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ABSTRACT

A framework for the probabilistic risk assessment of the rice (Oryza sativa L.) cropping schedule (PRARCS) is presented. The method accounts for interannual meteorological variation, as opposed to the traditional cultivation schedule planning method, which is based on the seasonal change in long-term average air temperature. PRARCS uses an arbitrary developmental index model to estimate the timing of the heading stage, which is required to assess the risks of cold or heat damage and productivity. All results of risk assessment and productivity are linked to transplanting date as the most important cultivation practice for irrigated rice paddies. The results of assessments using PRARCS at Iwamizawa, central Hokkaido, Japan, indicated that for the current climate the optimal transplanting period is the end of May, and this corresponds to the actual transplanting dates used and the increasing risks and decreasing productivity with earlier or later transplanting. Assessment using projected climatic data for the period 2031–50 showed that Akitakomachi and Hitomebore, present-day cultivars in the Tohoku region, could achieve satisfactory productivity in central Hokkaido. For the term 2081–2100, assessment using an extreme warming projection (4.7°C higher than at present) indicated that the probability of heat damage (white-based rice and heat sterility) is once every 2 yr for some transplanting dates and that cold risks (transplanting damage, cold injury, and immature ripening) are reduced. It was also found that the cultivar Koshihikari, at present suited to more southern regions, could be cultivated in central Hokkaido in 2081–2100 if transplanting is conducted in early May.

1. Introduction

Various risks to paddy rice (Oryza sativa L.) production from future climate change have been assessed. Under the projected climate conditions, the rice cultivation period will be prolonged in Japan (Ohta and Kimura 2007), and shifting the transplanting date in the warm region was thought to be one of the countermeasures to avoid heat damage (e.g., Okada et al. 2011) and to maximize production (Yokozawa et al. 2009). However, those results were not well considered from the point of view of comprehensive cultivation, which includes other risks, such as sterility by cold and heat and changes in

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productivity and quality of rice that arise from the interannual variability of weather conditions. In a case study of the probabilistic evaluation of climate change impacts (Iizumi et al. 2011), cultivation practices were assumed to be at the same level as in the present.

To stabilize the productivity of irrigated paddy rice in the cold northern climates of Japan, traditional rice cultivation planning is based on the seasonal change in long-term average (or normal) air temperatures (Yatsuyanagi 1960a–f; Murakami et al. 1982). In this method, three critical dates are identified: 1) the early limit for seedlings to take root, 2) the early limit for heading to avoid cold-induced sterility, and 3) the late limit for heading to avoid growth retardation from cold damage and secure enough time for ripening. These three dates are determined from long-term average air temperatures and rice cultivar characteristics. Transplanting dates are chosen after the first critical date so that seedlings will survive and to ensure that heading will occur between the early and late limits. This method is intended to use climate resources efficiently in cold areas in Japan, but it is not easy to decide upon the best cropping schedule because of independence among the three risk assessments, and it does not deal with interannual variability in meteorological conditions. In northern Japan, long-term analysis of variation shows that cool summers occur approximately once every 5 yr (Kurihara 2003; Kanno 2004); thus, cool summer crop damage has been a major problem impacting rice production in northern Japan.

In the traditional rice cropping schedule, to determine the transplanting and heading dates to satisfy the critical dates for different cultivars, the relationship between transplanting date and heading date was empirically determined from actual cultivation experiments or estimated from cumulative air temperature. In the 1960s, when the rice cropping schedule method was introduced, process models that accounted for the developmental process of rice crops (e.g., Horie and Nakagawa 1990), including developmental delays as a result of photoperiodism, were rarely used in Japan. The fact that the cumulative air temperature from transplanting to heading varied from year to year and differed between different transplanting dates suggested that a model that included photoperiodism was necessary. It was also important to enable the assessment of how a cultivar might perform in places with differing day lengths.

To improve both current and future potential productivity assessments, various initiatives for estimating yield from climatic conditions were implemented. One approach was to relate the climatic productivity index (or agroclimatic index of the quantity of ripening), which is the yield potential under ideal conditions, to the climatic conditions of the ripening period after heading (Murata 1964; Hayashi et al. 2001). Another was to relate an index of the yield reduction rate to air temperature at the booting stage, flowering stage, and during the ripening period (Hanyu et al. 1966). Process models such as “SIMREW” (Horie et al. 1995) and the Process-Based Regional-Scale Rice Yield Simulator with Bayesian Inference (PRYSBI) model (Iizumi et al. 2009) were developed and used to estimate rice yield. The effect of climate change on the optimal heading date was estimated by determining the maximum agroclimatic index of the quantity of ripening (Hayashi et al. 2001). Although the climatic conditions after heading were considered, the effects of interannual variation in meteorological conditions on the probability of crop success and crop productivity were not considered. Iizumi et al. (2011) presented a probabilistic evaluation of future rice productivity in Japan that included uncertainties in climate projections; however, the effect on the probability of cultivation success of current cultivars and potential changes in cultivation practices was not examined.

Although the frequency of low-temperature summers is predicted to decrease in northern Japan (Solomon et al. 2007), precautions against cool summers will continue to be needed because rice yield is strongly dependent on summer temperatures (Tsuboi 1986) and periodic cold damage can still be expected (Hayashi 2009). In addition, the frequency of extreme weather such as intense heat is predicted to increase (Solomon et al. 2007) and needs to be guarded against in future planning. Therefore, rice cropping planning that takes into account interannual variability in weather, including hot and cold temperature extremes, is important for stable rice production in Hokkaido in the future.

We propose here a framework for probabilistic risk assessment of rice cropping (PRARCS), a decision-support tool for climatically stable rice cultivation planning that considers interannual variability in meteorological conditions. PRARCS focuses on finding transplanting dates with low risks and high productivity, because transplanting of irrigated rice paddies is a most important cultivation practice that has to be timed to avoid unfavorable weather conditions (e.g., extremely cold or hot air temperature) at critical developmental stages. PRARCS combines the traditional method for planning the rice cultivation schedule in northern Japan with models that estimate rice development and yield from the transplanting date in accordance with meteorological conditions. As a practical application of the system, we used PRARCS to determine the optimal cultivation period and cultivars suitable for paddy rice cultivation in Hokkaido for a future climate scenario.
2. Materials and methods

The framework for PRARCS is presented in section 2a. The initial settings for PRARCS used in this study are explained in sections 2b–e.

a. Basic structure and procedure of PRARCS

A flowchart of the calculation process used in PRARCS to determine the optimal transplanting date and the possibility of successfully cultivating the intended cultivars, accounting for interannual variability in meteorological conditions, is shown in Fig. 1. The initial settings consist of four interrelated components (Fig. 1, components A–D). (A) The calculation conditions are defined by the site, time period, and cultivar. The location of the site to be assessed is needed for the calculation of day length to account for rice plant photoperiodism in the simulation model of rice development. The time periods refer to the years of simulation (e.g., 2031–50) and transplanting window (e.g., from 1 April to 31 August). (B) Risk factors refer to potential losses from transplanting damage, cold sterility, heat sterility, and occurrence of heat-induced grain defects, such as chalky rice. (C) Estimation models are used to simulate crop development, which is required to assess the possibility of losses from the risk factors and to predict the yield. A set of parameters is used in the models to account for cultivar attributes. For precise assessment, the models should be calibrated with experimental data derived from the same conditions and time period that we wish to assess. (D) The calculation models and risk assessments require meteorological data through the period of simulation at the selected site. Projected data (e.g., from a general circulation model) or actual past data can be used for assessments.

After selection of the initial settings, the risk assessment is calculated for every day \([d_1, d_2, \ldots, d_n]\) of every year \([y_1, y_2, \ldots, y_m]\) during the selected time period by a three-step procedure. The three steps are shown by the numerals 1–3 in Fig. 1. In step 1, the day of development stages of interest (e.g., heading date) and yield are estimated for every days of the transplanting window using the simulation model or models and meteorological dataset. In step 2, whether losses occur from each risk factor is determined from the estimated date of the relevant developmental stages and meteorological data. In step 3, the occurrence frequency of losses from each risk factor for each transplanting date \([d_1, d_2, \ldots, d_n]\) through the time period \([y_1, y_2, \ldots, y_m]\) is calculated.

The following sections present the initial settings and data used in this study.

b. Calculation conditions

The site chosen for our study was Iwamizawa (43°12.6’N, 141°47.1’E), which is 40 km east-northeast of Sapporo and a noted rice paddy area in central Hokkaido, Japan. We assessed the present and future cultivation possibilities of four cultivars, Kirara 397 (a cultivar used in...
Hokkaido), Akitakomachi (from the Tohoku region), Hitomebore (used from mid-Tohoku to southern Japan), and Koshihikari (used from southern Tohoku to southern Japan). We adopted three 20-yr time periods, the present (1981–2000), the mid-twenty-first century (2031–50, +50 yr), and the late-twenty-first century (2081–2100, +100 yr) in accordance with available data projections.

c. Risk factors and yield

We considered five risk factors and used them to adjust yield if losses arising from these risks were determined to have occurred. The occurrence of losses from three of the five risk factors was determined from whether the transplanting date or heading date occurred after or before (as applicable) their respective limit dates. The three limit dates were for stable rice production formulated previously for northern Japan (e.g., Uchijima 1983) and concerned low-temperature damage. They were the dates for the early limit for transplanting (EL-TP), the early limit for heading (EL-H), and the late limit for heading (LL-H). The other two risk factors concerned high temperature and heat and were sterility (HS) and high incidence (5%) of white-based rice kernels (WB). The critical dates EL-TP, EL-H, and LL-H are used in traditional rice cultivation schedule planning for northern Japan. We chose to examine losses from HS and WB from among other defects caused by high temperature because both have occurred in southern to middle Japan recently (Morita 2011), and because HS and WB can be predicted from heading date and air temperature (Matsui 2009; Wakiyama et al. 2010). The risk of water shortage to damage to rice crop development or productivity was not considered in this study. Because Japanese rice paddy fields are fundamentally using well-controlled irrigation systems, severe water shortages in rice paddy fields have not occurred for several decades in Japan (Yokozawa et al. 2009). Although the possibility of occurrence of severe water shortage in Hokkaido in the future is not zero, we assumed that the water supply to rice paddies is sufficient. This situation is different from areas in the tropics (e.g., Naylor et al. 2007).

The criteria for the critical dates EL-TP, EL-H, and LL-H for Hokkaido have been defined by Oda (1992) as follow: EL-TP is the earliest transplanting day that midage seedlings (four to five leaves) can take root based on the average temperature of the following 5 days being at least 12°C; EL-H, which is designed to avoid sterility caused by cold damage, is defined as the first day at which an average temperature of not less than 20.5°C can be assured for 30 days, commencing from 24 days before heading; LL-H, the purpose of which is to avoid growth retardation caused by cold damage, is defined as the last day at which an average temperature not less than 18.8°C can be assured for 40 days after heading. We called the period from EL-H to LL-H the period for averting cool injury at heading (HP-ACI; Oda 1992). The three threshold temperatures of EL-TP, EL-H, and LL-H specified above are those used for Hokkaido (Oda 1992). Different values are used in other areas of Japan, especially for LL-H, because temperature regimes are different and the prevailing rice cultivars were bred to suit the local climatic conditions. Therefore, the dates we used for LL-H were determined from the temperature thresholds used in Hokkaido for Kirara 397 (18.8°C), in the Tohoku region for Akitakomachi and Hitomebore (20°C), and in the Kanto region for Koshihikari (22°C; Uchijima 1983).

The criteria used to determine whether losses occur from the two heat risk factors were as follow: for HS, an average daily maximum temperature of >35°C for 5 days after heading (Matsui 2009), and for WB, an average temperature of >27°C for 20 days after heading (Wakiyama et al. 2010).

The climatic productivity index (CPI) proposed by Murata (1964) was used as an alternative for the real productivity of rice. Although CPI was originally calculated from air temperature and sunshine duration data (Murata 1964; Hanyu et al. 1966; Uchijima and Hanyu 1967), we estimated it from solar radiation using an equation developed by Hayashi et al. (2001):

\[
y/R_s = 0.128 - 0.00192(21.9 - T)^2, \tag{1}
\]

where \(y\) is the CPI (kg ha\(^{-1}\)), \(R_s\) is solar radiation for 40 days after the heading date, and \(T\) is the average air temperature for the 40 days after the heading date. Since the CPI was treated as potential productivity from the meteorological conditions after heading (Hayashi et al. 2001), the yield reduction from sterility caused by cold or heat prior to heading was not considered. Moreover, the developmental index (DVI) model used in this study does not include the process of death caused by transplanting before the EL-TP date. Thus, the CPI calculated from the heading date estimated by the DVI model suggests unrealistically high values. Therefore, we proposed a “risk-adjusted climatic productivity index” (R-CPI) as follows:

\[
Y_a = Y \times \alpha, \tag{2}
\]

where \(Y_a\) is the R-CPI, \(Y\) is the average value of CPI during the time period simulated with PRARCS, and \(\alpha\) is a risk-adjustment term, calculated as
where $R_{\text{EL-TP}}$, $R_{\text{EL-H}}$, and $R_{\text{HS}}$ are the probabilities of occurrence of losses from EL-TP, EL-H, and HS, respectively. In Eq. (3), the effect of $R_{\text{EL-H}}$ and $R_{\text{HS}}$ on $\alpha$ was limited to a maximum of 0.25 because yield reduction caused by cold or heat sterility is seldom lower than 25% (Hokkaido District Agriculture Office, 2011). The value of 0.25 was not validated with field experimental data. Moreover, CPI does not include the effect of increasing rice yields with elevated CO2 (e.g., Ainsworth 2008). However, we believe that R-CPI is useful for finding the peak value of CPI in the absence of losses from the various risk factors, and the main purpose of our study was to use R-CPI. The concept of reduction associated with LL-H is included in the idea of CPI, and the occurrence of WB affects the quality of rice but not productivity.

**d. Rice development model and parameter sets**

We used the development index model to estimate the heading dates that were required to assess the occurrence of losses from four of the five risk factors. The DVI model that we used to indicate the developmental stage of rice was that of Horie and Nakagawa (1990), which is based on the cumulative daily development ratio (DVR):

$$DVI = \sum_{i=0}^{n} DVR_i,$$  

where DVI is defined as 0 at emergence and 1 at heading, $i$ is the number of days since emergence, and DVR is calculated from

\[
DVR = \begin{cases} 
\frac{1}{G} \frac{1}{1 + \exp[-A(T - T_h)]} & (DVI < DVI^*), \\
\frac{1}{G} \frac{1}{1 - \exp[B(L - L_c)]} & (DVI \geq DVI^*, L < L_c), \\
0 & (DVI \geq DVI^*, L \geq L_c),
\end{cases}
\]

where $T$ is mean air temperature, $L$ is day length, $DVI^*$ is the development stage at which rice plants become sensitive to photoperiod, $A$ and $B$ are coefficients, $L_c$ is the critical day length for development, $T_h$ is the temperature at which DVR is half the maximum for a given day length, and $G$ is the minimum number of days required for heading for a given cultivar.

To determine the parameters of the DVI model for the four cultivars under temperature conditions extending from the present to the future, field experimental data were obtained from four sites in Japan (Fig. 2): Sapporo in Hokkaido (northern Japan), Morioka in the Tohoku region (northeast Japan), Tsukuba in the Kanto region (mid Japan), and Kumamoto in Kyushu (southern Japan). The cooperative experiments were conducted at the four sites during 2 yr (2009 and 2010) using an open-field day-length-extension experiment (ODE experiment) (Sameshima et al. 2011; Nemoto et al. 2011a), which provided pseudo–global warming conditions with light-bulb irradiation. The experimental data did not include the effects of CO2 enrichment. However, the effect on the earlier heading date was only a few days (e.g., Sasaki et al. 2007) and negligible with regard to the transplanting date in this study. The soil types at all experimental sites are the same as volcanic soil. Standard water and fertilization administration was done at each
site; thus, there was no water stress, and no excess or deficiency of fertilizer for cultivars used in this study. The average air temperature from June to August across all experiments ranged from 18.1°C to 25.8°C for the period of June–August (JJA), reflecting the regional and interyear variations. The data from the ODE experiment also included warmer areas with the same day length as Sapporo, corresponding to actual predicted future conditions (Fig. 3). The data from the interregional experiment, excluding the ODE data, reflect only the temperature differences between the experimental sites; the problem with these data is that temperature and day length are inversely correlated in Japan. That is, latitudes lower than Sapporo have higher temperatures and shorter day lengths in summer (Fig. 3).

The DVI parameters (Table 1) were determined from the experimental data using the simplex method (Nelder and Mead 1965). The DVI at transplanting (the 4.5–5.0 leaf stage) was approximately 0.28 on average, so the initial DVI at the transplanting date was set at 0.28 in the PRARCS calculations. We calculated day length for rice plant photoperiodism as the period between solar altitudes of −2° at dawn and −2° at dusk for both the DVI model and ODE experiment settings in accordance with the experimental results of Wakiyama et al. (2011). Day length was calculated using the equations of Nagasawa (1999).

e. Meteorological data from the present and future

We used the Metecrop database (Kuwagata et al. 2008, 16–17; available online at http://metecrop.dc.affrc.go.jp) for present (1981–2000) meteorological data at Iwamizawa because of the need to use solar radiation to calculate the climate productivity index in Eq. (1). In the Metecrop database, solar radiation is estimated from sunshine duration observed by the Japan Meteorological Agency using the equations of Kondo (1994).

Two daily climate models were used to provide the data for the assessment of future conditions at Iwamizawa. One was the Regional Climate Model, which has a 20-km mesh (RCM20), of the Japanese Standard Climate Scenario version 2 provided by the Japan Meteorological Agency (Kurihara et al. 2005). The other was the Model for Interdisciplinary Research on Climate (MIROC; Okada et al. 2009), which has a 1-km mesh and originated from a high-resolution version of MIROC (Hasumi and Emori 2004). The RCM20 and MIROC datasets used in this study were based on scenarios A2 and A1B, respectively, found in the Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart 2000). In the case of the RCM20 data, a distance-weighted average value of the nearest four grid points was used for Iwamizawa. The 1-km mesh data for the grid cell location that contained Iwamizawa was used from the MIROC data.

After calculating the daily climate values for the present (1981–2000), +50-yr (2031–50), and +100-yr (2081–2100) time periods, the differences between the present and the +50-yr and between the present and the +100-yr

![Fig. 3. Relationships between average day length and average air temperature for the combined months of JJA. The ODE experiments in 2009 and 2010 were conducted in Morioka, Tsukuba, and Kumamoto and are represented by the double diamonds and double circles, respectively. The solid circles represent 30-yr average data from Japan Meteorological Agency stations where the altitude is lower than 300 m.](image)

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>No. of data points</th>
<th>RMSE (days)</th>
<th>$A$</th>
<th>$T_p$ (°C)</th>
<th>$B$</th>
<th>$L_c$ (h)</th>
<th>$G$ (days)</th>
<th>DVI*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kirara 397</td>
<td>22 (14)</td>
<td>4.5</td>
<td>0.4847</td>
<td>16.50</td>
<td>0.17</td>
<td>23.50</td>
<td>50.53</td>
<td>0.27</td>
</tr>
<tr>
<td>Akitakomachi</td>
<td>41 (26)</td>
<td>3.8</td>
<td>0.3568</td>
<td>16.91</td>
<td>0.52</td>
<td>17.74</td>
<td>52.89</td>
<td>0.31</td>
</tr>
<tr>
<td>Hitomebore</td>
<td>63 (36)</td>
<td>4.2</td>
<td>0.2736</td>
<td>16.72</td>
<td>0.69</td>
<td>15.77</td>
<td>61.24</td>
<td>0.27</td>
</tr>
<tr>
<td>Koshihikari</td>
<td>68 (36)</td>
<td>4.2</td>
<td>0.2480</td>
<td>16.21</td>
<td>0.71</td>
<td>16.27</td>
<td>53.09</td>
<td>0.26</td>
</tr>
</tbody>
</table>

TABLE 1. Estimated parameters ($A$, $T_p$, $B$, $L_c$, $G$, and DVI*) for the DVI model used in this study and RMSE in heading dates between model estimation and in situ data. The number of data points is the total number of data points used for estimation of the parameters in difference experimental plots, sites, and years for each cultivar. The numbers in parentheses in the second column reflect the numbers of data points using an open-field day-length-extension experiment (ODE experiment).
values were extracted (Table 2). The differences in the climate values of the model outputs were added to the present daily 20-yr values to remove bias error between the model outputs and in situ data. Therefore, interannual variation of the future meteorological datasets was equivalent to that of observational data for the present.

### 3. Results

#### a. Traditional method

Figure 4a shows the traditional limit dates of EL-TP, EL-H, and LL-H for 30 yr (1981–2010) based on field experimental data from the Hokkaido Agricultural Research Center in Sapporo, Hokkaido. The dates of EL-TP, EL-H, and LL-H for this period are 22 May, 3 August, and 14 August, respectively. The HP-ACI period between EL-H and LL-H is 12 days and is shaded gray in Fig. 4a.

#### b. Probabilistic method by PRARCS

Because the change in air temperature with the advance of the season varies between years (Fig. 4b), the limit dates of each weather condition also vary with year. Figure 5a indicates the probability of breaching EL-TP on each potential transplanting date at Iwamizawa for the 20-yr period of 1981–2000. This shows that transplanting would have been unsuccessful if conducted before 29 April (probability equaled 1.0) in all years based on meteorological conditions. Conversely, transplanting after 2 June (probability equaled 0.0) would have been successful in all years.

Figure 5b shows the probability of heading occurring before EL-H for each potential transplanting date. The DVI model can be used to connect transplanting date and heading date from the meteorological conditions occurring in each year (e.g., Fig. 4c). Since the maximum probability was 0.25, heading would never have occurred before EL-H more often than 3 out of 4 yr for any transplanting date. Later transplanting reduced the probability of heading occurring before EL-H.

Figure 5c shows the probability of heading occurring after LL-H for each transplanting date. Later transplanting increases this probability. Transplanting after 10 July (probability equals 1.0) would not have permitted full ripening to have been achieved in any year. Even the earliest transplanting dates indicated a probability of 0.15 of heading occurring after LL-H.

Figure 5d combines the three probability profiles of breaching EL-TP, EL-H, and LL-H versus transplanting date. The large white area (lowest probabilities) indicates...
that the safest transplanting date with respect to climatic conditions is in late May.

Figures 5e and 5f show the average heading date and the CPI, respectively, against transplanting date simulated with the DVI model. The CPI was at a maximum and relatively constant before early May (Fig. 5f) because the simulated heading date was independent of transplanting date up to that point (Fig. 5e). Here, R-CPI was calculated from the CPI and probabilities of breaching limit dates following Eq. (3) (Fig. 5g). Heat sterility (HS) did not occur under the meteorological conditions of the term 1981–2000 at Iwamizawa. The value of R-CPI, which included the risks of rice death at transplanting and cold and heat sterility at heading, was zero for early transplanting before May and increased steeply through May, reaching a peak in late May to early June before declining back to zero by the beginning of August (Fig. 5g).

c. Assessment of four cultivars in present and future scenarios

Figure 6 shows the results of assessments using PRARCS at Iwamizawa for the four cultivars (Kirara 397, Akitakomachi, Hitomebore, and Koshihikari) and three time periods: the present, +50 yr, and +100 yr.

For the present, the minimum probability of breaching LL-H for Akitakomachi and Hitomebore was 0.7, showing that it is difficult for these two cultivars to fully mature. The probability of LL-H being breached for Koshihikari was 1.0 at any transplanting date for the present climate, indicating insufficient temperature can be accumulated after heading to ensure ripening for this cultivar in Iwamizawa. The probabilities of WB and HS occurring were zero for the present climate at Iwamizawa.

For the +50-yr climate, the probability of LL-H being breached decreased in all cultivars. Kirara 397 could be successfully cultivated at Iwamizawa even if transplanting was conducted at the end of June. Akitakomachi and Hitomebore were also capable of being cultivated. Very low probabilities of WB and HS emerged.

For the +100-yr climate, the probability of LL-H being breached decreased in all cultivars, even Koshihikari. The probabilities of WB and HS increased slightly and were higher than for the +50-yr climate.
4. Discussion

a. Comparison of PRARCS with the traditional rice cultivation planning method

The limit dates for EL-TP, EL-H, and LL-H used in the traditional method corresponded to a breach of the limit dates calculated by PRARCS about 50% of the time (Fig. 4b). Therefore, the PRARCS method suggests that under the traditional method of rice cropping planning, losses due to the various risk factors occur approximately once every 2 yr. Because PRARCS simultaneously displays risk as the probabilities of loss from each risk factor linked to the transplanting date using a rice developmental model, the variability in breach occurrence versus transplanting date and the relationships between the probabilities are easily comprehensible.

PRARCS can link any risks during growing period to transplanting date by using a developmental model. Therefore, PRARCS is thought to be applicable to the risk assessment of long droughts, logging by strong wind, and any risks other pointed out by Das (2005). PRARCS is not only useful for deciding optimal transplanting dates and selecting cultivars based on long-term climatic conditions. If long-range (4–5 months) weather forecasts are accurate, it can also be used to guide the raising of seedlings each year. For example, if a warmer summer than normal is predicted, we can adjust the timing of seedling raising to select a transplanting date with slightly higher cold risk (EL-H and LL-H) and lower heat risks (WB and HS) than we would from an assessment based solely on long-term meteorological data.

b. Rice cropping schedule for the present climate

At present at Iwamizawa for cultivar Kirara 397 (Fig. 6), the lowest risk period for transplanting is the end of May. The average transplanting date at present in this area for moderately developed seedlings of Kirara 397 is reported to be 21 May (Sasaki 2001). The PRARCS

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FIG. 6. Results of an assessment of rice cropping at Iwamizawa using PRARCS for four cultivars and three climate periods: the present (1981–2010, shown in the first row of panels), +50 yr (2031–50, second row of panels), and +100 yr (2081–2100, third row of panels). The first three rows of panels indicate the probabilities of breaching risk factors for each transplanting date at Iwamizawa. The fourth and fifth rows of panels indicate the R-CPI and heading date, respectively.
result closely corresponded to the real situation, suggesting that transplanting at the earliest possible time for the given meteorological conditions is a reasonable strategy to avoid cold injury associated with LL-H. Even with transplanting at the end of May, the probability of breaching EL-H and LL-H was up to 0.25. This result also corresponds with the actual situation because rice yield reduction has been shown to occur approximately once in 4 yr in Hokkaido (Hirota et al. 2011). These results show clear climatic constraints on rice planting in Hokkaido, the northernmost area of Japan, at present.

For the Tohoku region cultivars (Akitakomachi and Hitomebore), the minimum probability for breaching LL-H was 0.7, indicating that these cultivars can reach full maturity in only approximately 3 yr out of 10. Because this assumes that no other problems occur, the results clearly show that these cultivars cannot be reliably grown at Iwamizawa under the present climate.

c. Cultivation possibility for future climate

For the +50-yr climate (Table 2), Kirara 397 can be cultivated by transplanting from the end of May to the end of June with lower risks associated with EL-TP, EL-H, and LL-H than at present (Fig. 6). Akitakomachi and Hitomebore can also be cultivated at Iwamizawa by transplanting at the end of May with lower risks than exist for Kirara 397 under present conditions. Kirara 397, Akitakomachi, and Hitomebore have nearly identical values of R-CPI, around 6.0 Mg ha⁻¹. Nemoto et al. (2011b) reported that Hitomebore fully ripened and produced a yield of 6.3 Mg ha⁻¹ in an extremely hot year (2.2°C higher than normal) in 2010 in Hokkaido. However, it is still difficult to cultivate Koshihikari because the probability of a loss occurring from one of the risk factors is high for any transplanting date (Fig. 6). The heat risks (WB and HS) were slight for all cultivars, occurring approximately once per 10 yr.

For the +100-yr conditions (Table 2), a large temperature difference was apparent between the two different climate projections. Although the overall trend of the +100-yr results was similar to that of the +50-yr results for the data from the RCM20 projection (+2.4°C), the peak values of R-CPI for the four cultivars were higher from the +100-yr conditions than from the +50-yr and present conditions. Heat risks are greater with the MIROC data (+4.7°C) than with the RCM20 data. Under MIROC conditions, heat risks (WB and HS) arise 1 yr in 2 while at the same time reduced cold risks (EL-TP, EL-H, and LL-H) appear for some transplanting dates (Fig. 6). The peak values of R-CPI for Kirara 397, Akitakomachi, and Hitomebore are lower with MIROC than with RCM20 meteorological data because of the high HS risk with the latter. The highest R-CPI peaks with MIROC data are achieved with a late transplanting date, that is, in early to mid-July for Kirara 397 and early July for Akitakomachi and Hitomebore. For Koshihikari with MIROC conditions, transplanting around early to mid-May presents a risk profile for cultivation that is similar to that for Kirara 397 at present, and the peak R-CPI occurs with mid-May transplanting. Therefore, under the extremely hot conditions predicted by MIROC (+4.7°C), two optimal transplanting periods to avoid heat risks arise: mid-May (Koshihikari) and early July (Kirara 397, Akitakomachi, and Hitomebore).

Akitakomachi and Hitomebore, the present-day Tohoku cultivars, appear to be as suitable for cultivation at Iwamizawa as Kirara 397 is at present if temperatures rise by 1.5°–2.6°C from present levels (Table 2 and Fig. 6). This result is consistent with the results of open-field experiments designed to assess the effects of warmer conditions than present (Nemoto et al. 2011a).

5. Conclusions

We developed the new framework of PRARCS as a decision-support tool for climatically stable rice cultivation planning considering interannual variability in meteorological conditions. All results of risk assessment and productivity are linked to transplanting date as the most important cultivation practice for irrigated rice paddies. The prediction of transplanting dates with low risks and peak R-CPI using PRARCS successfully matched the present rice cultivation schedule in central Hokkaido. Our results indicated that heat risks not currently existing will occur in Hokkaido under the highest projections of climatic warming (+4.7°C). In fact, rice yield in Hokkaido decreased in 2010 owing to abnormally high temperatures (+2.2°C), especially from the end of June to early July, which shortened the vegetative growth period and reduced the number of tillers and number of grains per plant (Nemoto et al. 2011b). This was the first time a reduction in rice yield caused by hot conditions had been recorded in Hokkaido. The DVI model we used for PRARCS in this study could not adequately portray the process of heat-induced yield loss, and an improved model for more precise prediction of yield reduction by heat damage is needed to determine future rice cropping schedules. Moreover, our ODE experimental data for setting the parameters in the DVI model covered the range of air temperature of current estimates of climate change, but they were obtained without enrichment of the CO₂ concentration. A combination of an ODE experiment (Sameshima et al. 2011) and a free-air CO₂ enrichment (FACE) experiment (e.g., Okada et al. 2001) would be ideal as an open-field experimental method to...
obtain more accurate data on rice cultivation for risk assessment including its productivity and quality under projected climate change conditions. To assessment of uncertainty of GCM projections, an integrated dataset (e.g., Izumi et al. 2012) should be used for PRARCS.

The risk threshold temperatures could potentially change as new cultivars are introduced in accordance with ongoing global warming. For the present climate, the threshold temperature for LL-H varies among regions of Japan corresponding to differences in summer temperature regime and prevailing cultivars. An alternative approach would be to identify threshold temperatures with sufficiently low risk under the presumed meteorological conditions and use them as targets for new cultivation methods and breeding of new cultivars. Moreover, the adjustment of management or environmental attributes not included in the simulation of the PRARCS framework in this study (e.g., fertilizer usage, water temperature in paddies) may be possible with an improved model or by changing the threshold temperatures of the various risk factors.

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