Impact assessment of climate change on the major rice cultivar Ciherrang in Indonesia

Yoshiyuki KINOSIE, Yuji MASUTOMI, Fumitaka SHOTSU, Keiichi HAYASHI, Daikichi OGAWADA, Martin GOMEZ-GARCIA, Akiko MATSUMURA, Kiyoshi TAKAHASHI and Kensuke FUKUSHI

Abstract

In Asia, where rice is a major crop, there is high concern about the detrimental effects of climate change on rice productivity. Evaluating these effects, considering the country-specific cultivars’ responses to climate, is needed to effectively implement the national adaptation plans to maintain food security under climate change. However, to date, information on the effects of climate change on the local rice cultivars used in developing countries is extremely limited. In the present study, we used a process-based crop growth model, MATCRO-Rice, to predict the impact of climate change on yields of the major local rice cultivar Ciherrang in Indonesia during the next 25 years (2018–2042). This model simulated the effects of current to future air temperature, precipitation, and atmospheric carbon dioxide concentration on rice yield. A total of 14 future climate scenarios, derived from a combination of four general circulation models and three or four representative concentration pathway scenarios in the Coupled Model Intercomparison Project Phase 5, were used to consider the uncertainty of the future climate. The results showed that the rice yield was reduced under all climate scenarios, mainly because of the higher air temperature, leading to reduced photosynthetic rates, increased respiration rates, and phenological changes such as acceleration of senescence. The mean yield reduction across the 14 future climate scenarios was 12.1% for all of Indonesia in 2039–2042. Therefore, to maintain yields in Indonesia, rice production needs to adapt to climate change, and especially to higher air temperatures, in the near future.

Key words: Climate change, Indonesia, Local rice cultivar, Model simulation, Yield

1. Introduction

The Paris Agreement, a legal framework on global warming countermeasures, was adopted at the 21st Conference of the Parties in 2015 (UNFCCC, 2015); it was officially enacted in 2016. All countries under the agreement, including developing countries, must implement mitigation plans, that is, reduce greenhouse gas emissions, with the goal of preventing the global average temperature from increasing by over 2°C compared with preindustrial levels. Furthermore, in a nod to the detrimental impacts of climate change already observed around the world, the Paris Agreement states that each party shall, as appropriate, plan and implement adaptation strategies to climate change. To create and implement national adaptation plans, it is necessary to evaluate climate change impacts at a national scale.

Climate change is caused mainly by atmospheric carbon dioxide (CO₂), which is the major greenhouse gas. The CO₂ concentration has increased from approximately 280 μmol mol⁻¹ (ppm) in 1750 to approximately 400 ppm presently, owing to fossil fuel combustion and biomass burning (Joos and Spahni, 2008; Dlugokencky and Tans, 2019). On the other hand, rising air temperatures and changes in precipitation have occurred along with the increase in the CO₂ concentration (IPCC, 2014). These climate change will continue in the future (IPCC, 2014).

Many studies have shown that agricultural yields are detrimentally affected by climate change (e.g., Rosenzweig and Parry, 1994; Parry et al., 2004; Porter et al., 2014). Climate change has the potential to decrease the production of rice, posing a high risk to people already suffering from food shortage in developing countries in Asia (Masutomi et al., 2009; Wassmann et al., 2009; Babel et al., 2011). In general, as CO₂ is the substrate for photosynthesis, an increased atmospheric CO₂ concentration results in a higher photosynthetic rate and
yield of rice (Kim et al., 2003; Hasegawa et al., 2013). On the other hand, at lower latitudes, where the air temperature is relatively high, a further increase in air temperature is likely to have a negative effect on rice yields, although its increase is positive for rice grown at higher latitudes (Parry et al., 2007; Rosenzweig et al., 2014). Furthermore, because rain-fed paddy fields are common in Asian developing countries, precipitation changes could also affect rice yields. Therefore, in the future, rice production may be reduced by the rising air temperature and reduced precipitation in these developing countries, even though the atmospheric CO₂ concentration increases.

Indonesia, located along the equator in Southeast Asia, is ranked as the third highest country for rice production and the sixth for rice consumption per capita in the world (Maclean et al., 2013). Following Indonesia’s National Medium-Term Development Plan (Rencana Pembangunan Jangka Menengah Nasional [RPJMN]) established by the Joko Widodo administration in 2015–2019, the Indonesian Ministry of Agriculture (MoA) aims to achieve self-sufficiency in rice (MoA, 2016). To achieve this, it will be important to predict and adapt to climate change and its effects on locally used rice cultivars.

Released in 1986, IR64 is historically one of the major rice cultivars grown in Indonesia, so it has been used previously to study the effects of climate change on rice production in Indonesia (Matthews et al., 1997). However, since 2000, the major rice cultivar has changed gradually from IR64 to Ciherang, which was developed from International Rice Research Institute (IRRI) lines (IRRI, 2015). Currently, the cultivated area of Ciherang in Indonesia accounts for approximately 50% (GRIISP, 2012). Although Ciherang has high similarity in the gene, grain quality, and morphological characteristics to IR64 (Yoshida et al., 2009; IRRI, 2015; Sakagami et al., 2016), its pest resistance is stronger and the actual yield is approximately 1.0 t ha⁻¹ higher than that of IR64 (USDA, 2010). On the other hand, in general, the phenological characteristics, such as the timing of anthesis, heading, and the growth period, morphological and physiological characteristics, and responses to climate all vary with the rice cultivar. However, to date, there have been no studies on the risk assessment of climate change impacts on Ciherang in Indonesia. Therefore, the clarification of the impacts of climate change on Ciherang, a major local rice cultivar in Indonesia, is needed to create and implement a national climate change adaptation plan.

Recently, a process-based crop growth model, MATCRO-Rice, was developed by Masutomi et al. (2016a, b). This model is useful in assessing climate change impacts on rice yield because growth and yield can be predicted using meteorological data, which influence plant phenology and physiological characteristics, such as photosynthesis, respiration, and the allocation of photosynthetic products to plant organs.

In the present study, by modifying the crop growth parameters used in the MATCRO-Rice model for the Indonesian major local rice cultivar Ciherang, we simulated the impacts of climate change on the rice yields all over Indonesia. Our results provide valuable information for the planning and implementation of strategies to prioritize climate change adaptation measures for rice production in Indonesia.

### 2. Methods

#### 2.1 Overview of procedure for simulating climate change impacts on rice yield

To simulate climate change impacts on rice yield from 1998 to 2002 and 2018 to 2042, we used the process-based crop growth model MATCRO-Rice (Masutomi et al., 2016a, b). First, we parameterized Ciherang-specific phenological and physiological parameters for the MATCRO-Rice model. Next, to validate the model’s yield predictions for Ciherang rice, we compared the simulated yield from the model output with the observed yield reported by the Statistics Indonesia institute (BPS, 2016). Finally, we simulated the climate change impacts on rice yield within 0.5° grids covering the whole of Indonesia (latitudinal range: -12°–7.5°; longitudinal range: 94°–142°), considering a range of future climate change scenarios. A summary of information on simulation settings, required data, and data sources is listed in Table 1.

#### 2.2 Modifications to MATCRO-Rice for yield simulation

The MATCRO-Rice model can calculate the rice yield by simulating the photosynthetic rate, respiration rate, allocation of photosynthetic products to each plant organ, and phenology (such as the timing of heading and senescence), which are dependent on meteorological conditions. For example, the photosynthetic

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>Oryza sativa cv. Ciherang</td>
</tr>
<tr>
<td>Base year (current)</td>
<td>1998–2002</td>
</tr>
<tr>
<td>Targeted year (future)</td>
<td>2018–2042</td>
</tr>
<tr>
<td>Time step</td>
<td>3 hours</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>0.5° × 0.5° grid</td>
</tr>
<tr>
<td>Latitude</td>
<td>From -12° to 7.5°</td>
</tr>
<tr>
<td>Longitude</td>
<td>From 94° to 142°</td>
</tr>
<tr>
<td>Current climate</td>
<td>WATCH-Forcing-Data-ERA-Interim (WFDEI) (Weedon et al., 2014)</td>
</tr>
<tr>
<td>Future climate</td>
<td>Four GCMs (BNU-ESM, CNRM-CM5, IPSL-CM5A-LR, and IPSL-CM5A-MR) in CMIP5 (Taylor et al., 2012) with four RCP scenarios (van Vuuren et al., 2011)</td>
</tr>
<tr>
<td>Atmospheric CO₂ concentration</td>
<td>Meinschaeusen et al. (2011)</td>
</tr>
<tr>
<td>Soil texture</td>
<td>Harmonized World Soil Database (FAO et al., 2012)</td>
</tr>
<tr>
<td>Cropping number and planting date</td>
<td>Laborte et al. (2017)</td>
</tr>
<tr>
<td>Harvested area</td>
<td>Sacks et al. (2010)</td>
</tr>
<tr>
<td>Nitrogen fertilization</td>
<td>Lu and Tian (2017)</td>
</tr>
<tr>
<td>Irrigation area</td>
<td>Global Map of Irrigation Areas (FAO, 2016)</td>
</tr>
<tr>
<td>Photosynthetic response to drought</td>
<td>Bouman et al. (2001)</td>
</tr>
<tr>
<td>Growth response to CO₂</td>
<td>Tubiello et al. (2007)</td>
</tr>
</tbody>
</table>
rate is affected by the air temperature, solar radiation, and air humidity, among other conditions.

To apply MATCRO-Rice to all of Indonesia, we made the following simplifications and modifications to the original model. Leaf and soil temperatures in the present study were assumed to be the same as air temperature because without this simplification, applying the model to all of Indonesia would lead to a prohibitively large number of calculations. The effect of CO₂ fertilization in the present study was considered by multiplying the simulated yield at 390 ppm of CO₂ by a fertilization coefficient (Tubiello et al., 2007). To simulate rice yields in rain-fed paddy fields, the effect of soil drought on yield through effects on photosynthesis was added to the model based on Bouman et al. (2001). The yield was calculated for rain-fed and irrigated fields simulated for each 0.5° grid by considering the ratio of rain-fed paddy to total paddy area in each grid (FAO, 2016). To calculate the soil water content in each grid, soil texture data from the Harmonized World Soil Database (FAO et al., 2012) was used. Grids with sand and sandy soil texture were excluded from the simulations because these soil types are not used for rice cultivation. Unlike the original MATCRO-Rice, we considered the effects of nitrogen fertilization on photosynthesis based on the relationship between the amount of fertilizer supplied to the soil with seasonal changes in the photosynthetic capacity (the maximum carboxylation rate). The current fertilization amount of nitrogen in Indonesia was collected from Lu and Tian (2017), and the future fertilization amount assumed to not change. Sterility induced by extremely low or high air temperatures was incorporated into the model according to Horie et al. (1995) and Bouman et al. (2001). Planting dates at each grid were given by Laborte et al. (2017). Growing degree hours required for Ciherang to mature were parameterized in the present study (see section 2.3). Double cropping was assumed, but only in irrigated areas.

2.3 MATCRO-Rice parameterization and validation

We used data from an IRRI-Japan collaborative research project (IJCPR) funded by the Ministry of Agriculture, Forestry and Fisheries of Japan (unpublished data) to parameterize Ciherang-specific phenological and physiological parameters. In IJCPR, a field experiment was conducted at the Jakenan Experiment Station (latitude: 6°45’ S; longitude: 111°10’ E; 7 m a.s.l.) in 2012 with a split-split plot design with three levels of nitrogen treatments as the main plots (0, 60, and 120 kg N ha⁻¹ year⁻¹), two irrigation types in subplots (irrigated and rain-fed), and two rice cultivars in sub-subplots, replicated four times. We utilized the data to parameterize Ciherang-specific phenological and physiological parameters, such as the timing of heading and partitioning of photosynthetic products to each plant organ, along with the plant developmental stage (Dₖ) using the WATCH-Forcing-Data-ERA-Interim (WFDEI) dataset for meteorological inputs (Weedon et al., 2014). Using the WFDEI data, we also parameterized the growing degree hours required for Ciherang to mature, so as to match the simulated yields over the whole of Indonesia with observations reported by the BPS (2016). Growing degree hours until harvest at all grids over Indonesia were set as 48,000 degree hours for Ciherang in the present study. Details of the methods for model parameterization are available in Masutomi et al. (2016b).

The period of studying yield validation was set as 2001–2010 because Ciherang has become popular gradually since the 2000s (USDA, 2010). The yield in each province was calculated according to the simulated yield per grid, considering the ratio of rice paddy area in each grid (Sacks et al., 2010), and then compared with the yield in each province reported by the BPS (2016).

2.4 Climate change impact assessment and analysis

We simulated the combined effects of the changes in air temperature, precipitation, and atmospheric CO₂ concentration on rice yield from 1998–2002 to 2018–2042 in five-year increments, that is, 2019–2023, 2024–2028, 2029–2033, 2034–2038, or 2039–2042, according to the planning periods in the Regional Medium-Term Development Plan. Historical climate data from the WFDEI (Weedon et al., 2014) were used for the simulation of the current rice yield, whereas the future temperature and precipitation data were obtained by four general circulation models (GCMs), BNU-ESM, CNRM-CM5, IPSL-CM5A-LR, and IPSL-CM5A-MR from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (WCRP, 2011), to simulate future rice yields. These GCMs were used owing to their high reliability and accurate reproduction of the current climate in Indonesia (Gomez-Garcia et al., 2017). Biases between the observed climate and the simulated climate of these models were corrected using the WFDEI data from 1981 to 2005 (Gomez-Garcia et al., 2017). Using each of the four GCMs with three or four available representative concentration pathway (RCP) scenarios, 14 future climate scenarios were utilized in the analysis of the present study. For the other climate data required for MATCRO-Rice, including radiation, humidity, wind speed, and air pressure, the WFDEI data were used. Current and future CO₂ concentrations from Meinshausen et al. (2011) were used and assumed to be the same in all grids. The current and future daily mean air temperatures, annual precipitation, and CO₂ concentrations used in the models are shown in Table 2.

To analyze which change in climate parameter is a key factor affecting rice yield in the future, we performed a sensitivity analysis on each of the single effects of future air temperature, precipitation, or CO₂ concentration on rice yield. As the air temperature can affect rice yield through several physiological processes, sensitivity analysis was also performed to assess

<table>
<thead>
<tr>
<th>Period</th>
<th>Air temperature (°C)</th>
<th>Precipitation (kg m⁻² year⁻¹)</th>
<th>Atmospheric [CO₂] (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998–2002</td>
<td>26.2</td>
<td>3010</td>
<td>369</td>
</tr>
<tr>
<td>2019–2023</td>
<td>26.7</td>
<td>2753</td>
<td>414</td>
</tr>
<tr>
<td>2024–2028</td>
<td>26.9</td>
<td>2768</td>
<td>426</td>
</tr>
<tr>
<td>2029–2033</td>
<td>27.0</td>
<td>2778</td>
<td>438</td>
</tr>
<tr>
<td>2034–2038</td>
<td>27.1</td>
<td>2830</td>
<td>450</td>
</tr>
<tr>
<td>2039–2042</td>
<td>27.2</td>
<td>2880</td>
<td>462</td>
</tr>
</tbody>
</table>

Each future value was the mean based on 14 future climate scenarios.
the effects of each of the following single factors affected by the air temperature on yield from MATCRO-Rice modules: photosynthesis, respiration, sterility, or phenology.

3. Results

3.1 MATCRO-Rice parameterization and validation

We found no remarkable differences in most of the growth parameters among the irrigation and nitrogen treatments, although the leaf death rate at $D_{vs} = 0.7$ (early reproductive stage) tended to be lower with increased nitrogen supply (Fig. 1). According to these results, we parameterized changes in these crop growth parameters along with $D_{vs}$ and assumed that they would be similar across the soil water and nitrogen conditions, which are shown as solid lines in Fig. 1.

MATCRO-Rice accurately simulated seasonal changes in the leaf, stem, and panicle weights (Fig. 2). However, MATCRO-Rice underestimated those weights under the N0 treatments, although conditions of no fertilization are unrealistic in the field.

The observed rice yields were extremely different among provinces, ranging from ca. 2700 to 5700 kg ha$^{-1}$. Nevertheless, analysis of the observed and simulated yields in each province of Indonesia showed that MATCRO-Rice can predict the rice yield to some extent (Fig. 3; $r = 0.418$, $P < 0.05$). Root mean squared error (RMSE) = 1115 kg ha$^{-1}$.

Furthermore, the RMSE between the observed and MATCRO-Rice simulated yields all of Indonesia from 2001 to 2010 was 149 kg ha$^{-1}$ (Fig. 4), and a significant correlation was detected in the observed and simulated yields ($r = 0.743$, $P < 0.05$; figure not shown). These results indicate that MATCRO-Rice can estimate Cihherang rice yields cultivated in the fields of Indonesia.
3.2 Impacts of climate change on rice yield

Yield reduction was predicted in all ranges of years from 2019 to 2042, regardless of which of the 14 future climate scenarios was considered (Fig. 5). The degree of reduction in simulated yields increased year by year from 5.6% in 2019–2023 to 12.1% reduction in 2039–2042.

The mean yield changes from 2039 to 2042 compared to the baseline 1998 to 2002 yields were negative for almost all grids over Indonesia, especially in Kalimantan and New Guinea Islands, whereas the yield change was positive in some grids in New Guinea Island (Fig. 6). These results were similar across all 14 climate scenarios analyzed (Fig. 7). Thus, we found large spatial differences in the impact of climate change on rice yields in Indonesia under all future climate scenarios.

Considering the effects of individual climate change factors, changes in the CO$_2$ concentration increased the rice yield each year, up to 8.0% in 2039–2042, whereas changes in precipitation had no impact on yield, and air temperature induced yield reductions depending on location (Figs. 8 and 9). The increasing air temperature decreased the yield by 19.3% in 2039–2042 averaged across the whole of Indonesia. Thus, the increased air temperature was the critical climate factor predicted to decrease the future rice yield in Indonesia.

Air temperature–dependent sterility, phenological changes such as shortening of the growth period, increased respiration, and reduced photosynthesis caused yield reductions of 1.8%, 4.2%, 7.2%, and 6.6%, respectively, in 2039–2042 (Fig. 10). However, the degree of reduction varied with the location (Fig. 11). Higher yield reductions through the impacts of air temperature on photosynthesis and respiration were observed in the northeast of Sumatra Island and south of Kalimantan Island, which were unlike the phenology results.

4. Discussion

We estimated that climate change induced reductions in rice yield averaged over all of Indonesia will reach 12.1% in
2039–2042. Furthermore, almost all areas in Indonesia will have reduced rice yields under all 14 future climate scenarios used for predictions (Figs. 5, 6, and 7). The IMoA aims to achieve self-sufficiency in rice in the near future (IMoA, 2016). Therefore, creating and implementing national climate change adaptation plans for rice production in Indonesia are needed to sustain food security in the near future.

We found that the magnitude of predicted yield reductions induced by climate change varied between locations within Indonesia (Figs. 6 and 7). For example, climate change induced relatively high yield reductions in Kalimantan and New Guinea Islands. This information on spatial differences in the effects of climate change would be useful for policymakers to determine areas where support should be prioritized, for example, in determining where to grow rice and where to implement adaptation measures. Owing to limitations in human, land, and financial resources, the concept of prioritization is important in developing a national climate change adaptation plan. Furthermore, we expect that our results will be useful in the planning and implementation of the National Medium-Term Development Plan in Indonesia.

Our results suggested that the climate factor most critical in decreasing rice yield in Indonesia is increased air temperature. Prasad et al. (2006) presented 14 cultivar differences in tolerance to high air temperature. As a result, there was no effect of elevated air temperature on the yield of the rice cultivar N-22, while cultivars L-204, M-202, Labelle, Italica Livorna, WAB-12, CG-14, and CG-17 were highly sensitive, and cultivars M-103,  

---

Fig. 7. Percentage yield change induced by climate change in 2039–2042 compared with 1998–2002 yields based on model simulations from each of 14 climate scenarios (four GCMs, columns; and four RCPs, rows; no data for two of the combinations) in 0.5° grids across all of Indonesia. The yield change was not calculated in the white grids as the soil texture is sand (FAO et al., 2012), which is an unrealistic soil for the rice.

---

Fig. 8. Percentage yield change induced by individual climate change factors of atmospheric CO₂ concentration (CO₂), precipitation (PRC), or air temperature (TMP), compared with 1998–2002 yields over all of Indonesia. Horizontal solid lines show the median yield change predicted by models based on the 14 future climate scenarios, boxes show the first through third interquartile ranges, and whiskers show the minimum and maximum predictions for each range of years.
Fig. 9. Percentage yield change induced by individual climate change factors of atmospheric CO$_2$ concentration (CO$_2$), precipitation (PRC), or air temperature (TMP), in 2039–2042 compared with 1998–2002 yields averaged across the yield changes predicted in 14 future climate scenarios in 0.5° grids across all of Indonesia. The yield change was not calculated in the white grids as the soil texture is sand (FAO et al., 2012), which is an unrealistic soil for the rice.

S-102, Koshihikari, IR-8, and IR-72 were moderately sensitive to high air temperature. The high tolerance of N-22 to high air temperature would be related to its characteristics: N-22 could be easily shed on to stigma, because the dehiscence of the anther starts right after the glumes open and is completed when the anthers are still located inside the glumes on short filaments (Satake and Yoshida, 1978). To maintain rice yields in the future, existing cultivars should be screened for tolerance to high air temperature, as Prasad et al. (2006) recommended. New cultivars also need to be bred, and systems for the distribution and sale of heat-tolerant cultivars should be strengthened.

Furthermore, the critical effect of increased air temperature on decreasing yield in our models was due to its effects on multiple plant characteristics, including phenology (e.g., shortening the growth period), photosynthesis, and respiration (Figs. 8–11). A less thermosensitive cultivar in phenological pattern would be an effective strategy, especially if used in areas where our model predicts the largest yield reductions. On the other hand, to keep the photosynthetic rate high under high air temperature, an approach introducing the C$_4$-like photosynthetic pathway into rice, reported in Fukayama et al. (2003) and Taniguchi et al. (2008), would be an effective measure, because C$_4$ plants have the high ability of photosynthesis under elevated air temperatures. However, the fertilization effects of CO$_2$ on yield may be not observed in C$_4$ plants (Kimball et al., 2002; Leaky et al., 2006), as their CO$_2$ saturation point for photosynthesis is low owing to the condensation system of CO$_2$. On the other hand, Horie et al. (2006) suggested that the canopy temperature of the cultivar with the higher transpiration rate was relatively low. Shifting to cultivars with higher transpiration rates may be an effective strategy to avoid the detrimental effects of air temperature on photosynthesis, respiration, and phenology. Moreover, continuous irrigation with running water may be also effective in decreasing the leaf temperature (Nishida et al., 2018). However, to implement these strategies, limited water resources and decrepit irrigation systems in Indonesia should be resolved by constructing and/or consolidating the dam and irrigation system.

The predicted yield reductions from climate change depend on individual climate change factors of atmospheric CO$_2$ concentration (CO$_2$), precipitation (PRC), or air temperature (TMP), in 2039–2042 compared with 1998–2002 yields averaged across the yield changes predicted in 14 future climate scenarios in 0.5° grids across all of Indonesia. The yield change was not calculated in the white grids as the soil texture is sand (FAO et al., 2012), which is an unrealistic soil for the rice.

Fig. 10. Percentage yield change induced by air temperature–dependent sterility (TMP-STRLT), phenology (TMP-PHEN), photosynthesis (TMP-PHSYN), or respiration (TMP-RESP) compared with 1998–2002 yields over all of Indonesia. Horizontal solid lines show the median yield change predicted by models based on the 14 future climate scenarios, boxes show the first through third interquartile ranges, and whiskers show the minimum and maximum predictions for each range of years.
not only on the crop growth models and climate scenarios used (Matthews et al., 1997; Aggarwal and Mall, 2002; Rosenzweig et al., 2014) but also on rice cultivars (Prasad et al., 2005). However, country-specific local rice cultivars have not been targeted in global assessments of climate change impacts on crops. Our study addressed this shortcoming by using a model that was tuned to the major local rice cultivar Ciherang using field experimental data, and incorporating uncertainty in the future climate across all of Indonesia. These results can contribute to the development of a national adaptation plan in Indonesia with a scientific basis.

5. Conclusion

Our study predicted that climate change will increasingly impair the productivity of a local rice cultivar across Indonesia in the next 25 years owing to increasing air temperatures inducing reductions in photosynthesis, increases in respiration, and phenological changes across all future climate scenarios considered. The predicted yield reduction averaged over all of Indonesia reached 12.1% in 2039–2042, but the degree of reduction was different among regions. Therefore, to sustain food security in Indonesia, the design and implementation of a national climate change adaptation plan for rice production should consider that increased air temperature is the critical climate factor that decreases rice yield. Furthermore, as predicted yield reductions differed among regions, our data can be used to decide where to prioritize adaptation measures.

Acknowledgments

This study was supported by the Program on Development of Regional Climate Change Adaptation Plans in Indonesia of the Ministry of the Environment of Japan, and by the Environment Research and Technology Development Fund (S-12) of the Environmental Restoration and Conservation Agency. This study was performed in collaboration with the Indonesian Ministry of National Development Planning (BAPPENAS; Badan Perencanaan Pembangunan Nasional). We acknowledge the World Climate Research Program’s Working Group on Coupled Modeling, which is responsible for CMIP, and we thank the climate modeling groups listed in Table 1 for producing and making available their model output. For CMIP, the U.S. Department of Energy’s Program for Climate Model Diagnosis and Intercomparison provided coordinating support and led the development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

References

Bouman BAM, Kropff MJ, Tuong TP, Wopereis MCS, ten Berge HFM, van Laar HH, 2001: ORYZA2000: Modeling Lowland Rice. International Rice Research Institute, and Wageningen:
Y. Kinose et al.: Impact assessment of climate change on the major rice cultivar Ciherang in Indonesia

Wageningen University and Research Centre, Los Baños, Philippines, pp. 235.


IRRI (International Rice Research Institute), 2015: Growing Rice, Cultivating Partnerships: 40 Years of Indonesia-IRRI Collaboration. International Rice Research Institute, Los Baños, Philippines, pp. 32.


WCRP (World Climate Research Programme), 2011: Coupled Model Intercomparison Project – Phase 5 – CMIP5 –. CLIVAR Exchanges, 56, 16, 2.