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ORIGINAL PAPER

Future changes in rice yields over the Mekong River Delta due to climate change—Alarming or alerting?

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Abstract
The crop simulation model Decision Support System for Agrotechnology Transfer (DSSAT) was applied over the Mekong River Delta (MRD), Southern Vietnam, to assess future (2020–2050) impacts of climate change on rice production. The DSSAT model was driven using observed station data and projected climate data derived through the dynamical downscaling of three global climate models (GCMs) using the Weather Research and Forecasting (WRF) model. The WRF model was simulated at a spatial resolution of 30 km over the study region, and the large-scale driving fields for future climates were taken from the Coupled Model Inter-Comparison Project Phase 3 (CMIP3) global models ECHAM5, CCSM3, and MIROC5 under the A2 emission scenario. Rice growth during two main seasons, namely, the winter-spring (winter) and summer-autumn (summer), were selected to quantify impacts under both irrigated and rain-fed rice cultivation. The results from this climate-crop study suggest that under rain-fed conditions, winter rice yield was likely to experience nearly 24% reduction while summer rice yield was projected to decrease by about 49%. Without irrigation, the annual rice yield was projected to decrease by about 36.5%, and under irrigated conditions, climate change is likely to reduce annual irrigated rice yields by about 1.78%. Winter rice yield was likely to decrease by 4.7% while summer rice yield was projected to marginally increase by about 0.68%. Increasing temperatures and seasonal variations of precipitation are likely to significantly reduce rice yields under rain-fed condition. In addition, (1) a decrease (increase) in the number of rainy days during the dry (wet) season and (2) positive effects of elevated CO_2 for rain-fed rice growth under each of the three WRF model realizations would markedly influence rice yields. With Vietnam being one of the largest exporters of rice, these findings have serious implications for the local agricultural sector. This also serves an early warning for the policymakers and stakeholders for effective planning of not only crop production but also water resource management. The findings call for prudent diversification strategy planning by those countries which import rice.

Keywords Rice · Crop productivity · Climate change · Food security · Adaptation

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1 Introduction

Climate and agriculture are inextricably linked as weather and climate are principal factors in agricultural productivity. Due to high levels of CO_2, future projections of climate change predict rising temperatures and altered precipitation patterns which will have major impacts on the agricultural sector. The broad international view reckons that food prices are likely to remain high in the coming decades as global food production cannot keep up with demand, with adverse weather conditions affecting harvests, degrading soils, water scarcity for

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irrigation, increasing population, and rapid urbanization. If climate change projections are included, most of today's key agriculture regions will potentially experience more extreme rainfall distribution, which can severely impact food production through more frequent/severe droughts and floods (Osborne and Wheeler 2013). In addition, crop production needs to be doubled by 2050 to meet the demands of an increasing population and economic growth in developing countries (FAO 2009). As a staple food for half of the global population, particularly from Asia and some parts of Africa and Latin America (IRRI 2009), rice is one of the most important food grains.

Owing to many efforts, crop growth models have been steadily developed and improved at large spatial scales (i.e., coarser than or equal to country size). Using diverse crop models, many studies have been carried out to assess the impacts of climate change on crop production (Balkovič et al. 2014), yield gaps and food security (Van Wart et al. 2013), devising adaptation options (Chen et al. 2012; Olesen et al. 2011), and strategy planning for policymakers (Ewert et al. 2011). For instance, with sufficient global datasets such as crop planting and harvesting methods and dates, fertilizer and irrigation application, cultivated and harvested area, the General Large Area Model (GLAM) (Challinor et al. 2004), Predicting Ecosystem Goods And Services Using Scenarios (PEGASUS) (Deryng et al. 2011), and improved Global Agro-Ecological Zones (iGAEZ) (Tatsumi et al. 2011), models were created to assess the impacts of climate change on global food production. Elliott et al. (2014) developed a global gridded crop simulation system named parallel system for integrating impact models and sectors (pSIMS) based on the crop models, Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al. 2003), and Agricultural Production Systems sIMulator (APSIM) (Keating et al. 2003). However, these crop simulations at large scales were usually derived from remote sensing, country-level data, or expert judgments, which can be subject to many uncertainties, particularly in areas lacking good data collection and having a complicated crop system. Indeed, the global fertilizers and manure dataset provide uniform values for some large areas or countries, particularly in the developing countries, and the available variables and periods contained in the global datasets are far below the requirements of most process-based crop models (Xiong et al. 2016). Moreover, global climate data with coarse spatiotemporal resolutions are unable to capture the high spatial variability in key climate variables, as in temperature and especially in precipitation, which highly depend on complex topography and physical processes.

Several studies on high-resolution crop growth modeling have been performed in Asia, mainly in China and India, which used sufficient and well-qualified data, including climate, soil, crop yield, planted area, production, and crop management. Piao et al. (2010) found that improved regional climate simulations, especially for precipitation, were important to reach concrete conclusions of climate change impacts on China's water resources and agriculture. Yao et al. (2007) showed that temperature increase due to climate change resulted in significant rice yield reduction in Northeast China. In India, researchers found that climate change was likely to reduce rice yields under both irrigated and rain-fed conditions (Naresh Kumar et al. 2013). Chun et al. (2016) and Li et al. (2017) provided an overview of climate change impacts on rice productivity over Cambodia based on the field experiments. They showed that the majority of this region was projected to be affected by climate change and that the reduction in rice yields under climate change will be substantial (a decrease of approximately 45% in the 2080s under RCP 8.5, relative to the baseline period 1991–2000) without adequate adaptation.

However, few studies have been performed underpinning the link of climate change and its impact on crop productivity over Southeast Asia, and in this context, this paper evaluates the vulnerability of crop yields under future climate changes over Southern Vietnam (Mekong River Delta, MRD) using the outputs from a regional climate model coupled to an offline physical crop model.

In this study, we applied high-resolution climate data generated by the regional climate model (Weather Research and Forecasting, WRF) as input data to the DSSAT cropping system model (Jones et al. 2003). Soil data and crop phenology, planting and harvesting, and management information were obtained from field measurements conducted in the Hau Giang Province. We selected winter-spring (winter) and summer-autumn (summer) seasonal rice as indicator crops to quantify impacts for irrigated and rain-fed rice cultivation in future climate over MRD. The fragrant rice (OM4900), a short duration cultivar, was investigated as it is the most cultivated rice type in Southern Vietnam.

2 Study region and data

2.1 Study region

Over Southeast Asia, where agriculture is a major source of livelihood, approximately 115 million ha of land are devoted to the production of rice, maize, oil palm, natural rubber, and coconut (Weiss 2009). Rice has been feeding the region's population for well over 4000 years and is the staple food of about 557 million people (Manzanilla et al. 2011). Vietnam is one of the centers of origin of rice cultivation and the world's fifth largest rice-producing country. Rice occupies 74% of Vietnam's 5.7 million ha of arable land (IRRI 2008). Rice production is dominated by small, irrigated farms based around the MRD in the south and the Red River Delta in the north, which accounts for 56% and 15% of total paddy production in Vietnam in 2014 (General Statistics Office of Vietnam 2014).

Southern Vietnam is dominated by a tropical climate and thus can be divided into two seasons, cold/wet and hot/dry periods. The hot/dry season is from November through to April, whereas the cold/wet season is from May through to October. These two seasons are distinguished by tropical monsoons occurring from May to October over the southern part of Vietnam. The southwest monsoon brings heavier rainfall and strong winds primarily the reasons for wetter and colder climate conditions.

The specific study site of this paper is the Hau Giang Province, situated within the MRD (Fig. 1). Hau Giang Province was selected as a test-bed area because (1) the agriculture land of Hau Giang Province is about 5% of the MRD, (2) the cultivated area of Hau Giang is also about 5% of the total MRD cultivation, and (3) the rice production in Hau Giang is close to 5% of the MRD. We assume that studying rice production over Hau Giang will be representative of MRD and we believe that initial assessments from this study would also widen the scope of this study to other MRD regions.

2.2 Data

2.2.1 Station data

Present climate data from 2005 to 2014 over the Hau Giang Province were provided by Can Tho Meteorology Centre. Crop management practices adapted in the field was gathered by the team from College of Agriculture and Applied Biology, Can Tho University. The field survey was carried out through interviewing 30 leading farmers at Vi Binh Village where the soil data were collected. The survey focused mainly on rice varieties used, rice yields, fertilizer and irrigation application, and field management. Historical rice yield and production information from 2004 to 2014 in MRD and Hau Giang was collected from Statistical Documentation and Service Centre of General Statistics Office of Vietnam, and calibration was conducted using the data in 2010 whereas data from 2011 to 2014 were used for model validation. The predominant type of soil over the study site was riverine alluvial soil with silty clay, and soil samples taken from a pedon of 60 cm (width) × 80 cm (length) × 60 cm (depth) were analyzed at the Department of Soil Science, College of Agriculture and Applied Biology, Can Tho University. The chemical and physical parameters were adapted into the soil profile that DSSAT requires for crop simulations. The rice crop variety used in the study was OM4900 with growth duration of 90–95 days. This is a short-duration growing variety but with higher average yield (t/ha) (Lang et al. 2015).

Fig. 1 Study region and study site: (left) Mekong River Delta and Hau Giang Province is circled (Figure Source: www.vietnam-tour.biz); (right) Vietnam and Mekong River Delta (shown within box)

2.2.2 Climate data

The climate data inputs for DSSAT were obtained through a dynamical downscaling of three global climate models (GCMs) using the WRF model. The WRF model was simulated over the study domain, and the boundary conditions were provided by the global models ECHAM5, CCSM3, and MIROC5, from the Coupled Model Inter-Comparison Project (CMIP) Phase 3, A2 emission scenario. The WRF model configuration consisted of a single domain at a spatial resolution of 30 km with 28 vertical levels. For the model physics schemes, we selected the Grell cumulus parameterization (Grell 1993), Thompson microphysics (Thompson et al. 2004), the RRTMG longwave and shortwave radiation (Mlawer et al. 1997), the Yonsei University planetary boundary layer physics (Hong et al. 2006), and the NOAH land surface scheme (Chen and Dudhia 2001). These physical schemes were selected on the basis of earlier sensitivity experiments over the area of interest. Six variables, namely, minimum and maximum surface temperatures, precipitation, solar radiation, wind speed, and relative humidity, at daily temporal scales were extracted from the WRF model output, to suit the required DSSAT input data. The simulations for the historical period were performed from 1961 to 1990 and for future climate from 2020 to 2050. For climate projections, the climate anomalies (difference between the future and baseline simulations) were considered. Also called as the "delta factor" approach, this method gives a clear signal of climate change with the systematic biases in the simulations removed. ERA-Interim reanalysis-driven simulations were also performed for 1961–1990 and for 2005–2014 baseline periods for WRF model validations and for simulating historical yields, respectively.

The DSSAT model was used to simulate the future rice yield with the abovementioned climate data (delta approach). It is to be mentioned that we consider only rain-fed and irrigated crop scenarios under one future climate scenario, A2.

A flowchart that describes the overall study methodology is shown in Fig. 2.

3 Results and discussions

3.1 Regional climate model WRF

Regional climate simulations using the WRF model were performed for two different periods using the ERA-Interim reanalysis. Model validations were performed for the period 1961–1990. Historical rice yield validations against station records were also performed using the outputs from the WRF simulations (2005–2014) as inputs to DSSAT. For brevity, we refer to the simulations of the WRF model driven by the global models CCSM3, ECHAM5, and MIROC-medres as WRF/CCSM, WRF/ECHAM, and WRF/MIROC, respectively. Some modeling studies over Vietnam using the WRF model have been discussed by Raghavan et al. (2015).

With respect to long-term monthly mean time series of precipitation at Can Tho, the WRF simulation well captured the study area's annual cycle marked by a heavy rainfall in summer and a dry season in winter, although tending to overestimate precipitation during April–May. In quantitative terms, the ensemble mean of the three WRF realizations resulted at an average of 5.7 mm/day compared to the station data having a mean value of 4.3 mm/day. In case of temperature, the maximum temperature showed a negative

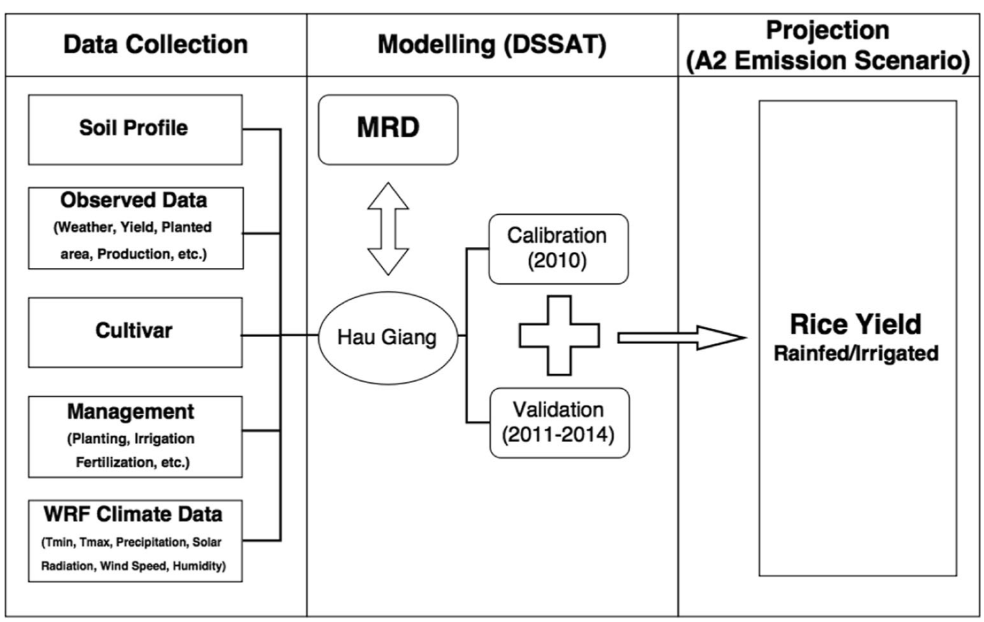


Fig. 2 Flowchart of the study approach

Table 1 The number of rainy days derived from the recent station data (over 2005–2014) and A2 future projection (averaged over 2020–2050) at Can Tho Meteorological Center

Month		January	February	March	April	May	June	July	August	September	October	November	December
Station (2005–2014)	Mean	2.8	1.0	2.4	6.4	16.1	19.3	20.6	20.2	21.9	20.1	13.1	6.2
	S.D.	1.5	1.2	2.3	3.7	4.1	3.8	3.0	2.6	3.8	3.7	5.8	4.7
WRF/CCSM (2020–2050)	Mean	2.2	0.2	0.3	5.2	12.8	22.7	23.4	20.1	22.3	25.2	10.4	3.8
	S.D.	1.4	0.6	1.2	1.4	2.5	3.3	1.6	1.7	1.2	2.1	2.5	2.5
WRF/ECHAM (2020–2050)	Mean	1.9	0.2	0.3	5.2	13.4	23.4	23.4	20.5	22.4	25.2	10.7	5.0
	S.D.	1.3	0.6	1.2	1.4	2.1	1.8	1.6	1.3	1.1	2.1	2.4	1.3
WRF/MIROC (2020–2050)	Mean	1.7	0.2	0.3	5.2	13.4	23.6	23.5	19.8	22.3	25.3	10.7	5.0
	S.D.	1.5	0.6	1.2	1.4	2.1	1.8	1.6	1.5	1.1	2.1	2.3	1.2

**S.D.* stands for standard deviation

bias (− 1.9 °C) and the minimum temperature exhibited a positive bias (0.5 °C), in general. In this study, such systematic biases were reduced in model projection by taking the climate anomalies, as aforementioned.

As the main objective of this paper is study of rice productivity, we focus more on the results from the DSSAT modeling study (Table 1). However, as future climate change determines the future productivity of rice cultivation, we briefly discuss the WRF model simulated changes over the future, 2020–2050.

Figure 3 shows the future changes in daily maximum and minimum temperatures and precipitation relative to the baseline period.

The temperature increase is the highest for the WRF/CCSM simulations, followed by the WRF/MIROC and WRF/ECHAM simulations. Overall, the difference between the climate projections is in the range of 0.0–0.5 °C. These warming patterns occur during all months and with similar magnitudes. This infers that temperatures are expected to rise by about 1 °C in the near future. It is to be mentioned here that the climate change signals (using the "delta factor" approach) from each of the three WRF model realizations have been added to the station data which were used as inputs to the DSSAT model.

The future changes in precipitation or rather the precipitation anomaly (%) (not shown) suggested two different shift

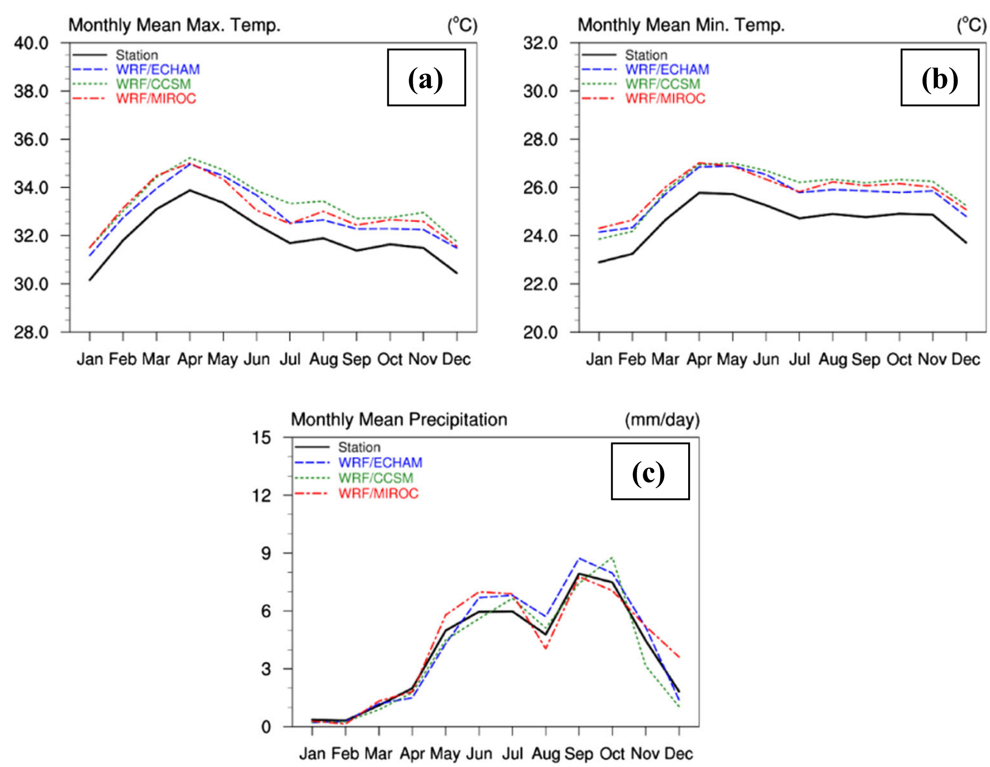


Fig. 3 Monthly mean future changes from WRF model projections under the A2 emission scenario (averaged over 2020–2050) at Can Tho Meteorological Center. **a** Maximum temperature. **b** Minimum temperature. **c** Precipitation

Table 2 Sequence Analysis setup in DSSAT

		Inputs	Source/name/type
Present	Calibration	Weather	Observed data
		Cultivar	Fragrant rice (OM4900)
		Soil	Riverine alluvial soil
		Management	Constant flood depth; with fertilization
	Validation	Weather	Observed data
		Cultivar	Fragrant rice (OM4900HG, as in calibration)
		Soil	Riverine alluvial soil
		Management	Constant flood depth; with fertilization
Future		Weather	WRF/GCMs: CCSM3, ECHAM5, MIROC-medres
		Cultivar	Fragrant rice (OM4900HG, as in calibration)
		Soil	Riverine alluvial soil
		Management	(1) Rain-fed: no irrigation; with fertilization
			(2) Irrigated: constant flood depth; with fertilization

patterns in monthly time scales. Climate model results reveal that precipitation in the near future is likely to decrease in the most dry seasons (except March, November, and December) but increase in the most wet season (except May), under the A2 scenario. In terms of annual mean changes, future precipitation decreases in WRF/ECHAM and in WRF/CCSM whereas increases in WRF/MIROC. However, these three models do not have the same signals of change. The future projections showed that while temperatures show linear responses to global warming, the precipitation changes are non-linear and highly variant.

Table 1 illustrates the number of rainy days at Hau Giang study site derived from the WRF model projections and compared against historical station observations. These were calculated by the WGEN weather generator in the DSSAT model. In the baseline climate, the numbers of rainy days are about 32 and 118 days during the dry and wet seasons, respectively, which is characteristic of Hau Giang. Under a future warming scenario (A2 scenario), the difference between the number of rainy days during dry and wet seasons was projected to be higher. In quantitative terms, on an average, the number of rainy days during the dry season is likely to decrease from 45 days to about 23 days by the 2030s. On the contrary, the number of rainy days during the wet season is likely to increase from 118 to about 128 days. This is significant because such changes could induce considerable negative effects on both winter and summer rice yields due to shortage and excess water availability due to rainfall.

3.2 DSSAT model

3.2.1 Model calibration and validation—historical simulations

The Sequence Analysis program (Tsuji et al. 1994) allows the user to carry out simulations of crop rotations or crop sequences (i.e., any combination of crops grown one after another) using the DSSAT crop model and then to analyze the

Table 3 Calibrated cultivar coefficients

Coefficient	Explanation	Unit	Initial value	Calibrated value
P1	Thermal time between emergence and basic vegetative phase	°C	625.5	594.2
P2R	Extent to which phasic development leading to panicle initiation is delayed (thermal time)	°C	312.6	282
P5	Thermal time between grain filling and physiological maturity	°C	393.6	499.9
P20	Critical photoperiod or longest day length at which the development occurs at maximum rate	h	12	13.23
G1	Potential spikelet coefficient	–	55	69.3
G2	Potential single grain weight under ideal growing conditions	g	0.0265	0.0265
G3	Tillering coefficient under ideal conditions	–	1	1
G4	Temperature tolerance coefficient	–	1	1
PHINT	Thermal time between emergence of successive leaf tips	°C	83	83

results. Table 2 gives the Sequence Analysis setup used by DSSAT for the study site, Hau Giang. Irrigation method adopted constant flood depth, and four applications were applied in total which includes as follows: (1) land preparation, 1 day before planting with 5 mm constant flood depth; and (2) constant flood depth 10 mm, 20 mm, and 20 mm at time of 8, 33, and 48 days after planting, respectively. Nitrogen was applied as urea at 50 kg N ha^{-1} for both winter and summer crops at the time of 5, 30, and 45 days after the planting. Principally, fertilizers were applied before irrigation. We assumed that crop was maintained free of pests and diseases in the field, as this should be considered to quantify the direct impacts of climate change on crop yield (Naresh Kumar et al. 2013).

The cultivar coefficients were calibrated against the field observed average above ground biomass and yield. The Genotype Coefficient Calculator was used for calibration and the cultivar coefficients are presented in Table 3, while the results from the simulations of calibration and validation are given in Table 4.

The validation of simulated historical rice yields at Hau Giang, using DSSAT driven using WRF model climate outputs, is shown in Table 5. Overall, the DSSAT model was able to well reproduce observed yields. Higher productivity during the winter season was observed in both station and simulations and could be attributed to less pests and less pollination failure due to less heavy rain and hence easier crop management due to smaller cultivated area.

3.2.2 Future projections of rice yield

The changes in rice yield over the future period (2020–2050) were assessed using DSSAT over two seasons, winter-spring and summer-autumn, for rain-fed and irrigated crop scenarios (Fig. 4a, b). During the winter-spring season, the crop simulations (Fig. 4a) indicate that climate change, under A2 climate scenario, is likely to reduce rain-fed rice yields by ~35% during the 2020s (2020–2029), by ~16% during the 2030s (2030–2039), and by ~21% during the 2040s (2040–2050). On the other hand, irrigated rice yields in Hau Giang are likely to be increased by ~11% in the 2020s, but in the 2030s and 2040s, they are projected to decrease by ~0.5% and ~23%, respectively. However, when the rainfall is sufficient for rice growth, additional irrigation could have a negative effect on rice yield due to excess water availability and crop loss, as projected by the WRF/MIROC simulations during the 2040s. Meanwhile, during the summer season, the crop simulations indicate that climate change is likely to reduce rain-fed rice yields by ~49% during the 2020s, by ~56% during the 2030s, and by ~40% during the 2040s while irrigated rice yields in Hau Giang are likely to be decreased marginally by ~5% during the 2020s, but during the 2030s and 2040s, they are projected to increase by ~2% and ~5%, respectively.

Overall, under rain-fed conditions, the winter-spring season is likely to experience about 24% reduction while the summer-autumn season is projected to decrease by ~49%. Without any irrigation, the annual rice yield is projected to be decreased by ~36.5% in Hau Giang Province. On the other hand, under irrigated conditions, the crop model results indicate that climate change is likely to reduce rice yields by about 2%. Winter rice yield is likely to experience about 4.7% reduction while summer rice yield is projected to increase marginally by ~0.68%. Therefore, based on these results, we reckon that climate change is likely to affect rain-fed rice crop production by about 35% in the whole of MRD yearly, which is a significant reduction compared to the current productivity over the region. This is consistent with the results discussed by Chun et al. (2016), who observed 0–30% yield reduction over MRD in 2040s under the RCP8.5 climate change scenarios. There were other crop models and studies predicting that recent and future climate change may have adverse effects on crop yields (Lobell et al. 2011; Parry 2007).

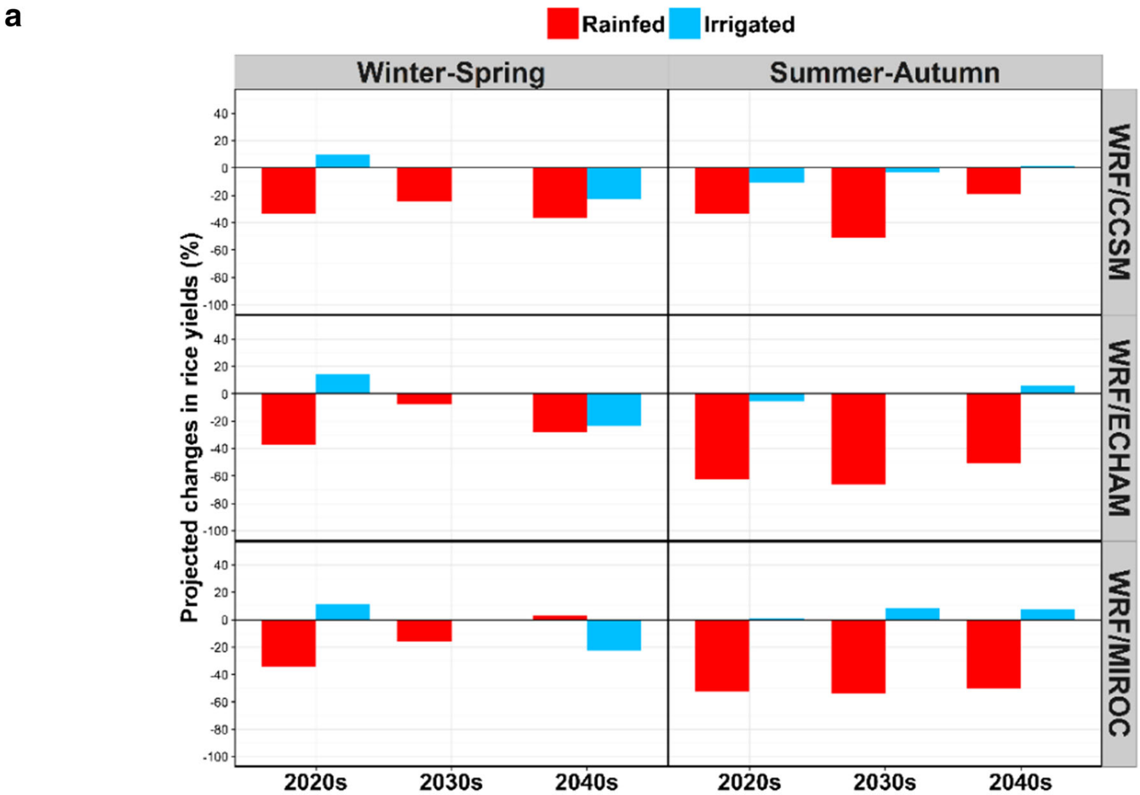
On a closer inspection on the future changes in the rice yields on an annual scale between 2020 and 2040, the (rain-fed) reduction on the summer-autumn period of more than 50% during many of these years is substantial and striking than during winter-spring (Fig. 4b). The similar responses in

Table 5 Validation of simulated historical rice yield at Hau Giang

Rice yield (kg/ha)	Winter-spring				Summer-autumn			
	2011	2012	2013	2014	2011	2012	2013	2014
Observed	6702	7114	7105	7519	4412	4594	4721	4844
Simulated	6847	6981	6936	7009	4771	4734	4832	4847

Table 4 Calibration and validation simulations

Main growth and development variables	Calibration		Validation	
	Simulated	Observed	Simulated	Observed
Anthesis day (dap)	62	62	63	60
Physiological maturity day (dap)	95	95	95	95
Yield at harvest maturity (kg [dm]/ha)	5824	5827	5573	5490
Unit weight at maturity (g [dm]/unit)	0.0265	0.026	0.0265	0.026



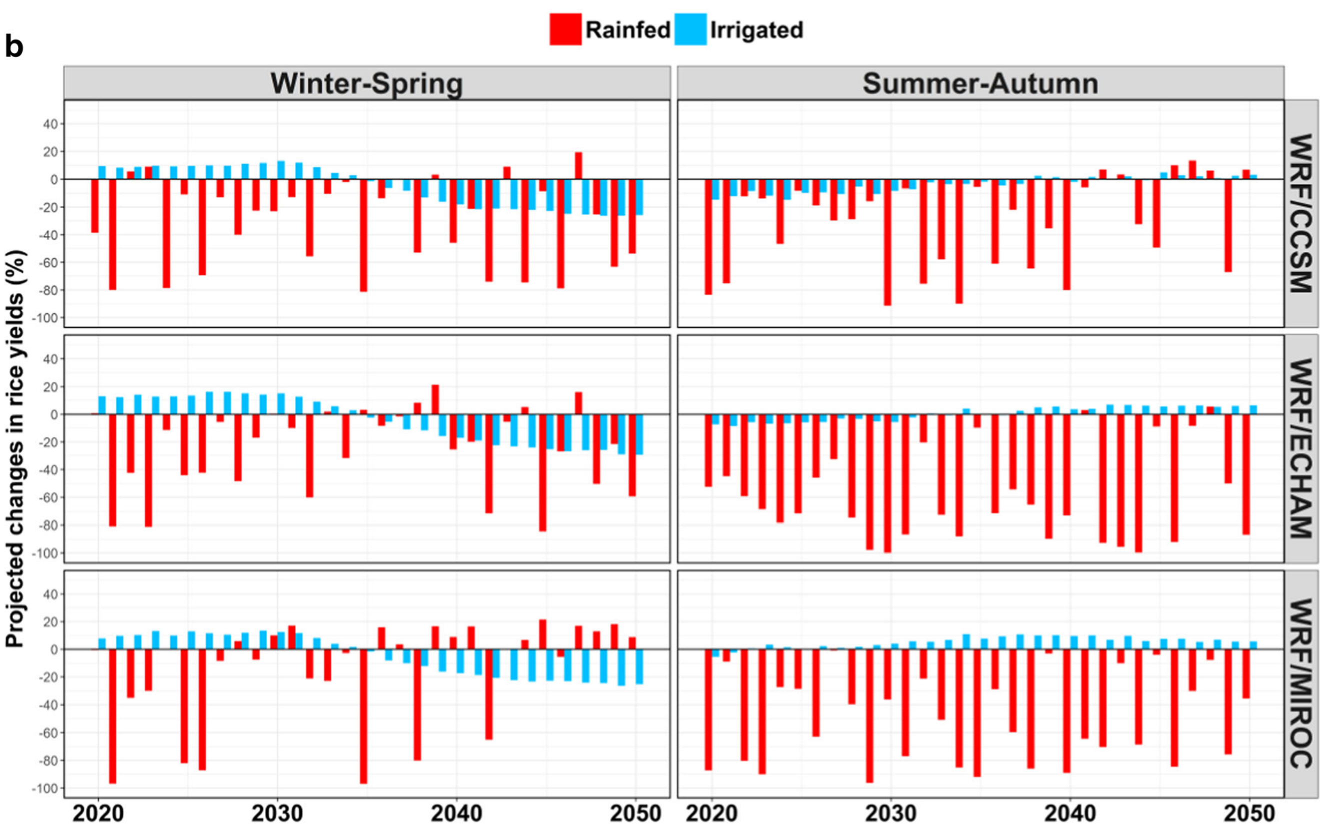


Fig. 4 **a** Projected future rice yields in Hau Giang (2020–2040). **b** Projected annual future rice yields in Hau Giang (2020–2040)

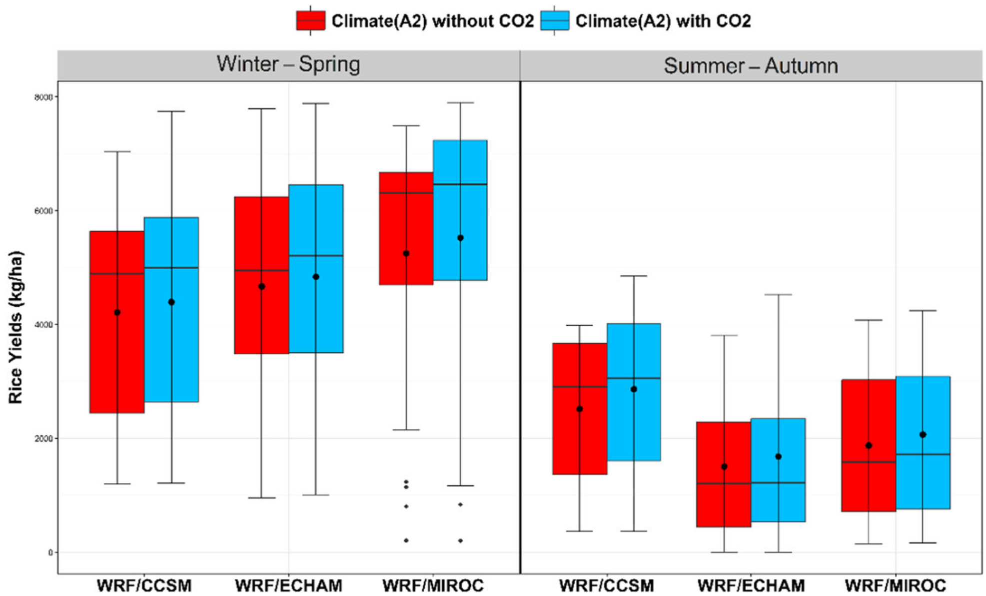


Fig. 5 Boxplots of simulated rice yields: with and without CO_2

reduction from all three downscaling results seem to highlight the confidence in such possible changes to come. Nevertheless, this result would need detailed evaluations in being able to better understand these changes. The increases due to irrigation are, yet, marginal.

We also analyzed the positive effects of elevated CO_2 for crop growth, for both winter-spring and summer-autumn seasons under rain-fed conditions (Fig. 5). Results showed that the rice yield is likely to increase 4.25%, 3.68%, and 5.21%, under each of the three WRF model realizations, WRF/CCSM, WRF/ECHAM, and WRF/MIROC, respectively, during the winter season. During the summer season, rice yield is yet again projected to increase by 13.9%, 11.7%, and 10.4%, respectively. In summary, the beneficial effects of CO_2 fertilization could contribute to an average yield growth of 4.38% and 12.0%, during winter-spring and summer-autumn seasons, respectively.

However, the uncertainties in climate projections, especially precipitation, cause uncertainties in assessments of future crop yield (Erda et al. 2005). Further, there are other effects of climate that are not included in the current generation of crop models (Piao et al. 2010). Third, the advances in agrotechnology, new drought/flood-resistant crop varieties, and sufficient resources for local farmers can be another important uncertain factor. With potential adaptations mentioned above, the adverse effects of climate change might be overcome easily (Piao et al. 2010). In our study, adaptation potentials from new rice varieties were not taken into consideration. Therefore, the assessments of climate change impacts on rice production in MRD might need more scrutiny with continued research on both climate and crop models supplemented by assessments of other crop growth factors and with the use of multiple and newer climate scenarios.

4 Summary and conclusions

This paper described a study that investigated rice crop productivity in a future climate (2020–2050) over the Hau Giang Province located in the Mekong Delta Region of Southern Vietnam. The DSSAT crop simulation model was used to assess crop yields driven by the climate data generated from the WRF regional climate model, under different global climate model realizations. Changes in rice production under both rain-fed and irrigated crop scenarios were considered during two main rice growth seasons, winter-spring and summer-autumn. The results suggest that climate change is likely to reduce crop yield in MRD, Vietnam, by about 36.5%, which is a significant reduction for Vietnam given the MRD region's rice production is about 56% of Vietnam's total rice production.

Combined with responses to high temperature and variations of precipitation, it appears that without adaptation measures, yield reduction from severe climatic changes cannot be compensated, even accounting for the fertilizing effects from CO_2. Reduced number of rainy days during the dry season along with an increased number of rainy days during the wet season is likely to cause considerable negative effects during both growth seasons.

The findings from this study suggest that rain-fed crops, in general, produce less yield than irrigated crops. Significant rain-fed rice production reduction of about 35% is projected in 2020–2050 period due to decreases in future rainfall amounts. Though irrigation could significantly improve crop yields, the main challenge is to find water sources given decreases in rainfall. Given MRD falls in the category of high vulnerability to climate changes, prudent planning is necessary to counter such natural risks and the risks to lives and economy. This study provides some assessments of possible changes in the future and by no means, exhaustive in its findings as the science is growing with more research remains to be performed both on the climate and crop modeling aspects. However, while these are in progress, it is important to have reliable seasonal forecasting in order to help farmers get an early warning on the evolving weather-climate patterns so that they have adequate time and adaptive measures for their cropping patterns and harvests, in order to make best use of the rains. It is also time to consider new breeds of rice cultivars which require less water consumption and high tolerance of soil salinity, droughts, and floods.

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