

Impact of climate change on rainfed rice and options for adaptation in the lower Mekong Basin

Mohammed Mainuddin · Mac Kirby · Chu Thai Hoanh

Received: 22 February 2012 / Accepted: 10 December 2012 / Published online: 28 December 2012
© Springer Science+Business Media Dordrecht 2012

Abstract We assessed the potential impact of climate change on the yield of rainfed rice in the lower Mekong Basin and evaluated some adaptation options, using a crop growth simulation model. Future climate projections are based on IPCC SRES A2 and B2 scenarios as simulated by ECHAM4 global climate model downscaled for the Mekong Basin using the PRECIS system. We divided the basin into 14 agro-climatic zones and selected a sub-catchment within each zone for the model and assessed the impact for the period of 2010–2030 and 2030–2050. In general, the results suggest that yield of rainfed rice may increase significantly in the upper part of the basin in Laos and Thailand and may decrease in the lower part of the basin in Cambodia and Vietnam. The increase is higher during 2030–2050 compared to the period of 2010–2030 for A2 scenario. For B2 scenario, yield increase is higher during 2010–2030. The impact is mainly due to the change in rainfall and CO₂ concentration in the atmosphere. We have tested widely used adaptation options such as changing planting date, supplementary irrigation, and reduction in fertility stress and found that negative impact on yield can be offset and net increase in yield can be achieved.

Keywords Climate change · Adaptation · Rainfed rice · Mekong Basin · AquaCrop

1 Introduction

Rice is the world's most important food crop, serving as a staple food for about half of the world's population (Sawano et al. 2008). The demand for rice is expected to increase with

M. Mainuddin (✉) · M. Kirby
CSIRO Land and Water, GPO Box 1666, Canberra, ACT 2601, Australia
e-mail: Mohammed.mainuddin@csiro.au

M. Kirby
e-mail: Mac.Kirby@csiro.au

C. T. Hoanh
International Water Management Institute, Southeast Asia Regional Office, P. O. Box 4199, Vientiane,
Laos PDR
e-mail: c.t.hoanh@cgiar.org

population growth. The rising temperatures and carbon dioxide and uncertainties in rainfall associated with climate change may have serious direct and indirect consequences on rice production and hence on food security (Aggarwal and Mall 2002; Gerardeaux et al. 2012; Iizumi et al. 2011; Jalota et al. 2012). In Southeast Asia, sustainability of rice is of great concern from the viewpoint of food security of the ever-increasing population and livelihood of farmers (Jalota et al. 2012). Thus, rice cultivation faces greatly increased demands for food on the one hand due to population increase and threats to production due to climate change on the other. Against this backdrop, we examined the potential impact of climate change on the yield of rainfed rice in the lower Mekong Basin (LMB) and evaluated options for adaptations.

The LMB, comprising parts of Laos, Thailand, Cambodia, and Vietnam, is one of the most dynamic, productive, and diverse river basins in the world (Fig. 1). It is home to 67 million inhabitants (UN Population Division 2006) most of who are rural poor with livelihoods directly dependent on the agricultural production, which is dominated by rice (MRC 2010). Rainfed rice, grown in the wet season (May–October), produces more than 90 % of the total annual rice production of the basin, covers more than 85 % of annual total rice harvested area and more than 75 % of total annual crop (rice and other crops) harvested area (Mainuddin and Kirby 2009a, b). Thailand and Vietnam are two of the world's top five rice-exporting countries in the world and responsible for about 51 % of world total rice exports in 2008 (FAOSTAT 2008). Most of the export comes from the areas of these countries within the LMB (Mainuddin and Kirby 2009a, b). Therefore, vulnerability of the rainfed rice production system in the LMB to the change in climate will have severe impacts on food security and livelihood of the riparian countries and also on the world rice market and food supply.

Extensive studies have projected the potential impacts of future climate change on rice productivity on the basis of crop models with climate change scenarios derived from general circulation models (GCMs) to assess the climate risks in global and regional scales (Auffhammer et al. 2012; Bhatia et al. 2010; Gerardeaux et al. 2012; Iizumi et al. 2007, 2008, 2011; Jalota et al. 2012; Tao et al. 2008). Despite being one of the major rice production regions in the world, studies on the impact of climate change on rice of the Mekong Basin are very limited. Matthews et al. (1995, 1997) simulated potential rice yield in South and Southeast Asian countries including Thailand using two crop simulation models. However, the studies were at the regional level (for Asia) and included only Thailand among the riparian countries of the LMB. Sawano et al. (2008), Hasegawa et al. (2008), and Toritani et al. (2007) developed models and demonstrated the potential of these models as a tool to assess the regional impact of climate change on rice. However, none of these used generated climatic data for future to assess the potential impact and adaptation. Chinvanno and Snidvongs (2005) and SEA START RC (2006) simulated the yield of rice by MRB rice shell using simulated weather data from the CCAM climate model in a few locations in Laos and northeast Thailand but they did not study adaptations. The study by Eastham et al. (2008) is comprehensive in terms of climatic data used and its spatial extent but the impact assessment was done using FAO crop–water production functions which did not take into account the impact of temperature and CO₂ directly on plant growth. Nhan et al. (2011) studied the impact of weather variability on rice and aquaculture production in the Mekong Delta in Vietnam using statistical data of 1990–2008. They did not study the impact considering future scenarios. In this study, we analyzed the inter-annual change in the yield of rainfed rice associated with inter-annual climatic variability using a crop growth model. We also evaluated some widely used adaptation options. Information on the impact of climate change on rice yield is important for planning and policy of food security and national development strategies.

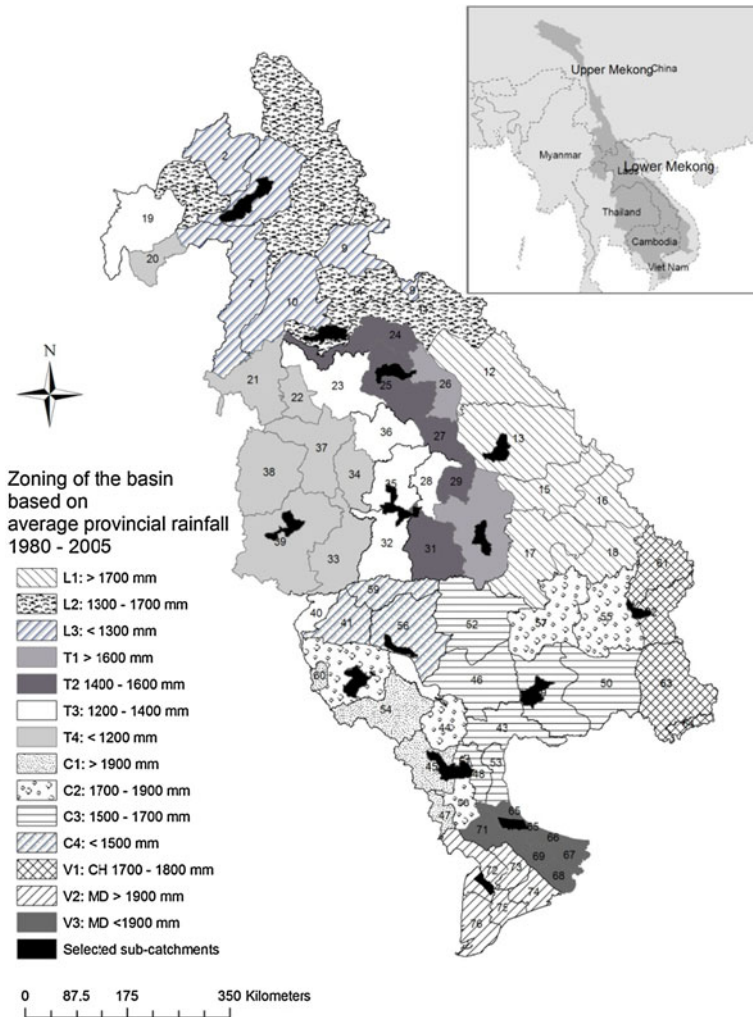


Fig. 1 Zoning of the lower basin based on spatial average provincial rainfall. Number shown inside a polygon is the province id. Provinces 1–18 (zones L1–L3) are in Laos, 19–40 (zones T1–T4) are in Thailand, 41–60 (zones C1–C4) are in Cambodia, 61–64 (zone V1) are in Central Highlands of Vietnam, and 65–76 (zones V2 and V3) are in the Mekong Delta of Vietnam. White polygon represents the selected case study districts. Inset map shows the location of the whole Mekong Basin

2 Materials and methods

2.1 Study sites, soil, and observed yield

Data of agricultural production are available at the provincial level. We divided the 76 provinces within the basin into 14 agro-climatic zones using spatial average provincial rainfall. As shown in Fig. 1, there are three zones in Laos, four each in Thailand and Cambodia, and three in Vietnam (two in the Mekong Delta and one in Central Highlands). For hydrological modelling within the Mekong river commission’s decision support

framework (MRC-DSF), the basin is divided into 700 sub-catchments of varying size covering the LMB's 76 administrative provinces (some partly). One sub-catchment within each agro-climatic zone was selected to represent that zone (Fig. 1).

Provincial time series data of planted and harvested area and yield of rainfed rice were obtained from the official statistical Web sites of the riparian countries. General crop planting time and growing periods were based on the cropping pattern used by the MRC (Nesbitt 2005). Soil-related information required for modelling was taken from the soil classification map with physical and hydraulic properties for the whole basin used in SWAT model of the MRC-DSF (Halcrow Group Ltd 2004).

2.2 Climate change scenarios and projections

The providing regional climates for impacts studies (PRECIS) is one of the most frequently used regional climate models (RCM) in Southeast Asia over the last 5 years (Hoanh et al. 2010; TKK and SEA START RC 2009; Tuan and Chinvano 2011; Ty et al. 2012). This RCM was forced by the global climate model (GCM) ECHAM4 at its lateral boundaries, under the IPCC SRES scenarios A2 and B2 (IPCC 2000). Climate output of the PRECIS RCM includes daily precipitation, temperature, solar radiation, and wind speed, produced by the “Southeast Asia System for Analysis, Research and Training” (SEA START) Regional Centre. The downscaled grid of the PRECIS model includes 2,225 cells covering the entire Mekong River Basin at a resolution of $0.2^\circ \times 0.2^\circ$ for 1985–2000 and 2010–2050. The PRECIS data for the baseline 1985–2000 were adjusted by comparing them with the available observed data as described by Hoanh et al. (2010). The rainfall and temperature projections are similar to the results obtained by other recent studies (Eastham et al. 2008; MacSweeney et al. 2008a, b).

2.3 AquaCrop model and its parameterizations

The “AquaCrop” model developed by the Food and Agricultural Organization (FAO) was used to study the impact of climate change on the yield of rainfed rice grown in the Basin. AquaCrop requires few parameters and input data to simulate the yield response to water, environmental conditions, and climate change. Its parameters are explicit and mostly intuitive and the model maintains a balance between accuracy, simplicity, and robustness (Raes et al. 2009a, b; Steduto et al. 2009). Its performance has been tested for several crops with satisfactory results (Araya et al. 2010; Farahani et al. 2009; García-Vila et al. 2009; Geerts et al. 2009; Heng et al. 2009; Todorovic et al. 2009).

2.4 Model set up, calibration, and validation

The model was set up for the sub-catchment assuming that the yield of the crop in the sub-catchment equals the average yield of the province within which the sub-catchment is located. The yield of a crop depends on the planting date, fertilizer applications, pesticides and herbicides applications, and crop management. These parameters vary from field to field and year to year. To minimize the effect of this variation from year to year, the baseline period for model calibration was taken as the last 5 years (1996–2000) of the baseline climatic period (1985–2000). The transplanting date of rainfed rice depends on the onset of the wet season as good rainfall is required for land preparation and therefore varies from year to year (Nesbitt 2005). The use of fertilizer in the basin is below the optimum

Table 1 Parameters (planting date, growing period—transplanting to harvest, harvest index, and fertilizer stress) used in calibration and validation of the model, average observed and model simulated grain yield, and the root-mean-square error (RMSE) for the calibration and validation period (1996–2000) of rainfed rice

Site	Planting date	Growing period, day	Harvest index (%)	Fertilizer stress (%)	Observed average yield, t/ha	Simulated average yield, t/ha	RMSE, t/ha
L1	20 May	130	36	40	3.19	3.17	0.04
L2	1 June	137	33	35	3.28	3.31	0.12
L3	15 June	144	36	35	3.41	3.42	0.21
T1	1 July	137	27	40	1.61	1.59	0.08
T2	20 June	137	30	40	1.78	1.77	0.07
T3	20 June	134	30	39	1.75	1.73	0.18
T4	10 July	130	31	39	1.75	1.84	0.45
C1	20 June	129	41	50	1.71	1.65	0.15
C2	15 May	131	30	40	1.98	2.22	0.45
C3	20 June	132	38	59	1.85	1.90	0.09
C4	20 June	132	25	59	1.43	1.34	0.05
V1	20 April	130	38	30	4.62	4.58	0.34
V2	1 July	120	27	31	3.38	3.38	0.27
V3	1 July	120	28	25	3.59	3.45	0.35

level, particularly in Laos, Thailand, and Cambodia (Hasegawa et al. 2008; Fukai and Basnayake 2001). Harvest index varies as a function of water availability and rice variety (Hayashi et al. 2007; Homma et al. 2004). To calibrate the model, we matched the modelled yield with the observed yield for the first year (1996) by varying the planting date, but within the crop calendar published by the MRC (Nesbitt 2005), fertilizer stress (nutrient deficiency), and harvest index. Then, we ran the model with unchanged parameters for the rest of the baseline period (1997–2000) to validate the model.

The planting date used in the model for calibration and validation of rainfed rice varies from location to location from April 20 to July 10 (Table 1). The planting date and the growing period (Table 1) are well within the range used for the basin by other researchers (Fukai and Basnayake 2001) (Table 1). The harvest index used in calibration and validation for rainfed rice varied by location from 0.25 to 0.41, which is within the range reported by Hayashi et al. (2007) and Hasegawa et al. (2008). Hayashi et al. (2007) evaluated 14 rice genotypes in northeast Thailand and found that the harvest index varied from 0.21 to 0.46 for transplanted rice. Hasegawa et al. (2008) used a constant value of 0.30 (30 %) for two of the primary rice cultivars grown in northeast Thailand. We have found harvest index as 0.27, 0.30, 0.30, and 0.31 for the four sites in northeast Thailand at calibration and validation.

Comparison of average (1996–2000) yield with the model average yield for all sites is presented in Table 1. The accuracy of the model was evaluated with the root-mean-square error (RMSE), widely used as an indicator of model performance of this type of studies (Gerardeaux et al. 2012; Iizumi et al. 2011; Jalota et al. 2012; Yao et al. 2007):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (S_i - O_i)^2}$$

where S_i and O_i are the simulated and observed yield, respectively, and n is the number of observations. The unit of RMSE is the same as that for S_i and O_i , and fitness improves as RMSE approaches zero.

As shown in Table 1, RMSE for the sites varies from 0.04 to 0.45 t/ha; few sites have values above 0.30 t/ha. Iizumi et al. (2011) reported RMSE for simulated rice yield in as 0.412, 0.303, 0.281, and 0.256 t/ha, respectively, for Hokkaido, Niigata, Aichi, and Kumamoto in Japan, which is similar to the values reported here. The performance of the model is therefore considered to be satisfactory for the simulation of rainfed rice in the study sites.

For climate change scenarios of A2 and B2, we ran the model with generated daily climatic parameters such as rainfall, potential evapotranspiration (PET, estimated using generated maximum and minimum temperatures, solar radiation, and wind speed), maximum and minimum temperature for the period of 2010–2050 keeping the soil, crop, and management parameters unchanged from the baseline (calibration and validation) period. In brief, A2 is corresponding to a story line of high population with slower per capita economic growth and technological change, and B2, a story line of moderate population growth and economic development with less rapid and more diverse technological change. AquaCrop considers 369.47 ppm by volume as the reference atmospheric CO₂ concentration. It is the average atmospheric CO₂ concentration for the year 2000 measured at the Mauna Loa Observatory in Hawaii (Raes et al. 2009a). In the simulation of A2 and B2 scenarios, we considered that CO₂ concentration varies linearly from 401 to 536 ppm for A2 scenario and 389 to 478 ppm for B2 scenario for the period of 2010–2050 (IPCC 2000).

3 Results

3.1 Impact of climate change

Cumulative probability diagrams of projected yield of rainfed rice for A2 and B2 scenarios are shown in Fig. 2 for all 14 sites. The cumulative probability curve presents yield at certain level of probability and is useful for policy decisions on agricultural production and food security and assessing risk management of agriculture (Iizumi et al. 2011; Yao et al. 2007). As shown in the figures, there is variation in projected yield due to climate variability from year to year, ranging from 0 to 7.14 t/ha for A2 scenario and 0–6.19 t/ha in B2 scenario in one site (V1). This indicates a significant impact of climate variability on yield. There is no harvest at all in some years indicating a total crop failure due to climate variability. In general, total crop failures occur in the lower half of the basin in the sites of Cambodia and Vietnam. Site C1 has the highest frequency of failure (6 years) for both A2 and B2 scenario. Two sites in Laos (L2 and L3) and two sites in Thailand (T1 and T2) have no crop failure during the simulation period.

Considering the projected time period for future scenarios is very long, we have analyzed the simulation results by dividing the simulation period into two: 2010–2030 and 2030–2050, as well as combined. Table 2 presents change in average rainfall and PET during the growing period and projected average yield due to climate change from the baseline average. The impact of climate change on yield significantly varies between two periods and two scenarios. For scenario A2, increase in yield is significantly higher (except sites T4 and C2) and decrease in yield is significantly lower during 2030–2050 compared to 2010–2030 period (Table 2). For example, change in projected average yield for site L1 is 2.8 and 18.3 %, respectively, during 2010–2030 and 2030–2050. The same for site V2 is

–2.4 and 26.9 %. For scenario B2, both increase and decrease in yield are higher during 2010–2030 compared to 2030–2050 for most sites.

The results suggest that average rice yield will increase for all sites in Laos and Thailand for both scenarios except for the B2 scenario in site L1 (Table 2). In general, considering the total simulation period, the projected average yield is higher in A2 scenario in Laos and for B2 scenario in Thailand (except site T2). For the sites in Cambodia and Vietnam, projected yield is slightly higher than the baseline yield for two sites in

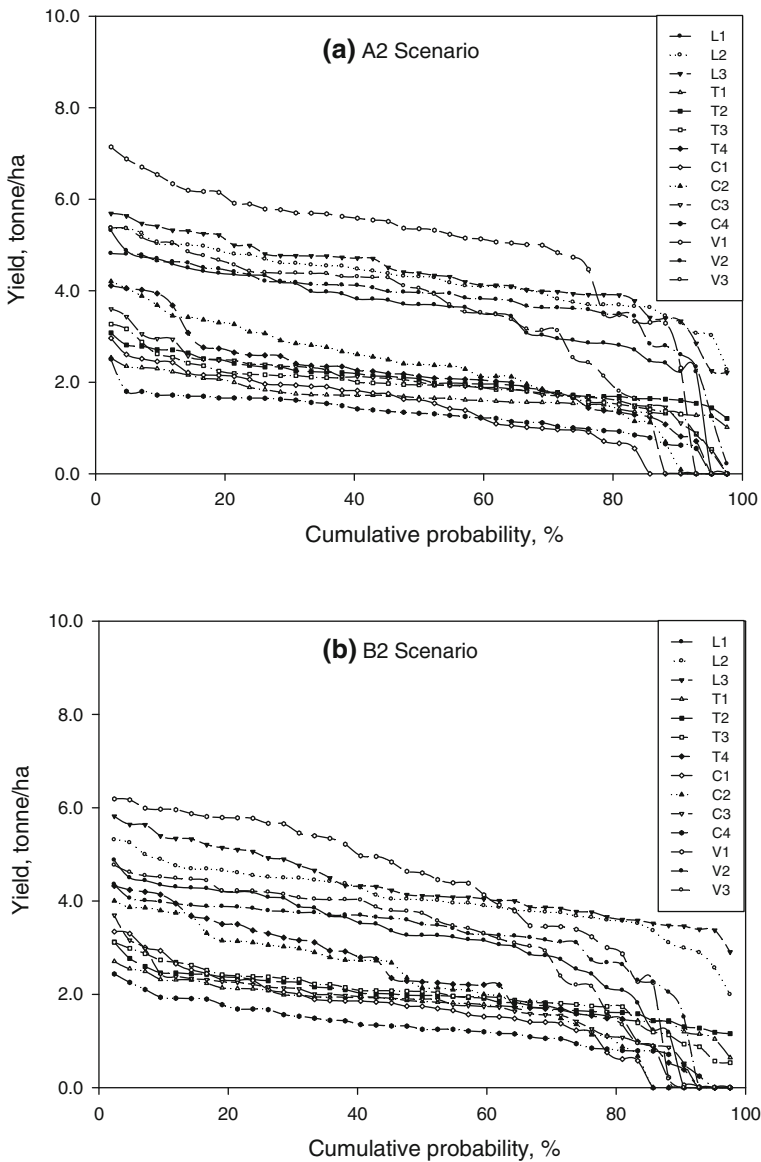


Fig. 2 Cumulative probability diagrams of projected rainfed rice yield from 2010 to 2050 where **a** and **b** correspond to scenarios A2 and B2, respectively

Cambodia and two sites in Vietnam for A2 scenario only. Yield decreases in all sites for B2 scenarios in these two countries. The reduction in yield is highest (14.2 %) in the site C1 followed by C4 (5.1 %) for A2 scenario. For the B2 scenario, the reduction is highest in site V3 (11.0 %) followed by V1 (10.1 %) and C3 (8.4 %). In general, the increase in yield is higher in A2 and decrease in yield is higher in B2.

3.1.1 Impact of rainfall and potential evapotranspiration (PET)

The variation in yield is due to the net impact of the variation in climatic parameters such as rainfall (Fig. 3), PET (Fig. 4), the direct impact of temperatures, and CO₂ concentration in the atmosphere on plant growth. PET is estimated using generated maximum and minimum temperatures, wind speed, and solar radiation so the variation in PET is due to the net impact of the variation of these parameters. Figures 3 and 4 suggest that the variation in rainfall is much higher than the variation in PET. PET indicates crop water requirements, which in rainfed agriculture is supplied by rainfall if supplementary irrigation is not provided. Therefore, the impact of PET on yield depends on the availability of rainfall. Rainfall is the most important factor affecting agricultural productivity in rainfed agriculture (Laux et al. 2010; Rockstrom et al. 2010). As shown in Table 2, growing season rainfall increases generally in the upper part of the basin and decreases in the lower part of the basin. There is no significant variation in rainfall between two periods except few sites in Thailand for scenario A2. The change in PET is predominantly positive all over the basin except part of the basin in northeast Thailand.

In general, yield changes are in the same direction as the change in total rainfall except in some sites where increase or decrease in rainfall resulted in reverse change in yield (Table 2). For example, considering the total period for site L2 in Laos, though the total amount of rainfall during the growing period decreases and PET increases, yield increases. Projected rainfall in this area is much higher (1,693 and 1,864 mm, respectively, for A2 and B2 scenarios) than the water requirements (projected PET is 528 and 521, respectively, for A2 and B2 scenarios) of rainfed rice. Therefore, though the rainfall decreases, the reduced amount is still much higher than the requirement of the crop and therefore yield is not affected. For the site C4, though projected average rainfall is higher than the baseline average rainfall (976 and 990 mm, respectively, for A2 and B2 scenarios compared to 846 mm for baseline), yield is lower than the baseline. Apart from the increase in PET which may have offset some of the increase in rainfall, the rainfall distribution over the growing period may have also affected the yield. The crop may suffer from water stress because of a prolonged dry spell within the growing period affecting yield.

Figure 5 presents projected daily rainfall and PET of A2 scenario for 2013, 2015, and 2023 for site L1 during the growing period. The projected total rainfall during the growing period in 2013 and 2015 is 1,025 and 952 mm, respectively, compared to 603 mm in 2023 (bold line in Fig. 5). Yet, there is no harvest in 2013 and 2015 but the yield is 3.44 t/ha for 2023. As we can see in Fig. 3a, there is almost no rainfall during the period of day 11–41 for the year 2013 and 2015 but PET was very high (up to about 8.0 mm/day, Fig. 3b). Therefore, the crop may have suffered severe water stress because of this prolonged drought and could not recover even though there is plenty of rain afterward. In 2023, there is 2.0–4.0 mm of rainfall almost every day during that period, and the requirement is also low (PET is up to 4.0 mm/day). The crop therefore may not have experienced water stress to the extent that it wipes out the crop completely. The analysis suggests that total crop failure in some years could be due to prolonged drought within the crop period and the distribution of rainfall and PET is important.

Table 2 Change of average rainfall, potential evapotranspiration (PET) during the growing season (transplanting to harvest), and projected average yield due to climate change from the baseline average (1996–2000)

Site	Change (%) relative to baseline, scenario A2								
	Rainfall		PET		Yield				
	2010–2030	2030–2050	Total period	2010–2030	2030–2050	Total period			
L1	16.7	30.5	23.4	9.9	8.0	9.0	2.8	18.3	10.3
L2	-16.5	-7.6	-12.2	16.5	15.3	15.9	20.6	36.0	28.1
L3	-9.9	-5.8	-7.9	9.7	9.4	9.6	22.2	33.3	27.6
T1	0.9	4.9	+2.9	9.2	9.3	9.3	6.0	9.6	7.7
T2	4.6	22.1	13.2	-6.9	-7.8	-7.3	12.8	21.9	17.2
T3	13.0	21.6	17.2	8.0	7.4	7.7	6.6	15.2	10.8
T4	39.5	23.2	31.5	13.7	18.0	15.8	18.3	14.6	16.5
C1	-17.6	-15.1	-16.4	11.0	10.3	10.7	-15.2	-13.0	-14.2
C2	14.1	11.1	12.7	7.6	5.6	6.7	5.3	-0.1	2.7
C3	-4.3	1.9	-1.3	9.5	8.4	9.0	-0.4	13.3	6.3
C4	13.9	16.9	15.4	8.4	8.4	8.4	-7.8	-2.4	-5.1
V1	9.9	12.7	11.3	27.1	21.5	24.4	-2.4	15.5	6.4
V2	-14.6	-7.1	-10.9	11.7	7.2	9.5	-2.4	26.9	11.9
V3	-10.1	-7.4	-8.8	4.4	1.4	2.9	-10.4	7.8	-1.6

Table 2 continued

Site	Change (%) relative to baseline, scenario B2									
	Rainfall			PET			Yield			Total period
	2010–2030	2030–2050	Total period	2010–2030	2030–2050	Total period	2010–2030	2030–2050	Total period	
L1	16.1	12.1	14.1	5.7	12.6	9.0	-1.5	-7.3	-4.3	
L2	-2.8	-3.9	-3.3	12.5	16.7	14.5	22.9	20.9	21.9	
L3	-9.9	-11.4	-10.6	4.4	7.0	5.7	25.9	27.4	26.6	
T1	-3.4	2.0	-0.8	3.8	8.8	6.3	18.0	12.1	15.1	
T2	3.6	6.7	5.1	0.3	3.4	1.8	14.2	8.5	11.4	
T3	10.8	11.7	11.2	2.9	7.0	4.9	20.2	9.9	15.1	
T4	28.2	33.5	30.8	6.1	7.8	6.9	28.4	26.9	27.7	
C1	-18.9	-12.2	-15.6	7.0	9.7	8.3	0.8	-6.7	-2.9	
C2	12.1	12.3	12.2	2.5	6.5	4.5	-6.4	0.6	-3.0	
C3	-0.8	-0.3	-0.6	6.7	12.3	9.4	-4.3	-12.7	-8.4	
C4	14.6	19.6	17.0	4.8	8.8	6.8	-5.2	-5.2	-5.2	
V1	1.8	4.0	2.8	27.4	32.3	29.8	-17.8	-2.1	-10.1	
V2	-7.7	-11.8	-9.7	39.3	42.0	40.6	-7.8	-5.7	-6.8	
V3	-9.1	-6.1	-7.6	2.4	3.9	3.1	-12.4	-9.5	-11.0	

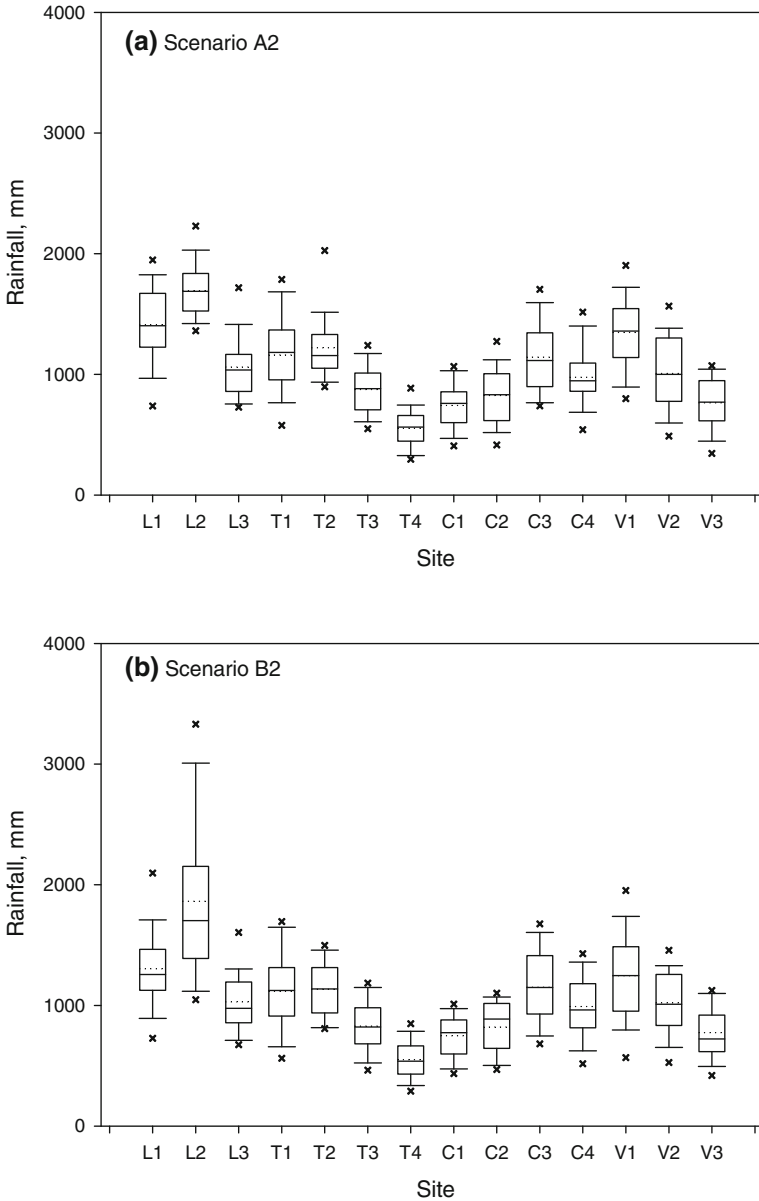


Fig. 3 Rainfall during the growing period of rainfed rice for scenario A2 and B2 from 2010 to 2050 at the selected sites in the lower Mekong Basin. The *box plot* shows the 5, 25, 50, 75, and 95 %. The *dots and lines* in the *box plots* indicate the mean and median, respectively. The *crosses* indicate the minimum and maximum

3.1.2 Impact of temperature

Tables 3 and 4 show the average maximum and minimum temperature during the growing period and during the flowering stage of rainfed rice for all 14 sites, respectively, for

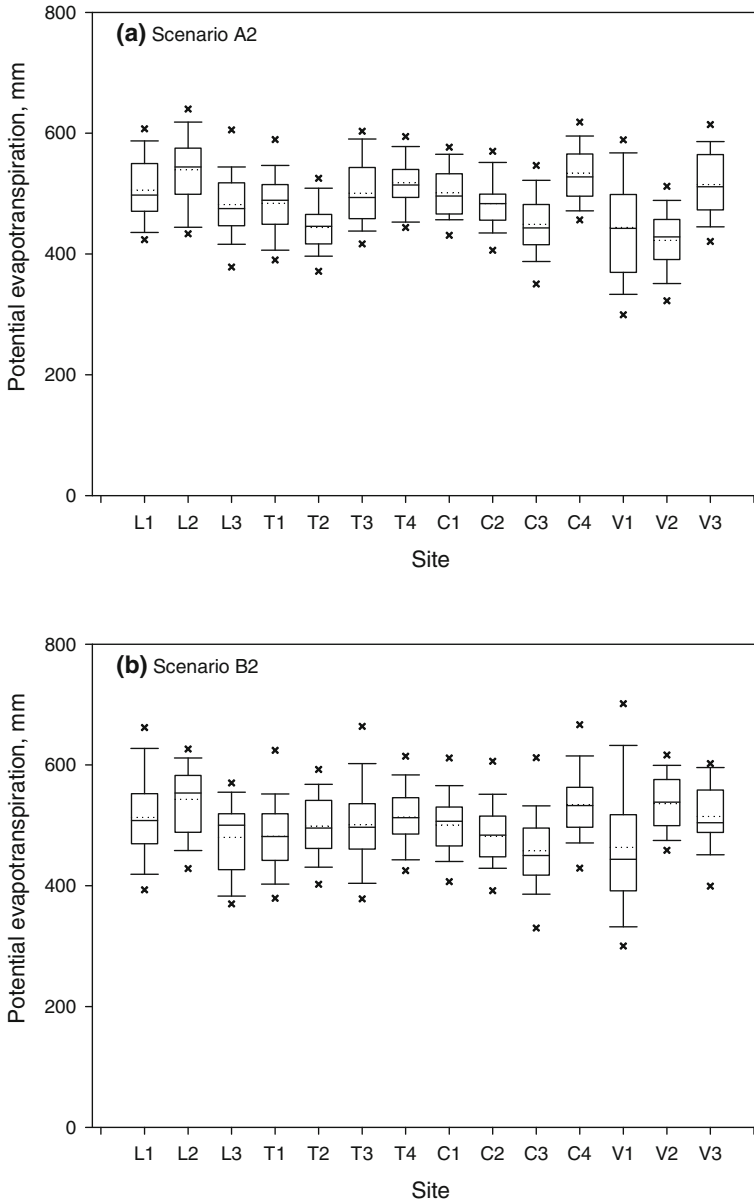


Fig. 4 Potential evapotranspiration during the growing period of rainfed rice for scenario A2 and B2 from 2010 to 2050 at the selected sites in the lower Mekong Basin. The *box plot* shows the 5, 25, 50, 75, and 95 %. The *dots* and *lines* in the *box plots* indicate the mean and median, respectively. The *crosses* indicate the minimum and maximum

scenarios A2 and B2. Both projected average maximum and minimum temperatures increase about 1 °C from the baseline for both A2 and B2 scenarios for the growing period and at flowering stage. The rate of increase, in general, is higher in the first half of the simulation period (2010–2030) than the second half (2030–2050) for total growing season

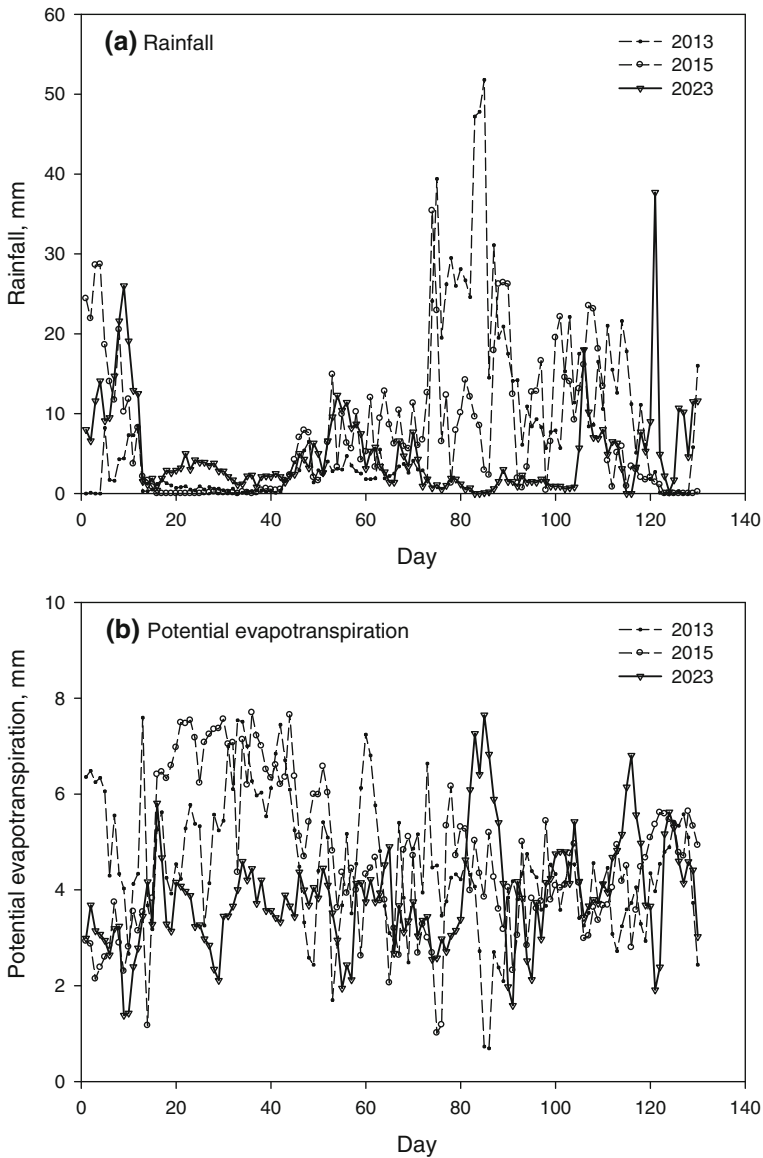


Fig. 5 Projected daily rainfall and potential evapotranspiration of A2 scenario for site L1 in years 2013, 2015, and 2023

as well as at the flowering stage for scenario A2. For scenario B2, there is no such trend and the rate of increase is higher in some sites during 2010–2030 while for the others, the increase is higher during 2030–2050. However, even with the increase, average maximum temperature is well below 35 °C and within the optimum range of 28–35 °C for good growth as specified by Doorenbos and Kassam (1979). Average minimum temperature is also within the range for good growth. Average maximum and minimum temperatures do not indicate whether the plant was subject to cold and heat stress, which might affect

Table 3 Comparison of average maximum and minimum temperature during the total growing period (transplanting to harvest), and the flowering stage of rainfed rice for scenario A2

Site	Total growing period				Minimum temperature, °C				
	Maximum temperature, °C		Increase relative to baseline		Baseline 1985–2000		Increase relative to baseline		
	2010–2030	2030–2050	Total period	2010–2030	2030–2050	2010–2030	2030–2050	Total period	
L1	31.4	1.0	0.8	0.6	1.0	24.2	0.7	1.1	0.9
L2	31.5	1.1	0.9	0.8	1.1	24.3	1.3	1.7	1.5
L3	31.6	0.8	0.5	0.1	0.8	22.9	1.1	1.4	1.2
T1	32.0	1.7	1.4	1.2	1.7	23.2	0.3	1.0	0.6
T2	31.4	1.2	1.0	0.8	1.2	23.2	0.7	1.2	1.0
T3	31.6	1.3	1.0	0.8	1.3	23.9	0.6	1.3	0.9
T4	31.0	1.4	1.0	0.6	1.4	23.2	0.4	1.4	0.9
C1	31.2	1.2	1.0	0.8	1.2	24.3	0.1	0.8	0.4
C2	31.3	1.4	1.1	0.9	1.4	23.9	0.6	1.3	0.9
C3	32.0	1.0	0.9	0.8	1.0	23.8	0.8	1.2	1.0
C4	31.0	1.3	1.0	0.8	1.3	23.5	0.5	1.2	0.8
V1	23.8	1.5	1.3	1.2	1.5	22.1	0.8	1.1	0.9
V2	27.9	1.0	0.9	0.8	1.0	26.7	0.6	0.8	0.7
V3	28.6	0.9	0.8	0.6	0.9	26.7	0.3	0.7	0.5

Table 3 continued

Site	Flowering stage	Maximum temperature, °C				Minimum temperature, °C			
		Baseline 1985–2000		Increase relative to baseline		Baseline 1985–2000		Increase relative to baseline	
		2010–2030	2030–2050	2010–2030	2030–2050	2010–2030	2030–2050	2010–2030	2030–2050
L1	30.8	0.4	0.8	0.6	24.1	0.6	1.0	0.6	0.8
L2	30.8	0.7	0.8	0.8	24.1	1.1	1.2	1.1	1.1
L3	31.5	0.6	1.5	1.1	23.2	1.1	1.4	1.1	1.3
T1	31.8	1.1	1.6	1.4	23.7	0.1	0.9	0.1	0.5
T2	31.1	0.9	1.4	1.1	23.4	0.7	1.4	0.7	1.0
T3	31.1	0.6	1.3	0.9	24.0	0.6	1.3	0.6	1.0
T4	30.7	0.6	1.8	1.2	23.5	0.4	1.8	0.4	1.1
C1	30.7	0.9	1.3	1.1	24.2	0.2	0.8	0.2	0.5
C2	31.2	0.9	1.4	1.1	23.7	0.8	1.5	0.8	1.1
C3	31.5	0.8	1.3	1.0	23.7	0.8	1.3	0.8	1.0
C4	30.9	0.8	1.3	1.0	23.5	0.8	1.4	0.8	1.1
V1	23.2	1.3	1.1	1.2	21.5	0.9	0.7	0.9	0.8
V2	28.0	0.7	0.9	0.8	26.8	0.6	0.7	0.6	0.7
V3	28.5	0.5	0.7	0.6	27.0	0.4	0.6	0.4	0.5

Table 4 Comparison of average maximum and minimum temperature during the total growing period (transplanting to harvest), and the flowering stage of rainfed rice for scenario B2

Site	Total growing period				Minimum temperature, °C			
	Maximum temperature, °C		Increase relative to baseline		Baseline 1985–2000		Increase relative to baseline	
			2010–2030	2030–2050	Total period		2010–2030	2030–2050
	2010–2030	2030–2050	2010–2030	2030–2050	2010–2030	2030–2050	2010–2030	2030–2050
L1	31.4	0.6	1.5	1.0	24.2	0.7	1.7	1.2
L2	31.5	0.7	1.5	1.1	24.3	1.1	2.1	1.6
L3	31.6	0.1	1.1	0.6	22.9	1.0	1.6	1.3
T1	32.0	1.3	1.7	1.5	23.2	0.4	1.1	0.8
T2	31.4	0.6	1.4	1.0	23.2	0.6	1.6	1.1
T3	31.6	0.8	1.5	1.1	23.9	0.7	1.6	1.1
T4	31.0	0.9	1.5	1.2	23.2	0.8	1.6	1.2
C1	31.2	0.9	1.4	1.1	24.3	0.7	1.3	1.0
C2	31.3	1.0	1.6	1.3	23.9	0.7	1.6	1.1
C3	32.0	0.8	1.5	1.2	23.8	0.8	1.7	1.2
C4	31.0	0.8	1.4	1.1	23.5	0.6	1.4	1.0
V1	23.8	1.4	2.2	1.8	22.1	1.1	1.8	1.4
V2	27.9	0.7	1.2	1.0	26.7	1.2	1.6	1.4
V3	28.6	0.6	1.1	0.8	26.7	0.3	0.9	0.6

Table 4 continued

Site	Flowering stage	Maximum temperature, °C					Minimum temperature, °C				
		Baseline 1985–2000		Increase relative to baseline		Total period	Baseline 1985–2000		Increase relative to baseline		Total period
		2010–2030	2030–2050	2010–2030	2030–2050		2010–2030	2030–2050	2010–2030	2030–2050	
L1		30.8	0.5	1.3	0.9	24.1	0.7	1.5	1.1		
L2		30.8	0.6	1.0	0.8	24.1	0.9	1.2	1.0		
L3		31.5	0.5	1.5	1.0	23.2	1.0	1.4	1.2		
T1		31.8	1.2	1.5	1.4	23.7	0.2	0.8	0.5		
T2		31.1	0.7	1.5	1.1	23.4	0.6	1.5	1.1		
T3		31.1	0.8	1.4	1.1	24.0	0.8	1.5	1.1		
T4		30.7	1.1	1.5	1.3	23.5	0.8	1.6	1.2		
C1		30.7	1.1	1.9	1.5	24.2	1.0	2.0	1.5		
C2		31.2	1.2	1.9	1.5	23.7	1.1	2.0	1.6		
C3		31.5	0.9	1.5	1.2	23.7	0.8	1.6	1.2		
C4		30.9	1.0	1.7	1.3	23.5	1.0	1.8	1.4		
V1		23.2	0.6	2.5	1.5	21.5	0.2	2.1	1.1		
V2		28.0	0.5	1.0	0.7	26.8	1.1	1.5	1.3		
V3		28.5	0.4	0.8	0.6	27.0	0.3	0.7	0.5		

pollination (Raes et al. 2009a). In AquaCrop, the upper threshold for the minimum air temperature is 8 °C (cold stress) and the lower threshold of the maximum air temperature at which pollination starts to fail is 35 °C (heat stress). The temperature at the time of flowering affects the spikelet fertility and hence the yield (Sheehy et al. 2006).

The minimum temperature is never below 8 °C during the growing period of rainfed rice for all scenarios for all sites. So there is no modelled impact from cold stress. Table 5 shows the projected number of days/year the maximum temperature is above 35 °C for baseline and A2 scenario at flowering stage of the crop. The maximum temperature is above 35 °C for 3–10 days of the total flowering period (40–50 days) for all sites in Laos, Thailand, and Cambodia. There is almost no change in Vietnam. The number is higher in the first half than (2010–2030) that in the second half (2030–2050). The number of days/year maximum temperature >35 °C decrease sharply with increase in temperature. Temperature of higher than 38 °C is experienced about a day/year except at few sites (L2, L3, and C3). The trend is similar in scenario B2 but the increase is higher. For the total simulation period, maximum temperature is above 35 °C for 5–12 days/year with more days during 2030–2050. Mainuddin et al. (2010) showed that the impact of temperature on the yield of irrigated rice is negligible (<2 %) in these locations even with more days with higher temperature. Therefore, the adverse impact of this slight increase in temperature at the flowering stage on the yield of rainfed rice could be either none or negligible.

3.1.3 Impact of CO₂ concentration in the atmosphere

To see the impact of increased CO₂ concentration in the atmosphere, we carried out simulations for two sites (L3 and C1, higher increase and decrease in yield) keeping CO₂ concentration at 369.47 ppm (reference atmospheric CO₂ concentration at 2000). Table 6 compares projected average yield with varied and constant CO₂ concentration. In site C1, for the total simulation period, yield decreases from the baseline average of 1.65–1.14 t/ha (–31.0 %) at constant CO₂, while with varied (linearly since 2010–2050) CO₂ concentration yield decreases to only 1.42 t/ha (–14.2 %) for A2 scenario. But the decrease in yield is not linearly distributed between the two simulation periods. While decrease in yield is 0.45 t/ha during 2010–2030, the additional decrease during 2030–2050 is only 0.13 t/ha. With varied CO₂ concentration, yield increase is higher during 2030–2050 (1.08–1.44 t/ha) compared to the same (1.20–1.40 t/ha) during 2010–2030. The reason for this could be increase in CO₂ concentration during the later period. Overall, projected average yield is about 25 % higher with varied CO₂ concentration than with the CO₂ concentration at the reference level. For scenario B2, the results follow the overall trend for the total simulation period (16 % increase in yield with varied CO₂) but differs on distribution between the two periods; decrease in yield is lower (0.14 t/ha) during 2010–2030 with additional decrease of 0.24 t/ha during 2030–2050. The results are similar for site L3, with yield increases of about 25 and 16 % for A2 and B2 scenarios.

3.2 Adaptation options

Reilly and Schimmelpfenning (1999) identified several adaptation options with broad applicability across the agricultural sector and defined seasonal changes and sowing dates, different variety, water supply and irrigation system, new crop varieties, and other inputs (fertilizer, tillage methods, grain drying, other field operations) as major classes of adaptations. In this study, we tested the changing of planting dates, water supply in the form of

Table 5 Average number of day/year maximum temperature is above 35 °C at the flowering stage of rainfed rice for scenario A2

Site	Temperature >35 °C				Temperature >38 °C				Temperature >40 °C			
	Baseline 1985–2000	2010–2030	2030–2050	Total period	Baseline 1985–2000	2010–2030	2030–2050	Total period	Baseline 1985–2000	2010–2030	2030–2050	Total period
	L1	0.0	2.6	3.8	3.1	0.0	0.3	1.3	0.8	0.0	0.0	0.5
L2	0.2	8.1	7.4	7.8	0.0	1.8	2.6	2.2	0.0	0.4	1.2	0.8
L3	0.0	8.2	12.5	10.3	0.0	1.2	3.1	2.1	0.0	0.2	0.7	0.5
T1	0.4	6.3	10.9	8.6	0.0	0.1	1.1	0.6	0.0	0.0	0.1	0.0
T2	0.0	4.0	8.9	6.4	0.0	0.0	1.2	0.6	0.0	0.0	0.2	0.1
T3	0.0	3.4	7.7	5.5	0.0	0.2	1.0	0.6	0.0	0.0	0.1	0.0
T4	0.0	4.1	8.8	6.4	0.0	0.1	0.4	0.2	0.0	0.0	0.0	0.0
C1	1.6	6.4	6.1	6.3	0.0	0.4	0.6	0.5	0.0	0.0	0.0	0.0
C2	2.0	7.8	9.6	8.7	0.0	0.8	0.6	0.7	0.0	0.0	0.0	0.0
C3	0.0	5.8	7.2	6.5	0.0	0.9	1.4	1.1	0.0	0.1	0.4	0.2
C4	1.4	4.9	7.2	6.0	0.0	0.3	0.5	0.4	0.0	0.0	0.2	0.1
V1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
V2	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
V3	0.0	0.5	0.7	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6 Projected average yield (t/ha) with varied and reference CO₂ concentration in the atmosphere for sites C1 and L3

Site	Baseline average yield (1996–2000)	Scenario A2				Scenario B2							
		CO ₂ concentration at year 2000		CO ₂ concentration varied from year to year		CO ₂ concentration at year 2000 level		CO ₂ concentration varied from year to year					
		2010–2030	2030–2050	Total period	2010–2030	2030–2050	Total period	2010–2030	2030–2050	Total period			
L3	3.42	3.40	3.49	3.49	4.17	4.55	4.36	3.88	3.56	3.72	4.30	4.35	4.32
C1	1.65	1.20	1.08	1.14	1.40	1.44	1.42	1.51	1.27	1.39	1.67	1.54	1.61

supplementary irrigation, and fertilizer applications as adaptations to adverse impacts of climate change.

3.2.1 Changing planting date

The rainfall available for the crop during the growing season, and the timing of dry spells or water stress at sensitive crop growth stages, depends on the date of transplanting. We carried out simulations of shifting the planting date 2 weeks later and 2 weeks earlier from the baseline planting date for all sites for both A2 and B2 scenarios.

Figure 6 shows the percentage change in yield with respect to the baseline average yield of rainfed rice for A2 and B2 scenarios with baseline, 2 weeks earlier, and 2 weeks later planting date for the total simulation period (2010–2050). As shown in the figure, changing the planting date may further increase yield (in some sites where yield increases with baseline planting date) or minimize the negative impact in the areas where yield is adversely affected. Changing the planting date later greatly increases yield in sites in Cambodia and Vietnam. The changes in some sites are quite significant.

As discussed previously, there is no or negligible direct adverse impact of slight increase in temperature on the yield of rainfed rice. Therefore, change in yield due to changing planting date is mainly due to the change in rainfall (both total amount and distribution over the growing period). Figure 7 shows the change in rainfall from the baseline condition for different planting dates for the total simulation period. In general, except for a few sites, higher increase in yield is related to the increase in total amount of rainfall for both scenarios. In addition to the amount of rainfall, due to change in planting date, crops may have experienced less water stress during the critical stages of crop growth. This is evident in the CV of yield for the simulation with adaptive planting date (Tables 7, 8) which decreases from that of baseline planting.

There is no definitive trend in the simulation results with adaptive planting date between two simulation periods (Tables 7, 8). The variation in yield is higher in some sites (T2, C3 in Table 7) during 2010–2030 while lower in other sites (C1, C3 in Table 8).

3.2.2 Supplementary irrigation and increase fertilizer input

In most areas, changing the planting dates results in a positive increase in yield—that is, any negative climate change impact is more than offset, and an increase in yield results. However, in few areas, neither of the strategies resulted in an increase in yield (Tables 7, 8). In two such sites (C1 and V3), we simulated considering supplementary irrigation when required with baseline planting date and 10 % reduction in fertility stress (that is increasing fertilizer input by 10 % of the total required) separately with baseline planting and 2 weeks later planting date. Fertilizer applications vary from 40 to 75 % of the requirements in the baseline conditions with lowest application in Cambodia and highest in Vietnam. Here, we considered 10 % increase to demonstrate its potential though increasing fertilizer to the maximum required will further increase yield.

The projected average yields are shown in Table 9. In site C1 for the A2 scenario, supplementary irrigation completely offsets the negative impact on yield with baseline planting date and increases the projected yield from 1.40 (A2) to 1.83 t/ha during 2010–2030 and from 1.44 to 1.92 t/ha during 2030–2050. For the total period, yield increases from 1.42 to 1.87 t/ha, an increase of 31.6 %. Reduction in fertility stress increases the overall yield again to 2.96 t/ha (2.90 and 3.02 t/ha, respectively, during 2010–2030 and 2030–2050), an increase of 78.7 % from the baseline average yield. The

highest increase (3.27 t/ha, 97.5 % increase from the baseline average) results from 2 weeks later planting with 10 % reduction in fertility stress. The result is similar for B2.

In site V3 for B2, 10 % reduction in fertility stress offsets the negative impact on yield and increases yield from the projected average yield of 3.07–3.51 t/ha for the total period, an increase of 14.3 %. However, supplementary irrigation provides highest increase in

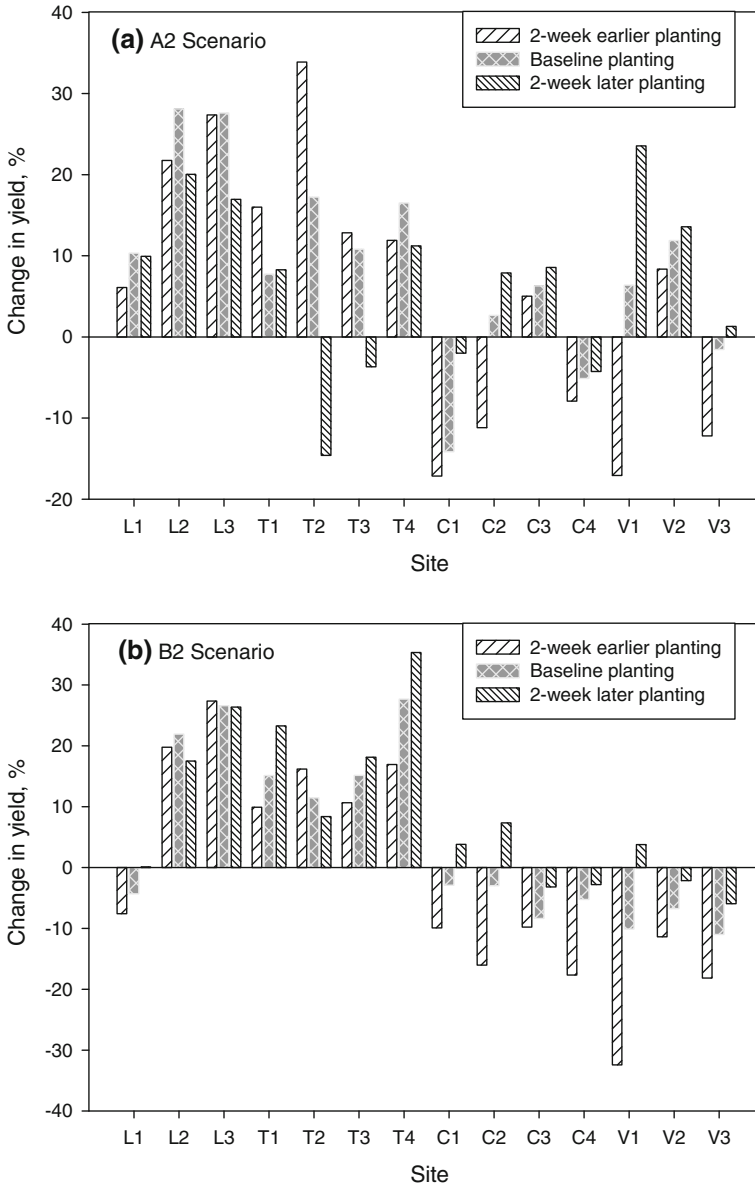


Fig. 6 Percentage change in projected average (2010–2050) yield with respect to the baseline average yield (1996–2000) of rainfed rice for A2 and B2 scenarios with baseline, 2 weeks earlier and 2 weeks later planting date

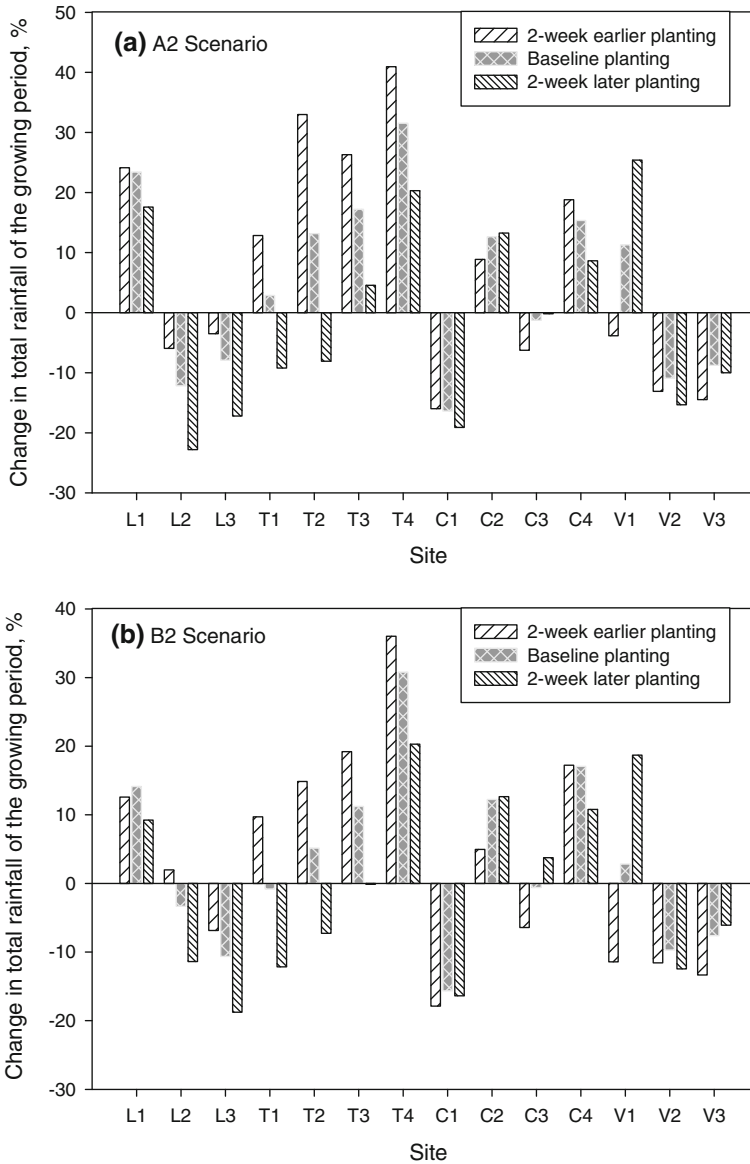


Fig. 7 Percentage change (2010–2050) in total growing period rainfall of rainfed rice with respect to the baseline average rainfall (1996–2000) for A2 and B2 scenarios with baseline, 2 weeks earlier, and 2 weeks later planting date

yield from baseline average of 3.45–4.28 t/ha, a net increase of 24.2 % after offsetting 11 % decrease in yield without supplementary irrigation. The reduction in fertility stress is more effective in site C1 or in areas with poor fertilizer application, while supplementary irrigation is more effective in site V3 or in areas with higher fertilizer application. These adaptation options are likely to be applicable to the other sites, and similar increases in yield may be expected.

Table 7 Coefficient of variation (CV) of projected yield and change in projected average yield with adaptive planting date in relation to baseline (1996–2000) average yield (values within the bracket show the additional change in average yield due to planting date adaptation), scenario A2

Site	Adaptive planting date with higher yield	2010–2030		
		CV of projected yield with baseline planting date	CV of projected yield with adaptive planting date	Change in yield with adaptive planting date w r to baseline, %
L1	Baseline	0.40	0.40	2.8 (0.0)
L2	Baseline	0.16	0.16	20.6 (0.0)
L3	Baseline	0.22	0.22	22.2 (0.0)
T1	Earlier	0.21	0.24	9.8 (3.6)
T2	Earlier	0.21	0.17	25.3 (11.1)
T3	Earlier	0.25	0.30	8.8 (2.1)
T4	Baseline	0.40	0.40	18.3 (0.0)
C1	Later	0.60	0.55	-5.1 (12.0)
C2	Later	0.39	0.38	3.9 (-1.3)
C3	Later	0.40	0.38	3.2 (3.6)
C4	Later	0.37	0.29	-6.4 (1.5)
V1	Later	0.41	0.22	14.3 (17.0)
V2	Later	0.30	0.21	2.5 (5.0)
V3	Later	0.45	0.43	-8.6 (2.0)

Table 7 continued

Site	Adaptive planting date with higher yield	2030–2050					
		Total period			Total period		
		CV of projected yield with baseline planting date	Change in yield with adaptive planting date w r to baseline, %	CV of projected yield with baseline planting date	Change in yield with adaptive planting date w r to baseline, %	CV of projected yield with baseline planting date	Change in yield with adaptive planting date w r to baseline, %
L1	Baseline	0.22	18.3 (0.0)	0.32	10.3 (0.0)	0.32	10.3 (0.0)
L2	Baseline	0.14	36.0 (0.0)	0.16	28.1 (0.0)	0.16	28.1 (0.0)
L3	Baseline	0.15	33.3 (0.0)	0.19	27.6 (0.0)	0.19	27.6 (0.0)
T1	Earlier	0.19	22.5 (11.8)	0.20	16.0 (7.7)	0.22	16.0 (7.7)
T2	Earlier	0.20	42.9 (17.2)	0.20	33.9 (14.2)	0.18	33.9 (14.2)
T3	Earlier	0.36	17.0 (1.6)	0.32	12.8 (1.8)	0.35	12.8 (1.8)
T4	Baseline	0.51	14.6 (0.0)	0.45	16.5 (0.0)	0.45	16.5 (0.0)
C1	Later	0.57	1.2 (16.4)	0.58	-2.0 (14.1)	0.51	-2.0 (14.1)
C2	Later	0.59	12.0 (12.2)	0.49	7.9 (5.1)	0.38	7.9 (5.1)
C3	Later	0.28	14.2 (0.8)	0.34	8.6 (2.1)	0.34	8.6 (2.1)
C4	Later	0.40	-2.0 (0.4)	0.38	-4.3 (0.9)	0.32	-4.3 (0.9)
V1	Later	0.29	33.3 (15.4)	0.36	23.6 (16.2)	0.19	23.6 (16.2)
V2	Later	0.09	25.2 (-1.3)	0.24	13.6 (1.5)	0.18	13.6 (1.5)
V3	Later	0.49	11.7 (3.7)	0.48	1.3 (2.9)	0.43	1.3 (2.9)

Table 8 Coefficient of variation (CV) of projected yield and change in projected average yield with adaptive planting date in relation to baseline (1996–2000) average yield (values within the bracket show the additional change in average yield due to planting date adaptation), scenario B2

Site	Adaptive planting date with higher yield	2010–2030		
		CV of projected yield with baseline planting date	CV of projected yield with adaptive planting date	Change in yield with adaptive planting date w r to baseline, %
L1	Later	0.40	0.25	3.4 (5.0)
L2	Baseline	0.17	0.17	28.9 (0.0)
L3	Earlier	0.16	0.18	26.7 (2.4)
T1	Later	0.22	0.22	16.9 (7.4)
T2	Earlier	0.20	0.22	20.6 (2.3)
T3	Later	0.27	0.33	30.8 (0.3)
T4	Later	0.51	0.51	3.8 (1.8)
C1	Later	0.53	0.45	3.6 (3.1)
C2	Later	0.64	0.43	-0.7 (10.6)
C3	Later	0.42	0.38	-2.9 (3.8)
C4	Later	0.39	0.38	-6.4 (2.4)
V1	Later	0.51	0.46	-4.4 (13.8)
V2	Later	0.36	0.23	-6.0 (3.6)
V3	Later	0.44	0.35	3.4 (7.4)

Table 8 continued

Site	Adaptive planting date with higher yield	2030–2050				Total period			
		CV of projected yield with baseline planting date	CV of projected yield with adaptive planting date	Change in yield with adaptive planting date to baseline, %	CV of projected yield with higher yield	CV of projected yield with baseline planting date	CV of projected yield with adaptive planting date	Change in yield with adaptive planting date to baseline, %	CV of projected yield with higher yield
L1	Later	0.49	0.32	-3.4 (4.1)	0.44	0.28	0.1 (4.6)	0.49	
L2	Baseline	0.19	0.19	25.8 (0.0)	0.17	0.17	21.9 (0.0)	0.19	
L3	Earlier	0.18	0.19	19.7 (-1.2)	0.17	0.19	27.4 (0.6)	0.18	
T1	Later	0.23	0.23	15.5 (6.7)	0.23	0.22	23.3 (7.1)	0.23	
T2	Earlier	0.25	0.30	15.6 (6.4)	0.22	0.26	16.2 (4.3)	0.25	
T3	Later	0.34	0.25	40.1 (5.2)	0.30	0.29	18.1 (2.6)	0.34	
T4	Later	0.54	0.38	3.8 (10.4)	0.52	0.44	35.3 (6.0)	0.54	
C1	Later	0.63	0.54	11.3 (11.3)	0.57	0.49	3.8 (6.9)	0.63	
C2	Later	0.52	0.42	-5.9 (10.6)	0.57	0.42	7.3 (10.6)	0.52	
C3	Later	0.49	0.40	-2.7 (7.8)	0.45	0.39	-3.2 (5.6)	0.49	
C4	Later	0.49	0.43	14.4 (2.7)	0.44	0.40	-2.8 (2.6)	0.49	
V1	Later	0.41	0.29	0.2 (16.8)	0.46	0.38	3.8 (15.4)	0.41	
V2	Later	0.33	0.22	-5.9 (6.3)	0.34	0.22	-2.2 (4.9)	0.33	
V3	Later	0.55	0.51	-3.4 (3.9)	0.49	0.43	-5.9 (5.7)	0.55	

4 Discussion

Estimates of impact of climate change on crop production could be biased depending upon the uncertainties in climate change scenarios, region of study, crop models used for impact assessment, and the level of management (Aggarwal and Mall 2002; Iizumi et al. 2011). In this study, we have used only one of the 24 GCMs used in the 4th Assessment Report of the IPCC (IPCC 2007). There are significant differences between GCMs with regard to climate changes simulated at the regional scale, particularly for precipitation (Eastham et al. 2008). Therefore, GCMs can at best be used to suggest the likely direction and rate of change of future climates (Krishnan et al. 2007). Also, several crop models for any crop can be employed for impact assessment of climate change and the results vary from model to model (Aggarwal and Mall 2002; Krishnan et al. 2007).

However, the trend of the results in this study is broadly similar to that of the other studies based on different crop models and climate projection of different GCMs (Matthews et al. 1995; Matthews et al. 1997; Chinvarno and Snidvongs 2005; SEA START RC 2006). Matthews et al. (1995, 1997) predicted changes in rice production in Thailand using three GCMs (GFDL, GISS, and UKMO) and two crop models (ORYZA1 and SIMRIW). The change in yield varies from -12.8 to $+9.3$ % with change in temperature from $+4.0$ to $+5.2$ °C. The main reason for this change is the impact of increased temperature on the spikelet fertility of that particular variety of rice. When a more tolerant (to temperature) genotype was used as varietal adaptation, models predicted that rice production in Thailand would change by $+18.7$ to $+40.7$ %. In this study, change in temperature for the growing period of rainfed rice in northeast Thailand varies from $+1.0$ to $+1.5$ °C, much lower than considered by Matthews et al. (1995, 1997). The impact of this was found very low or negligible in this study. The result of this study (increase in yield up to about 28 %) is therefore comparable and in agreement. Studies by Chinvarno and Snidvongs (2005) and SEA START RC (2006) simulated the yield of rice by CERES rice and DSSAT models using simulated weather data from the CCAM GCM at few places in Laos and Thailand and reported an increase in yield of rice up to 15 %, which support the results of this study.

The study found high variation in yield (Fig. 2; Tables 7, 8) during the simulation period due to the variation in rainfall (Fig. 3). There is no significant difference between yield variation between the two periods of simulation (Tables 7, 8) which indicates that no significant difference in rainfall variability as well. The results generally suggest increases in projected yield in the upper half of the basin in Laos and Thailand and decreases in the lower half in Cambodia and Vietnam. This is because of a net increase in water availability (increase in rainfall minus the increase in PET) in the upper part of the basin and net decrease in water availability in the lower part of the basin. However, water stress at the critical stages of growth may also affect yield (Iizumi et al. 2011) as discussed in Sect. 3.1.1 based on Fig. 5.

Rice yields are expected to undergo a general decline in many countries in south Asia due to increase in temperature (Auffhammer et al. 2012; Hossain 2008; Jalota et al. 2012). This prediction reflects the fact that most rice crops are grown in south Asia at the upper limit of this crop's temperature tolerance (Gerardeaux et al. 2012). This is not the case in the LMB for rainfed rice grown in the wet season (Tables 3, 4). Thus, the analysis suggests that the direct impact of temperature on rice yield may be negligible in the LMB.

AquaCrop model considers the effect of high temperature on spikelet sterility at the time of flowering. The accuracy of modelling temperature effects on spikelet sterility, however, depends on the diurnal time course of temperature and on the accuracy of the model in predicting flowering rate (Matthews et al. 1997). Peng et al. (2004) provide

evidence of decreased rice yields from increased night temperature associated with global warming. Auffhammer et al. (2012) showed that night time warming at the end of the growing season had an even greater impact on yield during 1966–2002 in India than changes in monsoon characteristics. Other mechanisms also may contribute to the observed yield reduction such as differential effects of night versus day temperature on tillering, leaf area expansion, stem elongation, grain filling, and crop phenological development (Peng et al. 2004). These issues are not included in many current crop models, which will need further refinement to account for the differential effects of minimum and maximum temperatures on respiration, morphological traits, and phenological development and thus more accurately simulate the influence of increased temperature under climate change scenarios (Peng et al. 2004).

Increased CO₂ concentration in the atmosphere in our simulations had a significant positive impact on the yield of rainfed rice all over the basin. In the upper part of the basin in Laos and Thailand, CO₂ concentration augments yield further in addition to the increase due to increase in rainfall. In the lower part of the basin in Cambodia and Vietnam, CO₂ concentration offsets a significant part of the negative impact of climate change on yield. In the absence of temperature increase, many studies have shown that the net effect of increased CO₂ was increase in the yield of rice (Bachelet et al. 1992; Iizumi et al. 2011; Jalota et al. 2012; Krishnan et al. 2007).

There are many adaptation options (Gaydon et al. 2010; Reilly and Schimmelpfenning 1999) for dealing with climate variability which will provide resilience against the potential negative impacts of climate change. Some of these options are climate-specific and some are non-climate-specific adaptation (Resurreccion et al. 2008) and adaption for climate change cannot be separated from other management options within agro-ecosystems (FAO 2008). In this study, we tested a climate-specific adaptation, change in planting date, and non-climate-specific adaptations of supplementary irrigation and increased fertilizer input. Previous studies (Blanche and Linscombe 2009; Hasegawa et al. 2008; Jalota et al. 2012; Krishnan et al. 2007; Laux et al. 2010; Matthews et al. 1997) suggested that adjusting planting dates might be a simple and powerful tool for mitigating the effects of a potential global warming. The result of the current study supports the suggestion, as shifting the planting date offsets negative impacts of climate change on yield and further augments yield where it has already increased due to climate change.

Changing the planting date as adaptation strategy has the potential to affect the overall annual crop calendar. In the LMB, however, the crop calendar under rainfed lowland conditions spans a wide transplanting or sowing window (Nesbitt 2005). Variability in the water conditions due to variability in rainfall appears to explain the wide windows for sowing and transplanting (Sawano et al. 2008). Changing the planting date is unlikely to have any impact on the overall cropping pattern of the region, as this variation is already accommodated in the crop calendar.

Reduction in fertility stress or application of more fertilizer was simulated in two sites in Cambodia and Vietnam. Among the riparian countries, fertilizer use is lowest in Cambodia and highest in Vietnam. The results (Table 9) show that yield is more sensitive to fertilizer application in Cambodia than that in Vietnam. Low fertilizer application, low use of high-yielding varieties, periodic drought, and inadequate management practices are the major causes of low productivity of rice in Cambodia (Fukai and Basnayake 2001). Soil fertility is also a major problem in Laos and Thailand due to the permeable nature of the sandy soils in the region (Fukai et al. 1998). Reduction in fertility stress is expected to have significant positive impact on the productivity of rice in these countries.

Drought is a major production constraint for rainfed lowland rice grown in Laos, Thailand, and Cambodia, but the frequency of drought problem is the highest in Northeast Thailand (Fukai et al. 1998). Increased rainfall due to climate change, which minimize the occurrence of drought, is the predominant factor in higher yield of rainfed rice in these countries. The variation in yield (Fig. 2; Tables 7, 8) can be further minimized and net increase in yield can be achieved by applying supplementary irrigation when required as the results suggest. Supplementary irrigation is practiced where there is irrigation infrastructure, in the areas near the confluence of major rivers, and along the tributaries. Field survey by Shimizu et al. (2006) in Cambodia revealed that some rainfed paddy fields do not depend solely on rainfall, and that they have supplementary sources of water such as small ponds close to paddy fields or water in lowlands along the farm road. Groundwater from shallow tubewells is also used as supplementary irrigation in some provinces in Cambodia (IDE 2009). However, supplementary irrigation is limited in Laos, Thailand, and in some parts of Cambodia mainly due to the lack of irrigation infrastructure. In the Mekong Delta, supplementary irrigation is already used for rainfed rice (Mainuddin and Kirby 2009a).

The objective of using adaptation option is to inform the policy makers who require an assessment of the benefits derivable from the adoption of the various adaptation measures. The computation of such benefits would require knowledge of the pre- and the post-adoption yields in addition to the costs of the adaptation itself, in order to make the choice among potential adaptation options (Krishnan et al. 2009). The success in the assessment of impacts and adaptations does not depend on the accuracy of yield predictions as much as it depends on the extent to which the differences between pre-impact (adaptation) and post-impact (adaptation) yields are reflected. What is more needed for the assessment of impacts of climate variability is the difference between pre- and post-impact productivity and production (Krishnan et al. 2009). In this study, we showed the difference between pre- and post-impact productivity. We did not assess the costs and economic benefits of the adaptation options.

Our study does not take into account the impact of extreme events such as floods, extreme drought, sea level rise, cyclones, and storm, which may become more frequent and more intense due to climate change. Flooding, salinity intrusion, and sea level rise may have a severe impact on the agriculture of the Mekong Delta (Carew-Reid 2007). Wassmann et al. (2004) showed that rice production will be affected through excessive flooding in the tidally inundated areas and longer flooding periods in the central part of the Vietnamese Mekong Delta as a result of the sea level rise due to climate change.

5 Conclusion

We examined the impact of climate change and adaptation strategies on the productivity of rainfed rice in the LMB for climate scenarios A2 and B2 for the period of 2010–2050. The results suggest that the yield of rice will increase for much of the basin except for part of Cambodia and Vietnam. The impact on the yield of rainfed rice is mainly due to the variability of rainfall during the growing season and increased CO₂ concentration in the atmosphere. The impact of increased temperature is negligible. However, the model is not able to consider all possible impacts of temperature such as increased night temperature.

Changing the planting date of rainfed rice may increase yield and minimize the impact in the areas where yield is adversely affected. Reducing the fertility stress and providing supplementary irrigation can further enhance yield.

This study marks significant progress in our understanding of how future climates are likely to affect rainfed rice cultivation in the LMB. The information generated is expected to help to properly anticipate and adapt farming to maximize rainfed rice production. The study, however, does not take into account the impact of extreme climate events due to global warming which may have catastrophic impact on yield and productivity.

Acknowledgments The authors express their sincere thanks to AusAID for funding this study and to SEA START RC for the provision of using PRECIS climate data.

References

- Aggarwal PK, Mall RK (2002) Climate change and rice yields in diverse agro-environments of India: II. Effect of uncertainties in scenarios and crop models on impact assessment. *Clim Chang* 52:331–343
- Araya A, Habtu S, Hadgu KM, Kebede A, Dejene T (2010) Test of AquaCrop model in simulating biomass and yield of water deficient and irrigated barley. *Agric Water Manag* 97:1838–1845
- Auffhammer M, Ramanathan V, Vincent JR (2012) Climate change, the monsoon, and rice yield in India. *Clim Chang* 111:411–424
- Bachelet D, Brown D, Bohm M, Russell P (1992) Climate change in Thailand and its potential impact on rice yield. *Clim Chang* 21:347–366
- Bhatia A, Pathak H, Aggarwal PK, Jain N (2010) Trade-off between productivity enhancement and global warming potential of rice and wheat in India. *Nutr Cycl Agroecosyst* 86:413–424
- Blanche SB, Linscombe SD (2009) Stability of rice grain and whole kernel milling yield is affected by cultivar and date of planting. *Agron J* 101(3):522–528
- Carew-Reid J (2007) Rapid assessment of the extent and impact of sea level rise in Vietnam. Climate change discussion paper 1. International Centre for Environmental Management (ICEM), Brisbane
- Chinvanno S, Snidvongs A (eds) (2005) The study of future climate changes impact on water resource and rain-fed agriculture production. In: Proceedings of the APN capable CB-01 synthesis workshop, Vientiane, Lao PDR, 29–30 July 2004. SEA START RC technical report no. 13, p 113
- Doorenbos J, Kassam AH (1979) Yield response to water. FAO irrigation and drainage paper 33. FAO, Rome
- Eastham J, Mpelasoka F, Mainuddin M, Ticehurst C, Dyce P, Hodgson G, Ali R, Kirby M (2008) Mekong River basin water resources assessment: impacts of climate change. CSIRO, Water for a Healthy Country National Research Flagship, Australia
- FAO (2008) Climate change and food security: a framework document. Food and Agricultural Organization of the United Nations, Rome
- FAOSTAT (2008) <http://faostat.fao.org>, accessed on 11 Jan 2011
- Farahani HJ, Izzi G, Oweis TY (2009) Parameterization and evaluation of the AquaCrop model for full and deficit irrigated cotton. *Agron J* 101:469–476
- Fukai S, Basnayake J (eds) (2001) Increased lowland rice production in the Mekong region. In: ACIAR proceedings 101, Canberra
- Fukai S, Sittisuang P, Chanphengsay M (1998) Production of rainfed lowland rice in drought prone environments: a case study in Thailand and Laos. *Plant Prod Sci* 1(1):75–82
- García-Vila M, Ferreres E, Mateos L, Orgaz F, Steduto P (2009) Deficit irrigation optimization of cotton with AquaCrop. *Agron J* 101:477–487
- Gaydon DS, Beecher HG, Reinke R, Crimp S, Howden SM (2010) Rice. In: Stokes C, Howden M (eds) Adapting agriculture to climate change: preparing Australian agriculture, forestry and fisheries for the future. CSIRO, Australia
- Geerts S, Raes D, Garcia M, Miranda R, Cusicanqui JA, Taboada C, Mendoza J, Huanca R, Mamani A, Condori O, Mamani J, Morales B, Osco V, Steduto P (2009) Simulating yield response of Quinoa to water availability with AquaCrop. *Agron J* 101:499–508
- Gerardeaux E, Giner M, Ramanantsoanirina A, Dusserre J (2012) Positive effects of climate change on rice in Madagascar. *Agron Sustain Dev* 32:619–627
- Halcrow Group Limited (2004) Technical reference report DSF 620. SWAT and IQQM models. Water utilisation project component A: development of basin modelling package and knowledge base (WUP-A). Mekong River Commission, Phnom Penh, Cambodia

- Hasegawa T, Sawano S, Goto S, Konghakote P, Polthane A, Ishigooka Y, Kuwagata T, Toritani H, Furuya J (2008) A model driven by crop water use and nitrogen supply for simulating changes in the regional yield of rainfed lowland rice in Northeast Thailand. *Paddy Water Environ* 6:73–82
- Hayashi S, Kamoshita A, Yamagishi J, Kotchasatit A, Jongdee B (2007) Genotypic differences in grain yield of transplanted and direct-seeded rainfed lowland rice (*Oryza sativa* L.) in northeastern Thailand. *Field Crop Res* 102:9–21
- Heng LK, Hsiao TC, Evett S, Howell T, Steduto P (2009) Validating the FAO AquaCrop model for irrigated and water deficient field maize. *Agron J* 101:488–498
- Hoanh CT, Jirayoot K, Lacombe G, Srinetr V (2010) Comparison of climate change impacts and development effects on future Mekong flow regime. In: Swayne DA, Yang W, Voinov AA, Rizzoli A, Filatova T (eds) Fifth biennial meeting in modelling for environment's sake, Ottawa, Canada
- Homma K, Horie T, Shiraiwa T, Sripodok S, Supapoj N (2004) Delay of heading date as an index of water stress in rainfed rice in mini-watersheds in Northeast Thailand. *Field Crop Res* 88(1):11–19
- Hossain SG (2008) Assessing impacts of climate change on cereal production and food security in Bangladesh. In: Lal R et al (eds) Climate change and food security in South Asia, vol 459. doi: [10.1007/978-90-481-9516-9_28](https://doi.org/10.1007/978-90-481-9516-9_28)
- IDE (International Development Enterprises) (2009) Strategic study of groundwater resources in Prey Veng and Svay Rieng (phase 2), final report. International Development Enterprises Cambodia, Phnom Penh, Cambodia
- Iizumi T, Hayashi Y, Kimura F (2007) Influence on rice production in Japan from cool and hot summers after global warming. *J Agric Meteorol* 63:11–23
- Iizumi T, Yokozawa M, Hayashi Y, Kimura F (2008) Climate change impact on rice insurance payouts in Japan. *J Appl Meteorol Climatol* 47:2265–2278
- Iizumi T, Yokozawa M, Nishimori M (2011) Probabilistic evaluation of climate change impacts on paddy rice productivity in Japan. *Clim Chang* 107:391–415
- IPCC (2000) Special report on emission scenarios (SRES). Cambridge University Press, Cambridge
- IPCC (2007) Climate change 2007: synthesis report. In: Core Writing Team, Pachauri RK, Reisinger A (eds) Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, p 104
- Jalota SK, Kaur H, Ray SS, Tripathi R, Vashisht BB, Bal SK (2012) Mitigating future climate change effects by shifting planting dates of crops in rice–wheat cropping system. *Reg Environ Chang*. doi: [10.1007/s10113-012-0300-y](https://doi.org/10.1007/s10113-012-0300-y)
- Krishnan P, Swain DK, Bhaskar BC, Nayak SK, Dash RN (2007) Impact of elevated CO₂ and temperature on rice yield and methods of adaptation as evaluated by crop simulation studies. *Agric Ecosyst Environ* 122:233–242
- Krishnan P, Ramakrishnan B, Rao KS, Dash RN (2009) Simulation studies to characterize the impact of climate change on crop production and to identify strategies for adaptation and mitigation. In: Singh SN et al (eds) Climate change and crops. *Environ Sci Eng*. doi:[10.1007/978-3-540-88246-63](https://doi.org/10.1007/978-3-540-88246-63)
- Laux P, Jackel G, Tingem RM, Kunstmann H (2010) Impact of climate change on agricultural productivity under rainfed conditions in Cameroon—a method to improve attainable crop yields by planting date adaptations. *Agric For Meteorol* 150:1258–1271
- MacSweeney C, New M, Lizcano G (2008a) UNDP climate change country profiles: Cambodia. School of Geography and the Environment of the University of Oxford, UNDP, Oxford, p 27
- MacSweeney C, New M, Lizcano G (2008b) UNDP climate change country profiles: Vietnam. School of Geography and the Environment of the University of Oxford, UNDP, Oxford, p 27
- Mainuddin M, Kirby M (2009a) Spatial and temporal trends of water productivity in the lower Mekong river basin. *Agric Water Manag* 96:1567–1578
- Mainuddin M, Kirby M (2009b) Agricultural productivity in the lower Mekong basin: trends and future prospects for food security. *Food Secur* 1:71–82
- Mainuddin M, Hoanh CT, Jirayoot K, Halls AS, Kirby M, Lacombe G, Srinetr V (2010) Adaptation options to reduce the vulnerability of Mekong water resources, food security and the environment to impacts of development and climate change. CSIRO, Water for a Healthy Country National Research Flagship, Australia, p 152
- Matthews RB, Kropff MJ, Bachelet D, van Laar HH (eds) (1995) Modelling the impact of climate change on rice production in Asia. IRRI/CAB International, p 289
- Matthews RB, Kropff MJ, Horie T, Bachelet D (1997) Simulating the impact of climate change on rice production in Asia and evaluating options for adaptation. *Agric Syst* 54(30):399–425
- MRC (2010) State of the basin report 2010. Mekong River Commission, Vientiane
- Nesbitt HJ (2005) Water used for agriculture in the lower Mekong Basin. MRC technical paper no. 11. Mekong River Commission, Vientiane, p 58

- Nhan DK, Trung NH, Sanh NV (2011) The impact of weather variability on rice and aquaculture production in the Mekong Delta. In: Stewart MA, Coclanis PA (eds) Environmental change and agricultural sustainability in the Mekong Delta. *Adv Glob Chang Res* 45. doi:[10.1007/978-94-007-0934-8_12](https://doi.org/10.1007/978-94-007-0934-8_12)
- Peng S, Huang J, Sheehy JE, Laza RC, Visperas RM, Zhong X, Centeno GS, Khush GS, Cassman KG (2004) Rice yields decline with higher night temperature from global warming. *Proc Natl Acad Sci* 101(27):9971–9975
- Raes D, Steduto P, Hsiao T, Fereres E (2009a) AquaCrop version 3.0: reference manual. FAO, Land and Water Division, Rome
- Raes D, Steduto P, Hsiao TC, Fereres E (2009b) AquaCrop—the FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agron J* 101:438–447
- Reilly JM, Schimmelpfenning D (1999) Agricultural impact assessment, vulnerability, and the scope for adaptation. *Clim Chang* 43:745–788
- Resurreccion BP, Sajor EE, Fajber E (2008) Climate adaptation in Asia: knowledge gaps and research issues in South East Asia. ISET-International and ISET-Nepal, Kathmandu, p 76
- Rockstrom J, Karlberg L, Wani SP, Barron J, Hatibu N, Oweis T, Bruggeman A, Farahani J, Qiang Z (2010) Managing water in rainfed agriculture—the need for a paradigm shift. *Agric Water Manag* 97:543–550
- Sawano S, Hasegawa T, Goto S, Konghakote P, Polthanee A, Ishigooka Y, Kuwagata T, Toritani H (2008) Modelling the dependence of the crop calendar for rainfed rice on precipitation in Northeast Thailand. *Paddy Water Environ* 6:83–90
- Sheehy JE, Mitchell PL, Ferrer AB (2006) Decline in rice grain yields with temperature: models and correlations can give different estimates. *Field Crop Res* 98:151–156
- Shimizu K, Masumoto T, Pham TH (2006) Factors impacting yields in rain-fed paddies of the lower Mekong river basin. *Paddy Water Environ* 4:145–151
- SEA START RC (Southeast Asia START Regional Centre) (2006) Final technical report: Southeast Asia regional vulnerability to changing water resources and extreme hydrological events due to climate change. SEA START RC technical report no. 15, Bangkok, Thailand, p 142
- Steduto P, Hsiao TC, Raes D, Fereres E (2009) AquaCrop—the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agron J* 101:426–437
- Tao F, Hayashi Y, Zhang Z, Sakamoto T, Yokozawa M (2008) Global warming, rice production, and water use in China: developing a probabilistic assessment. *Agric For Meteorol* 148:94–110
- TKK, SEA START RC (2009) Water and climate change in the Lower Mekong Basin: diagnosis and recommendation for adaptation. Water and Development Research Group, Helsinki University of Technology (TKK), and Southeast Asia START Regional Centre (SEA START RC), Chulalongkorn University. Water and Development Publications, Helsinki University of Technology, Espoo, Finland
- Todorovic M, Albrizio R, Zivotic L, Abi Saab M, Stöckle C, Steduto P (2009) Assessment of AquaCrop, CropSyst, and WOFOST models in the simulation of sunflower growth under different water regimes. *Agron J* 101:509–521
- Toritani H, Hasegawa T, Kuwagata T, Ohno H, Ishigooka Y, Goto S, Sakamoto T, Sawano S, Hayano M, Polthanee A, Konghakote P (2007) Evaluation of the relationship between the variability in the water cycle and the demand for water for food production in the Northeastern region of Thailand. In: Proceedings of the international workshop on assessment of changes in water cycles on food production and alternative scenarios—implications for policy making, November 22, 2007, Epochal Tsukuba, Japan
- Tuan LA, Chinvano S (2011) Climate change in the Mekong River Delta and key concerns on future climate threats. In: Stewart MA, Coclanis PA (eds) Environmental change and agricultural sustainability in the Mekong Delta. *Adv Glob Chang Res* 45. doi:[10.1007/978-94-007-0934-8_12](https://doi.org/10.1007/978-94-007-0934-8_12)
- Ty TV, Sunada K, Ichikawa Y, Oishi S (2012) Scenario-based impact assessment of land use/cover and climate changes on water resources and demand: a case study in the Srepok River Basin, Vietnam—Cambodia. *Water Resour Manag* 26:1387–1407
- UN Population Division (2006) World population prospects: the 2006 revision. <http://www.un.org/esa/population/publications/wpp2006/wpp2006.htm>
- Wassmann R, Hien NX, Hoanh CT, Toung TP (2004) Sea level rise affecting the Vietnamese Mekong Delta: water elevation in the flood season and implications for rice production. *Clim Chang* 66(1–2):89–107
- Yao F, Xu Y, Lin E, Yokozawa M, Zhang J (2007) Assessing the impacts of climate change on rice yields in the main rice areas of China. *Clim Chang* 80:395–409