ORIGINAL PAPER

Simulation of the impacts of climate change on phenology, growth, and yield of various rice genotypes in humid sub-tropical environments using AquaCrop-Rice

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Abstract

In the light of continuing anthropogenic climate change, it is important to gain a deep understanding of rice genotypic behavior under climate change. Most efforts on modeling rice performance under climate change focused on studying some aspects of climate change only such as CO_2 concentration ($[CO_2]$) or temperature. A comprehensive study on the role of genotypic variability in rice under diverse $[CO_2]$ × temperature × rainfall × representative concentration pathway (RCP) × environment is rare. The objective of the present study was to use AquaCrop-Rice model to study the impact of climate change on different rice cultivars in northern Iran. Three common improved and local rice cultivars were chosen, and their growth and yield behavior were simulated under three environments, three RCPs (2.6, 4.5 and 8.5), four temperature (+ 1 °C, + 2 °C, + 3 °C, + 4 °C), and two rainfall (± 20%) scenarios under two future timeframes (2020–2051 and 2052–2083). Results indicated different responses of rice cultivars under climate change. In general, improved cultivars acted better than the local cultivar although interaction with environment was also observed. Increase in $[CO_2]$ and temperature most often favored rice yield. However, RCP8.5 along with temperature scenario + 1 °C resulted in the highest aboveground biomass and yield. Rainfall variation was not of considerable importance. Phenology (flowering and physiological maturity) was accelerated especially by temperature. The length of the vegetative phase was more influenced by temperature than the length of the generative phase. Our simulations also indicated a potential for adaptation of improved cultivars under increasing $[CO_2]$ through their reduced stomatal conductance.

Keywords AquaCrop · Canopy cover · Climate change · Rice · Simulation · Yield

Introduction

Climate is changing and one of the most important challenges of the current century is to achieve solutions to the problems caused by climate change. Crop growth could be strongly affected by changes in main climatic variables (precipitation and temperature) thus compromising agricultural production and food security both globally and locally.

Average global temperature has increased over the last few decades and is predicted to continue to rise with more frequent extreme hot days. Global mean surface temperature has increased by about 1 °C over the past 30 years and is expected to increase between 1 and 3.7 °C by the end of the twenty-first century (IPCC 2014). Daily minimum temperature is projected to increase faster than daily maximum temperature (IPCC 2014), which in turn has higher influence on soil temperature and thus onset of crop-growing season in spring. There has also been a faster increase in night-time (daily minimum) temperature than daytime (daily maximum) temperature, leading to a global decrease in the diurnal temperature amplitude. Precipitation will be also undergoing significant changes (Ding et al. 2017), which indicates that water scarcity is likely to be exacerbated in future, especially in arid, semi-arid, and semi-Mediterranean environments.

Developing countries are confronted by more serious challenges of climate change through limited capacity to adapt. Different aspects of climate change such as higher atmospheric CO_2 concentration ($[CO_2]$), increased temperature, and lower rainfall have different impacts on plant production and crop yield. Anticipated changes are expected to have large and far-reaching effects predominantly in the developing

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countries. Global climate change has substantially impacted on crop phenologies (Tao et al. 2013), crop yields, global food prices, and food security (Challinor et al. 2014).

The impact of higher temperature on crop grain yield and associated traits has so far been assessed by simulation and field experiments for variety of crops such as wheat (Lizana and Calderini 2013), sunflower (Van der Merwe 2010), rice (Zhang et al. 2015), barley (Hogy et al. 2013), and canola (Gan et al. 2004). However, the effects of climate change on crop performance are likely to vary greatly from one region to the next.

Global climate change is a main challenge for grain crops such as rice. Rice is one of the major foods cultivated extensively in the world and provides food for approximately half of the world's population (Mohanty 2014). Thus, increasing demand for rice resulting from burgeoning population is a big threat in Asia, as the major rice producing continent. With about 557.000 ha cultivation area and 38 to 42 kg per capita consumption, rice is the second important staple food crop after wheat in Iran (Raoufi et al. 2018).

The effect of high temperatures on rice yield formation appears to be related to changes in crop-growing period (Zhang et al. 2013) and flowering dynamics, to reduction in grain set, and to lower grain weight (Mohammed and Tarpley 2009). Temperature increase around anthesis and at grain filling reduces grain yield substantially (Lizana and Calderini 2013). However, genotypic differences have been shown in response of rice to climate change (Wang et al. 2015). Tao et al. (2013) showed that the magnitude of reduction in length of rice-growing period varies between single, early, and late rice varieties. They found that maturity occurred earlier for early and late rice but delayed for single rice when exposed to climate warming (Tao et al. 2013). Changes in maturity date may also be linked to decreases in solar radiation during the growing season (Tao et al. 2013).

In addition to phenology, rice growth and yield also need further investigation and should be considered when formulating plans and policies for adapting the rice agroecosystems to the changing climate. The purpose of this study was to assess the effects of temperature and precipitation variability combined with increase in $[CO_2]$ (through RCPs) in Haraz river basin in Iran on genotypic response of rice growth and yield using crop growth modeling as crop growth simulation models can aid breeding programs targeting crop adaptation (Soufizadeh et al. 2018). However, almost little is known about the interaction between rice cultivars and major climatic variables; i.e., $[CO_2]$, temperature, and precipitation. This issue gets more important when comparing local and improved varieties in this regard.

Materials and methods

Study area

Mazandaran Province (36° 29′ N, 52° 23′ E, elevation 23.7 m above sea level (masl)) is located in the north of Iran and is representative of the main irrigated paddy areas at the Caspian Sea coast in Haraz river basin (Fig. 1). The climate of the province is divided into three groups. Group *A* starts from the western part of the province and extends to the central and eastern parts of the province which mainly includes low-elevation lands. Mean annual rainfall in this region is about 980 mm. This region has the dominant climate in the province and almost all the agricultural areas fall within this plain. Groups *B* and *C* moves toward the Alborz mountain chain and experience high-elevation mountainous areas starting from 1500 to higher than 3000 masl. Mean annual minimum and maximum temperatures in the province vary from 10.5 to 11.6 °C and 19.7 to 21.1 °C, respectively.

The province is ranked first in terms of rice production in the country, and more than half of the total rice national acreage belongs to this province. During the last decade, the rainfall and temperature variability in the province have increased as a result of climate change. Such a great variability puts high pressure on rice production both due to decreased in-season and out-season water availability and increased heat stress on rice.

Regarding soil characteristics, the province consists of three major classes including fine-textured alluvial soils, brown forest soils (including gray brown podzolic soils), and lithosols (brown forest soils and rendzinas). The agricultural plain of the province is dominated by fine-textured alluvial soils. The soil texture shows a slight variation from loamy sand and loam on the eastern side of the province to slight clay on the western side. The last two classes mainly occur at high altitudes that are almost non-agricultural areas covered by high-density rainforests.

As Mazandaran is a west-to-east province, three counties were selected along this direction to provide a good coverage of the agricultural plain. The selected counties are Ramsar, NowShahr, and GhaemShahr (Fig. 1). Ramsar and Nowshahr are coastal counties, while GhaemShahr is an inland county. Many rice cultivars have been bred to be used by farmers. However, among these, the three rice cultivars Tarom, Ghaem, and Fajr were chosen as the most common genotypes cultivated by farmers. Tarom and Ghaem are both short-maturing genotypes with the former being a local indica rice and the latter being an improved indica rice. Fajr (F; IR7328) is a mid-maturing high-yielding genotype introduced by the International Rice Research Institute (IRRI) (Raoufi et al. 2018).

Weather data

In order to study the impact of climate change on rice production, the long-term weather data (32 years) of the selected counties were gathered from the Iranian Meteorological
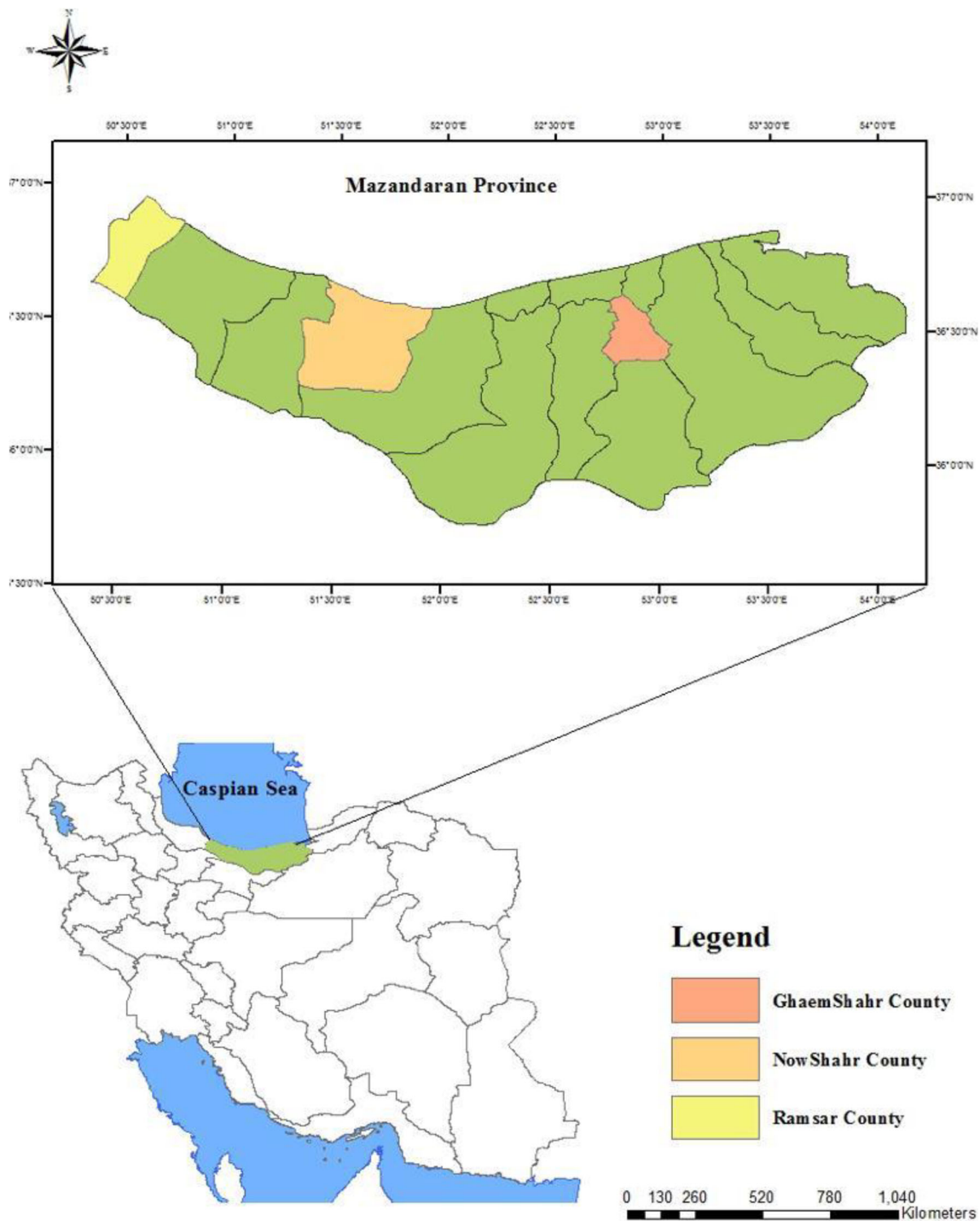
Fig. 1 Map of Iran, Mazandaran province along the Caspian Sea coast, and the counties where the study has been done

Organization (IRIMO). Each county had its own weather station that was representative of the weather condition of the county. Weather data included minimum and maximum temperatures, rainfall, and sunshine hours at daily basis from 1984 to 2015. Weather data were quality checked by the IRIMO. Almost no missing values existed in the weather files. In case of any missing value, long-term average of that day/period was used instead.

Future climate scenarios

The last and the most comprehensive assessment of climate change has been done by the Intergovernmental Panel on Climate Change (IPCC) in 2013 through its Fifth Assessment Report (AR5). In this report, projections of future Green House Gas (GHG) emissions have been done based on a new approach called the Representative Concentration

Pathway (RCP). The RCPs describe the pathways of GHG emissions and atmospheric concentrations, air pollutant emissions, and land use based on population size, economic activity, lifestyle, energy use, land use patterns, technology, and climate policy. In total, four RCPs have been defined. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ("baseline scenarios") lead to pathways ranging between RCP6.0 and RCP8.5. RCP2.6 is representative of a scenario that aims to keep global warming likely below 2 °C above pre-industrial temperatures. Multiple lines of evidence indicate a strong, consistent and almost linear relationship between cumulative CO_2 emissions and projected global temperature change to the year 2100 in the RCPs. Any given level of warming is associated with a range of cumulative CO_2 emissions, and therefore, e.g., higher emissions in earlier decades imply lower emissions later.

Future climate scenarios are usually generated using various approaches ranging from incremental (synthetic) scenarios to analogue scenarios and climate model-based scenarios (Mearns et al. 2001; Santoso et al. 2008). Each of these approaches has its advantages and disadvantages. Incremental scenarios and climate model approaches are the two widely used approaches worldwide. Asseng et al. (2015) stated that constructing future climate scenarios by using general circulation models (GCMs) has large uncertainties mainly arising from three sources including the modeled processes used in the GCMs themselves, the initial conditions and future greenhouse gas emissions (IPCC 2013). In addition to the aforementioned disadvantageous, downscaling GCM scenarios output to local/field scale adds another source of uncertainty (Wilby et al. 2004). Asseng et al. (2015) criticized the "change factor method" or "delta method" in that this approach does not consider any potential changes in rainfall distribution or intensity when trying to obtain higher spatial resolution projections.

In the present study, the future climate change scenarios were generated by the incremental approach (Mearns et al. 2001) to produce daily weather in near and far future from historical weather data at each site. This approach has been widely used in climate change impact studies on crop performance, including rice (Wang et al. 1992, 2009; Van Ittersum and Donatelli 2003; Ludwig and Asseng 2006; Yuan et al. 2014; Asseng et al. 2013; Li et al. 2015; Dias De Oliveira et al., 2015; Kim et al. 2013). The main advantage of such an approach is that the variability structure of historical weather data is retained and shifts for future, and the effects of extreme weather values could be captured more realistically (personal communication). Another important advantage of this approach is that the relative sensitivity of (rice) crop to changes in climate can be quickly explored (Santoso et al. 2008; Lobell et al. 2013).

The climate change scenarios were based on factorial combination of $[CO_2]$, temperature, and rainfall. In total, 24 climate scenarios plus the baseline period (1984–2015) were generated for each study location for near future (2020–2051) and far future (2052–2083), which will be explained in the following paragraphs.

To build future climate scenarios, the three most important weather variables were considered, i.e., $[CO_2]$, temperature and rainfall. AquaCrop model allows for changes in $[CO_2]$ through providing the user to choose among various RCP scenarios. In the present study, RCPs 2.6 ($\approx$ 450 ppm CO_2 equiv.), 4.5 ($\approx$ 650 ppm CO_2 equiv.) and 8.5 ($\approx$ 1370 ppm CO_2 equiv.) were chosen to cover a wide range of $[CO_2]$. It should be noted that the choice of RCP in AquaCrop only allows for $[CO_2]$ adjustment and does not consider the interaction of climate variables inherent in each RCP. Instead, temperature and rainfall are input to the model through separate user-defined files.

Regarding temperature, four levels of increase were considered, i.e., + 1, + 2, + 3, and + 4 °C. The minimum and maximum daily temperatures in the baseline period were manipulated according to the respective amounts stated above. Also, daily rainfall during the baseline period was either decreased or increased by − 20% or + 20%, respectively, to capture the effects of possible variation in this weather variable in future. The range of variability in temperature and rainfall was in accordance with the last IPCC report (2014) and also many similar studies conducted elsewhere (Lobell et al. 2013). Regarding the rainfall, Abbaspour et al. (2009) showed that wet regions in Iran will receive more rainfall, while dry regions will receive less. On the other hand, Nazemosadat (2001) showed that severe drought is highly probable in northern coastal areas of Iran during warm episodes. As a result, ± 20% variation in rainfall was superimposed on baseline rainfall in line with these findings.

AquaCrop model

The AquaCrop crop growth simulation model (version 6, released in 2017) was used to assess the response of rice genotypes to climate change. Detailed description of the model has been given by Raoufi et al. (2018); thus, a brief description of the model is given here only. AquaCrop is a general dynamic water-driven model for practical decision-making in agroecosystem managements. The model is based on complex biophysical processes (Raoufi et al. 2018) governing soil, plant, and atmosphere systems in a continuous manner, through which crop response to water and temperature stress and also field management (mulch, irrigation, fertilization, and water salinity) is simulated. Biomass production is simulated based on adjustment of crop transpiration under actual condition and through a crop-specific water productivity coefficient (WP*) (Equation 2 in Vanuytrecht et al. 2014). This

enables the AquaCrop to be used in different climatic conditions.

The capability of AquaCrop for simulation of crop response to elevated CO_2 is based on the adjustment of (a) crop growth through affecting canopy cover (CC) and thus transpiration, and (b) WP* in response to CO_2. By multiplying WP* with a correction factor (fCO$_2$), AquaCrop adjusts WP* when running simulations for a year at which [CO_2] differs from its reference value (369.41 ppm) in the year 2000.

As AquaCrop is responsive to changes in CO_2 concentration (Vanuytrecht et al. 2011), it would be possible to evaluate the interaction between temperature increase, rainfall variation, and the rise in CO_2 concentration under future climate.

Experimental information used for simulations

The AquaCrop-Rice model which was successfully parameterized and evaluated by Raoufi et al. (2018), for the three dominant rice genotypes stated earlier, was employed to reliably study the impact of climate change on this crop.

For the sake of the present study, soil characteristics were kept constant and non-limiting across locations (and simulations also) as the soils are of similar texture and class. This was based on the explanations given in the "Study area" section and personal contacts with agricultural experts in the region.

The base field information applied in the present study was those of Amiri et al. (AmiriLarijani et al. 2011) and Raoufi et al. (2018). In essence, three common rice genotypes had been studied under three seedling ages in two growing-seasons of 2008 and 2009 in Amol, Mazandaran province. The experimental design was split-plot in three replications where rice genotypes (Tarom (local short-maturing indica rice), Ghaem (short-maturing improved indica rice) and Fajr (IR7328; mid-maturing and high-yielding cultivar introduced by (IRRI) were assigned to main-plots, while rice seedling ages (17-, 24- and 33-days old) were assigned to sub-plots. All management practices including fertilization, irrigation, and pest control were done accordingly and as needed to keep the rice plants under stress-free conditions. Experimental plots were consisted of 10 rows spaced 30 cm apart with within row-spacing of 16 cm and one plant per hill in the puddled soil. Phenological recording and destructive samplings were done regularly during the growing-seasons so that quality dataset was obtained for model calibration as explained in detail by Raoufi et al. (2018). In the present research, the response of three rice genotypes mentioned above, which are among common and widely grown rice cultivars by farmers, was evaluated for the optimum transplanting age (24-days old) under climate change context. All farming practices were done under optimum/recommended conditions. The date of rice transplantation was considered the 4th June each year. Simulations were run under no-water and no-nitrogen stress same as the field studies stated earlier.

Ultimately, the model was run for each climate scenario by inputting the appropriate weather file to the model considering the aforementioned soil and crop management conditions. Various crops traits that were output included flowering and maturity dates, maximum canopy cover (CCmax), grain yield, final biomass, average leaf expansion stress, and average stomatal stress.

All graphs were made in the SigmaPlot and MicroSoft Excel. Boxplots were plotted in the SigmaPlot.

Results and discussion

Rice phenology

Results show that rice phenology could be considerably affected by climate change regardless of genotype (Fig. 2a). Among the three climatic variables ([CO_2], temperature and rainfall), temperature had the highest effect followed by [CO_2] (i.e., RCPs) and rainfall (almost no effect). In general, increase in temperature accelerates flowering and physiological maturity in rice, although exceptions existed in this regard. However, acceleration is higher for flowering, which indicates that under future climate, the length of rice vegetative phase will be more influenced than the length of generative phase. One reason may be that the average temperature during the vegetative phase in all locations is about 2 °C lower than the average temperature of the generative phase. As the development rate of all crops including rice increases linearly above the base temperature to optimum temperature, such an accelerating effect is greater under lower temperatures that rice experiences during its vegetative period. Lv et al. (2018) also found that flowering dates advanced for the entire rice production region studied under climate change. A body of literature also shows that under future climate scenarios, rice-growing duration generally shortens as a result of climate warming (Zhang and Tao 2013; Tao et al. 2013; Zhang et al. 2013). Acceleration in phenology of rice due to temperature increase could also be a result of the approach through which phenology is modeled by AquaCrop. It has been shown that models with asymptotic response showed shortened growth duration at almost all temperature ranges, while the phenology was prolonged in models with an optimum response of development rate (Li et al. 2015).

Looking at the genotypes provides good findings. As observed in Fig. 2a, almost all genotypes show similar responses to increase in temperature in GhaemShahr and NowShahr. However, the degree of response varies between genotypes. Cultivar Fajr shows the highest shortening in flowering date compared with cultivars Ghaem and Tarom under almost all scenarios. The percentage acceleration in this cultivar and at these two locations ranged between 5.09% and 18.05% depending on RCP. Considering all cultivars, the lowest

Near future (2020-2051)

Far future (2052-2083)
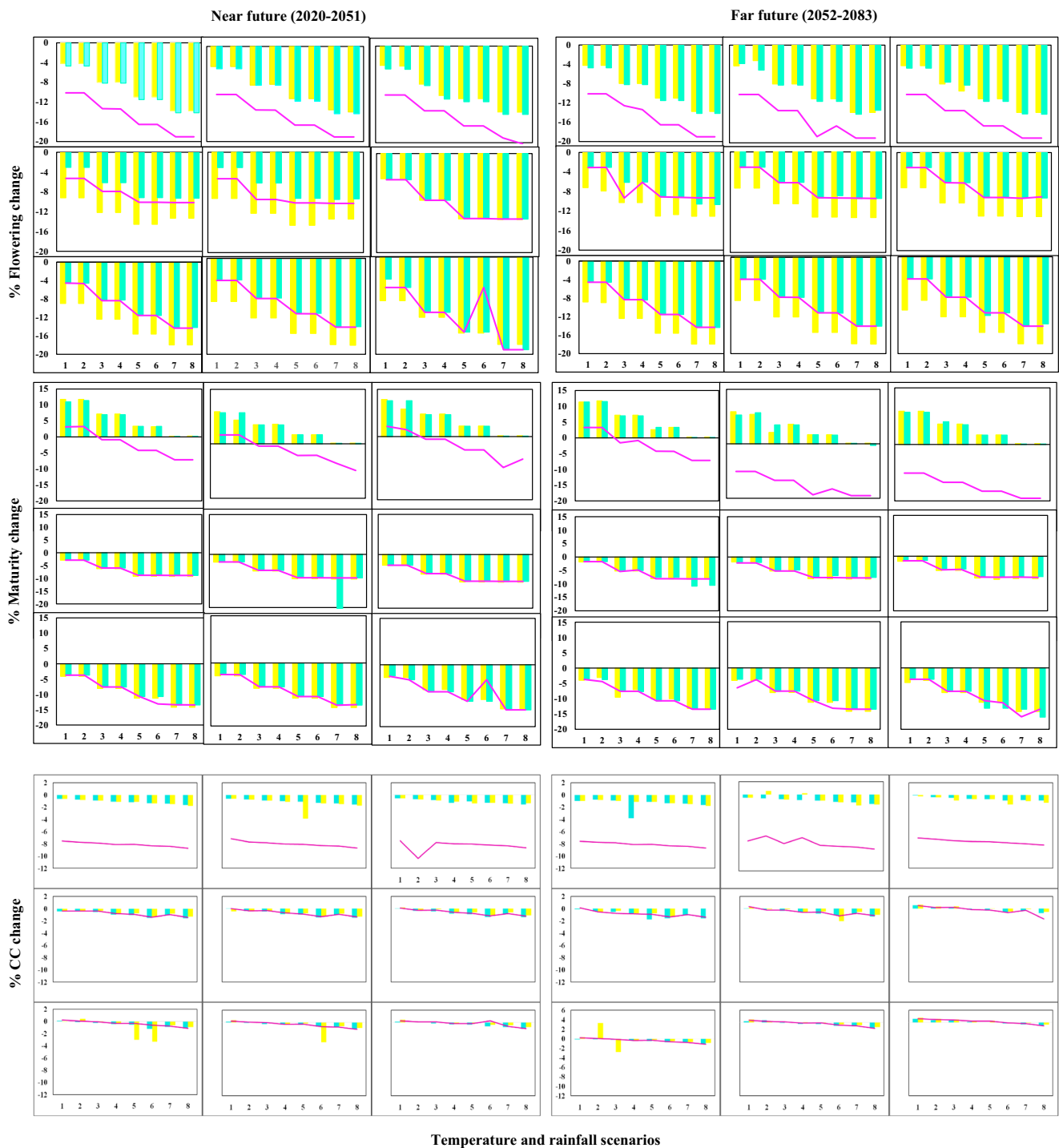
Fig. 2 Percentage of change in the dates of flowering (upper panel) and maturity (middle panel), and canopy cover (lower panel) of the three rice genotypes (yellow: Fajr, blue: Ghaem, pink: Tarom) in Ramsar (top-row in each panel), GhaemShahr (mid-row in each panel) and NowShahr (bottom-row in each panel) counties of Iran relative to baseline period (1992-2017) as affected by various RCPs (2.6: left column in each panel; 4.5: middle column in each panel; 8.5: right column in each panel), temperatures and rainfall variations during 2020-2051 (left panel) and 2052-2083 (right panel). (The labels of X axis show temperature and rainfall variations; 1, + 1 °C and + 20%; 2, + 1 °C and − 20%; 3, + 2 °C and + 20%; 4, + 2 °C and − 20%; 5, + 3 °C and + 20%; 6, + 3 °C and − 20%; 7, + 4 °C and + 20%; and 8, + 4 °C and − 20%)

reduction in the length of the vegetative phase (between ∼ 3 and 9.2%) could be observed when temperature increases 1 °C, while the highest reduction (between ∼ 13 and 18.1%) could be obtained under 4 °C increase in temperature.

Cultivars Ghaem and Tarom show less acceleration in phenology compared with that of cultivar Fajr. The degree of acceleration in these two cultivars is more similar to each other than to Fajr. This is because both cultivars are of short-maturing

type. Also, more similarity was observed between the three cultivars in terms of percentage acceleration in the length of the generative phase than of the vegetative phase. Such a finding could be associated with higher temperature (but still lower than optimum of 30 °C for physiological maturity according to Yoshida (1981)) during the generative phase compared with the vegetative phase that results in that rice experiences closer to optimum temperature conditions during the generative phase under increased temperature. The acceleration in the maturity date of rice cultivars varied between a minimum of ~ 1.8% and a maximum of ~ 16% depending on cultivar and climate change scenario. However, averaging over all cultivars and climate change scenarios, the acceleration in the length of the generative phase of all cultivars was lower than that observed for the vegetative phase. These results show that there is an urgent need to explore the temperature sensitivities of major rice cultivars to change in temperature. A comparison between the performance of rice between GhaemShahr and NowShahr and under climate change shows that higher acceleration values occur in NowShahr on both dates of flowering and physiological maturity (Fig. 2a). This is attributable to lower minimum and maximum temperatures in NowShahr during the whole growing period of rice (24.65 °C) compared with that in GhaemShahr (25.66°°C). Between base and optimum temperatures, the closer the temperature to optimum, the less positive effect on the rate of development. Also, the phenological difference between the two locations gets more pronounced under warmer climate conditions. Asseng et al. (2015) showed that species with high base temperature for crop emergence (as is the case for rice) could benefit from increasing temperatures in cooler regions.

In Ramsar, however, the response of phenology to temperature differed completely and genotypes' response was also of different order in comparison with other locations (Fig. 2a). At this location, increase in temperature accelerated the date of flowering between ~ 3.8 and ~ 20.25% depending on cultivar and the RCP under consideration. However, opposite to the maturity response that was observed in GhaemShahr and NowShahr, the dates of physiological maturity of cultivars Fajr and Ghaem were delayed at this location in response to all climate scenarios. A negative association existed between temperature increase and percentage delay so that the highest delays were observed at + 1 °C scenarios (between ~ 8.5% and ~ 11.8%), while the lowest delays were observed at + 4 °C scenarios (< ~ 0.3%). Cultivar Tarom gave a different response compared with the other two cultivars. A 1 °C increase in temperature delayed the date of physiological maturity of this cultivar between 2.20 and 3.27%. However, higher increase in temperature accelerated physiological maturity in a positive manner. As the post-flowering phenology in many crops including rice is controlled by temperature alone, the observed variation in the reproductive phase duration of rice cultivars could be accounted for by their correlation with temperature. Slafer et al. (2015) reviewed

the environmental and genetic basis of crop development and argued that the three major environmental drivers of crop phenology are temperature, photoperiod, and vernalization, with all the phases of the development sensitive to temperature (as soon as the seed imbibes and continue until maturity). However, photoperiod and vernalization only affects development in certain crop species at certain vegetative stages only.

Long-term average ambient temperature during the baseline period in Ramsar was 0.35 °C higher than in NowShahr but 0.64 °C lower than in GhaemShahr. Long-term day (maximum temperature) and night (minimum temperature) temperature, however, were of different pattern. Long-term maximum temperature did not differ between Ramsar and NowShahr but was ~ 2 °C higher in GhaemShahr than in NowShahr. Regarding long-term minimum temperature, however, rice experienced 0.7 °C warmer nights in Ramsar than the other two locations. The present study proposes a direct effect of diurnal temperature (amplitude) on development from flowering to maturity in rice, which may explain a large part of different phenophase response observed at this location. However, the mechanism of effect is unknown. The cultivar × location × day/night temperature interaction observed in the present study warrants the necessity of a more-detailed experiment under controlled environment. Lobell (2007) showed that an increase in diurnal temperature range affects rice and maize yield negatively.

The results also indicate RCP × cultivar × location interaction on the length of the rice phenophases. Difference between RCPs is greatest in GhaemShahr followed by NowShahr and Ramsar, where in the latter almost no significant difference could be observed between various RCPs either under near or far future. In GhaemShahr, the worst RCP depends upon the cultivar but RCPs 4.5 and 8.5 cause the highest variation in the length of both the vegetative and reproductive phases. In NowShahr, cultivar Fajr shows almost similar response under various RCPs. Cultivar Ghaem has the highest phenological acceleration under RCP8.5, while RCPs 2.6 and 4.5 cause the highest acceleration in rice cv. Tarom phenology under near and far future, respectively. GhaemShahr is an in-land site compared with NowShahr and Ramsar which are coastal sites. Thus, it seems that the effect of various RCPs on rice depends almost greatly on the distance from sea.

Canopy cover

Figure 2b indicates that the percentage of CC change depends on rice cultivar and location of study. Comparison between locations shows that the growth response of rice cultivars (especially Tarom) to climate change is more negative in Ramsar compared with that in GhaemShahr and NowShahr. At this location and irrespective of climate scenarios, the CC of cultivar Tarom decreases between 6 and 11% compared with those in the baseline. The corresponding values for cultivars Fajr and Ghaem were less than 2% (except for minor cases in Fajr). A more detailed look at

Fig. 3 shows that Tarom acts much better under almost all scenarios in GhaemShahr and NowShahr so that the highest reduction in its CC is less than 2% and is comparable with the percentage of changes observed in the other two cultivars. This may indicate that Tarom could not be recommended in Ramsar under future climate condition. A reason of higher CC reduction in Ramsar may be related to higher night temperatures at this location, which could be translated into higher respiration rate and thus lower CC. Rice growth and yield has been shown to decline by 15% per °C increase in night-time temperature due to enhanced night respiration without any benefit to the crop (Peng et al. 2004).

Increase in temperature enhanced the reduction in CC so that in many cases, temperature increase up to + 3 °C and + 4 °C decreased the CC up to 2% (Fig. 2b). This was true for almost all the cultivars at all locations. However, temperature effect in GhaemShahr and Ramsar was more pronounced than

in NowShahr. This could be explained in part by warmer days in Ramsar and GhaemShahr during the vegetative phase, when CC builds up and reaches its maximum at flowering. There are also many instances at both locations that slight to moderate increases (+ 1 °C and + 2 °C) in temperature yielded in slightly higher CC (< 1% increase in most cases) compared with the baseline period.

Results also show that increase in [CO_2] (moving from RCP 2.6 to RCP 8.5) could partly compensate the negative effect of temperature on CC, so that the majority of instances with increased CC or very slight decrease in CC, fall in RCP 8.5 (especially in GhaemShahr and NowShahr). This highlights that enhanced CO_2 may favor rice growth positively by increasing the carbon available for photosynthesis and in turn positively affecting assimilated allocation to vegetative (leaves especially) organs. Devkota et al. (2013) also found similar results. They found that increasing CO_2 could surpass
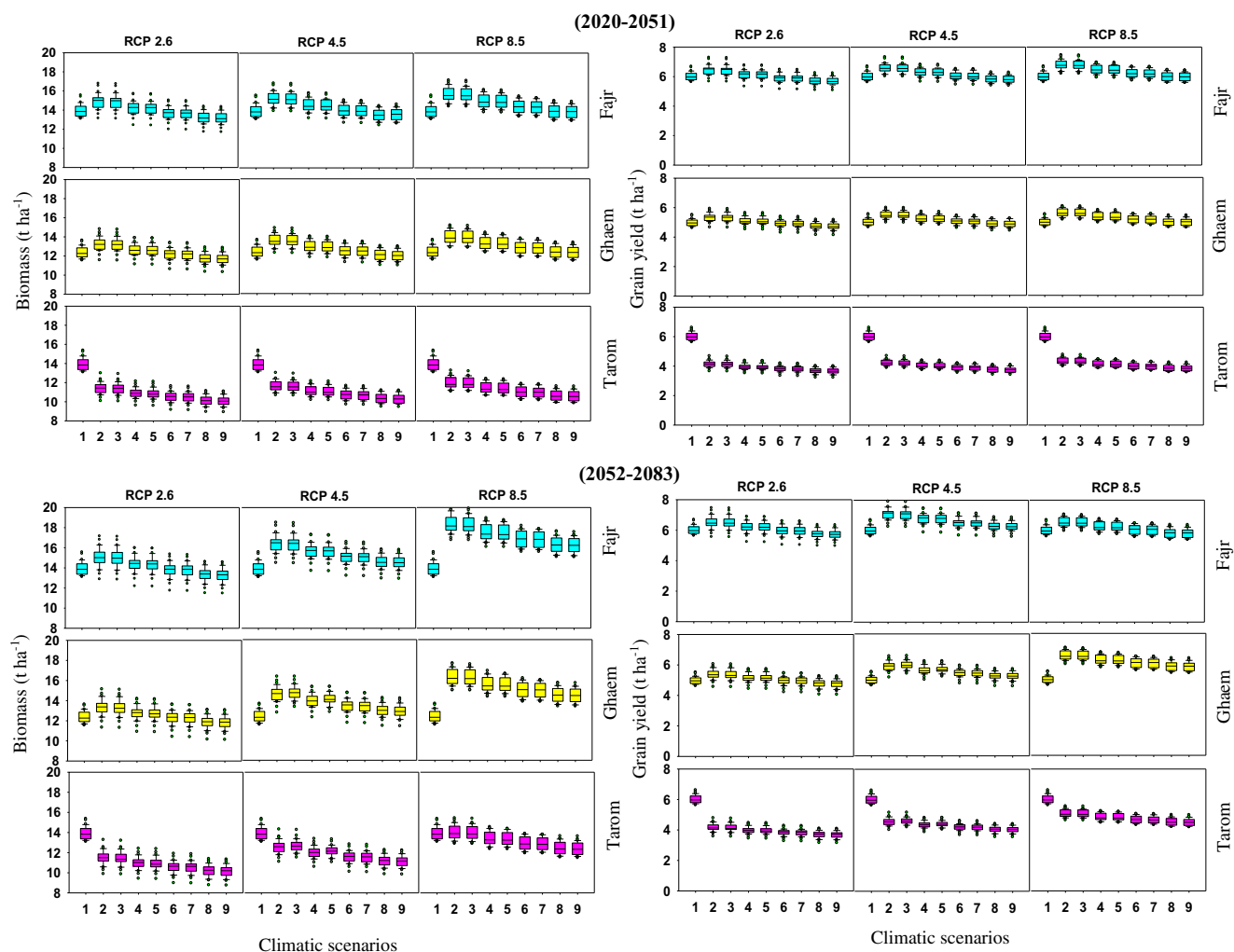
Fig. 3 Biomass (left panels) and grain yield (right panels) of the three rice genotypes (yellow (top-row): Fajr; blue (mid-row): Ghaem; pink (bottom-row): Tarom) in Ramsar county of Iran relative to baseline period (1992-2017) as affected by various RCPs, temperatures and rainfall variations during 2020-2051 and 2052-2083. (The labels of X axis show temperature and rainfall variations; 1, + 1 °C and + 20%; 2, + 1 °C and − 20%; 3, + 2 °C and + 20%; 4, + 2 °C and − 20%; 5, + 3 °C and + 20%; 6, + 3 °C and − 20%; 7, + 4 °C and + 20%; and 8, + 4 °C and − 20%)
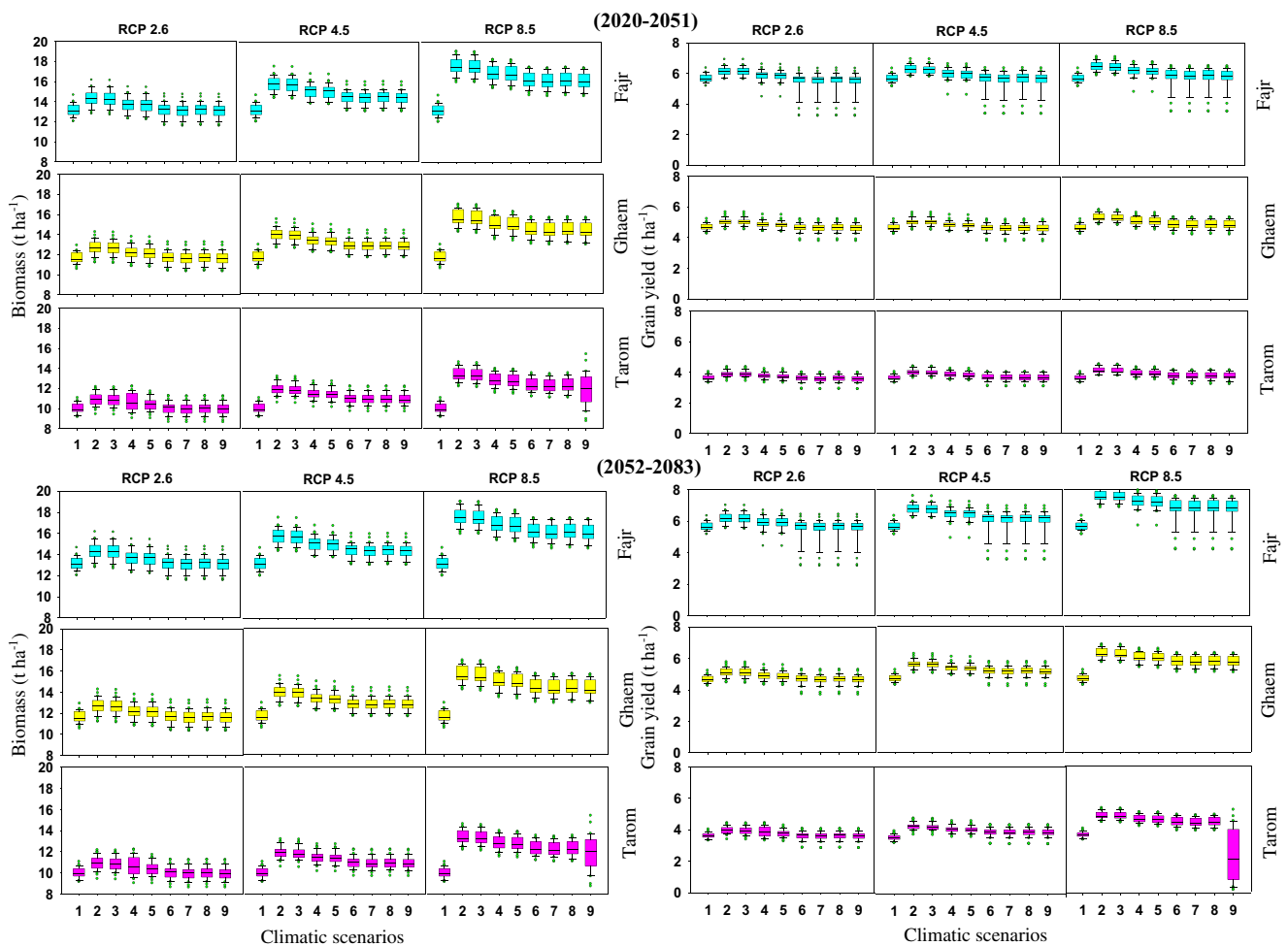
Fig. 3 (continued)

the negative effect of increased temperature on rice growth and yield. The response of cultivars to CO_2 increase depended on the location. In GhaemShar and NowShahr, Ghaem is more responsive to increase in CO_2 than the other two cultivars. However, Fajr shows less reduction in CC in Ramsar compared with that in Ghaem. Also, moving from near to far future reduces the possible negative impact of increased temperature and reduced precipitation on rice CC under RCPs 4.5 and 8.5, which highlights the compensative role of CO_2 for increased temperature.

Variation in precipitation is of little effect in the study although 20% reduction in this variable results in higher decrease in CC compared with the baseline and 20% increase scenarios. This could be attributed in part to the high precipitation of the whole province throughout the year on one side and the irrigated nature of the rice cropping in this area.

Overall, comparison between the cultivars shows that the improved cultivars Ghaem and Fajr are the least-affected rice cultivars regarding their CC, although the present study showed a considerable location × cultivar interaction when local and improved varieties are considered.

Biomass

Response of rice biomass to various RCPs and temperature scenarios depended on cultivar and location of study (Fig. 3a, b, and c). Climate change under the far future enhances rice biomass production compared with the near future. Under RCP2.6-near and -far, 1 to 3 °C increase in temperature enhances rice biomass in all genotypes in NowShahr. The degree of increase had a decreasing order when moving toward + 3 °C scenario (also under all cultivars, scenarios, and locations). This is almost the case for genotypes Fajr and Ghaem in Ramsar. Genotype Tarom gives negative response to all temperature increase levels and shows lower than baseline biomass in Ramsar. In GhaemShahr, all temperature scenarios increase the biomass of all rice genotypes compared with the baseline period. As could be observed, site-dependent variation exists in rice biomass simulations in response to climate change. Among others, this might be a result of the way AquaCrop simulates biomass. AquaCrop uses radiation use efficiency (RUE) approach for simulation of biomass. It has been shown that RUE-type models (Monteith and Moss 1977)
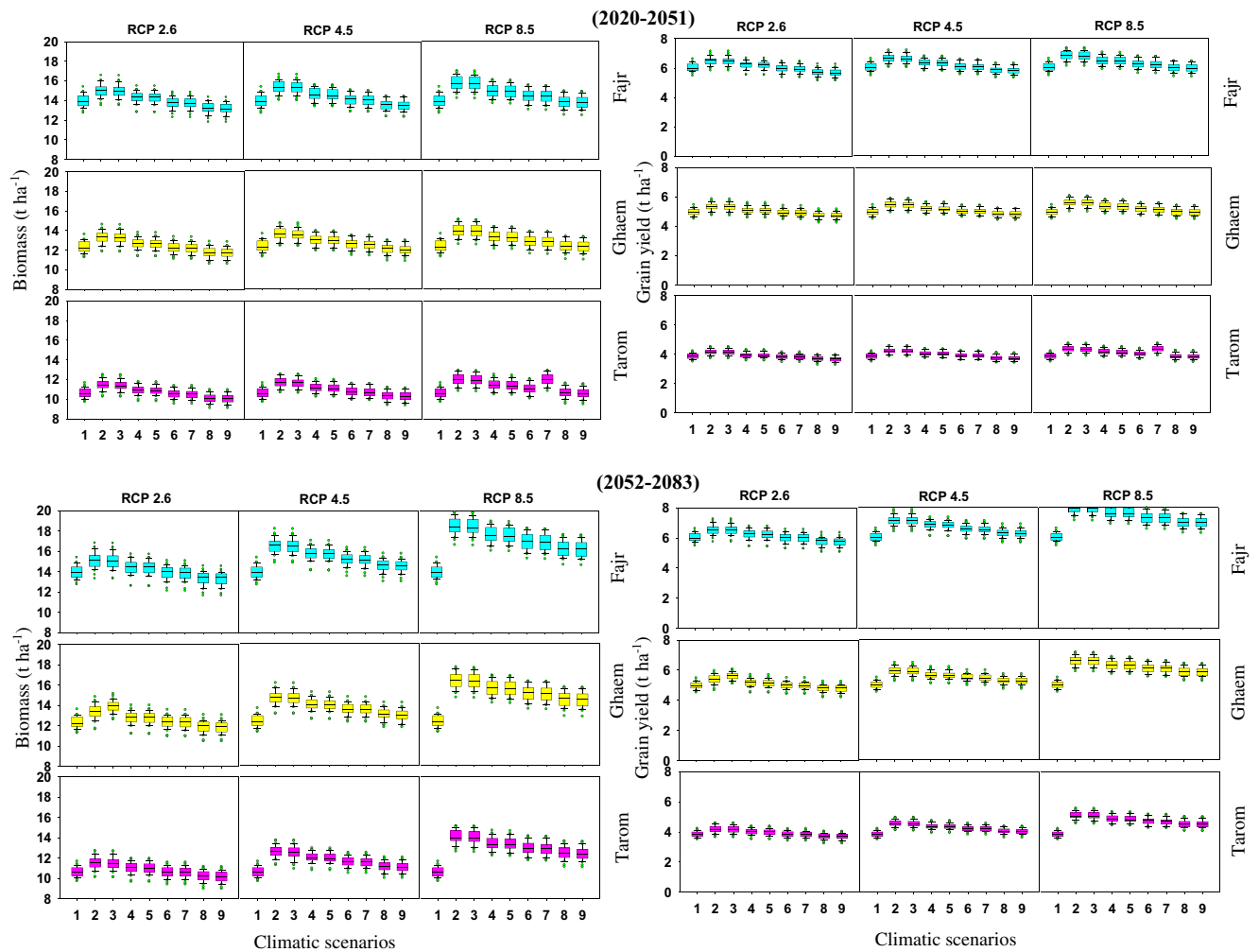
Fig. 3 (continued)

show larger variation among sites compared with those based on Farquhar-von Caemmerer-Berry biochemical model of leaf photosynthesis (Farquhar et al. 1980) (Li et al. 2015). It is worth noting that our current quantitative knowledge about the [CO$_2$] × temperature interaction effect on RUE is limited and needs further investigations.

A closer look at Fig. 3 shows that moving from RCP2.6 to RCPs 4.5 and 8.5 enhances biomass production of almost all genotypes at all locations notably especially in the far future. The higher the CO$_2$ level, the more biomass could be produced. This could be obviously observed in RCP8.5-near and -far. In this emission scenario, temperature scenarios + 1 to + 4 °C increase rice biomass of all genotypes positively although in a reverse order. The only exception was for cultivar Tarom in Ramsar under RCP8.5-near. At this location and under RCP8.5-far, scenario + 1 °C only resulted in comparable biomass with the baseline. Other temperature scenarios reduced biomass production same as the near scenario. In an ensemble modeling study, Li et al. (2015) showed that rice biomass was

decreased with increasing temperature while increased with rising [CO$_2$]. In this research, it was shown that variation among model simulations increased at higher temperature and [CO$_2$]. The response of rice to RCP-4.5 was almost in between of the other two scenarios. In GhaemShahr, all temperature scenarios increased biomass production of all genotypes. In NowShahr and Ramsar, genotypes Fajr, Ghaem, and Tarom (the latter in NowShahr only) responded positively to temperature increases between + 1 and + 3 °C under near-future scenario. Moving from near to far future (which means higher CO$_2$ concentration), resulted in enhanced biomass production under all temperature scenarios except for genotype Tarom in Ramsar, where biomass failed to increase compared with the baseline period. Comparing the cultivars with each other also indicates that the biomass production ability of cultivar Fajr was highest and followed by Ghaem and Tarom irrespective of climate change scenarios and locations. This could be explained by the improved nature of cultivars Fajr and Ghaem, which highlights the importance of rice cultivar characteristics. Overall, increase

Table 1 Percentage of leaf expansion stress experienced by rice genotypes (Fajr, Ghaem, and Tarom) in GhaemShahr, NowShahr, and Ramsar counties of Iran as affected by various RCPs, temperatures, and rainfall variations during 2020–2051

RCPs	Temp. (°C)	s	GhaemShahr			NowShahr			Ramsar		
			Fajr	Ghaem	Tarom	Fajr	Ghaem	Tarom	Fajr	Ghaem	Tarom
Baseline			25.22	24.88	22.41	19.84	19.50	17.66	16.53	16.41	16.53
2.6	+ 1	+ 20	6.14	5.05	3.90	20.69	20.34	18.34	19.28	18.84	16.88
		− 20	6.14	5.05	3.90	21.44	21.09	18.88	20.00	19.53	17.50
	+ 2	+ 20	5.86	4.87	3.76	21.72	21.38	9.34	20.41	20.03	17.88
		− 20	5.83	4.84	3.73	22.63	22.19	20.03	21.19	20.72	18.69
	+ 3	+ 20	5.46	4.65	3.59	22.75	22.13	20.09	21.75	20.59	18.59
		− 20	5.43	4.62	3.56	23.63	23.03	20.94	22.47	21.44	19.47
	+ 4	+ 20	5.46	4.65	3.58	24.25	23.03	21.00	23.00	21.72	19.59
		− 20	5.42	4.62	3.56	25.31	24.00	21.81	23.88	22.59	20.50
4.5	+ 1	+ 20	6.30	5.05	4.01	20.63	20.22	18.28	19.13	18.63	16.78
		− 20	6.27	5.05	3.99	21.31	21.06	18.84	19.88	19.41	17.44
	+ 2	+ 20	5.99	4.87	3.84	21.59	21.13	19.09	20.28	19.88	17.81
		− 20	5.96	4.84	3.82	22.56	22.03	19.97	21.03	20.63	18.50
	+ 3	+ 20	5.58	4.65	3.67	22.72	22.00	20.00	21.63	20.47	18.56
		− 20	5.55	4.62	3.64	23.53	22.91	20.78	22.38	21.34	19.34
	+	+ 20	5.57	2.63	3.66	24.16	22.75	20.88	22.91	21.50	19.44
		− 20	5.54	4.62	3.64	25.09	23.81	21.66	23.72	22.53	20.34
8.5	+ 1	+ 20	6.48	5.34	4.13	20.47	20.00	18.03	18.97	18.50	16.69
		− 20	6.45	5.31	4.10	21.16	20.69	18.75	19.66	19.13	17.28
	+ 2	+ 20	6.16	5.12	3.95	21.50	21.06	18.94	20.16	19.63	17.75
		− 20	6.13	5.09	3.93	22.19	21.88	19.88	20.84	20.41	18.38
	+ 3	+ 20	5.74	4.89	3.77	22.59	21.88	19.88	21.47	20.38	18.34
		− 20	5.70	4.86	3.75	23.34	22.72	18.03	22.25	21.13	19.28
	+ 4	+ 20	5.73	4.89	3.77	23.97	22.69	20.78	22.75	21.34	19.22
		− 20	5.70	4.86	3.74	24.94	23.53	21.56	23.63	22.38	20.25

in simulated biomass in response to temperature increase in the present study is also supported by experimental evidence (Kim et al. 1996; Ziska et al. 1997; Cheng et al. 2009) suggesting that AquaCrop may be able to account for plant acclimation to high growth temperature.

Many studies have emphasized at positive response of rice biomass to CO_2 enrichment (Wang et al. 2015; Devkota et al. 2013). As rice is a C_3 plant, it responds to CO_2 enrichment favorably. Wang et al. (2015) also found genotypic variation in rice in responding to [CO_2] increase so that hybrids showed the greatest biomass response to [CO_2].

Concluding the results based on biomass production shows that rice growth is thoroughly favored as a result of climate change either regarding [CO_2] or temperature increase in GhaemShahr. In NowShahr, the choice of the most adaptable rice genotype depended on RCP and temperature scenarios. Our results show that Tarom should be removed from the rice cropping program in the future in Ramsar. Also, irrespective of climate scenario, it looks that Fajr is more successful than Ghaem and Tarom, respectively. Similar to CC, our results

show that [CO_2] increase has compensatory effect on temperature increase. It seems that rice photosynthesis, as a C3 crop, increases due to increase in [CO_2] concentration, which compensates the effect of increase in temperature (Devkota et al. 2013).

Grain yield

Rice grain yield differed upon RCPs, locations, and temperature scenarios (Fig. 3a, b, and c). The general pattern of rice cultivars' grain yield response to different climate change scenarios followed rice biomass response. However, less variability in the response of rice grain yield could be observed compared with the biomass. In agreement with our findings, Wang et al. (2015) found that genotypic variation existed in rice grain yield response to elevated [CO_2]. They found that for hybrid rice cultivars, biomass gave larger response than grain yield to climate change.

Under RCP2.6-near, all cultivars show higher grain yield than baseline in temperature scenarios + 1 °C and + 2 °C,

Table 2 Percentage of leaf expansion stress experienced by rice genotypes (Fajr, Ghaem, and Tarom) in GhaemShahr, NowShahr, and Ramsar counties of Iran as affected by various RCPs, temperatures and rainfall variations during 2052–2083

RCPs	Temp. (°C)	Rainfall (% change)	GhaemShahr			NowShahr			Ramsar		
			Fajr	Ghaem	Tarom	Fajr	Ghaem	Tarom	Fajr	Ghaem	Tarom
Baseline			25.22	24.88	22.41	19.84	19.50	17.66	16.53	16.41	16.53
2.6	+ 1	+ 20	6.21	25.66	23.09	20.32	20.34	18.31	19.22	18.72	16.88
		− 20	6.18	26.75	24.28	21.47	19.06	18.91	19.94	19.50	17.50
	+ 2	+ 20	5.91	26.72	23.13	21.78	21.31	19.34	20.34	20.03	17.81
		− 20	5.87	27.94	25.16	22.53	22.09	20.00	21.16	20.69	18.66
	+ 3	+ 20	5.51	27.50	24.72	22.75	22.13	20.06	21.75	20.56	18.56
		− 20	5.47	28.59	25.81	23.63	23.06	20.91	22.47	21.38	19.47
	+ 4	+ 20	5.50	27.56	24.84	24.22	22.97	20.84	23.06	21.66	19.59
		− 20	5.47	28.66	25.91	25.25	23.97	21.78	23.88	22.63	20.41
4.5	+ 1	+ 20	25.34	25.16	22.53	20.16	19.72	17.78	18.56	18.19	16.19
		− 20	26.28	26.19	23.59	20.91	20.47	18.47	19.31	14.09	12.63
	+ 2	+ 20	26.44	26.22	23.53	21.25	20.78	18.66	19.84	19.34	17.47
		− 20	27.50	27.28	24.53	22.00	21.56	19.59	20.50	15.59	13.91
	+ 3	+ 20	27.69	26.91	24.34	22.25	21.59	19.66	21.13	20.06	18.19
		− 20	28.91	28.00	25.28	23.09	22.50	20.41	21.88	20.75	18.78
	+ 4	+ 20	27.78	27.00	24.44	23.78	22.38	20.47	22.47	21.13	19.06
		− 20	28.97	28.06	25.34	24.59	23.31	21.28	23.25	22.00	19.97
8.5	+ 1	+ 20	24.22	24.00	21.75	18.97	18.63	16.97	17.44	17.06	15.41
		− 20	25.25	25.06	22.72	19.94	16.57	17.50	18.25	17.84	15.97
	+ 2	+ 20	25.25	25.06	22.72	20.03	19.78	17.69	18.66	18.28	16.56
		− 20	26.44	26.03	23.66	20.91	20.34	18.59	19.41	19.03	17.22
	+ 3	+ 20	26.56	25.75	23.25	21.22	20.56	18.72	20.09	18.94	17.28
		− 20	27.81	26.88	24.28	22.06	21.38	19.50	20.88	19.69	17.97
	+ 4	+ 20	26.66	25.84	23.38	22.72	21.25	19.53	21.22	20.06	18.06
		− 20	27.91	26.97	19.84	23.56	22.25	20.47	22.25	20.94	19.06

respectively (Fig. 3a, b, and c). The only exception is the grain yield of cultivar Tarom in Ramsar, which decreases irrespective of the level of increase in temperature. This is the result of decrease in total biomass of this cultivar at this location under temperature increase. Temperature scenario + 3 °C gives either comparable or reduced grain yields at all locations and cultivars. Grain yield of all rice cultivars reduces when temperature increases 4 °C. In general, the frequency of comparable yields with the baseline under higher temperatures was highest in cultivar Ghaem, which may indicate potential adaptation ability to high temperatures in this cultivar. Any [CO$_2$] × temperature interaction on rice grain yield could be genotype-specific and may be controlled by diurnal temperature difference and other climatic factors such as humidity (Cho and Oki 2012). Moving from near to far future in this RCP could somehow improve rice performance under higher temperatures only. The response of rice yield is almost similar to those observed in the near phase with the number of comparable yields in temperature scenarios + 3 °C and + 4 °C increased. This is especially the case in scenario +3 °C. Magrin et al. (2017) also showed that crop

production increases by 5% for a range of crops including rice in the far future (2080) in Argentina.

Increase in [CO$_2$] as a result of moving toward RCP4.5 (either near or far) could generally improve grain yield of all cultivar (except for Tarom in Ramsar) in scenarios + 1 °C and + 2 °C at all locations (Fig. 3a, b, and c). However, the responsiveness of the improved rice cultivars to [CO$_2$] enrichment is higher than the local cultivar. Rice could produce higher than baseline grain yield in temperature scenarios + 3 °C and + 4 °C in this RCP (except for Tarom in Ramsar). Under such conditions, the best performance of all rice cultivars was achieved in GhaemShahr, which positively responded to higher temperatures in the far future. Aggarwal and Mall (2002) also showed that rice yield increases in India under climate change conditions (400–750 ppm CO$_2$ and 1–5 °C increase in temperature). The results of our study corroborates the findings of Kim et al. (2013), which has indicated that for the regions in the latitudinal range of between 34 and 42°, negative effects of elevated temperature could be compensated by CO$_2$ fertilization. However, inconsistent results were achieved in the near phase

Table 3 Percentage of stomatal stress experienced by rice genotypes (Fajr, Ghaem, and Tarom) in GhaemShahr, NowShahr, and Ramsar counties of Iran as affected by various RCPs, temperatures, and rainfall variations during 2020–2051

RCPs	Temp. (°C)	Rainfall (% change)	GhaemShahr			NowShahr			Ramsar		
			Fajr	Ghaem	Tarom	Fajr	Ghaem	Tarom	Fajr	Ghaem	Tarom
Baseline			2.00	2.09	1.91	0.88	0.88	0.84	0.25	0.28	0.34
2.6	+ 1	+ 20	1.49	1.34	1.07	0.94	1.00	0.97	0.72	0.66	0.66
		− 20	1.49	1.34	1.07	0.97	1.03	0.97	0.72	0.63	0.66
	+ 2	+ 20	1.43	1.30	1.04	1.22	1.25	1.06	0.81	0.91	0.84
		− 20	1.43	1.29	1.04	1.25	1.25	1.16	0.88	0.91	0.88
	+ 3	+ 20	1.35	1.25	1.00	1.47	1.38	1.34	1.13	1.09	1.00
		− 20	1.35	1.25	1.01	1.56	1.41	1.44	1.13	1.13	1.03
	+ 4	+ 20	1.35	1.25	1.00	1.78	1.6	1.59	1.34	1.28	1.25
		− 20	1.35	1.25	1.00	1.81	1.78	1.72	1.38	1.28	1.28
4.5	+ 1	+ 20	1.52	1.34	1.10	0.91	0.97	0.97	0.69	0.59	0.63
		− 20	1.52	1.34	1.10	0.97	1.00	0.97	0.69	0.59	0.63
	+ 2	+ 20	1.47	1.30	1.06	1.22	1.19	1.06	0.81	0.78	0.84
		− 20	1.47	1.29	1.07	1.25	1.22	1.09	0.84	0.84	0.88
	+ 3	+ 20	1.38	1.25	1.03	1.47	1.31	1.31	1.13	1.06	1.00
		− 20	1.38	1.25	1.03	1.53	1.31	1.41	1.13	1.06	1.00
	+ 4	+ 20	1.38	0.73	1.03	1.75	1.63	1.56	1.28	1.22	1.25
		− 20	1.38	1.25	1.03	1.78	1.69	1.66	1.28	1.28	1.25
8.5	+ 1	+ 20	1.57	1.41	1.13	0.88	0.94	0.88	0.66	0.59	0.56
		− 20	1.57	1.41	1.13	0.91	0.94	0.91	0.66	0.59	0.56
	+ 2	+ 20	1.51	1.37	1.10	1.16	1.13	1.06	0.75	0.72	0.75
		− 20	2.78	1.37	1.10	1.22	1.16	1.06	0.78	0.75	0.78
	+ 3	+ 20	1.43	1.33	1.06	1.38	1.28	1.28	1.00	1.03	0.94
		− 20	1.42	1.33	1.06	1.44	1.28	0.88	1.03	1.03	0.94
	+ 4	+ 20	1.42	1.32	1.06	1.69	1.63	1.50	1.25	1.22	1.22
		− 20	1.42	1.32	1.06	1.78	1.69	1.53	1.28	1.22	1.25

of RCP4.5 in NowShahr and Ramsar. In this phase, temperature scenario + 4 °C still gives lower than baseline yields, while this is not the case in the far phase of this RCP. As stated earlier, NowShahr and Ramsar are cooler than GhaemShahr. Cool spells in mid-summer (usually coinciding with microspore stage) can result in reduced sterility and thus substantial reduced yields (Li et al. 2015). Also, variable impacts of climate change on rice have been reported by other researchers which highlighted the non-uniformity across production regions (Liu et al. 2012, 2013b).

Occurrence of RCP8.5 emission scenario favors rice grain yield of all rice cultivars in NowShahr and GhaemShahr under both near and far future. Also, this RCP resulted in highest rice grain yield compared with other RCPs. The order of cultivars' yielding ability was Fajr, Ghaem, and Tarom, respectively. In Ramsar, a temperature-dependent grain yield response is observed under this RCP, i.e., cultivar Fajr shows positive response to all temperatures in the near future, while this is only the case for temperature scenarios + 1 °C and + 3 °C in the far future. However, this cultivar showed better performance under RCP4.5 at higher temperatures. New cultivars of rice are able to partly mitigate the negative effect of global warming through extending the grain-filling period and increasing their harvest index under such conditions (Liu et al. 2013a). Regarding genotype Ghaem, complete positive response is observed to temperature increases between 1 and 4 °C under the far future, while this is only true for temperatures + 1 to + 3 °C in the near future. Similar to the other two RCPs, cultivar Tarom gives lower than baseline yield under both timeframes of RCP8.5.

Body of literature exists that indicates the positive effect of [CO_2] increase on rice (Hasegawa et al. 2013; Wang et al. 2015). However, many of these studies did not synthesize the combined effect of cultivar variation, [CO_2] increase, rising temperature, and variable rainfall under different RCPs. The present study revealed considerable interaction between these factors in terms of grain yield and showed that rice response to climate change scenarios differs based upon local and improved cultivars especially when considered at different environments. Lv et al. (2018) showed that CO_2

Table 4 Percentage of stomatal stress experienced by rice genotypes (Fajr, Ghaem, and Tarom) in GhaemShahr, NowShahr, and Ramsar counties of Iran as affected by various RCPs, temperatures, and rainfall variations during 2052–2083

RCPs	Temp. (°C)	Rainfall (% change)	GhaemShahr			NowShahr			Ramsar		
			Fajr	Ghaem	Tarom	Fajr	Ghaem	Tarom	Fajr	Ghaem	Tarom
Baseline			2.00	2.09	1.91	0.88	0.88	0.84	0.25	0.28	0.34
2.6	+ 1	+ 20	1.50	2.22	2.06	0.90	1.00	0.97	0.72	0.66	0.66
		− 20	1.50	2.22	2.09	0.97	1.03	0.97	0.72	0.66	0.66
	+ 2	+ 20	1.44	2.47	1.56	1.22	1.22	1.13	0.81	0.91	0.81
		− 20	1.44	2.56	2.44	1.25	1.22	1.13	0.88	0.91	0.84
	+ 3	+ 20	1.36	2.66	2.56	1.53	1.38	1.34	1.03	1.09	1.03
		− 20	1.36	2.72	2.69	1.53	1.38	1.38	1.03	1.09	1.03
	+ 4	+ 20	1.36	2.66	2.56	1.78	1.63	1.63	1.38	1.28	1.25
		− 20	1.36	2.72	2.72	1.81	1.75	1.69	1.41	1.28	1.31
4.5	+ 1	+ 20	2.00	1.94	1.84	0.84	0.84	0.81	0.59	0.56	0.53
		− 20	2.06	2.06	1.91	0.84	0.88	0.84	0.59	0.13	0.13
	+ 2	+ 20	2.28	2.25	2.28	1.06	1.09	1.03	0.75	0.66	0.63
		− 20	2.34	2.28	2.34	1.09	1.13	1.06	0.75	0.25	0.22
	+ 3	+ 20	2.63	2.50	2.34	1.34	1.25	1.16	094	0.94	0.88
		− 20	2.72	2.59	2.44	1.34	1.25	1.19	0.94	0.94	0.88
	+ 4	+ 20	2.66	2.53	2.34	1.66	1.47	1.44	1.16	1.13	1.13
		− 20	2.75	2.59	2.47	1.69	1.63	1.47	1.16	1.13	1.13
8.5	+ 1	+ 20	1.59	1.63	1.59	0.59	0.53	0.56	0.31	0.31	0.28
		− 20	1.59	1.69	1.63	0.59	1.93	0.59	0.31	0.31	0.28
	+ 2	+ 20	1.91	1.78	1.75	0.81	0.84	0.84	0.47	0.44	0.44
		− 20	1.94	1.81	1.78	0.81	0.84	0.84	0.50	0.50	0.44
	+ 3	+ 20	2.25	2.09	2.09	0.97	1.06	1.00	0.69	0.66	0.66
		− 20	2.25	2.13	2.13	1.03	1.09	1.03	0.69	0.66	0.69
	+ 4	+ 20	2.25	2.13	2.09	1.31	1.19	1.09	0.94	0.88	0.84
		− 20	2.28	2.16	1.80	1.34	1.19	1.13	0.94	0.88	0.84

increase would reduce rice yield between 10 and 11% at different future eras of the present century if the planting date remains unchanged. Chen et al. (2016) found that weather effects on rice yield differed based on cultivar. They stated that higher daily minimum temperature negatively affected yield in indica rice only, while daily maximum temperature negatively affected indica and japonica rice yields. Variation observed in the impacts of climate change on rice emphasizes at the dependency of the crop growth and yield to the local soil-climatic condition and crop management.

The modeling approach used in the present study only took into account the environmental effects of $[CO_2]$, temperature, and rainfall and were run under no water and nutrient stresses. In practice, farmers often experience more complex conditions due to presence of weeds, insects, and diseases and also possible suboptimal management of water and nutrients, all of which affect crop growth and yield. However, the results of the present simulations were in line with many other findings, which indicate that AquaCrop can capture a substantial amount of yield variability caused by environments and variation in temperature and $[CO_2]$.

Average leaf expansion/stomatal stresses

Results indicate great variability in rice in terms of average leaf expansion and stomatal stresses in response to climate change and cultivar (Tables 1, 2, 3, and 4).

In terms of average leaf expansion stress, cultivar Fajr experiences the highest reduction in its leaf area expansion followed by cultivars Ghaem and Tarom in all RCPs, temperature scenarios and locations (Tables 1 and 2). In GhaemShar and under the near future, the degree of stress would be much lower (< ~ 6.5%) in all cultivars compared with other RCP × temperature × rainfall × location combinations (which was > ~ 12.5%). In NowShar and Ramsar, the degree that the cultivars could be affected by leaf expansion stress is about 3 to 6 times of that in GhaemShahr averaged over genotypes. A comparison between different RCPs also shows that RCP2.6 is the worst RCP with

regard to this type of stress, and moving toward RCPs 4.5 and 8.5 would decrease the intensity of stress (except for GhaemShahr under the near future which was opposite). This would be observed at all locations and cultivars. Comparing locations with each other also shows more uniformity between NowShahr and Ramsar. Higher temperatures also showed greater leaf expansion stress (except for GhaemShahr in the near future).

Percentage of stomatal stress shows greater variability depending on cultivar × RCP × temperature × location combinations (Tables 3 and 4). In the near future, the highest degree of stress would be observed in GhaemShahr followed by NowShahr and Ramsar, respectively, which indicates the similarity between the latter locations in this regard (Table 3). Rice response to temperature increase and RCPs was different in GhaemShahr. At this location, with increase in temperature, the percentage of stomatal stress decreases in all cultivars. However, opposite direction could be observed in NowShahr and Ramsar in this regard. Every degree of Celsius increase in temperature shows more negative effect on stomatal stress in NowShahr and Ramsar than in GhaemShahr. Also, moving from RCP2.6 toward RCP8.5 enhances this type of stress in rice irrespective of cultivar, while a slight decrease would be observed in other two locations. Elevated CO_2 reduces stomatal conductance and transpiration, while increased temperature has opposite effects namely increasing stomata size, stomatal conductance, and transpiration at the expense of transpiration efficiency (Soar et al., 2009). However, the combined effect of high [CO_2] and elevated temperature is still largely unknown (Asseng et al. 2015). Cultivar Fajr experiences the highest degree of stomatal stress. The least-affected cultivar is Tarom in this regard. A major response of C_3 plants to increasing [CO_2] in the atmosphere is to reduce water loss through transpiration by decreasing stomatal conductance and simultaneously increase assimilation rates (Lammertsma et al. 2011). This may indicate the higher ability of improved rice cultivars in adapting with the expected anthropogenic rise in [CO_2]. In the far future, generalization of rice response to cultivar and climate change scenarios is more difficult (Table 4). As previous, rice performed differently in GhaemShahr. At this location, RCP4.5 shows the highest percentage of stomatal stress, while RCP2.6 is the most-affecting in NowShahr and Ramsar. Increase in temperature, enhanced stomatal stress in almost all cases. However, the rank one of highest percentage of stomatal stress substituted between cultivars Fajr and Ghaem depending on temperature scenario, RCP, and location. Cultivar Tarom was the least-affected cultivar in this regard.

In general, the far/near (leaf expansion and stomatal) stress ratios is highest in Tarom (6.29 and 2.64) followed by Ghaem

(5.56 and 1.76) and Fajr (3.38 and 1.36) (data not shown). These results indicate that the choice of appropriate cultivar depends on which timeframe is considered.

Conclusions

As climate changes from near to far future, it gets more important to gain deeper insight of how rice reacts to such changes. In this study, a comprehensive combination of genotype × [CO_2] × temperature × rainfall × representative concentration pathway (RCP) × environment has been studied in rice by using AquaCrop model. Our results point to the fact that rice biomass and yield would be increased in the near and far future under increased [CO_2] and temperature. The highest yield would be obtained when temperature increases +1 °C especially under RCP8.5-far considered. Higher temperatures could still increase rice yield but to lower extent. [CO_2] enrichment could offset the negative effect of higher temperatures. The results showed a major effect of environment on genotypic response of rice to climate change so that some cultivars currently planted in an environment may not be suitable for planting as climate changes. In general, cultivar Fajr, which is a mid-maturing high-yielding genotype introduced by the IRRI, acted better than the local cultivar and is more promising under climate change conditions.

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