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Climate change impacts on irrigated crops in Cambodia

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ABSTRACT

Increasing heat-stress conditions, rising evaporative demand and shifting rainfall patterns may have multifaceted impacts on Cambodia's agricultural systems, including vegetable production. Concurrently, domestic vegetable supply is highly seasonal and inadequate to meet the domestic food demand, which consequently poses risks to food security locally, particularly in rural areas. This study assesses the impact of climate change on the yields and crop water productivity (CWP) of tomato, pak choi and yard-long bean cultivated year-round under different irrigated conditions (drip, furrow and net irrigation) in Siem Reap, Cambodia. The findings of this study show a similar annual precipitation decline (-23%) when comparing the 2017–2040 and 2070–2099 periods for both Representative Concentration Pathways (RCPs 4.5 and 8.5), though with significant seasonal differences between the two climate scenarios. Increasing water and heat-stress conditions are expected to have adverse impacts on tomato plants compared to pak choi and yard-long bean, which have a much higher heat tolerance. Differing yield trends are expected depending on the transplanting/sowing date, irrigation method and RCP. In tomato, for example, a -55% yield loss is projected by the end-century (2070–2099) when transplanting in January, whereas $a + 37\%$ yield increase is expected between November and December over the same period. In addition, pak choi yield enhancements of up to +30% are projected if sowing in May under RCP 8.5 for both drip and net irrigation conditions. Similarly, higher yard-long bean yields are simulated under RCP 8.5 (+29%) compared to RCP 4.5 (+11%) for the average of all sowing dates (January to December) and irrigation methods (drip, furrow and net irrigation). In sum, the findings of this work are relevant for evidence-based decision-making and the development of projects, policies and programmes increasingly informed by simulation results from bundling climate-crop approaches to transform agriculture in response to climate change.

1. Introduction

The agricultural sector contributed to 20.8% of Cambodia's gross domestic product in 2019, and crop production accounted for 57.7% of this sector, followed by fisheries, livestock and forestry (MAFF, 2020). According to the Ministry of Agriculture, Forestry and Fisheries (MAFF), in 2021 domestic vegetable production increased by 14% up to 908,595 tonnes. However, local production represented only 70–80% of the total national vegetable consumption. Over the past years, the national vegetable industry continued to face several challenges related to (i) low yields and difficulty to produce during the wet season, (ii) poor competitiveness with regional neighbours despite the higher quality (size, texture and nutritional content) of local vegetables, (iii) post-harvest losses as high as 40%, (iv) low quality and safety products, (v) insufficient offer compared to a high vegetable demand, (vi) lack of means to have greenhouses, irrigation and raised bed systems, and (vi) poor efficiency of the selling-purchasing activity and transaction costs, amongst others (SDC, 2014; ACIAR, 2020). Adverse weather and growing conditions, and limited knowledge on how to protect crops and support soil, water, and pest and disease management are additional constraints for the development of the vegetable industry in the country. Although future warming over Southeast Asia is expected to be lower than the global average, the total number of days per year with maximum temperatures above 35°C in Cambodia is likely to exceed 120

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Fig. 1. Study site considered for running the AquaCrop model.

and 180 days in a 1.5 and 4.0°C warmer scenario (IPCC, 2021). Changes relative to 1850–1900 also suggest a decrease in precipitation along the Gulf of Thailand, mostly during the boreal winter (December to February) and, to a lesser extent, over the summer months (June to August) in a 4°C global warming.

Tomatoes (*Solanum lycopersicum L.*) in Cambodia are produced in open-fields and greenhouses to support year-round production. However, most of the tomatoes found in local markets are imported from Thailand and Vietnam (Chhean et al., 2004). To minimize crop failure risks from pests and diseases and abiotic stresses, optimal production requires controlled environments such as greenhouses. Due to their high costs, small and medium holder farmers cannot access micro-climate controlling systems and are, consequently, increasingly exposed to frequent and intensified climatological, meteorological and hydrological hazards. Some of the major abiotic stresses reducing tomato production are heat and water stress and, to a minor extent, soil salinity. Ambient temperatures above 35°C adversely affect seed germination, seedling, vegetative growth, flowering, and fruit set and ripening (Wahid et al., 2007). In this line, recent investigations in Cambodia have identified heat tolerant genotypes (i.e., CLN1621L and Neang Tamm) which are seen as promising solutions to modulate intensified climate risks (Ro et al., 2021).

Pak choi (*Brassica rapa subsp. chinensis*) is amongst the most important leafy vegetables grown and consumed in Cambodia. Pests and diseases (diamondback moth, common armyworm and striped flea beetle etc.) are the major factors limiting crop production (Srinivasan et al., 2021). An increase in air temperatures from 28 to 32°C negatively affects nutrient quality (Hwang et al., 2018), while heat-stress conditions slow down the growth rate and result in yellow leaves, diseases and dysplasia (Yu et al., 2022). As shown in recent studies, high/low relative humidity under high temperatures (35/28°C day/night-time temperatures, respectively) reduces leaf net photosynthetic efficiency, yield and, finally, the quality of pak choi (Han et al., 2019). However, additional studies suggest that pak choi can withstand temperatures of up to 38°C (Ahmed et al., 2019), while others indicate a critical temperature threshold as high as 40°C (Wellens et al., 2013). Low light intensity and water deficits also reduces the photosynthetic capacity of pak choi (Shang and Shen, 2018); whereas drought stress, under constant nitrogen content, increases the root/shoot ratio and root dried weight (Xiong

Table 1
Variables used to parametrize tomato, pak choi and yard-long bean in the AquaCrop model.

Inputs	Units	Observed (calibrated) Tomato	Pak choi	Yard-long bean
Crop				
Development				
Plant density	plants/	20 000 (idem)	250 000	20 000
Type of planting	ha	Transplanting	(idem)	(idem)
method	-	(idem)	Direct	Direct
Initial canopy	%	n/d (0.40)	sowing	sowing
cover	cm^2/	n/d (20)	(idem)	(idem)
Canopy size	plant	n/d (19.8)	n/d (1.25)	0.30 (0.10)
seedling	%/day	n/d (33)	7 (idem)	n/d (5.0)
Canopy expansion	days	7–15 (12)	20.9 (25.1)	16.2 (29.5)
Canopy decline	days	45–50 (50)	n/a	0.78 (16.2)
Time to recovery/	days	65–75 (70)	5–7 (5)	4–7 (5)
emergence	days	80 (85)	20–35 (30)	35–37 (36)
Time to maximum	days	55–70 (60)	n/a	79 (idem)
canopy cover	%	55–65 (50)	40–45 (45)	90 (85)
Time to senescence	days	15–20 (15)	70–80 (75)	65–75 (75)
Time to maturity	days	30 (idem)	n/a	35 (idem)
Maximum canopy	days	60–90 (60)	n/a	30–35 (30)
cover	cm	45 (idem)	n/a	30 (45)
Time to flowering	days		30–40 (35)	150–170
Duration of the			n/d (30)	(160)
flowering		18 (idem)		40–60 (50)
Length building up	kg/m^3	30–55 (38)		
harvest index	%	93–95 (90)	15 (idem)	
Max. effective	%	0.10	45 (40)	15.0 (15.3)
rooting depth	-		85–90 (90)	60 (idem)
Time for maximum		0.15 (idem)	0.10	50–55 (55)
root depth	-	0.55 (idem)		0.45
	-	0.50 (idem)	0.50	
Crop Production	-	0.70 (idem)	(idem)	0.30 (idem)
Crop water	-		0.80	0.65 (idem)
productivity			(idem)	0.40 (idem)
Harvest index		16 (idem)	0.50	0.60 (idem)
Moisture content	°C	32 (idem)	(idem)	
Conversion factor	°C	33–38 (idem)	0.85	
(dry to fresh-	°C		(idem)	10 (idem)
matter)				36 (idem)
				40 (idem)
Response to stresses			15 (idem)	
(water)			30 (idem)	
Canopy expansion			n/a	
(upper threshold)				
Canopy expansion				
(lower threshold)				
Stomata closure				
(upper threshold)				
Early canopy				
senescence				
Response to stresses				
(temperature)				
Base temperature				
Upper temperature				
Pollination				
affected by heat-				
stress				
Field				
Management				
Soil fertility stress	%	(0)	(0)	(0)
Mulches	-	(none)	(none)	(none)
Relative cover of	%	(15)	(0)	(0)
weeds				

Source: Bailly et al. (2001), Kanda et al. (2011), MAFF, Raes et al. (2021), Ro et al. (2021), and Wellens et al. (2013).

Table 2
Irrigation management methods used in AquaCrop for tomato, pak choi and yard-long bean. Values adjusted from field trials in Cambodia (Palada et al., 2007; Edralin et al., 2017; Nut et al., 2017) and through FAO-MAFF consultations.

Irrigation method	Units	Tomato
Drip irrigation		
Irrigation frequency until 40 days	days	5
Irrigation frequency from 42 until 80 days	days	2
Amount (same throughout)	mm	10
Total amount	mm	290
Furrow irrigation		
Irrigation frequency until 35 days	days	5
Irrigation frequency from 37 days until harvest	days	2
Amount (same throughout)	mm	10
Total amount	mm	310
Net irrigation		
Readily available water (RAW)	%	70
Irrigation method	Units	Pak choi
Drip irrigation		
Irrigation frequency until 20 days	days	5
Irrigation frequency from 24 until 40days	days	2
Amount (1st / 2nd interval)	mm	5/10
Total amount	mm	115
Furrow irrigation		
Irrigation frequency until 20 days	days	5
Irrigation frequency from 24 until 40 days	days	2
Amount (1st / 2nd interval)	mm	5/10
Total amount	mm	115
Net irrigation		
Readily available water (RAW)	%	50
Irrigation method	Units	Long-bean
Drip irrigation		
Irrigation frequency until 35 days	days	5
Irrigation frequency from 37 until 97 days	days	2
Amount (1st / 2nd interval)	mm	8/10
Total amount	mm	314
Furrow irrigation		
Irrigation frequency until 35 days	days	5
Irrigation frequency from 37 until 97 days	days	2
Amount (1st / 2nd interval)	mm	8/10
Total amount	mm	314
Net irrigation		
Readily available water (RAW)	%	60

et al., 2018).

Yard-long bean (*Vigna unguiculata ssp. sesquipedalis*) is one of the most important legumes cultivated in Cambodia for human consumption (Tantasawat et al., 2010). The plant is known for its resilience to heat and drought stresses and, therefore, finds place in several cropping systems around the world (Suma et al., 2021). It also benefits from rising atmospheric CO_2 concentrations and its fertilization effect, where higher CO_2 concentrations leads to a higher number of pods and seeds, as well as an increase in seed weight over time (Angelotti et al., 2020). Agricultural pests, diseases and weeds can lead to complete crop failures, amongst which aphids, bean flies and armyworms are the insect pests with highest infestation scores (Malacrinò et al., 2020).

To our knowledge, little is known about climate change impacts on the growth and productivity of tomato and pak choi in Southeast Asia. Although crop-modelling literature is available for yard-long bean, most of these studies are found in Africa where legumes are portrayed as climate resilient crops, with an ecological role in improving soil fertility and provision of livestock feed (Kebede and Bekeko, 2020). In addition, the lack of streamlined production varies depending on the access to resources, giving an incomplete picture of climate change impacts on vegetable production in Cambodia. There is also an urgent need to analyse the effect of increasing drought stress conditions and shifts in monsoon season, altogether posing significant challenges to cereal production currently sustaining national food security. Therefore, the

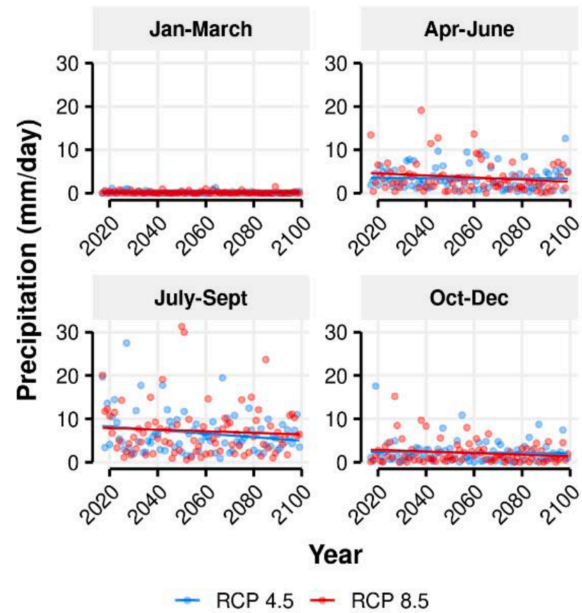

Fig. 2. Changes in seasonal precipitation (in mm/day) under RCPs 4.5 and 8.5 over the 2017–2099 period.

Tonle Sap Basin (TSB) presents a growth potential for the production of high-value and climate resilient upland crops, including vegetables which are increasingly envisioned to add value to smallholder farmers besides diversifying agriculture in a sustainable way. It is also important to invest in customized irrigation systems to address growing pressure on water resources and more erratic rainfall. Therefore, this study explores how future climate is expected to affect vegetable production in Cambodia. We also address some of the limitations of previous work on climate change impacts in agriculture. First, by downscaling future climate for different emission scenarios to empirically assess climate change, climate variability, including seasonality, and weather extremes as well as its effects on major vegetable systems (tomato, pak choi and yard-long bean) along the TSB. Then, we support transformative agricultural adaptation to climate change by testing different sowing dates throughout the year and, consequently, we offer a cost-effective measure for smallholder farmers to adjust to changes in climate. We conclude this work by providing guidance material to extension workers on how to improve yields and use water resources more efficiently based on the simulations results from the crop modelling work with AquaCrop.

2. Materials and methods

2.1. Study area

According to the Köppen climatic classification, the Tonle Sap Basin (TSB) has a tropical monsoon climate characterized by warm year-round temperatures, highest before the start of the monsoon season (March and April) and lowest during the boreal winter (December and January). The TSB is a unique fertile and freshwater system where its shores host one of the most important agricultural and ecological regions in Cambodia. Three main agroecosystems are found here, namely (i) the upland mixed crop zone, characterized by shrub/grazing land with some rice and upland crops; (ii) the lowland rainfed rice land zone, including wet season rice, cashew, vegetables and livestock; and (iii) the seasonally flooded zones dedicated to deep/floating rice and fishing during the wet season as well as receding rice, vegetables, fishing and livestock grazing over the dry season. In this study, we selected Siem Reap (13º22N and 104º10'), an area offering a myriad of opportunities for the expansion of vegetable production (Fig. 1).

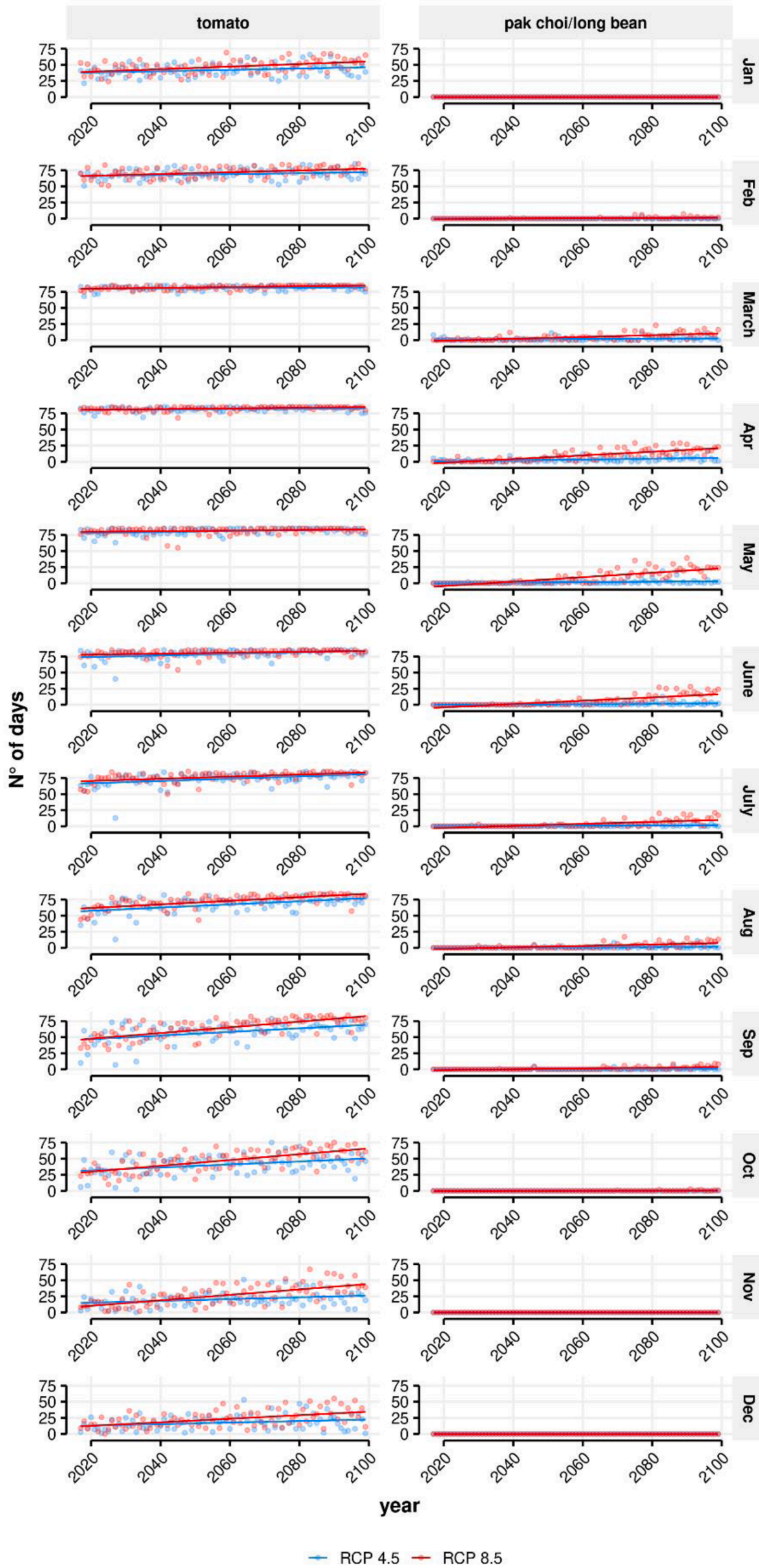

Fig. 3. Number of days during the growing season when the pollination stage is affected by high temperatures (tomato Tmax ≥33ºC, pak choi and yard-long bean Tmax ≥40ºC) for RCPs 4.5 and 8.5 over the 2017–2099 period.

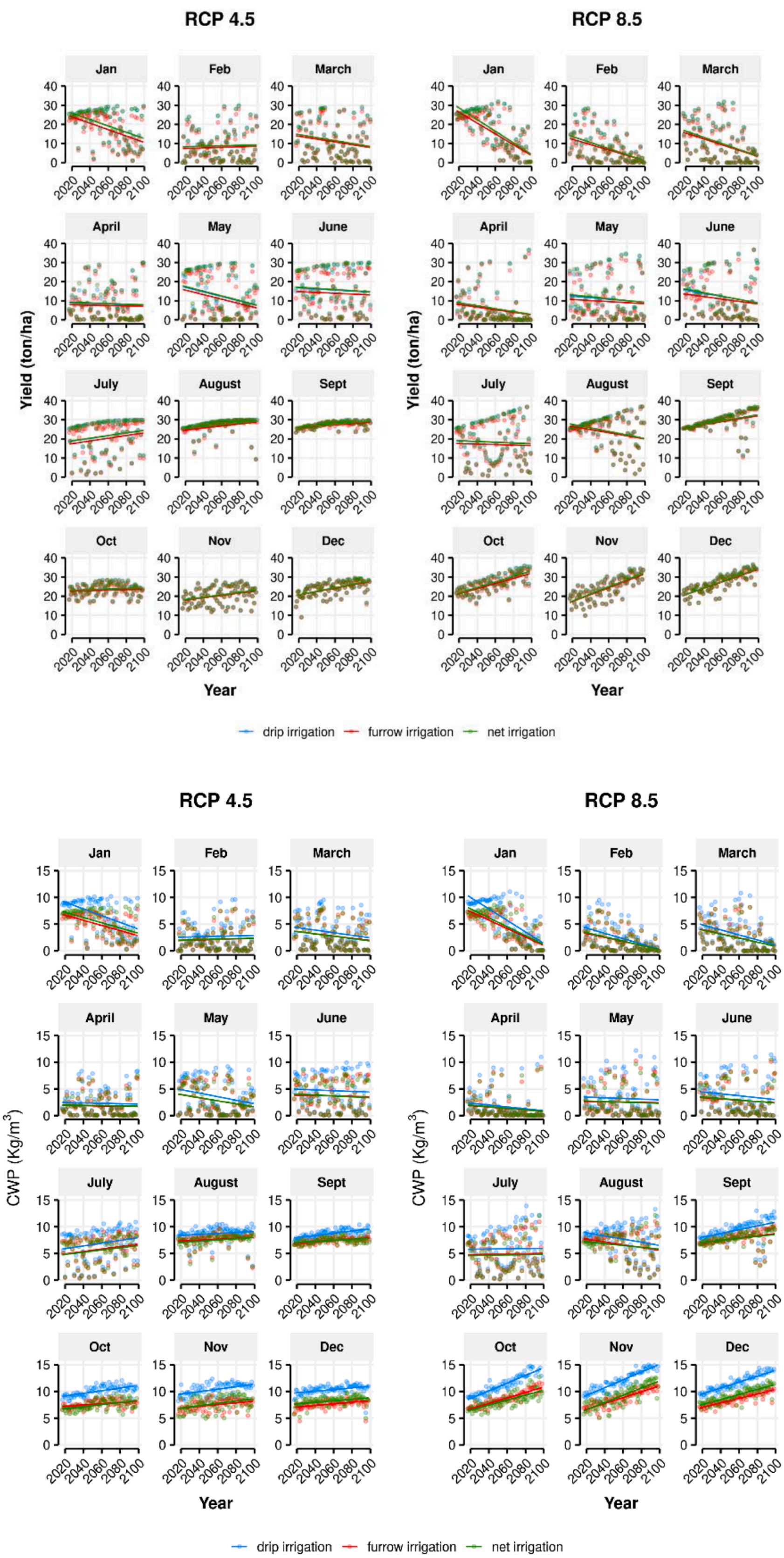

Fig. 4. (a) Projected tomato yields (in ton/ha) and (b) CWP (in kg of yield per m^3 of water evapotranspired) under future climate scenarios (RCPs 4.5 and 8.5) over the 2017–2099 period. Blue, red and green circles correspond to the annual yields and CWP under drip, furrow and net irrigation, respectively; while the red, green and blue lines to the yield and CWP trends.

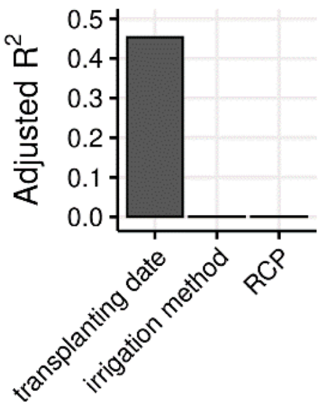

Fig. 5. Adjusted-R^2 values for different input variables (transplanting date, irrigation method and RCP). A lower adjusted-R^2 value indicates that the additional input variables are not adding value to the model. For example, if the R^2 value is 0.5, 50% of the variation in the output variable (yield) is explained by the input variables (transplanting date, irrigation method and RCP).

2.2. Model description

The AquaCrop tool has been developed by the Food and Agriculture Organization (FAO) to assess the effect of different environmental conditions and management strategies on crop production. The tool simulates yield in four steps: (i) crop development, (ii) crop transpiration, (iii) biomass production, and (iv) yield formation (Raes, 2017; Steduto et al., 2012; Vanuytrecht et al., 2014). The first step, the development of the green canopy cover (CC), is simulated as the fraction of the soil surface covered by the canopy. Then, the crop transpiration (Tr) is calculated by multiplying the reference evapotranspiration (ETo) by the crop coefficient (Kc) that depends on the CC. The third step estimates the above-ground biomass production, proportional to the cumulative water transpired by the crop. Lastly, through the harvest index, which is the fraction of harvestable product to the total above-ground biomass, the crop yield is obtained.

The AquaCrop model does not estimate the effect of extreme precipitation and destructive damages on plant growth, but it reflects the variation of soil-water balance to more erratic rainfall, increasing temperatures and rising evaporative demand. The model is capable of evaluating the concurrent effect of abiotic stresses such as drought, frost/heat, saline and poor soil fertility conditions, which are shown to be more detrimental to crop growth and production than if they occur separately (Mittler, 2006; Prasad et al., 2011). In contrast, the steady increase in atmospheric CO_2 concentration can have a positive effect on crop productivity and water use (Vanuytrecht and Raes, 2011). In this line, AquaCrop accounts for the direct effect of atmospheric CO_2 concentration on plant growth, with similar impact according to the crop's photosynthetic pathway. Hence, as atmospheric CO_2 increases, C4 plants do not have a comparative advantage over C3 plants from the stand-point of reduced photorespiration and enhanced light-use efficiency (Ehleringer and Cerling, 2002).

2.3. Data collection

2.3.1. Climate variables

In this work we considered daily maximum and minimum temperature, precipitation, wind speed and solar radiation, derived from the COnsortium for Small-scale MOdelling (COSMO) in CLimate Mode (CCLM) version 5–0–2 (Sørland et al., 2021). The CCLM5 regional climate model was driven by the CNRM-CM5 global climate model (Voldoire et al., 2013) within the framework of the Coordinated Regional Downscaling Experiment (CORDEX), providing dynamically downscaled (at 0.44° spatial resolution) outputs over the East Asian (EAS) domain (Giorgi et al., 2015). In addition to the historical scenario (which ends in 2005), two future Representative Concentration Pathways (RCPs, which extend up to 2100) accounting for different socio-economic and emission scenarios were considered here, namely the RCP 4.5 (Clarke et al., 2007) and the RCP 8.5 (Riahi et al., 2011). Whilst the former assumes a radiative forcing of 4.5 w/m^2 and 550 CO_2 ppm by 2100, the latter would reach 8.5 w/m^2 and 1000 CO_2 ppm by the end-century. Furthermore, in order to remove systematic model biases (see, e.g., Sørland et al., 2021 and references therein), the future simulations provided by the CCLM5 were properly re-scaled based on the differences (quotient for the case of precipitation) between the observed and simulated means over the 1979–2005 period. To do this, the WFDE5 (Cucchi et al., 2020) dataset, which provides daily data for different meteorological variables at 0.5° resolution globally for the 1979–2016 period, was used as a historical reanalysis reference. In particular, the nearest WFDE5 grid box was employed in the targeted location. Afterwards, the reference evapotranspiration (ETo) was calculated based on the approximated Penman Monteith equation (Raes, 2017). Note that WFDE5 builds on the ERA5 reanalysis (Hersbach et al., 2020) and was calibrated using the WATCH Forcing Data methodology, having proved suitable for hydrological and crop modelling purposes across the world (see, e.g., Cucchi et al., 2020 and references therein) and supporting impact assessments of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b).

2.3.2. Crop data

The AquaCrop model is underpinned by two sets of parameters, conservative and non-conservative, where the former does not change with time and its applicable over a large spatial variation (i.e., water stresses on crop growth and development), the latter changes with time, management practices and location (i.e., sowing date, sowing method and density, and plant phenology) (Dirwai et al., 2021). Crop variables were parametrized on AquaCrop based on field observations on crop development, including plant phenology, made by the Ministry of Agriculture, Forestry and Fisheries (MAFF) of Cambodia and shared with FAO for the purpose of this study (Table 1). On top of this information, secondary data sources have enhanced the crop parametrization process, where Ro et al. (2021) and Raes et al. (2010) AquaCrop studies were used for calibrating the crop development, crop production and response to stress of tomato plants, Wellens et al. (2013) for pak choi, and Kanda et al. (2020) and Schreinemachers et al. (2017) for yard-long bean. Since statistics for cabbage and other brassicas, tomato and pulses in Cambodia were not available on FAO databases and MAFF historical yield statistics are compiled and combined into one database on vegetable production, the baseline information used to validate historical yield simulations was based on consultations with MAFF under the "Public-Social-Private Partnerships for Ecologically-Sound Agriculture and Resilient Livelihood in Northern Tonle Sap Basin" (PEARL) project and on field trials conducted in Cambodia by Edralin et al. (2017), Srinivasan et al. (2019), and Kim Sreang et al. (2020).

2.3.3. Field and water management practices

The AquaCrop model simulates the development of annual crops and their final biomass based on the climatic conditions and the soil water availability during the growing cycle. The model provides different options of irrigation scheduling, such as full and deficit irrigation, or allows a certain soil water depletion level at which new irrigation events are triggered automatically. In this study, three irrigation methods have been selected based on the percentage of soil surface wetted (drip irrigation: 30%, furrow irrigation: 80%, and net irrigation: 100%) that would give the farmers the highest net benefits (yield) and water use efficiency (Table 2). For drip and furrow irrigation, the total amount of water (TAW) that can be used by the crop has been applied as irrigation criterion. In this case, the TAW remained above the threshold at which there is early senescence, stomata closure and restriction to the expansion of the canopy cover, and below the threshold at which there is water logging and water losses into the environment as direct evaporation.

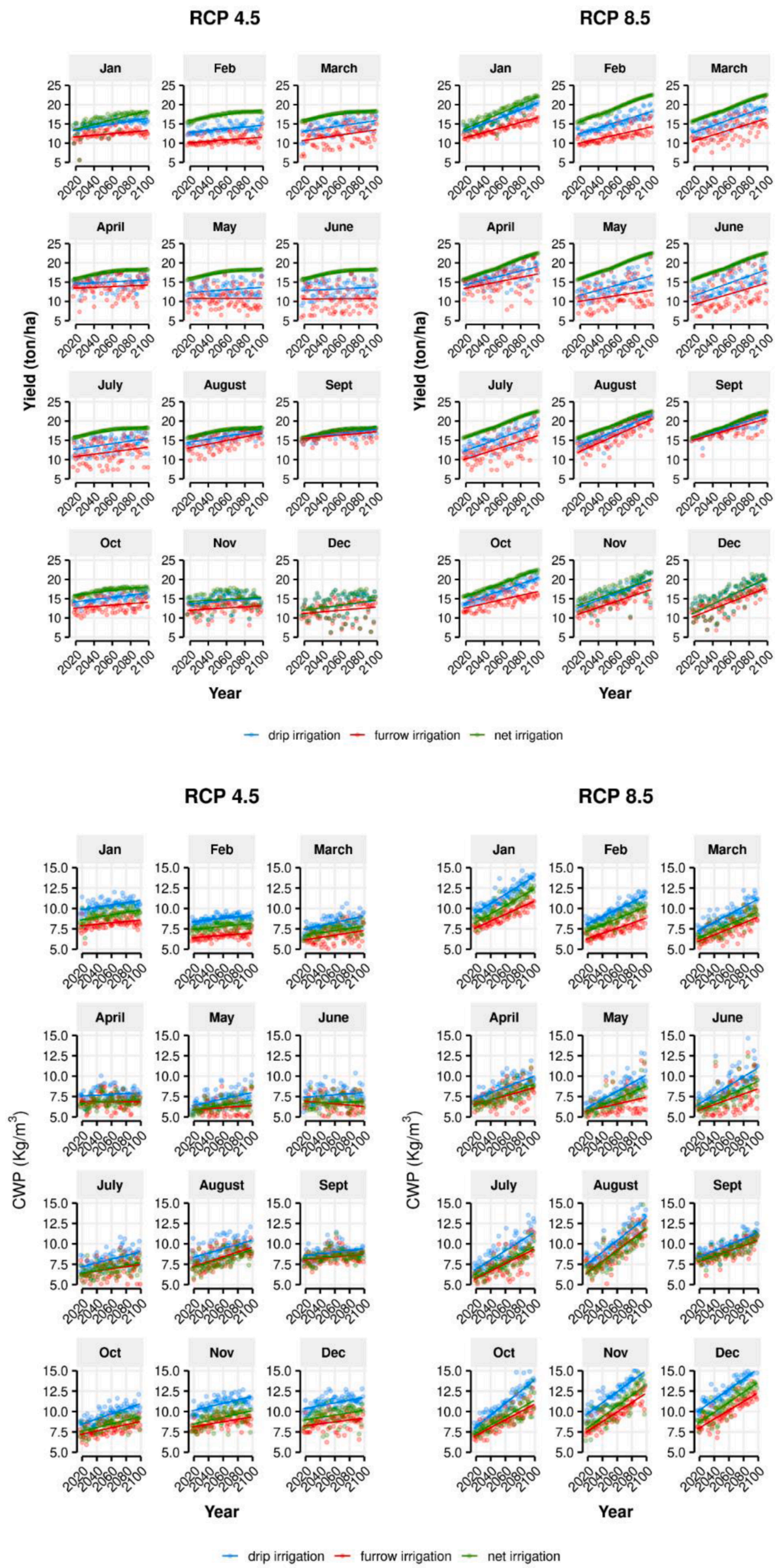

Fig. 6. a) Projected pak choi yields (in ton/ha) and b) CWP (in kg of yield per m^3 of water evapotranspired) under future climate scenarios (RCPs 4.5 and 8.5) over the 2017–2099 period. Blue, red and green circles correspond to the annual yields and CWP under drip, furrow and net irrigation, respectively; while the red, green and blue lines to the yield and CWP trends.

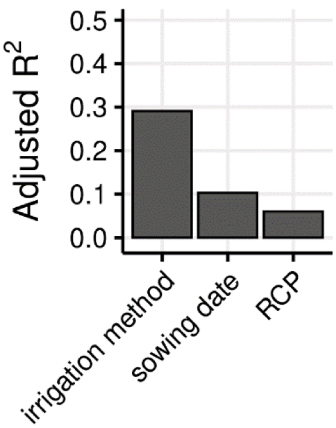

Fig. 7. Adjusted-R^2 values for different input variables (sowing date, irrigation method and RCP). A lower adjusted-R^2 value indicates that the additional input variables are not adding value to the model. For example, if the R^2 value is 0.5, 50% of the variation in the output variable (yield) is explained by the input variables (sowing date, irrigation method and RCP).

Therefore, soil water stresses that might affect the leaf and canopy expansion have not been considered and, therefore, manually adjusted to avoid both water losses into the environment and physiological stresses to the plant. In addition, the net irrigation water requirements is calculated based on the readily available water (RAW) in the field and/or through the threshold at which the root zone depletion may not drop below a specific level. It is also defined as the water that a plant can easily extract from the soil without constraining the expansion of the canopy cover. In this scenario, optimal water applications are prioritized on top of the water losses into the environment as direct evaporation, surface run-off and deep percolation.

Lastly, the field management module in AquaCrop allows the user to specify the impact of soil fertility, weed management, and soil surface practices on biomass production. In this work, we considered high input levels and perfect management, where plants developed under close to optimal conditions throughout the entire growing cycle (Table 2).

2.3.4. Soil data

The soil file in AquaCrop includes information about the soil horizons, soil texture, field capacity, permanent wilting point, saturated hydraulic conductivity, and volumetric content at saturation. In this study, soil texture information for three soil horizons (0–50cm: sandy-loam, 50–95cm: sandy-clay-loam, and 95–120cm: clay-loam) is provided by the Department of Agricultural Land Resources Management (DALRM), General Directorate of Agriculture (GDA), Ministry of Agriculture, Forestry and Fisheries for the same location (Siem Reap) as that used for downscaling climate information. The data gap in soil information is satisfied by the AquaCrop model, which contains default values on the saturated hydraulic conductivity and the soil water content at saturation, field capacity, and permanent wilting point for various soil texture classes, including those used in this work (Raes et al., 2013).

2.4. Experimental design & statistical analysis

Once the climate, crop, field management, and soil modules are parametrized in AquaCrop, we set-up an experimental simulation scheme for the selected site. In this study, the interaction between these modules is determined by two climate scenarios (RCPs 4.5 and 8.5), twelve transplanting/sowing dates (first day of each month), three irrigation methods (drip, furrow and net water requirements), one location (Siem Reap), and a simulation period running from 2017 until 2099. The outputs analysed in this work are related to (i) seasonal precipitation changes and climate extremes, and to (ii) crop yield and crop water productivity (CWP) responses to forthcoming changes in climate. Lastly, the outputs of each simulation were analysed using the adjusted-R2, which showed a corrected goodness (model accuracy) of fit measure for linear models. The latter allowed us to identify the percentage of variance in the output variable (yield) explained by the input variable (sowing date, irrigation method and RCP).

3. Results

3.1. Projected exposure to abiotic stresses

3.1.1. Climatic indicators: seasonal precipitation

Quarterly precipitation assessments (January-March, April-June, July-September, October-December) highlight the differences between the four study periods and RCPs (Fig. 2). First and most significant, we found a precipitation decline in all seasons and RCPs. Seasonal precipitation changes over the summer months (July-September) are larger under RCP 4.5 (−28%) than RCP 8.5 (−6%). The latter changes correspond to a loss of approximately 200 and 40 mm/season, respectively, when comparing the baseline period (2017–2040) to the far-future (2070–2099). A significant precipitation decline is also projected during the pre/post monsoon months, especially under RCP 8.5. For example, precipitation is expected to decrease by −36% (April and June) and −51% (October and December), respectively when comparing the baseline period (2017–2040) to the end-century (2070–2099). Between January and March, the already low precipitation observed in this period is likely to be further reduced into the future; mostly under RCP 4.5, where climate simulations indicate a −69% precipitation decline, from 26 to 8 mm/season when comparing the baseline period (2017–2040) to the end-century (2070–2099). As a result, the total annual precipitation is expected to decrease by −22% (RCP 4.5), from 3.49 to 2.73 mm/day, and by −24% (RCP 8.5), from 3.69 to 2.79 mm/day, respectively when comparing the baseline period (2017–2040) to the end-century (2070–2099). Thereby, the latter changes in seasonality and precipitation decline elucidate a shortening of the growing window and suggest and increase in agricultural inputs (i.e., irrigation) to offset growing climate risks.

AquaCrop findings for the baseline period (2017–2040) show that tomato plants are exposed on average 3.0% of the growing season to water stresses in RCP 4.5 (4.9% of the time reducing canopy expansion and 1.1% inducing stomata closure) and 3.3% in RCP 8.5 (5.5% of the time reducing canopy expansion and 1.2% inducing stomata closure) for the average of all sowing dates and irrigation methods. In the far-future (2070–2099), the average water stresses increase up to 3.5 and 3.6%, respectively under RCP 4.5 and 8.5. However, there are large differences on water stresses over the year, namely in March and April when water stresses may occur on average 6.1% of the growing season for both RCPs by the end-century (2070–2099). In addition, the average duration of water stresses on pak choi is of 6.7% for RCP 4.5 (4.5% of the time reducing canopy expansion and 8.8% inducing stomata closure) and 7.3% for RCP 8.5 (5.1% of the time reducing canopy expansion and 9.6% inducing stomata closure) in the baseline period (2017–2040) for the average of all sowing dates and irrigation methods. Unlike tomato, the average duration of water stress in pak choi plants may remain constant into the future. Finally, yard-long bean is barely exposed to water stresses both in the present and into the future. Hence, despite of the different irrigation methods and future climate scenarios, water stresses are expected to remain invariable over the entire century, with an average stress of 0.5% over the growing season.

3.1.2. Agroclimatic indicators: heat-stress conditions

Tomato plants are consistently affected by heat-stress conditions (Tmax ≥ 33°C) when transplanting between March and June in the baseline period (2017–2040), and where high temperatures are likely to extend to February, August and September under both RCPs by the end-century (2070–2099) (Fig. 3). In addition, while the duration of heat-

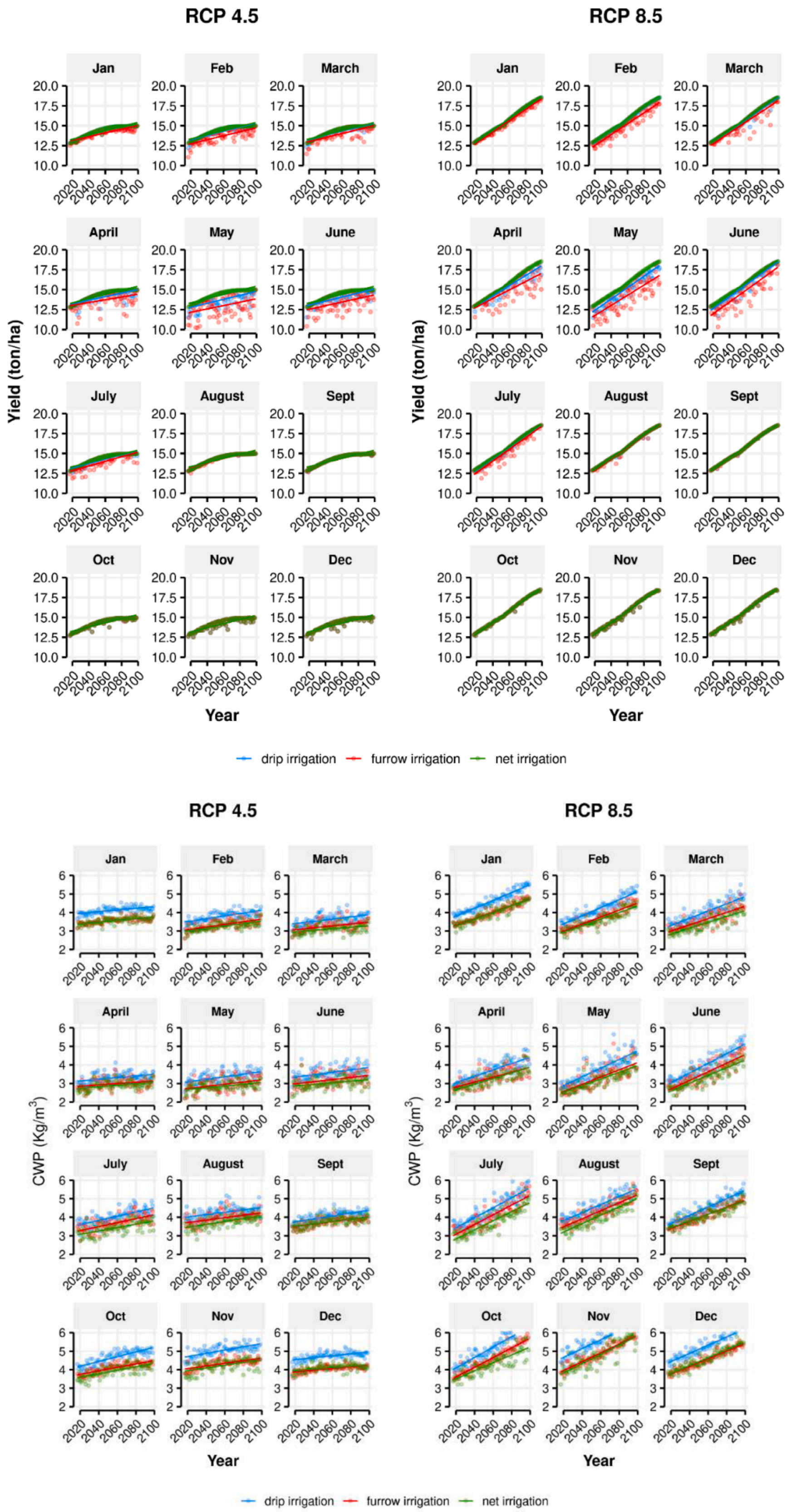

Fig. 8. (a) Projected yields of yard-long bean (in ton/ha) and (b) CWP (in kg of yield per m^3 of water evapotranspired) under future climate scenarios (RCPs 4.5 and 8.5) over the 2017–2099 period. Blue, red and green circles correspond to the annual yields and CWP under drip, furrow and net irrigation, respectively; while the red, green and blue lines to the yield and CWP trends.

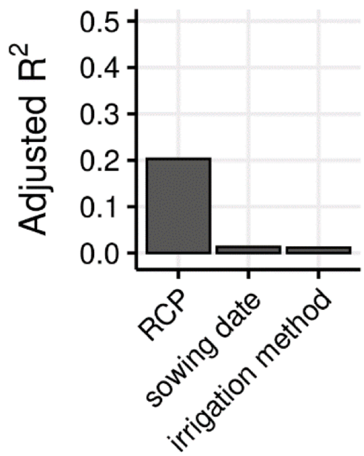

Fig. 9. Adjusted-R^2 values for different input variables (sowing date, irrigation method and RCP). A lower adjusted-R^2 value indicates that the additional input variables are not adding value to the model. For example, if the R^2 value is 0.5, 50% of the variation in the output variable (yield) is explained by the input variables (sowing date, irrigation method and RCP).

stress conditions ranges between 0 and 50 days from September to January, it exceeds 70 days between February and August. However, as for the rest of the year, the duration of heat-stress conditions is also projected to increase between September and January, from 29 to 40 days/season (RCP 4.5) and from 31 to 41 days/season (RCP 8.5) when comparing the baseline period (2017–2040) to the far-future (2070–2099). On the contrary, tomato plants are expected to develop under close to optimal growing temperatures when transplanting in fall (October to December).

Pak choi's exposure to heat-stress conditions is low because of its high heat tolerance (Tmax ≥40°C). In the herein simulations, the plant is harvested (45 days after sowing) before it reaches the flowering stage and, therefore, minimising the impact of high temperatures at sensitive phenological phases (Fig. 3). Along the study area, the aforementioned critical threshold is exceeded only during the pre-monsoon months (March and April) and at the start of the monsoon season (May and June), mostly under RCP 8.5 by the end-century (2070–2099). For instance, when sowing between March and June, the number of days with heat-stress conditions increases from 1 to 15 days/season when comparing the baseline period (2017–2040) to the end-century (2070–2099) in RCP 8.5.

Yard-long bean is increasingly exposed to heat-stress conditions (Tmax ≥36°C) during the pre-monsoon months (March and April) and at the departure of the monsoon season (May and June) (Fig. 3). For example, the number of days with heat-stress conditions increases when sowing between March and June, from 55 to 67 days/season (RCP 4.5) and from 60 to 75 days/season (RCP 8.5), respectively when comparing the baseline period (2017–2040) to the far-future (2070–2099). Heat-stress conditions affect the plant on average 79% (RCP 4.5) and 88% (RCP 8.5) of the growing cycle, which lasts about 90 days. In addition, most of the simulated differences between RCPs are projected during the monsoon months (August to October), when the number of days with heat-stress conditions in RCP 8.5 exceeds (i.e., September) that of RCP 4.5 by two-fold. On the contrary, heat-stress conditions are not simulated when sowing between November and December.

3.2. Climate change impacts on crop production

3.2.1. Tomato: changes in yield and crop water productivity

Yield increases of +37% (from 20.1 to 27.5 ton/ha) are expected between November and December (Fig. 4a) when comparing the baseline period (2017–2040) to the end-century (2070–2099) (average of both transplanting dates, ensemble of RCPs and three irrigation methods). On the contrary, in January, a yield decline of −55% (from 24.2 to 10.9 ton/ha) is simulated when comparing the baseline period (2017–2040) to the far-future (2070–2099) (average of both RCPs and three irrigation schemes). Similar increasing/decreasing yield trends are foreseen in both RCPs, except when transplanting in February, August and October. Between January and June, an increase in the inter-annual yield variability is expected over time, particularly under RCP 8.5. In addition, the adjusted-R^2 indicates that the transplanting date is the most relevant independent variable determining the yield change over time, explaining up to 45% of the yield variation (Fig. 5).

While a decrease in crop water productivity (CWP) is foreseen in the first-quarter (January to March), a strong increase is simulated in the fourth (October to December) (Fig. 4b). For the aforementioned transplanting dates (October to December), the CWP increases by +14% under RCP 4.5 (from 7.9 to 9.0 kg/m^3) and by +41% (from 8.1 to 11.4 kg/m^3) under RCP 8.5 when comparing the baseline period (2017–2040) to the end-century (2070–2099). However, differences in CWP are expected depending on the irrigation method. For example, the average CWP value for all RCPs and sowing dates is 28 and 26% higher under drip irrigation than for furrow and net irrigation.

3.2.2. Pak choi: changes in yield and crop water productivity

For all sowing dates, increasing yields are simulated for pak choi by the end-century (Fig. 6a). While a small yield improvement is foreseen under RCP 4.5, a strong yield increase is expected under RCP 8.5, indicating pak choi's capacity to improve its yields in a CO_2 enriched environment. In addition, yields are expected to rise by +25% (from 15.4 to 19.2 ton/ha and from 13.4 to 16.8 ton/ha under drip and net irrigation, respectively) and by +24% (from 11.7 to 14.5 ton/ha under furrow irrigation) when comparing the baseline period (2017–2040) to the far-future (2070–2099) for the ensemble of RCPs. However, forecasted net irrigation yields by the end-century are significantly higher than those simulated under drip and furrow irrigation, particularly at the start of the monsoon season. For example, if sowing in May under

Table 3
Summary of crop calendars for tomato, pak choi and yard long-bean based on the yield trends simulated on AquaCrop under RCPs 4.5 and 8.5

		Sowing/Transplanting month											
		J	F	M	A	M	J	J	A	S	O	N	D
Tomato	RCP 4.5	Decrease	Stabilize	Decrease	Stabilize	Decrease	Decrease	Moderate	Moderate	Moderate	Stabilize	Moderate	Moderate
	RCP 8.5	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease	Moderate	Strong	Strong	Strong
Pak choi	RCP 4.5	Moderate	Moderate	Moderate	Stabilize	Stabilize	Stabilize	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
	RCP 8.5	Strong	Strong	Strong	Strong	Strong	Strong	Strong	Strong	Strong	Strong	Strong	Strong
Long bean	RCP 4.5	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
	RCP 8.5	Strong	Strong	Strong	Strong	Strong	Strong	Strong	Strong	Strong	Strong	Strong	Strong

Strong Moderate Stabilize Decrease

RCP 8.5, the yields increase by +24% (from 10.2 to 12.7 ton/ha) under furrow irrigation, by +30% (from 16.6 to 21.5 ton/ha) under net irrigation, and by +33% (from 12.1 to 16.1 ton/ha) under drip irrigation, respectively when comparing the baseline period (2017–2040) to the end-century (2070–2099). In addition, a low interannual yield variability is projected under net irrigation. However, this is not the case under drip and furrow irrigation, where a high interannual variation in yield is expected over time. The adjusted-R^2 also indicates that the irrigation method is the most relevant independent variable determining the yield change over time, explaining about 30% of the variation in yield; whereas 10 and 5% of this change is described by the sowing date and RCP, respectively (Fig. 7).

With regards to the crop water productivity (CWP), pak choi's water use efficiency is expected to increase over time, mostly under RCP 8.5 (Fig. 6b). While the CWP rises by +12% (from 7.6 to 8.5 kg/m^3) under RCP 4.5, it is likely to increase by +37% (from 7.6 to 10.4 kg/m^3) under RCP 8.5, respectively when comparing the baseline period (2017–2040) to the far-future (2070–2099) for all sowing dates and irrigation methods. In addition, the average CWP value for all RCPs and sowing dates is 22 and 14% higher under drip irrigation than in furrow and net irrigation, respectively. Overall, the highest simulated yields, with same or lower amount of water inputs, are simulated over the dry season (November and February) when temperatures are milder and so the evapotranspiration rates are lower.

3.2.3. Yard-long bean: changes in yield and crop water productivity

No significant yield changes are reported neither for different irrigation methods (drip, furrow and net irrigation) nor different sowing dates, with a similar yield performance year-round under both RCPs (Fig. 8a). Over the pre-monsoon months, slightly higher yields are expected under net irrigation compared to drip and furrow irrigation. Increases in yield are notable over the century in RCP 8.5 while moderate in RCP 4.5, but only up until the mid-century. For all irrigation methods, yields are projected to increase by +11% (from 13.2 to 14.7 ton/ha) under RCP 4.5 and by +29% (from 13.5 to 17.4 ton/ha) under RCP 8.5 when comparing the baseline period (2017–2040) to the end-century (2070–2099). In addition, the adjusted-R^2 shows that the RCP is the most relevant independent variable determining the yield change over time, explaining up to 20% of the variation in yield (Fig. 9).

As a result of increasing yield trends, the crop water productivity (CWP) likewise experiences a notable increase over time (Fig. 8b). For instance, the CWP is increased by +11% (from 3.5 to 3.9 kg/m^3) under RCP 4.5 and by +34% (from 3.5 to 4.7 kg/m^3) under RCP 8.5 when comparing the baseline period (2017–2040) to the end-century (2070–2099) (average of all sowing dates and three irrigation methods). In addition, different CWP trends are expected when comparing drip to furrow and net irrigation. While the average CWP over the century is of 4.0 and 4.5 kg/m^3 under drip irrigation, that of furrow and net irrigation is of 3.5 and 3.9 kg/m^3, respectively for RCPs 4.5 and 8.5. Therefore, simulation results suggest a 15% higher CWP value when comparing drip to furrow and net irrigation. In addition, significant CWP differences are displayed when selecting different sowing dates. For example, for all irrigation methods, the average CWP value over the century is of 3.1 and 3.8 kg/m^3 (RCP 4.5) and of 3.4 and 4.3 kg/m^3 (RCP 8.5) when comparing the pre-monsoon months (April to May) to the rest of the year (June to March). These differences in CWP increase by 20% if pre-monsoon season sowing is avoided.

4. Discussion

Downscaled climatic data from this work show agreement with those reported by the IPCC-AR6 (IPCC, 2021), indicating, with medium confidence, a decrease in rainfall of about 20% along the maritime continent of Southeast Asia in a 4ºC global warming. Tangang et al. (2018) show a statistically significant (at 95% level) annual precipitation decline over western and central parts of Cambodia under a global warming of 2ºC. Similarly, in this research, we report a 22% (RCP 4.5) and 24% (RCP 8.5) precipitation decline in central parts of the country by the end-century. Teixeira et al. (2013) also suggest that continental areas are at higher risk of heat-stress than the coastal zones, where temperatures are modulated by oceanic winds and air masses essential for insulating and moderating extreme temperatures occurring before the start of the monsoon season (March and April). Regional hot-spots of heat-stress conditions along agricultural areas in continental Southeast Asia have been found for rice (Wassmann et al., 2009), but not yet for vegetables as demonstrated in this study. In addition to more erratic rainfall, our findings indicate that heat extreme events may become more frequent and intense over the century in Siem Reap. However, the sensitivity to extreme heat conditions differs between crops, as discussed below.

This study reveals important information about the detrimental impacts of increasing heat-stress conditions, rising evaporative demand and altered rainfall patterns on crop growth and development. However, distinct impacts are reported depending on the crop type as well as on the duration, intensity and timing of the abiotic stress within the cropping cycle. In tomato, for example, reproductive processes are adversely affected by high temperatures. Studies using crop growth chambers and greenhouses show that high temperatures are most harmful when tomato flowers are first visible, and sensitivity continues over the following 10–15 days (Foolad, 2005). In our study, the maximum air temperature value above which pollination starts to fail is set at 33ºC and 38ºC at full stress. Although plants transplanted between March and June are more exposed to heat-stress conditions than those transplanted between January and February, the intensity and timing at which the stress occurs (55–65 days lag between transplanting and flowering stage) makes tomato plants just as susceptible, or even more, as those exposed to longer but less intense periods of heat. Aligned findings are reported by Ro et al. (2021) in Cambodia, indicating that near to maximum temperatures at the end of the dry season (March and April) are too high, resulting in low or no production in yield.

Increasing heat-stress conditions in Cambodia are likely to have adverse impacts on most crops, except for those with a very high tolerance to heat-stress conditions such as pak choi and cassava (Jarvis et al., 2012). Although high-temperature stresses are uninterruptedly projected over the pre-monsoon months, key genes related to the response of heat are revealed in pak choi plants and explain, to a large extent, the absence of heat-stress throughout the simulations regardless of the sowing date and RCP (Xu et al., 2016). In addition, performance assessments for irrigated pak choi have been successfully evaluated in arid environments (Wellens et al., 2013; Pawar et al., 2017). In Burkina Faso, for example, pak choi's crop water productivity (CWP) varies between 5.0 and 6.9 kg/m^3, with a higher water use efficiency under deficit irrigation and mulching conditions. Similarly, in this study, the average CWP value for all sowing dates and irrigation methods is of 5.6 kg/m^3 for the baseline period (2017–2040). In our work, higher CWP values are reported under drip irrigation compared to furrow and net irrigation. Comparable findings to the herein (22% higher CWP when comparing drip and furrow irrigation) are found in North China, where pak choi's CWP increases by 15 to 28% when using drip irrigation preferably than furrow irrigation over the spring and summer growing seasons, respectively (Xie et al., 2020). Although pak choi is not affected by heat-stress conditions, water-stress have an adverse effect on crop growth (6.7% of the growing season for the average values of different irrigation methods, sowing dates, RCPs over the 2017–2099 period). As a shallow rooted crop (maximum effective rooting depth: 35 cm), pak choi's water extraction effective root zone rapidly decreases with depth. Consequently, the crop does not benefit as much from the upward flow of shallow groundwater tables to the top-soil in comparison to other crops. Notwithstanding, the calibrated upper/lower soil water-stress coefficient responsible for reducing canopy expansion, affecting pollination, accelerating canopy senescence, and inducing stomata closure makes this plant extremely tolerant to water-stresses in terms of canopy expansion and early canopy senescence, while moderately sensitive to water-stress in terms of stomata closure (Wellens et al., 2013).

Lastly, plants with a nitrogen fixation potential are of ecological importance, especially when they have a low water demand and a high drought tolerance (Alidu, 2018). This is the case of yard-long bean, which can withstand increasing abiotic stresses and also benefit from increasing atmospheric CO_2. The AquaCrop model treats C3 and C4 crops differently, as the positive CO_2 effect on C4 crops is mainly confined to a decrease in crop transpiration (Vanuytrecht and Raes, 2011). In this line, a study considering multiple abiotic stresses (elevated CO_2: 720 μmol mol^{-1}, high temperatures: 38/30°C and ultraviolet radiation: 10 kJ $m^{-2} d^{-1}$) showed ameliorative effects for most of the vegetative and photosynthetic traits, but not for pollen production, pollen viability and, consequently, final yield (Singh et al., 2010). The former study and our work are in agreement with respect to crop growth, where temperature stress does not alter crop transpiration throughout the growing cycle and into the future, neither under different sowing dates nor irrigation methods. However, the studies are in disagreement with the effect of high temperatures on crop production, mostly because a higher heat-stress threshold at pollination has been calibrated in our study (40°C pollination starts to fail) compared to the former one (38°C).

5. Conclusions

The present work evaluates the impacts of future climate on three vegetable crops ubiquitous in Southeast Asia. Our results are relevant both for planning and policy making in Cambodia and countries within the region, especially in light of promoting an agenda targeting agricultural transformation in response to climate change. The results of this work can be used as evidence to identify the most appropriate responses (i.e., crop switching, shifting crop planting calendar) and large-scale interventions (i.e., drip irrigation) to reduce the exposure and vulnerability to climate risks. These results also assist decision-makers and project developers with robust scientific simulation-based information that can inform water allocation and water policies. Further research could further explore new agricultural areas of Cambodia where vegetables are envisioned as income options for smallholder farmers besides diversifying agriculture and livelihoods income in a more sustainable way. We finalize this study by providing the following conclusions and recommendations for adaptation measures:

- Erratic precipitation and rising temperatures are detrimental for crop growth and production and, consequently, may elevate pressure on water resources. The former abiotic stresses may be compensated, in some cases, by the CO_2 fertilization effect.
- As a result of increasing crop water requirements, we recommend more efficient use of water resources (drip irrigation) which have shown to optimize water resources by as much as 15% for yard-long bean.
- Shifting crop calendars to changing climate regimes is a cost-effective solution to more frequent and intensified weather hazards (Table 3).
- Promote breeding programmes and climate resilient practices could support vegetable production better withstand critical growing periods.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2022.109105.

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