ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.30, n.1, e291433, 2026
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

Original Article

Climate variability on cassava water requirements in Song Hinh District of Phu Yen province, Vietnam[1]

Variabilidade climática nas necessidades de água da mandioca no distrito de Song Hinh, província de Phu Yen, Vietnã

Hoang T. V. Ha[2], Dang T. An[3,4] & Nguyen T. T. Thanh[5*]

[1] Research developed at Faculty of Social Sciences Education, Vietnam
[2] Dong Thap University, Vietnam
[3] University of Science, HCM City, Vietnam
[4] Vietnam National University-HCM City, Vietnam
[5] Vinh University, Nghe An Province, Vietnam

HIGHLIGHTS:

CSM-MANIHOT-model projections reveal divergent trends in water requirements under different climate scenarios in Vietnam.
Crop water demands for the cultivation season are projected to increase more significantly under RCP8.5 by 2085.
Strategic adjustments to planting calendars can optimize rainfall utilization and reduce irrigation demands in the future.

ABSTRACT: Climate variability is expected to alter global temperatures and precipitation, significantly impacting cassava (*Manihot esculenta*) water requirements. This study investigated the impacts of climate variability on rainfed cassava in the Song Hinh district, Phu Yen province of Vietnam, utilizing the CSM-MANIHOT-Cassava (Version 4.8) crop simulation model. The model was calibrated and validated using local field data, demonstrating strong model performance (R^2 up to 0.93, RMSE of 12.84%, and NRMSE of 2.74% for root yield validation). Future cassava water requirements were simulated for the Vu Xuan and Vu He cassava crops under RCP4.5 and RCP8.5 scenarios for the 2025s, 2055s, and 2085s time windows, relative to a climate baseline of 1986-2005 and a crop parameter baseline of 2001-2021. The results revealed divergent trends in the cassava water requirements. Under the moderate RCP4.5 scenario, total cassava water requirements were projected to decrease for both Vu Xuan (by 11.8 to 16.9%) and Vu He (by 9.0 to 13.7%). In contrast, the high-emission RCP8.5 scenario indicated a significant eventual increase by 2085, with requirements rising by 13.6% for Vu Xuan and 21.3% for Vu He. These findings highlight the critical need for adaptive solutions. Adjusting planting schedules to better align with changing rainfall patterns emerges as a key strategy to sustain cassava production. For instance, under future scenarios, particularly RCP8.5, strategic adjustments such as delaying planting for Vu Xuan and advancing planting for Vu He could optimize water use efficiency and sustain cassava production in the Song Hinh district.

Key words: *Manihot esculenta*, cassava water requirements, CSM-MANIHOT-Cassava, climate variability, adaptation strategies

RESUMO: Projeta-se que a variabilidade climática altere as temperaturas e a precipitação globais, impactando significativamente as necessidades hídricas da mandioca (Manihot esculenta). Este estudo investigou os impactos da variabilidade climática na mandioca de sequeiro no distrito de Song Hinh, província de Phu Yen, Vietnã, utilizando o modelo CSM-MANIHOT-Cassava (Versão 4.8). O modelo foi calibrado e validado com dados de campo locais, demonstrando bom desempenho (R^2 de até 0,93, Erro Quadrático Médio - RMSE de 12,84% e RMSE Normalizado - NRMSE de 2,74% para a validação da produtividade de raízes). As futuras necessidades hídricas da mandioca foram simuladas para as safras Vu Xuan e Vu He sob os cenários de Caminhos de Concentração Representativos (RCPs) 4.5 e 8.5, para as janelas de tempo de 2025, 2055 e 2085, em relação a uma linha de base climática de 1986-2005 e uma linha de base de parâmetros da cultura de 2001-2021. Os resultados projetaram tendências divergentes nas necessidades hídricas da mandioca. Sob o cenário moderado RCP4.5, projetou-se que as necessidades hídricas totais diminuiriam tanto para a safra Vu Xuan (de 11,8 a 16,9%) quanto para a Vu He (de 9,0 a 13,7%). Em contraste, o cenário de altas emissões RCP8.5 indicou um eventual aumento significativo até 2085, com um acréscimo de 13,6% para Vu Xuan e 21,3% para Vu He. Estes resultados destacam a necessidade crítica de soluções adaptativas. O ajuste dos calendários de plantio, para melhor alinhamento com as mudanças nos padrões de chuva, surge como uma estratégia-chave para sustentar a produção de mandioca. Por exemplo, em cenários futuros, particularmente o RCP8.5, ajustes estratégicos como o adiamento do plantio para a safra Vu Xuan e a antecipação para a Vu He poderiam otimizar a eficiência do uso da água e sustentar a produção de mandioca no distrito de Song Hinh.

Palavras-chave: *Manihot esculenta*, necessidades hídricas da mandioca, CSM-MANIHOT-Mandioca, variabilidade climática, estratégias de adaptação

• Ref. 291433 – Received 25 Oct, 2024
* Corresponding author - E-mail: thanhntt@vinhuni.edu.vn
• Accepted 28 Jul, 2025 • Published 18 Aug, 2025
Editors: Geovani Soares de Lima & Carlos Alberto Vieira de Azevedo

Introduction

Cassava (*Manihot esculenta*) is a vital food crop and a significant income source for millions of smallholder farmers in tropical and subtropical regions (Janket et al., 2018; Lee & Dang, 2020a). In Vietnam, cassava ranks as the fourth largest crop and is widely cultivated in rainfed regions, playing a pivotal role in rural livelihoods and the national agricultural economy (Lee & Dang, 2018). Particularly in south-central coastal provinces like Phu Yen, where agriculture is heavily reliant on rainfall, cassava serves as a staple crop, contributing to food security and income generation for local populations (Lee & Dang, 2018).

However, cassava production, particularly under rainfed conditions, is highly vulnerable to the impacts of climate variability (ICV), manifested by significant shifts in temperature and rainfall patterns (Ropo & Ibraheem, 2017; Dang et al., 2021). This heavy reliance on predictable climatic factors makes the agricultural sector particularly susceptible to these changes (Janket et al., 2018; Nguyen et al., 2023). Climate variability is projected to severely affect rainfed agricultural regions by influencing water availability, cassava water requirements (CWR), and consequently, crop yields (Vongcharoen et al., 2018; Dang et al., 2021). Increased magnitude, intensity, and frequency of extreme meteorological events, such as droughts and intense rainfall, can alter plant growth durations and strongly impact CWR (Phoncharoen et al., 2018; Lee & Dang, 2020a), thereby necessitating adjustments in cassava cultivation practices (Ropo & Ibraheem, 2017; Zhang et al., 2018). Therefore, there is a pressing need to develop adaptive solutions to mitigate the adverse impacts of ICV on cassava cultivation (Moreno-Cadena et al., 2021; Nguyen et al., 2023).

Crop simulation models are powerful tools for assessing the potential impacts of ICV and evaluating adaptation options in agriculture (Lee & Dang, 2020a; Moreno-Cadena et al., 2021; Nguyen et al., 2023). Various models, including SUCROS, LINTUL-Cassava, CSM-CROPSIM, AQUACROP, CROPWAT, and CSM-MANIHOT, have been employed to simulate crop growth, yield, and water dynamics under different environmental conditions. For instance, Ezui et al. (2018) used the LINTUL model to simulate drought impacts on cassava in Togo, demonstrating potential yield reductions due to decreased rainfall. Lee & Dang (2019) applied the FAO-AquaCrop model to predict cassava yield in Phu Yen province, Vietnam, reporting its suitability for estimating root yield under local conditions. Among these, the CSM-MANIHOT model, part of the Decision Support System for Agrotechnology Transfer (DSSAT), is recognized for its capability to simulate cassava growth duration and yield under changing climatic conditions by incorporating detailed physiological processes relevant to cassava development (Lee & Dang, 2018; Rankine et al., 2021; Moreno-Cadena et al., 2021), making it particularly well-suited for assessing CWR and crop responses to water stress conditions.

While studies in Vietnam have investigated the impacts of ICV on cassava cultivation (e.g., Lee & Dang, 2018 on cassava yield; Nguyen et al., 2023 on altering cropping calendars), a significant knowledge gap remains. Specifically, more detailed assessments are needed on how future ICV will affect CWR and how adaptation solutions, such as optimized cropping calendars, can be developed. Previous work by Lee & Dang (2020b) assessed efficient cropping calendars for cassava using the AquaCrop model in Phu Yen. However, employing a process-based model like CSM-MANIHOT can provide deeper insights into cassava's physiological responses and water use dynamics, aspects that AquaCrop might not fully capture. Understanding these dynamics is crucial for developing sustainable and resilient cassava production systems in vulnerable regions such as the Song Hinh district, Phu Yen province.

This study aims to investigate the impacts of ICV on the CWR in the Song Hinh district, Phu Yen province, by applying the CSM-MANIHOT-Cassava model. The specific objectives are: (1) to calibrate and validate the CSM-MANIHOT-Cassava model for local conditions; (2) to simulate future CWR for two common cropping patterns under Representative Concentration Pathways (RCP4.5 and RCP8.5) for different future time windows (2025s, 2055s, 2085s); and (3) to assess the implications of these changes for cassava cultivation and identify potential adjustments to cropping patterns as an adaptation measure.

Material and Methods

The study was conducted in the Song Hinh district of Phu Yen province, located in the south-central coastal region of Vietnam (Lee & Dang, 2019). The specific area of focus stretches from 12° 45′ to 13° 06′ N latitude and 108° 40′ to 109° 07′ E longitude, and an altitude of 40 m (Figure 1). The province has a total agricultural soil area of approximately 300,000 ha, with a significant portion dedicated to upland crops including cassava. The population of the agricultural regions considered is around 46,000 people (Pham et al., 2021). The terrain of the Song Hinh district is characterized by considerable variation, with mean elevations over 60 m a.m.s.l (Figure 1). This topographical diversity can influence local microclimates and cultivation practices.

The region is dominated by a tropical monsoon climate, with two distinct wind circulations: the northeast monsoon

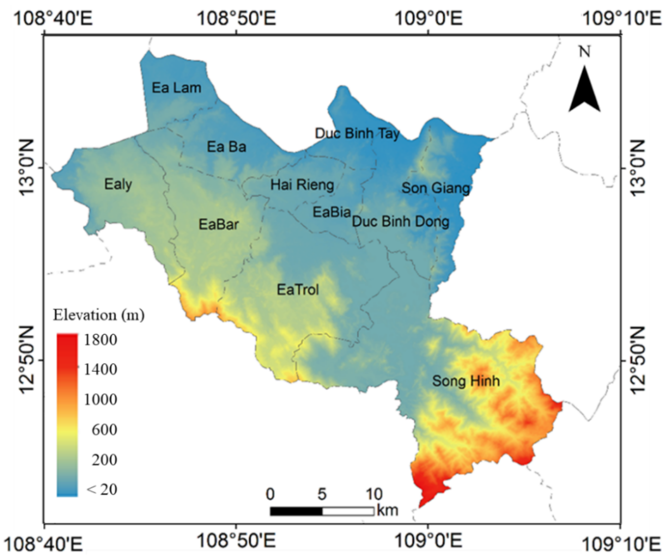

Figure 1. Map of the study area

(typically bringing drier conditions) and the southwest monsoon (associated with the rainy season) (Lee & Dang, 2019; Pham et al., 2021). The annual mean temperature is approximately 26.0 °C, with average air humidity around 80%. The mean annual rainfall is about 1,650 mm (Lee & Dang, 2019). The hilly topography is generally well-suited for root crop cultivation (Lee & Dang, 2019; Pham et al., 2021).

Baseline climate data (1986-2005), comprising daily sunshine hours, relative air humidity, wind speed, maximum and minimum temperatures, and precipitation, were collected from the Phu Yen Provincial Hydro-meteorological Station. Future climate data were constructed based on adjusted projection outputs from six Global Climate Models (GCMs) (Table 1). These GCMs, including ECHAM4, UKMO-HadCM3, CGCM2.0, CSIRO-Mk3.0, CCSR, and GFDL-R30 (Table 1), were selected for this study due to their demonstrated capability in simulating regional climate variables pertinent to agricultural impact assessments, their established effectiveness in estimating crop water requirements within Vietnam, and their extensive application in national agricultural research projects (Deb et al., 2016; Lee & Dang, 2018). The RCP4.5 and RCP8.5 scenarios were chosen as they represent a moderate mitigation pathway and a high emissions pathway, respectively, providing a range of potential future climate conditions commonly used in impact studies.

An inherent limitation of GCMs is the coarse spatial resolution of their output, which inadequately captures localized characteristics such as complex topography, vegetation cover, and microclimatic effects (Deb et al., 2016). Consequently, for studies at a local scale, the transformation of data from coarse to finer resolutions via bias correction and downscaling techniques is an indispensable step. In this investigation, recognizing the spatial dependency of biases within GCM-projected temperature and precipitation data, bias correction was deemed essential for station-level analysis. Although the Song Hinh district in Phu Yen province hosts three meteorological stations (Ealy, Son Giang, and Song Hinh), the Song Hinh station was exclusively selected for this study, predicated on the completeness of its observational data series, which is crucial for robust bias correction. Biases in GCMs-projected temperature data were rectified using the power law transformation method, a technique suitable for normally distributed data. This method systematically adjusts the mean and variance of the projected dataset to align with the observed data at the station (Moreno-Cadena et al., 2021; Phoncharoen et al., 2021). The procedural details for daily station temperature correction are presented in Deb et al. (2016).

Projections were subsequently developed for two Representative Concentration Pathways (RCPs): RCP4.5 and RCP8.5. Three future time periods were analyzed: 2025s (2011-2040), 2055s (2041-2070), and 2085s (2071-2099). Table 2 and Figure 2 summarize the projected changes in mean temperature and rainfall for these scenarios and periods compared to the baseline. The selection of these periods allows for an examination of the potential impacts of climate variability on CWR over different time horizons, enabling a more comprehensive understanding of the impacts of ICV on cassava cultivation in the study area.

The cassava variety KM419 was selected for this study, as it is widely cultivated in the region due to its high root yield potential (up to 50 t ha^{-1}) and relatively short life cycle of approximately nine months (Pham et al., 2021). Two common cropping seasons were simulated: Vu Xuan (typically sowed around January 15th and harvested around October 15th) and Vu He (sowed around March 25th and harvested around December 25th) (Lee & Dang, 2019). In the Song Hinh district, cassava cultivation covers about 6,100 ha. Farmers commonly sow cassava cuttings with a spacing that results in a density of 15,625 plants ha^{-1} (Table 3).

These planting densities and life cycle durations were directly applied as input coefficients in the CSM-MANIHOT model. Fertilizer application followed recommended practices for the region: 10 t ha^{-1} of manure, 80 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1}, and 80 kg K_2O ha^{-1}. The application schedule involved 100% manure, 50% N, and 30% P_2O_5 at land preparation; 30% N, 40% P_2O_5, and 50% K_2O at 25 days after sowing (DAS); and the remaining 20% N, 30% P_2O_5, and 50% K_2O at 60 DAS (Table 3). These fertilization practices represent typical farmer recommendations and were input into the model.

Table 1. Category of the global circulation models applied in this study

No.	Model	Country	Center	References
1	ECHAM4	Germany	Max-Planck Institute for Meteorology	Roeckner et al. (1992)
2	UKMO-HadCM3	United Kingdom	Hadley Centre for Climate Prediction and Research Met Office United Kingdom	Gordon et al. (2000)
3	CGCM2.0	Canada	Canadian Centre for Climate Modelling and Analysis	Paolino et al. (2011)
4	CSIRO-Mk3.0	Australia	CSIRO Atmospheric Research	Gordon et al. (2002)
5	CCSR	Japan	Atmosphere and Ocean Research Institute	Hiroyasu (2015)
6	GFDL-R30	United States	National Oceanic and Atmospheric Administration	Delworth et al. (2002)

Table 2. Current and future climate scenarios in rainfall and temperature in the study area with standard deviation showing the uncertainty range of applied model projections

Baseline (1986-2005)	Future periods	RCP4.5 scenario	Change	RCP8.5 scenario	Change
Mean temperature 26.5 (°C)	2025s	27.2 ± 0.4 °C	0.7 °C	27.3 ± 0.6 °C	0.8 °C
	2055s	27.8 ± 0.9 °C	1.3 °C	28.3 ± 1.3 °C	1.8 °C
	2085s	28.3 ± 1.3 °C	1.8 °C	29.6 ± 2.5 °C	3.1 °C
Mean rainfall 1,650 (mm)	2025s	1,815.0 ± 3.2 mm	10.0%	1,854.6 ± 3.2 mm	12.4%
	2055s	1,871.1 ± 5.2 mm	13.4%	1,821.6 ± 2.7 mm	10.4%
	2085s	1,887.6 ± 0.9 mm	14.4%	1,816.6 ± 1.0 mm	10.1%

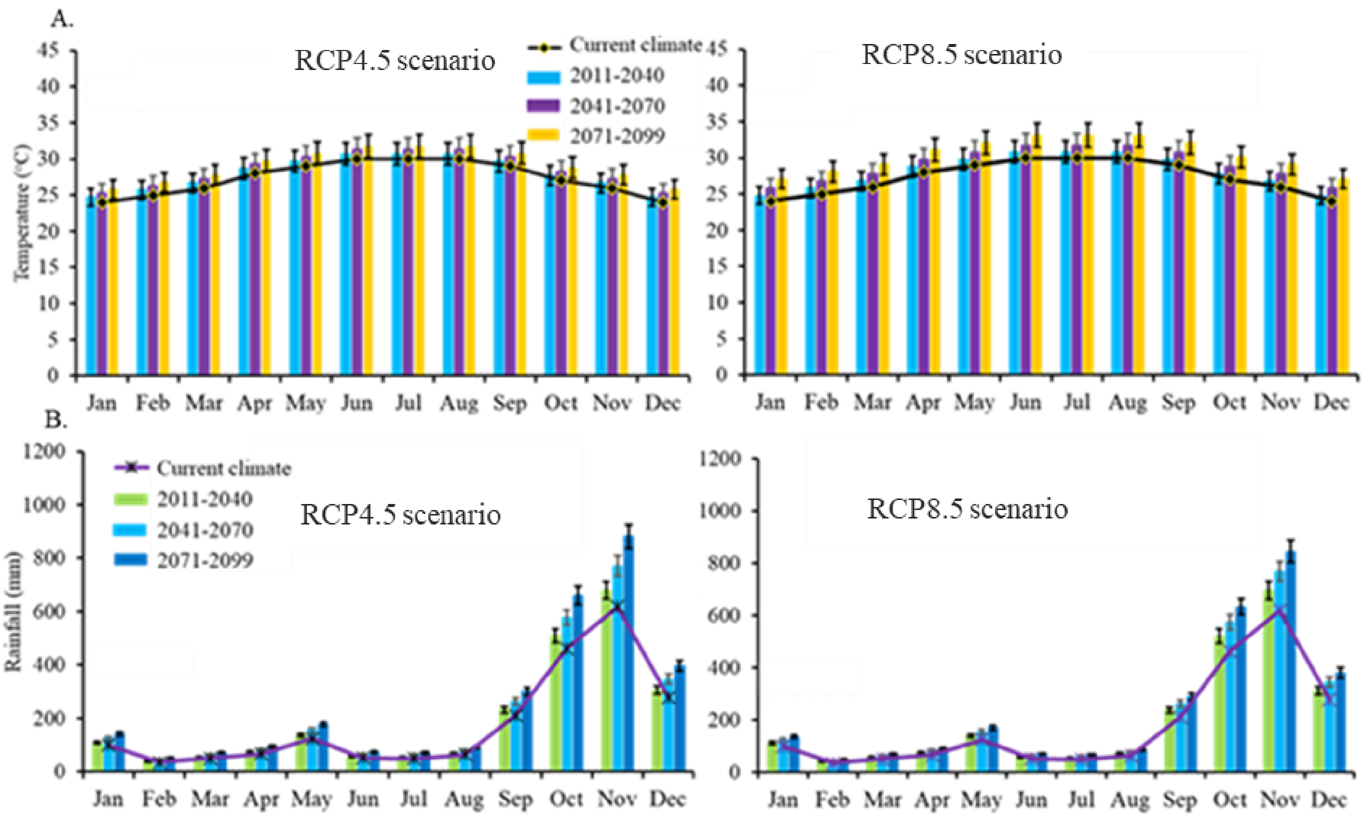

Figure 2. Comparison of current and projected future scenarios for mean monthly temperature (A) and precipitation (B) across the study area. Error bars show the uncertainty range in projection due to the application of different GCMs

Table 3. Crop characteristics of the cassava-growing regions in the study area

Crop	Seasonal schedule		Variety	Density (cutting ha^{-1})	Method	Fertilizer (kg ha^{-1})			
	Sowing	Harvesting				N_2O	P_2O_5	K_2O	Manure
Vu Xuan	15-Jan	15-Oct	KM419	15625	Sow	80	40	80	10 tons
Vu He	25-Mar	25-Dec	KM419	15625	Sow	80	40	80	10 tons

Soil physical properties were surveyed for depth layers from 0 to 120 cm. Soil samples were analyzed to determine texture (sand, silt, clay), soil water content at saturation (SAT), field capacity (FC), permanent wilting point (PWP), and saturated hydraulic conductivity (Ksat) (Table 4). The predominant soil textures ranged from sandy loam to sandy clay loam.

The CSM-MANIHOT-Cassava model, part of the DSSAT platform, was used to simulate cassava growth, development, and CWR. This model simulates daily photosynthesis, crop growth stages, and biomass accumulation based on climate inputs (temperature, radiation, rainfall), soil characteristics (texture, composition, hydraulic properties), crop management practices (planting date, fertilization, and irrigation), and cassava genetic coefficients (Phoncharoen et al., 2021; Rankine et al., 2021). An advantage of this model is its incorporation of processes specific to cassava physiology, allowing for a detailed simulation of its growth and yield responses to environmental factors (Moreno-Cadena et al., 2021; Diego et al., 2025).

The CSM-MANIHOT-Cassava model was subjected to a parameter sensitivity analysis (Table 5) and calibrated using experimental data on biomass yield (BY) and root yield (RY) of cassava (variety KM419) collected from the study region for the period 2001-2011. Validation was performed using an independent dataset from 2012-2021. While a formal sensitivity analysis of all model parameters was not explicitly conducted for this study, the calibration process inherently involves adjusting the most sensitive parameters that govern crop growth, development, and water use to match observed local data. The performance of the model was evaluated using several statistical indices (Table 5).

Table 4. Texture and hydraulic characteristics of soils across the study area

Depth (cm)	Texture (%)			Classification	Contents			
	Sand	Silt	Clay		SAT	FC	PWP	Ksat
0-20	76	11	13	Sandy loam	37.3	16.2	8.0	210
20-40	73	10	17	Sandy loam	36.4	15.3	8.7	189
40-60	68	10	22	Sandy clay loam	35.6	14.9	9.5	167
60-80	64	13	23	Sandy clay loam	34.2	15.6	8.7	156
80-100	58	16	26	Sandy clay loam	33.7	16.9	9.8	135
100-120	53	22	25	Sandy clay loam	32.8	17.4	12.6	124

SAT - Soil water content at saturation (m^3 m^{-3}); FC - Field capacity (-): PWP – Permanent wilting point (-); Ksat – Saturated hydraulic conductivity (mm per day)

Table 5. Information on the phenotypic characteristics and the eco-physiological response of the K419 cassava cultivar

Index	Definition
BxyND	Thermal interval between X and Y branching (°Cd)
BRxFX	Number of apices that developed from X branching
LAXS	Leaf area of leaves developed without stress (cm^2)
SLAS	Specific leaf area of cassava (cm^2 g^{-1})
LLIFA	Thermal time between maximum leaf expansion and the beginning of senescence (°Cd)
LPEFR	Fraction of petiole weight in full leaf weight
LNSLP	Slope of the growth curve associated with leaf production
NODWT	Node weight for the first level of branching of the aerial part at 3400 °CD (g)
NODLT	Distance between nodes at the first lignified branching level of the aerial part (cm)
KCAN	Extinction coefficient of photosynthetically active radiation (PAR)
PARUE	Conversion factor of photosynthetically active radiation into dry matter (g MJ^{-1})
HMPC	Percentage of dry matter weight in the reserve roots (%)

The performance of the model was evaluated using several statistical indices:

The RMSE is calculated by Eq. 1

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

and NRMSE is defined by Eq. 2

$$\mathrm{NRMSE}=\frac{\mathrm{RMSE}}{\bar{O}} \tag{2}$$

The d-index is calculated by Eq. 3

$$d=1-\frac{\sum_{i=1}^{n}(S_i-O_i)^2}{\sum_{i=1}^{n}(S_i-\bar{O}_i)^2} \tag{3}$$

and R^2 is given by Eq. 4

$$R^2=\frac{\sum_{i=1}^{n}S_i\times O_i-\sum_{i=1}^{n}S_i\times\sum_{i=1}^{n}O_i}{\sqrt{\sum_{i=1}^{n}S_i^2-\left(\sum_{i=1}^{n}S_i\right)^2}\times\sqrt{\sum_{i=1}^{n}O_i^2-\left(\sum_{i=1}^{n}O_i\right)^2}} \tag{4}$$

In Eqs. 1, 2, 3 and 4, n is the number of observation samples, Si is the simulated result, O_i is the observed result and O are the average of the observed data.

Actual evapotranspiration (ETa), effective rainfall (Peff), and crop water requirements (CWR, often equivalent to irrigation requirements in rainfed systems when Peff is less than ETa) were simulated for the baseline period and the future scenarios (RCP4.5 and RCP8.5 for 2025s, 2055s, and 2085s). CWR was determined for different growth stages: I (initial), II (development), and III (maturity).

Results and Discussion

The CSM-MANIHOT-Cassava model was calibrated and validated for simulating biomass yield (BY) and root yield (RY) for both the Vu Xuan and Vu He cassava crops. The statistical indicators demonstrated strong agreement between simulated and observed data (Table 6). For root yield, the calibration process yielded a RMSE = 13.73-14.62%, NRMSE = 3.83-3.87%, d-index = 0.83-0.89, and R^2 = 0.83-0.87. The validation results were similarly robust, with a RMSE = 12.84-13.93%, NRMSE = 2.74-2.87%, d-index = 0.84-0.96, and R^2 = 0.89-0.93. Specifically for Vu Xuan root yield validation, R^2 was 0.93 and NRMSE was 2.74%. For biomass yield, R^2 values ranged from 0.82 to 0.87 during calibration and validation.

Table 6 illustrates the model's performance in simulating root yield for the Vu Xuan crop. While the overall agreement is strong, a closer examination reveals a slight tendency for the model to marginally overestimate lower observed yields and slightly underestimate higher yields during the validation phase, though the data points largely cluster around the 1:1 line. This behavior is common in crop model validation and does not detract significantly from the model's overall reliability for assessing general trends in CWR under varying climate scenarios. Limitations of this validation approach include the reliance on data from a specific region; further testing across diverse environments could enhance model robustness.

Under baseline climate conditions, the simulated mean annual ETa for the Vu Xuan and Vu He cassava crops were approximately 928.5 and 824.3 mm, respectively (Table 7). Both RCP4.5 and RCP8.5 scenarios projected general increases in ETa across future periods for both crops, with RCP8.5 showing more substantial increases, particularly by the 2085s (e.g., up to 18.2% for Vu Xuan and 10.8% for Vu He). This rise in ETa is primarily driven by projected temperature increases, which enhance the atmospheric demand for water (Figure 3).

Effective rainfall (Peff) during the baseline period was highest in the maturity stage for both crops (Table 8), reflecting monsoon rain patterns. Future projections generally indicated an increase in total annual Peff under both scenarios, though with variations across time periods and crop types. For instance, under RCP4.5, Peff for Vu Xuan showed a consistent

Table 6. The performance of the CSM-MANIHOT-Cassava model through the error indices

Yield	Crop	Calibration				Validation			
		RMSE (%)	NRMSE	d	R^2	RMSE (%)	NRMSE	d	R^2
Biomass	Vu Xuan	14.17	3.19	0.86	0.85	14.76	3.16	0.86	0.85
	Vu He	14.25	3.34	0.83	0.82	13.27	3.27	0.83	0.87
Root	Vu Xuan	13.73	3.83	0.89	0.87	12.84	2.74	0.96	0.93
	Vu He	14.62	3.87	0.83	0.83	13.93	2.87	0.84	0.89

RMSE - Root mean squared error; NRMSE - Normalized root mean square error; d - Index of agreement; R^2 - Coefficent of determination

Table 7. The actual evapotranspiration (mm) of Vu Xuan and Vu He crops cassava simulated corresponding to windows of the RCP4.5 and RCP8.5 scenarios

Crop	Growth stages	Baseline	Future climate scenarios					
			RCP4.5			RCP8.5		
			2025s	2055s	2085s	2025s	2055s	2085s
Vu Xuan	I	180.8	218.2	222.4	217.7	219.3	221.4	217.9
	II	223.9	232.5	227.9	237.2	233.5	238.7	232.6
	III	523.8	532.7	550.5	554.9	572.6	589.3	647.2
Total		928.5	983.4	1000.8	1009.8	1025.4	1049.4	1097.7
Changed		-	+5.91%	+7.78%	+8.7%	+10.4%	+13.0%	+18.2%
Vu He	I	186.8	191.5	193.8	199.6	189.9	207.3	219.1
	II	171.6	181.7	189.4	188.3	187.0	198.4	205.1
	III	465.9	478.3	470.5	476.8	475.8	478.1	489.1
Total		824.3	851.5	853.7	864.7	852.7	883.8	913.3
Changed		-	+3.3%	+3.5%	+4.9%	+3.4%	+7.2%	+10.8%

I - The initial stage of cassava; II- The development stage of cassava; III- The maturity stage of cassava

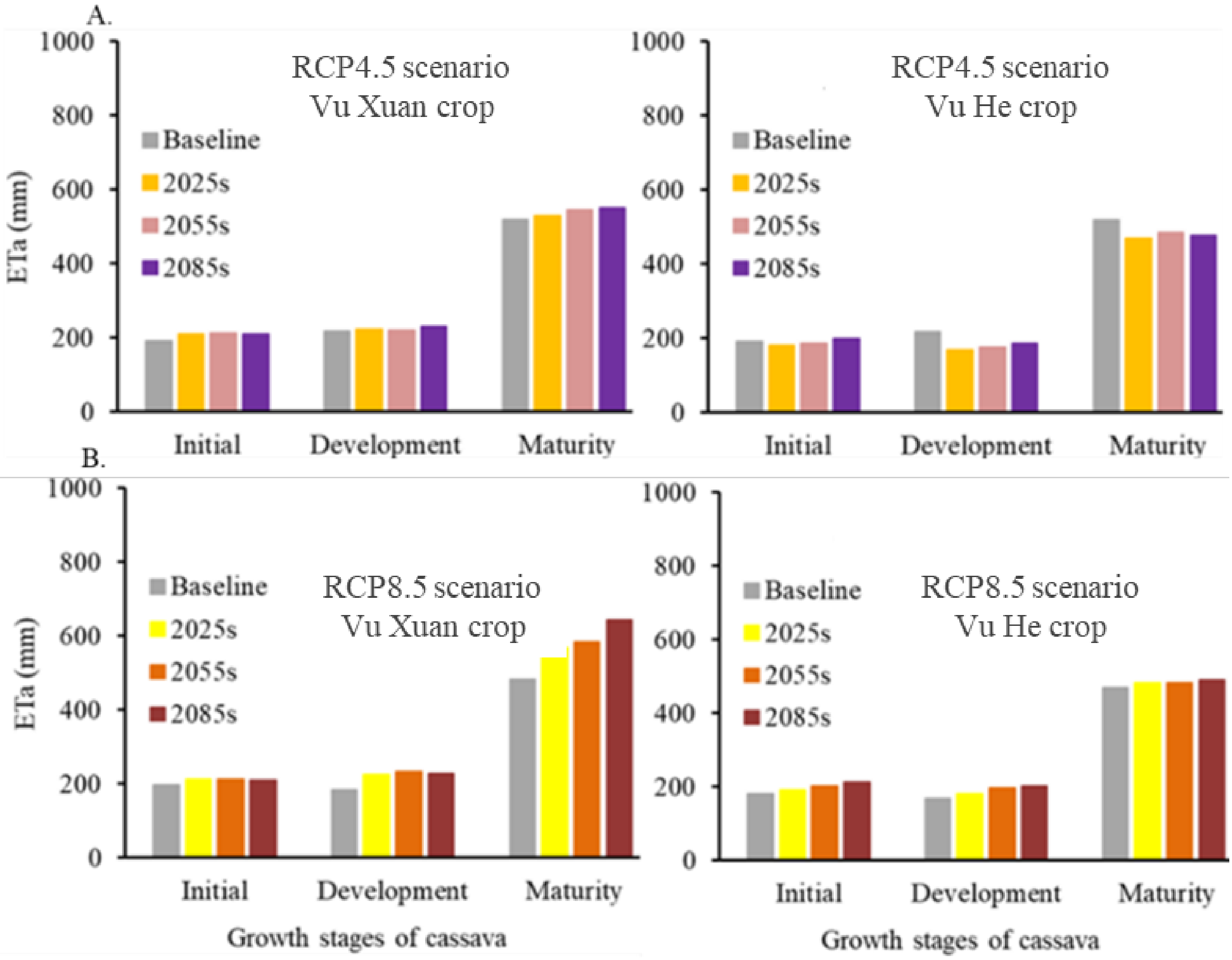

Figure 3. Simulated actual evapotranspiration (ETa) of Vu Xuan and Vu He crops for the baseline period and future time windows 2025s, 2055s and 2085s of the RCP4.5 scenario (A) and RCP8.5 scenario (B)

increasing trend (up to 19.7% by the 2085s), while under RCP8.5, the increase was also notable but with a slight dip in the rate of increase by the 2085s for Vu Xuan (Figure 4). These changes in ETa and Peff are critical drivers for the projected shifts in CWR. An increase in Peff can offset some of the increased atmospheric demand from ETa, but the balance between these two, and their seasonal timing, determines the net CWR.

The simulated CWR, representing the net irrigation needed when Peff is insufficient to meet ETa, showed divergent trends under the two RCP scenarios (Table 9). It is important to interpret negative CWR values in Table 9 as periods where Peff exceeds ETa, resulting in a water surplus rather than an irrigation deficit. This phenomenon is common during the peak rainy season, particularly in the maturity stage of cassava when rainfall is typically highest

Table 8. The effective rainfall (mm) of cassava sowing crops simulated corresponding to windows of the RCP4.5 and RCP8.5 scenarios

Crop	Growth stages	Baseline	Future climate scenarios					
			RCP4.5			RCP8.5		
			2025s	2055s	2085s	2025s	2055s	2085s
Vu Xuan	I	137.5	154.1	164.3	188.5	170.6	175.7	165.4
	II	90.5	124.5	139.4	128.6	136.5	132.0	139.0
	III	630.0	663.9	688.1	694.8	679.6	662.2	653.6
Total		858	942.5	991.8	1011.9	986.7	969.9	958
Changed		-	+9.8%	+15.6%	+19.7%	+15.0%	+13.0%	+11.7%
Vu He	I	150.5	174.0	177.5	173.7	181.8	185.2	179.2
	II	188.0	199.8	201.5	209.6	215.9	219.2	207.1
	III	694.2	766.1	781.5	790.2	772.8	764.4	763.2
Total		1021.8	1139.0	1169.5	1172.6	1188.5	1158.9	1139.6
Changed		-	+10.5%	14.3%	+14.7%	+16.3%	+15.3%	+16.0%

I - The initial stage of cassava, II- The development stage of cassava, III- The maturity stage of cassava

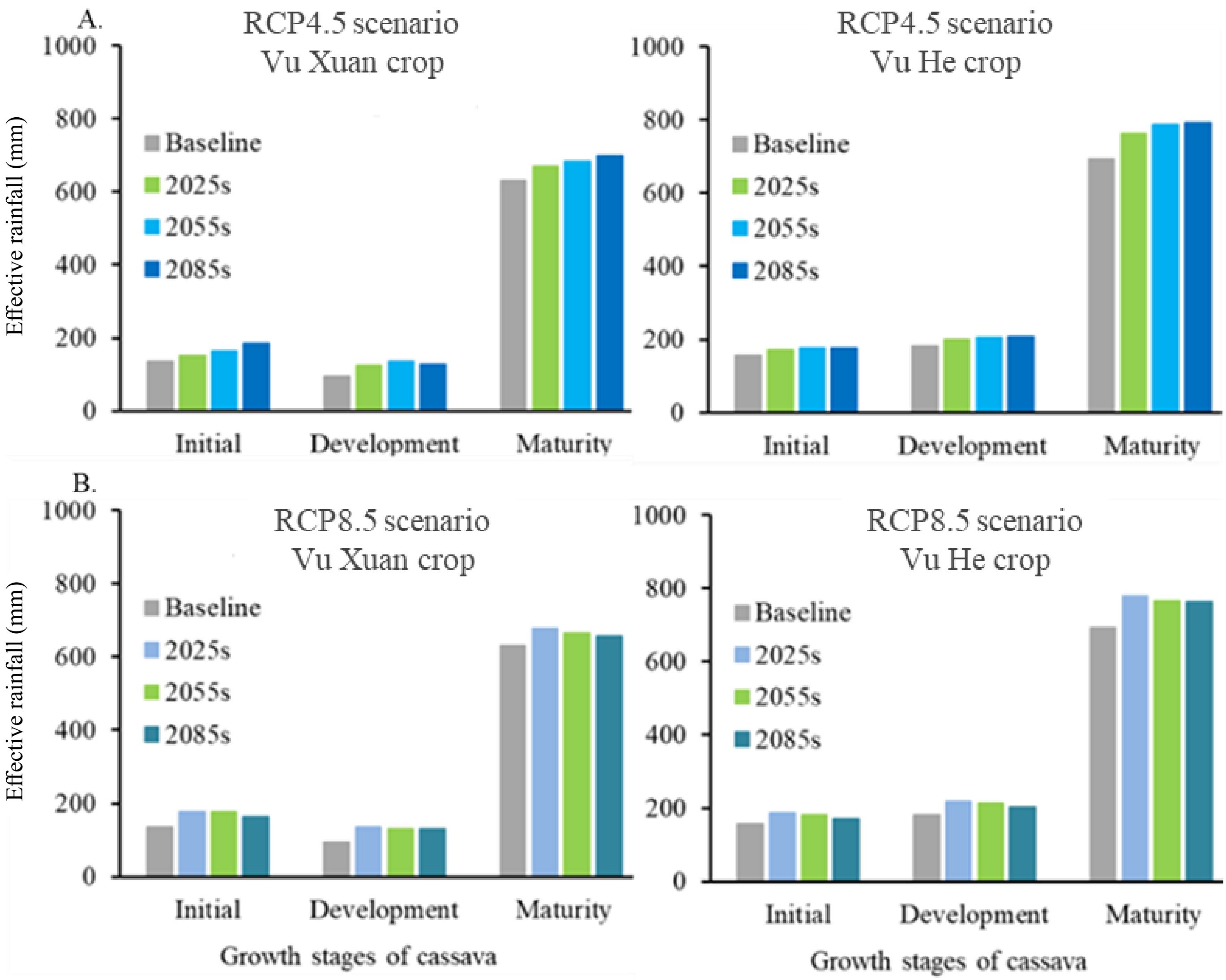

Figure 4. Simulated effective rainfall (Peff) for Vu Xuan and Vu He cassava crops corresponding to the baseline period and future time windows (2025s, 2055s, and 2085s) of the RCP4.5 scenario (A) and RCP8.5 scenario (B)

and crop water uptake may have plateaued or started to decline.

Under baseline conditions, the Vu Xuan cassava had a sum of positive CWRs (irrigation demand) of 469 mm, with the highest demand in the initial (54.0 mm) and development (129.0 mm) stages. The maturity stage exhibited a substantial water surplus (-113.1 mm). The Vu He cassava had a lower sum of positive CWRs (229.1 mm), with demand in the initial stage (20.6 mm) but surpluses in development (-12.4 mm) and maturity (-177.2 mm), reflecting its later planting aligning more with rainy periods. This seasonal deficit/surplus pattern is crucial for adaptation planning.

Under the moderate RCP4.5 scenario, a consistent decrease in the sum of positive CWRs (net irrigation deficit) was projected for both crops across all future time windows (Figures 5A and B). For Vu Xuan, the irrigation

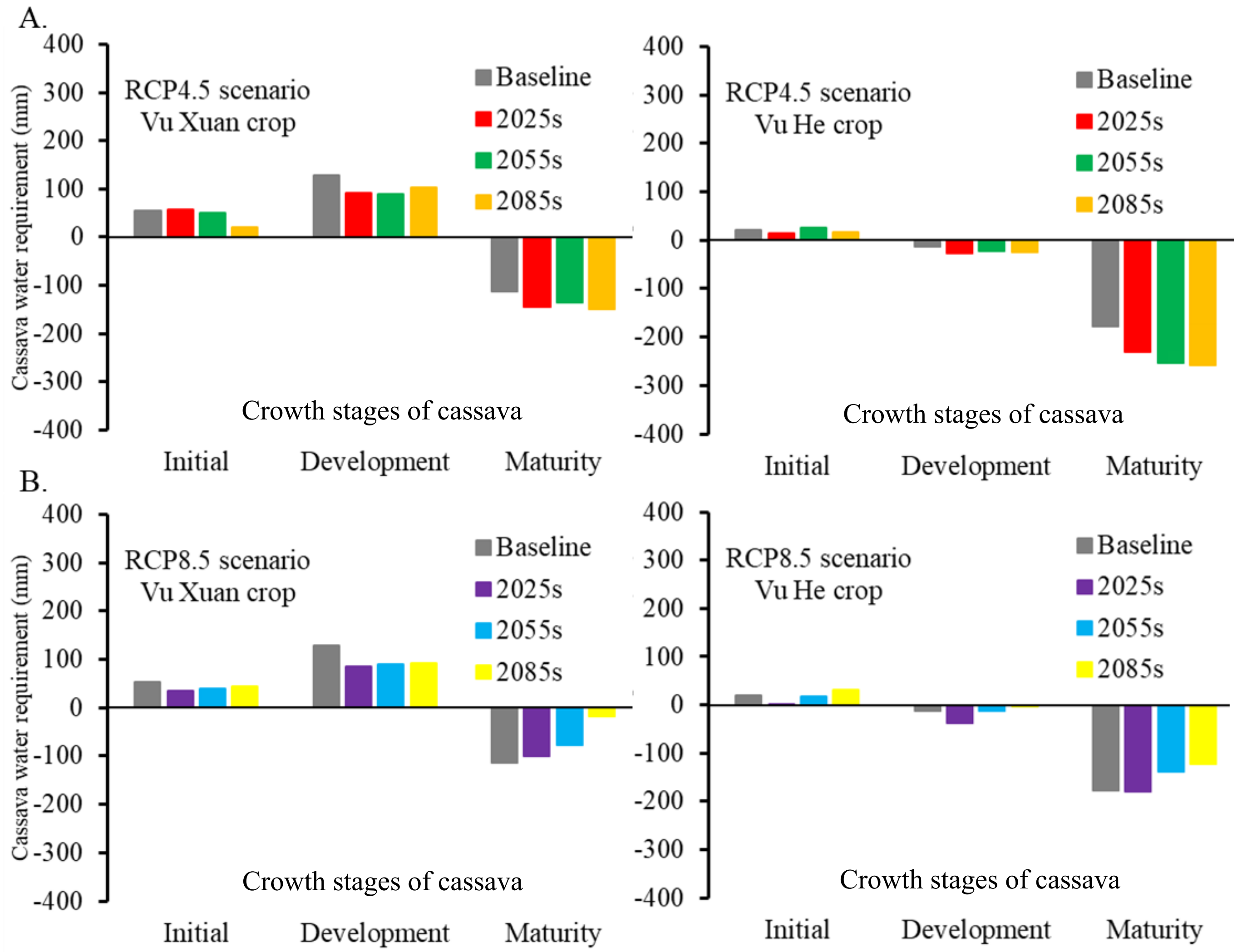

Figure 5. Simulated crop water requirement (CWR) of Vu Xuan and Vu He crops for the baseline period and future time windows (2025s, 2055s, and 2085s) of the RCP4.5 scenario (A) and RCP8.5 scenario (B)

deficit decreased by 11.8% (2025s), 12.4% (2055s), and 16.9% (2085s) compared to the baseline. For Vu He, the reduction was 9.0% (2025s), 11.3% (2055s), and 13.7% (2085s) (Table 9). Mechanistically, this decrease is primarily due to projected increases in Peff, outweighing the more modest increases in ETa under RCP4.5. The enhanced Peff, especially during traditionally drier early growth stages, more effectively meets crop water needs.

The high-emissions RCP8.5 scenario presented a more complex trend (Figure 5B). For Vu Xuan, an initial slight decrease in irrigation deficit was projected for the 2025s (-10.4%) and 2055s (-3.7%), followed by a significant

Table 9. Cassava water requirement (mm) of Vu Xuan and Vu He crops corresponding to windows of the RCP4.5 and RCP8.5 scenarios

Crop	Growth stages	Baseline	Future scenarios					
			RCP4.5			RCP8.5		
			2025s	2055s	2085s	2025s	2055s	2085s
Vu Xuan	I	54.0	57.5	49.8	21.2	34.2	38.4	44.3
	II	129.0	90.7	88.4	103.2	85.7	88.5	92.5
	III	-113.1	-144.1	-135.6	-149.8	-100.9	-76.8	-18.3
Total		69.9	4.1	4.1	2.6	-25.4	19	50.1
CWR (mm)		469.	414.3	382.7	355.7	408.1	435.5	529.4
Changed		-	-11.8%	-12.4%	-16.9%	-10.4%	-3.7%	-13.6%
Vu He	I	20.6	14.5	26.2	16.9	1.6	17.8	30.9
	II	-12.4	-27.2	-23	-24.3	-37.9	-11.8	-2.2
	III	-177.2	-279.5	-253.9	-257.4	-180.8	-138.2	-121.7
Total		-169.0	-282.3	-282.3	-250.7	-255.8	-220.5	-13.2
CWR (mm)		229.1	208.6	203.3	197.5	180.7	236.7	278.1
Changed		-	-8.98%	-11.26%	-13.7%	-21.1%	-3.3%	21.3%

"-" A negative value indicates a water surplus (Peff > ETa), not a deficit. CWR - Cassava water requirement increase of 13.6% by the 2085s (Table 9). For Vu He, a more pronounced initial decrease in deficit was seen in the 2025s (-21.1%) and 2055s (-3.3%), but this also shifted to a substantial increase of 21.3% by the 2085s. The eventual increase in CWR under RCP8.5 by the end of the century is driven by larger increases in ETa (due to significantly higher temperatures) that are no longer fully compensated by increases in Peff, especially during critical early growth phases. This creates a greater atmospheric water demand that outstrips available rainfall, even if total annual rainfall increases, highlighting the importance of rainfall distribution relative to crop demand.

The consistent seasonal CWR pattern—higher demand during early, drier stages (January-May for Vu Xuan; March-July for Vu He) and surplus during later, wetter stages—persists across scenarios and offers a clear avenue for adaptation. The divergent CWR projections, particularly the increased stress under RCP8.5 by 2085s, highlight the need for strategic adjustments to planting calendars: For Vu Xuan systems, under the increasing stress of the RCP8.5, delaying planting by approximately 15-20 days could shift the water-sensitive early development stages to better coincide with the onset of more reliable monsoon rainfall, mitigating early-season deficits.

For Vu He systems, which also face increased CWR in the initial stage under the RCP8.5 by 2085s, advancing planting by approximately two weeks might help the crop establish before the most severe water stress periods projected for the mid-to-late century, or better utilize any shifts in early rainfall patterns.

These potential adjustments resonate with findings from Lee & Dang (2020b), who also explored optimized planting calendars for cassava in Vietnam. The efficacy of these shifts will depend on the precise changes in local rainfall onset and distribution, underscoring the need for localized climate forecasting. While both Vu Xuan and Vu He varieties face challenges, these strategic adjustments represent adaptive pathways rather than any inherent resilience of one variety over another under future climate conditions.

Conclusions

1. Under the moderate RCP4.5 scenario, the projections show a consistent decrease in the net irrigation deficit for both the Vu Xuan (up to 16.9%) and Vu He (up to 13.7%) cropping systems by the 2085s. This optimistic outlook is driven by increases in effective rainfall that are projected to outpace the more modest rises in evapotranspiration, thereby reducing the crop's reliance on supplemental irrigation.

2. Conversely, the high-emissions RCP8.5 scenario paints a more challenging picture. While early and mid-century periods may see temporary relief, the long-term trend points to a significant increase in the net irrigation deficit by the 2085s, reaching 13.6% for Vu Xuan and a substantial 21.3% for Vu He. This shift is a direct result of temperature-driven increases in evapotranspiration that eventually overwhelm the benefits of increased rainfall, particularly during the critical initial and development stages of the crop.

3. A critical insight from this analysis is the persistent seasonal water-demand pattern: a deficit during the early, drier growth stages followed by a surplus during the later, monsoon-aligned maturity stage. This predictable cycle, consistent across all scenarios, represents both the primary vulnerability of the crop and the key leverage point for effective adaptation.

4. Consequently, strategic adjustments to planting calendars emerge as a crucial and accessible adaptation strategy. For Vu Xuan systems facing increased stress under RCP8.5, delaying planting by 15-20 days can better align water-sensitive growth phases with the onset of monsoon rains. For Vu He systems, advancing the planting date by approximately two weeks could allow the crop to establish before peak water stress periods. These adjustments represent proactive measures to synchronize crop phenology with future water availability.

Authors' contributions: Conceptualization, T. V. H. Hoang, T. A. Dang and T. T. T. Nguyen; methodology and validation, formal analysis, T. V. H. Hoang and T. A. Dang; writing-original draft preparation, T. V. H. Hoang and T. T. T. Nguyen; review and editing, T. V. H. Hoang, T. A. Dang and T. T. T. Nguyen. All authors have read and agreed to the published version of the manuscript.

Supplementary documents: No additional data from the inquiry.

Conflict of interest: Authors confirm that we have no conflict of interest.

Financing statement: Authors have not received research grants from any agency or organization.

Acknowledgements: The authors would like to sincerely thank the reviewers and the editorial board for reviewing this work and providing feedback to help improve the manuscript.

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