Agr. Nat. Resour. 58 (2024) 213–220

AGRICULTURE AND NATURAL RESOURCES

Journal homepage: http://anres.kasetsart.org

Research article

Climate change-induced irrigation water demand alteration in rain-fed cassava field

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Article Info

Article history:
Received 16 January 2024
Revised 14 February 2024
Accepted 20 February 2024
Available online 11 April 2024

Keywords:
Biomass yield,
Climate change,
CSM-MANIHOT,
Scenarios,
Timeframes

Abstract

Importance of the work: Climate change is anticipated to bring about a rise in temperature, which in turn could be expected to trigger an increase in irrigation water demand (IWD), especially in rain-fed plant cultivation (RPCs).

Objectives: To estimate the IWD of cassava fields in Dong Xuan district, Phu Yen Province, Vietnam under future scenarios.

Materials & Methods: The crop model CSM-MANIHOT was applied to estimate the IWD of cassava in rain-fed cultivation fields under current conditions and future climate scenarios.

Results: The IWD for the Vu Xuan crop showed a minor decrease across all stages (initial, development and maturity) compared to the current period, in the timeframes 2011–2040, 2041–2070 and 2071–2099 under both the RCP4.5 and RCP8.5 scenarios. Similarly, the Vu He crop experienced a slight decrease in IWD during the initial and development stages, while there was a significant reduction during all timeframes under the RCP4.5 and RCP8.5 scenarios compared to the current period.

Main finding: The findings highlighted the complex dynamics of IWD for different stages of cassava for both the Vu Xuan and Vu He crops under changing climatic conditions.

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https://doi.org/10.34044/j.anres.2024.58.2.06

Introduction

In recent years, the agricultural sector has experienced major climate change impact, which has had far-reaching consequences on various socioeconomic aspects (Kyu and An, 2019). Studies conducted in recent decades have highlighted the substantial shifts in temperature and rainfall patterns examined in deltaic regions worldwide (Lee and Dang, 2020). Agriculture, being intimately linked to climatic variables, is recognized as one of the sectors that is particularly vulnerable to climate change impact (Sawatraksa et al., 2019; Nguyen et al., 2022). Changes in crop cultivation practices have been mainly caused by climate change impact in recent decades (An et al., 2021). The frequent occurrence of drought events due to increased temperature and decreased rainfall has had evident effects on irrigation water demand (IWD) and consequently has altered the growth duration of crops and their life cycles (Phoncharoen et al., 2021). Therefore, the construction of an adaptive strategy to mitigate climate change impact has become imperative (An et al., 2021).

In the context of the agricultural sector being severely affected by climate change, crop models (such as the APSIM-Agricultural Production Systems Simulator, the CSM-CROPSIM-Cropping System Model, the LINTUL- Light Interception and Utilization Model, ROPGRO, SUCROS-Simple and the Universal CRop grOwth Simulation Model, CSM-MANIHOT) have been reviewed for their usefulness in simulating crop features and contributing to implementing appropriate management solutions (Kyu and An, 2017). For example, in Brazil, Santos et al. (2022) studied climate change impact on the cassava yield in the Guapimirim municipality using climate projections. Their results revealed that reductions of 8.6 t/ha and 9.7 t/ha occurred under the Representative Concentration Pathway (RCP) trajectory approach to greenhouse gas concentration adopted by the Intergovernmental Panel on Climate Change for the RCP4.5 and PCP8.5 scenarios, respectively (Intergovernmental Panel on Climate Change, 2014). In Nigeria, Emmanuel et al. (2023) evaluated the cassava yield under climate change impact based on 419 cassava farmers and showed that the main impacts influencing cassava production included meteorological (95.7%) and tradition and cultural (94.5%) factors. Adiele et al. (2021) used the LINTUL-Cassava model to estimate the IWD of cassava plants under different climatic scenarios and identified nutrient omissions in the cassava cultivation fields. In Vietnam, Kyu and An (2019) applied the Aquacrop model to simulate the cassava yield in the rain-fed plant cultivation fields of Phu Yen province and affirmed that the applied model was suitable for simulating the cassava yield across the study area. Among the crop models discussed earlier, the CSM-MANIHOT model has been recognized as a valuable tool for simulating the developmental phases and productivity of cassava under conditions of restricted irrigation (Moreno-Cadena et al., 2021; Sawatraksa et al., 2023).

Materials and Methods

Study area

The study was deployed in Dong Xuan district (12º45′–13º06′N; 108º40′–109º07′E), in the northwest of Phu Yen province (Fig. 1). Dong Xuan, a rural district in Phu Yen province, spans an area of 1,063 km² and has a population of 59,260. The region is renowned for its cassava cultivation, encompassing 4,100 ha and a cassava production of nearly 90,000 thousand t/yr (Kyu and An, 2018). However, agricultural endeavors in the area have confronted heightened vulnerability in recent years due to water scarcity, leading to diminished crop outputs (Pham et al., 2021). The current research was conducted in a region characterized by a tropical monsoon climate, experiencing two distinct wind seasons: northeast and southwest (Pham et al., 2021). Dong Xuan experiences high temperatures, reaching up to 26.5°C, with average annual precipitation of approximately 1,766 mm. Most of the rainfall, accounting for over 80%, is concentrated in the wet season spanning September to December. Conversely, the dry season, from January to August, receives only 20% of the total rainfall. This limited rainfall during the dry season exacerbates the scarcity of irrigation water, particularly in the context of climate change.

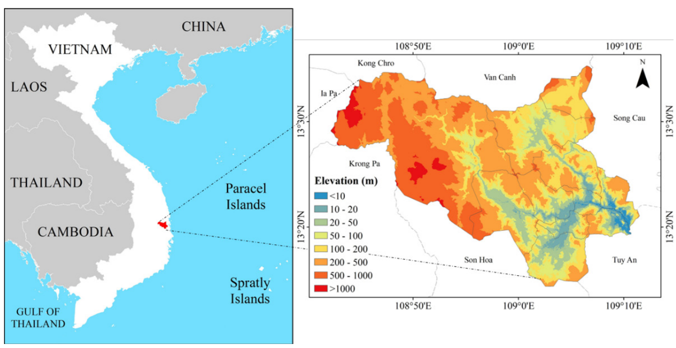

Fig. 1 Map of study area

Data collection

Current climatic data (2001–2023) were collected from the Phu Yen hydrometeorological station, while future climate scenarios, aligned with the RCPs, were obtained from downscaled climate projections generated using six global circulation models (GCMs), as shown in Tables 1 and 2. These GCMs were released by the Ministry of Natural Resources and Environment, Vietnam (Kyu and An, 2017). The climate projections encompassed three timeframes: 2011–2040, 2041–2070, and 2071–2099, for both the RCP4.5 and RCP8.5 scenarios (Figs. 2A, 2B).

The future projections indicated an upward trend in both precipitation and temperature relative to the reference period, as demonstrated by the chosen GCMs, for the timeframes of 2011–2040, 2041–2070 and 2071–2099. These alterations were examined uniformly across the entire study area, as illustrated in Fig. 2.

Accordingly, the GCMs were designed based on the global scale climate variables that were hypothesized for the different emission scenarios. Although their representativeness, spatial resolution, and quality could be debated based on different perspectives, the study applied six common GCMs to identify the climate change impact on local climate features (Table 2).

In the Dong Xuan district, several cassava varieties (KM419, KM414, KM444 and KM440) are commonly cultivated in the RPCs (Kyu and An, 2018). Among these varieties, KM419 is predominant (Pham et al., 2021). Notably, the KM419 variety offers advantages such as a high estimated yield of up to 45 t/ha, resistance to pests and a relatively short growth cycle in the range 9–11 mth (Table 3).

According to customary farming methods, farmers typically engage in weed clearance and land plowing prior to creating beds for planting the cassava cuttings. The spacing for sowing the cassava cuttings is 0.8 m ×0.8 m for the spring crop, ‘Vu Xuan’, commencing from the third week of January and lasting until the fourth week of November. In contrast, the summer crop, referred to ‘Vu He’, has a spacing of 0.8 m ×0.9 m and is sown from the second week of March to the fourth week of December (Table 3).

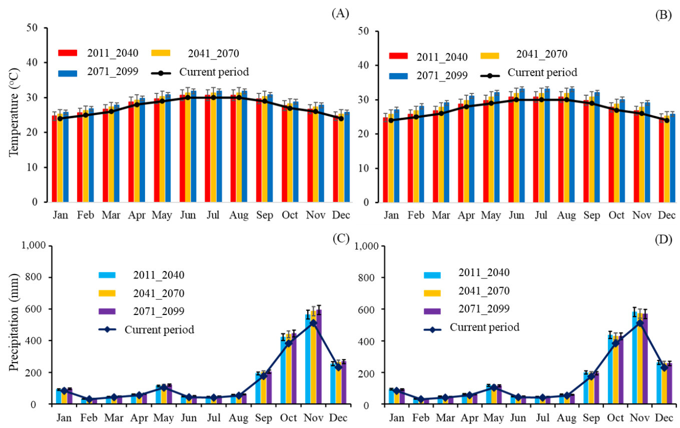

Fig. 2 Current climatic and projected future scenarios for: (A) RCP4.5 scenario for temperature change; (B) RCP8.5 scenario for temperature change; (C) RCP4.5 scenario for precipitation change; (D) RCP8.5 scenario for precipitation change (SD represents uncertainty range in projections resulting from application of alternative global circulation models)

Table 1 Current climatic conditions and projected future scenarios regarding rainfall and temperature (SD reveals range of uncertainty in projections resulting from application of alternative global circulation models)

Current period (2001–2023)	Future periods	RCP4.5	Change	RCP8.5	Change
Temperature 26.5 °C	2011–2040	27.2±0.4°C	0.7°C	27.3±0.6°C	0.8°C
	2041–2070	27.8±0.9°C	1.3°C	28.3±1.3°C	1.8°C
	2071–2099	28.3±1.3°C	1.8°C	29.6±2.5°C	3.1°C
Precipitation 1766 mm	2011–2040	1942.6±3.2mm	10.0%	1984.9±3.2mm	12.4%
	2041–2070	2002.6±5.2mm	13.4%	1949.6±2.7mm	10.4%
	2071–2099	2020.3±0.9mm	14.4%	1944.3±1.0mm	10.1%

Table 2 Category of global circulation models applied in this study

Model	Country	Center	References
ECHAM4	Germany	Max-Planck Institute for Meteorology	Röckner et al. (1992)
UKMO-HadCM3	UK	Hadley Centre for Climate Prediction and Research Met Office United Kingdom	Gordon et al. (2000)
CGCM2.0	Canada	Canadian Centre for Climate Modelling and Analysis	Paolino et al. (2011)
CSIRO-Mk3.0	Australia	CSIRO Atmospheric Research	Gordon et al. (2002)
CCSR	Japan	Atmosphere and Ocean Research Institute	Hiroyasu (2015)
GFDL-R30	USA	National Oceanic and Atmospheric Administration	Delworth et al. (2002)

Table 3 Crop characteristics of cassava cultivation fields across study area

Crop	Schedule		Variety	Method	Fertilizer (kg/ha)				Manure (t)
	Sow	Harvest			Urea	P_2O_5	K_2O	NPK	
Vu Xuan	20 Jan	22 Nov	KM419	Sow	120	220	180	180	10-15
Vu He	10 Mar	26 Dec	KM419	Sow	130	240	220	180	10-15

In the RPCs of Dong Xuan district, specific fertilizer recommendations are provided for both the Vu Xuan and Vu He crops, as outlined in Table 3. For optimal growth, it was advised to apply 100% (10–15 t/ha) manure in the land preparation stage, while 50% urea, P_2O_5, K_2O and NPK were recommended for the initial stage, 30% urea, P_2O_5, K_2O and NPK in the development stage and 20% urea, P_2O_5, K_2O and NPK as fertilizer fertilized for both the Vu Xuan and Vu He crops (Table 3).

Description of the CSM-MANIHOT model

The CSM-MANIHOT model has been developed to simulate the growth and development of root crops, encompassing the entire cycle from sowing to harvesting (Phoncharoen et al., 2021). This model is widely applied to simulate daily photosynthesis processes and the growth stages of root crops (Moreno-Cadena et al., 2021). It integrates four modules that incorporate climate variables (such as temperature, radiation and rainfall), soil characteristics (including texture and composition), crop management practices (such as crop schedule, irrigation and fertilizer application), and the genetic traits of cassava plants. Notably, the CSM-MANIHOT model incorporates novel processes that enhance the accuracy of simulating cassava growth and improve its capability to predict biomass yield and root yield (Phoncharoen et al., 2021; Sawatraksa et al., 2019). For a comprehensive description of the CSM-MANIHOT model, readers are referred to the work of Moreno-Cadena et al. (2021).

Model performance evaluation

To assess the accuracy of the applied model, simulated results of root yield were compared with examined data from the 2001_2023 crop seasons. Statistical metrics, consisting of root mean square error (RMSE), normalized root mean square error (NRMSE), the index of agreement (d) and the coefficient of determination (R^2), were used to evaluate the level of agreement between the simulated and examined data.

The RMSE, NRMSE, d and R^2 were calculated using Equations 1–4:

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

$$\mathrm{NRMSE} = 100\,\frac{\mathrm{RMSE}}{\bar{O}} \quad (2)$$

$$d = 1 - \frac{\sum_{i=1}^{N}(S_i - O_i)^2}{\sum_{i=1}^{N}(|S_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (3)$$

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

where n is the number of observation samples, S_i is the simulated results and O_i, $\bar{O}$ are the examined and average examined data, respectively.

Results and Discussion

Performance of CSM-MANIHOT model

The CSM-MANIHOT model underwent calibration and validation processes, where simulated results were compared with examined data for both the Vu Xuan and Vu He crops, as presented in Fig. 3. The calibration procedures produced favorable error indices (RMSE 10.1%; NRMSE 2.30; d 0.92; and R^2 0.85). Similarly, the validation procedures had promising outcomes (RMSE 11.8%; NRMSE 2.70; d 0.93; and R^2 0.86). These results confirmed the commendable performance of the utilized model.

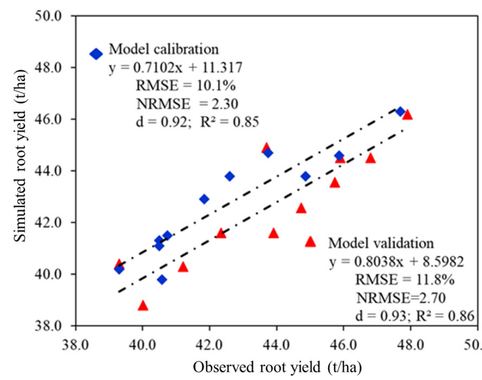

Fig. 3 Performance of CSM-MANIHOT model rated based on calibration (2001_2011) and validation (2012_2023) datasets, where RMSE = root mean square error, NRMSE = normalized root mean square error, d = index of agreement and R^2 = coefficient of determination

Actual evapotranspiration

Table 4 presents the simulation results for the actual evaporation (ETa) projections for the Vu Xuan and Vu He crops in the current period (2001–2023) and for the timeframes 2011–2040, 2041–2070 and 2071–2099 for the RCP4.5 and RCP8.5 scenarios. Based on the current climate parameters, compared to the current period, the simulated ETa for the Vu Xuan and Vu He crops was approximately 898.8 mm and 815.3 mm, respectively. Under the RCP4.5 scenario, there was a slight increase of 3.7–7.0% and 2.6–4.5%, respectively, in the simulated ETa values for the Vu Xuan and Vu He crops, respectively, (Fig. 4A).

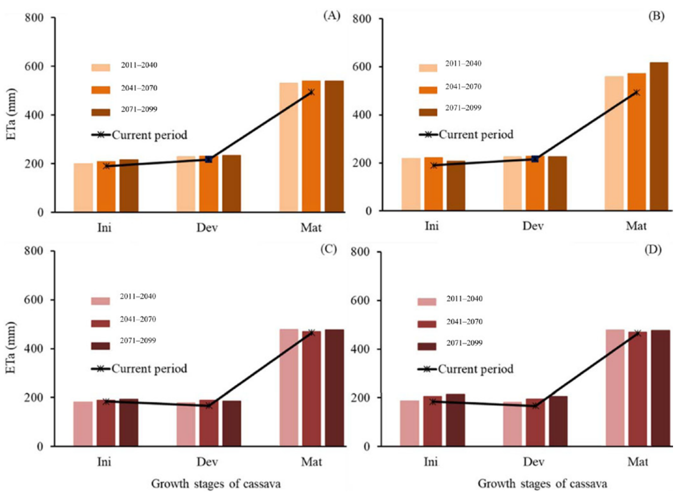

Fig. 4 Simulations of actual evapotranspiration (ETa) corresponding to timeframes for: (A) Vu Xuan cassava crop and RCP4.5 scenario; (B) Vu Xuan cassava crop and RCP8.5 scenario; (C) Vu He cassava crop and RCP4.5 scenario; (D) Vu He cassava crop and RCP8.5 scenario, where Ini = initial, Dev = development and Mat = maturity

Notably, the RCP8.5 scenario exhibited a substantial rise of 8.4–13.7% in the simulated ETa for Vu Xuan and a slight increase of 3.7–9.7% in the simulated ETa for Vu He during the specified timeframes (Fig. 4B).

Based on the simulated results provided in Table 4, the ETa was elevated during the development and maturity stages for the Vu Xuan cassava in the timeframes for the RCP4.5 scenario. Similarly, in the timeframes for the RCP8.5 scenario, there was an increase in the ETa during the development and maturity stages (Fig. 4B). These results suggested that the projected increase in ETa could be attributed to rising temperatures, as temperature has been identified as the primary driving factor for ETa (Lee and Dang, 2020). The temperature increase has been a major concern for farmers in recent years and has garnered considerable attention in agricultural discussions (Nguyen et al., 2022).

Effective rainfall

Table 5 presents the simulated outcomes for the effective rainfall (R_E) for the Vu Xuan and Vu He crops during the timeframes of the RCP4.5 and RCP8.5 scenarios. In the current period, the R_E values for the initial and development stages of the Vu Xuan cassava were 138.2 mm and 97.4 mm, respectively, while for the Vu He cassava, these values were 163.7 mm and 184.3 mm, respectively. Notably, there was a substantial increase in the range 10.5–16.3% for the Vu Xuan and 11.3–16.0% for the Vu He cassava crops during the timeframes of the RCP4.5 and RCP8.5 scenarios. Similarly, an appreciable rise (10.3–13.1% for the Vu Xuan and 9.3–17.3% for the Vu He cassava crops) was predicted compared to the current period (Table 5).

Table 4 Actual evapotranspiration of Vu Xuan and Vu He crops simulated corresponding to timeframes of RCP4.5 and RCP8.5 scenarios

Crop	Growth stage	Current period	Future climate scenario					
			RCP4.5			RCP8.5		
			2011–2040	2041–2070	2071–2099	2011–2040	2041–2070	2071–2099
Vu Xuan	Ini	189.7	198.9	208.4	215.8	218.7	222.3	207.9
	Dev	215.9	228.1	229.6	233.5	225.1	228.3	226.1
	Mat	493.2	531.3	539.7	539.3	557.9	571.3	616.8
Total		898.8	958.3	977.7	988.6	1001.7	1021.9	1050.8
Change		-	+3.7	+5.8	+7.0	+8.4%	+10.6	+13.7
Vu He	Ini	183.6	181.9	188.9	193.2	187.6	204.7	214.3
	Dev	166.4	177.5	189.2	184.7	181.3	193.9	205.8
	Mat	465.3	478.8	469.9	475.7	478.9	469.4	476.5
Total		815.3	838.2	848.0	853.6	847.8	868.0	896.6
Change		-	+2.6	+3.8	+4.5	+3.7	+6.2	+9.7

Ini = initial stage; Dev = development stage; Mat = maturity stage

Table 5 Effective rainfall of cassava crops simulated corresponding to timeframes of RCP4.5 and RCP8.5 scenarios

Crop	Growth stage	Current period	Future climate scenario					
			RCP4.5			RCP8.5		
			2011–2040	2041–2070	2071–2099	2011–2040	2041–2070	2071–2099
Vu Xuan	Ini.	138.2	157.8	168.6	187.4	169.7	180.6	167.2
	Dev	97.4	136.4	139.2	135.9	147.1	136.9	134.5
	Mat	647.0	681.2	694.5	703.4	679.4	680.7	671.8
Total		882.6	975.4	1002.3	1026.7	996.2	998.2	973.5
Change		-	+10.5	+13.6	+16.3	+12.9	+13.1	+10.3
Vu He	Ini	163.7	174.5	178.1	180.7	190.1	186.4	169.8
	Dev	184.3	201.2	205.6	210.2	221.9	216.4	200.1
	Mat	701.9	768.1	797.4	801.6	794.2	761.9	753.7
Total		1,049.9	1,143.8	1,181.1	1,195.2	1,206.2	1,164.7	1,123.6
Change		-	+11.3	+14.9	+16.0	+17.3	+13.3	+9.3

Ini = initial stage, Dev = development stage, Mat = maturity stage

The simulation results indicated that the levels of R_E during the maturity stage were substantially high in the current period, with values of 647.0 mm and 701.9 mm for the Vu Xuan and Vu He crops, respectively. Additionally, there were slight increases (5.3–8.7% for the Vu Xuan and 3.8–5.2% for the Vu He cassava crops) corresponding to the timeframes for the RCP4.5 scenario (Fig. 5A). Similarly, in the timeframes for the RCP8.5 scenario, there are notable increases (9.4–14.2%) for the Vu Xuan cassava crop and slight increases (7.3–12.4%) for the Vu He cassava crop (Fig. 5B).

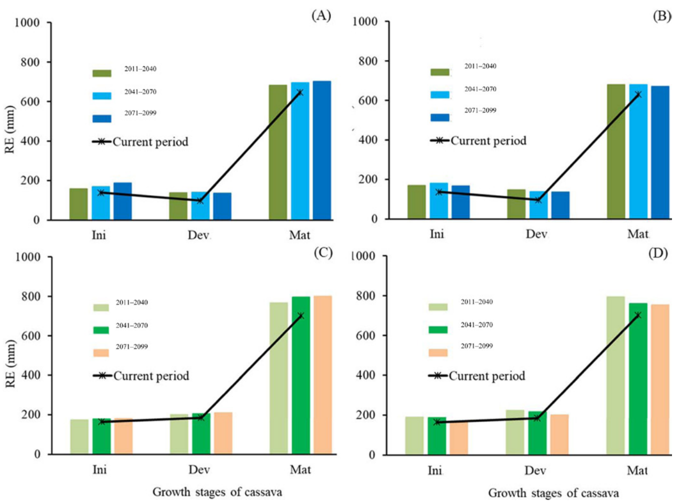

Fig. 5 Simulations of effective rainfall (RE) corresponding to timeframes for: (A) Dong Xuan cassava crop and RCP4.5 scenario; (B) He Thu cassava crop and RCP8.5 scenario; (C) Dong Xuan cassava crop and RCP4.5 scenario; (D) He Thu cassava crop and RCP8.5 scenario, where Ini = initial, Dev = development and Mat = maturity

Irrigation water demand

Table 6 presents the simulation results for the IWD of the Vu Xuan crops corresponding to the timeframes under the RCP4.5 and RCP8.5 scenarios. In the current period, the IWD for the Vu Xuan crop during the initial stage was 43.6 mm. However, in the future climate scenarios, a decrease in the IWD was projected, with values of 52.6 mm, 43.1 mm, 11.8 mm and of 38.8 mm, 31.9 mm and 84.3 mm for the timeframes 2011–2040, 2041–2070 and 2071–2099, respectively, for the RCP4.5 and RCP8.5 scenarios, respectively.

The development stage also had a decrease in IWD from 103.7 mm in the current period to values in the range 76.9–85.7 mm under the future climate scenarios. Surprisingly, there were negative values for the maturity stage, indicating a decreasing water requirement across all timeframes and scenarios. Overall, the simulation results demonstrated a varying trend in IWD for the Vu Xuan crop, with decreases in water demand during the initial, development and maturity stages (Table 6).

Table 6 showcases the simulation results for the IWD of the Vu He crop, corresponding to timeframes under the RCP4.5 and RCP8.5 scenarios. In the current period, the IWD for the Vu He crop during the initial stage was 23.7 mm. However, under the future climate scenarios, decreases in IWD were projected, with values in the range 13.1–33.6 mm for the timeframes of 2011–2040, 2041–2070, and 2071–2099 under the RCP4.5 and RCP8.5 scenarios (Fig. 6A, B). Furthermore, the development stage showed a decreasing trend in IWD, with negative values in the range -19.9 to -4.4 mm. Similarly, the maturity stage showed a substantial reduction in IWD, with negative values in the range -155.8 to -174.9 mm across all timeframes and scenarios. Overall, the simulation results demonstrated a consistent decrease in IWD for the Vu He crop, indicating the potential impact of future climate scenarios on water demand.

Table 6 Simulated irrigation water demand of Vu Xuan and Vu He crops corresponding to timeframes of RCP4.5 and RCP8.5 scenarios

Crop	Growth stage	Current period	Future climate scenario					
			RCP4.5			RCP8.5		
			2011–2040	2041–2070	2071–2099	2011–2040	2041–2070	2071–2099
Vu Xuan	Ini	43.6	52.6	43.1	11.8	38.8	31.9	84.3
	Dev	103.7	76.9	82.9	85.7	67.4	79.5	79.9
	Mat	-75.0	-63.9	-88.4	-49.6	-56.3	-73.9	-21.4
Total		72.3	65.6	37.6	47.9	49.9	37.5	142.8
Changed (%)		-	-9.3	-48.0	-33.7	-31.0	-48.1	97.5
Vu He	Ini	23.7	13.1	26.6	33.6	-2.5	18.3	44.5
	Dev	8.6	-19.9	-11.7	-4.4	-40.6	-22.5	5.7
	Mat	-128.4	-155.8	-174.9	-171.2	-168.7	-154.9	-145.6
Total		-96.1	-162.6	-160.0	-142.0	-211.8	-159.1	-95.4
Changed		-	-69.2	-66.5	-47.8	-120.4	-65.6	0.7

Ini = initial stage, Dev = development stage, Mat = maturity stage

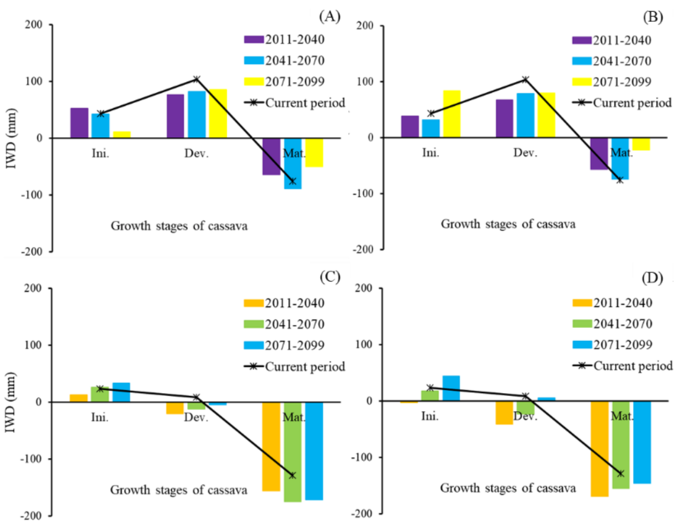

Fig. 6 Simulations of irrigation water demand (IWD) corresponding to timeframes for: (A) Vu Xuan cassava crop and RCP4.5 scenario; (B) Vu He cassava crop and RCP8.5 scenario; (C) Vu Xuan cassava crop and RCP4.5 scenario; (D) Vu He cassava crop and RCP8.5 scenario, where Ini = initial, Dev = development and Mat = maturity

Conclusion

The study applied the CSM-MANIHOT model to evaluate the irrigation water demand for rain-fed plant cultivation fields across Dong Xuan district, Phu Yen province, Vietnam under the current and future climate scenarios. The findings indicated that the abundance of irrigation water from rain-fed, along with an uptrend of rainfall corresponding to future timeframes and the RCP4.5 and RCP8.5 scenarios, contributed as a positive response to irrigation water demand across the study area. Overall, the simulation results demonstrated a consistent decrease in irrigation water demand for the Vu Xuan and Vu He cassava crops, indicating the potential impact of future climate scenarios on rain-fed irrigation water. These findings underscore the need for adaptive irrigation strategies in agricultural practices to ensure sustainable water management for cassava fields in Phu Yen province, Vietnam in the face of changing climatic conditions.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

The authors appreciate the constructive comments made by the reviewers.

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