



Research article

Capability of cassava model to determine biomass of two branching types at different plant spacings

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Abstract

Importance of the work: Evaluation of the Cropping System Model (CSM)-MANIHOT-Cassava provides the opportunity to apply for determining the suitable plant spacings.

Objectives: This research aimed to show potential of the CSM-MANIHOT-Cassava in simulating biomass of two cultivars using different plant spacings.

Materials & Methods: The Rayong 9 (RY9, non-branching) and Kasetsart 50 (KU50, branching) cultivars were planted at spacings of 120 cm × 80 cm (10,418 plants/ha) and 120 cm × 100 cm (8,331 plants/ha). The data recorded were soil properties before planting, daily weather parameters, crop management details and crop dry weight.

Results: The average values for the index of agreement and for the normalized root mean square error (*n*RMSE) for biomass accumulation were 0.91 and 34.1%, respectively. For biomass at final harvest, the average *n*RMSE value was 31.0%. However, the results from both the simulation and field experiment identified the KU50 cultivar with spacing at 120 cm × 80 cm as desirable treatment for total crop dry weight. Model application in different scenarios showed that a wider plant spacing tends to produce a higher simulated storage root dry weight per area under irrigated growing conditions, while a narrower plant spacing tends to give higher simulated crop productivity under rainfed conditions.

Main finding: This research demonstrated the possibility of applying the CSM-MANIHOT-Cassava as an informative tool to help identify a suitable plant spacing for cassava.

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Introduction

Cassava is an economically competitive crop in Thailand, which is the largest exporter of cassava globally (Food and Agriculture Organization of the United Nations, 2018). This crop is useful for human food, animal feed and various industrial products (Howeler, 2014). According to the latest available records, Thailand produced 31.08 million t of cassava root (fresh weight), with an average yield of 22.41 t/ha (Food and Agriculture Organization of the United Nations, 2021). This is lower than the potential root yield of approximately 80 t/ha (Howeler, 2013). Using the appropriate plant spacing or plant density is an optional strategy to improve cassava productivity and increase land-use efficiency. In addition, a shortage of labor and high labor costs are currently serious problems for the Thai agricultural sector (International Labour Organization, 2013). Therefore, the mechanization of cultural practices could overcome some of these limitations. Selection of plant spacing that facilitates mechanization of planting, weeding, fertilizer application and harvesting is a promising strategy. However, a study to determine the appropriate plant spacing involves a number of trials that consume time and resources.

The Decision Support System for Agrotechnology Transfer (DSSAT) is a software program that includes several dynamic crop models for simulating crop growth and yield based on data from many years, various growing environments and different management practices (Jones et al., 2003; Hoogenboom et al., 2019a, b). Potential applications of the models for agricultural research have been reported for various crops, such as peanut (Banterng et al., 2006), rice (Vilayvong et al., 2015), wheat (Andarzian et al., 2008; Ahmed et al., 2016), maize (Soler et al., 2007) and cotton (Paz et al., 2012).

A cassava cropping system model (CSM-MANIHOT-Cassava) has been developed and has been incorporated into DSSAT (Hoogenboom et al., 2019a, b). This model explains crop growth and development systems through mathematical equations which respond to climatic factors, soil properties and crop management practices (Moreno-Cadena et al., 2020). The model calculates crop photosynthesis by multiplying the solar radiation intercepted by the solar radiation use efficiency. The function for crop development is based on the summation of thermal time with different cardinal temperatures for the process of branching that is intimately related to flowering. The difference in branching habit leads to different sizes and structures of the cassava canopy that could affect crop photosynthate and biomass accumulation (Phoncharoen et al., 2019; Santanoo et al., 2020).

The CSM-MANIHOT-Cassava model allows researchers to quantify the impact of different growing environments on growth and yield, including plant spacing. The model has been used to evaluate the responses of cassava to certain rates of nitrogen fertilizer for some soil series (Kaweewong et al., 2013), different planting dates in a specific location (Phoncharoen et al., 2021b) and different upper paddy fields following rice (Sawatraksa et al., 2021). Validating the CSM-MANIHOT-Cassava model for the simulation of the growth and yield at different plant spacings is still pending. Therefore, the aim of this research was to assess and apply the CSM-MANIHOT-Cassava model to simulate the response of two different branching cultivars to plant spacings. If the model has potential to capture the performances of cassava planted at different spacings, then it can be used as a supporting tool to determine the appropriate plant spacing to improve crop productivity.

Materials and Methods

Experimental detail

The different performance levels of two cassava cultivars were evaluated under rainfed conditions and at two different plant spacings using a factorial experiment in a randomized complete block design with three replications. Rayong 9 (RY9, a non-branching cultivar) and Kasetsart 50 (KU50, a branching cultivar) were assigned as the first factor. Branching for KU50 arises from axillary bud growth from the apex of the main stem; this cultivar normally presents second and third branching before flowering. In contrast, the RY9 cultivar is erect and it generally has no branching during the crop vegetation period (Phoncharoen et al., 2019). This erect plant type generates late and rare flowering. However, the study by Pineda et al. (2020a) reported that an extended photoperiod with red light-emitting diodes with 625–635 nm wavelength all night long or through night-breaks could reduce cassava plant height and the number of days to first branching in nonflowering or late-flowering genotypes. Other factors that can help induce flowering in cassava are plant growth regulators, cool temperature (22°C) and pruning (Pineda et al., 2020b; Oluwasanya et al., 2021a, b).

The second factor considered in the current study was two different plant spacings, consisting of 120 cm × 80 cm (10,418 plants/ha) and 120 cm × 100 cm (8,331 plants/ha). The experiments were conducted at Khon Kaen (16° 29' N, 102° 49' E and 195 m above sea level) and Maha Sarakham (16° 11' N, 103° 12' E and 200 m above sea level) in Thailand, during July 2019–May 2020.

Land preparation before planting was done based on the ordinary procedures for cassava growth. The 20 cm stem cuttings from plants aged 8 mth were used as planting material. The trials were planted on 20 July 2019 and 27 July 2019 in Khon Kaen and Maha Sarakham, respectively. At 30 days after planting (DAP), weed control was carried out manually and fertilizer application was conducted for all plots, consisting of N, P₂O₅ and K₂O at 46.9 kg/ha, 21.9 kg/ha and 56.3 kg/ha, respectively. At 60 DAP, weed management and fertilizer application were carried out using the same techniques as at 30 DAP.

Soil samples down to a depth of 210 cm were collected before planting and split into 14 layers (15 cm each) for both experimental sites. The soil samples were used to determine pH, organic carbon, total nitrogen, ammonium and nitrate concentrations, bulk density and the proportions of sand, silt and clay. The Khon Kaen soil in the depth range 0–30 cm was

sandy (Table 1) and the values for all depths for soil pH were in the range 4.7–6.6, organic carbon was in the range 0.056–0.661% and total nitrogen was in the range 0.001–0.018%. The soil properties at Maha Sarakham were more uniform through different depths with a sandy loam texture and a bulk density of 1.51–2.02 g/cm³, soil pH values in the range 4.44–5.00, soil organic carbon in the range 0.144–0.665% and nitrogen in the range 0.005–0.024% (Table 1).

Crop data were observed from six sampled plants per plot at 60 DAP, 120 DAP, 180 DAP, 210 DAP, 240 DAP and 270 DAP. The sampled plants were separated into leaf, petiole, stem, root and storage root and the fresh weights of all plant organs were recorded. The samples (approximately 10% fresh weight of each organ) of all plant organs were oven-dried at 80°C until a constant weight. For final harvest (300 DAP), total crop dry weight (TW) and storage root dry weight (SW) were recorded from 12 sampled plants.

Table 1 Soil characteristics before planting for Khon Kaen and Maha Sarakham provinces

Location	Depth (cm)	pH (1:1 H ₂ O)	Organic carbon (%)	Total nitrogen (%)	Ammonia (mg/kg)	Nitrate (mg/kg)	Bulk density (g/cm ³)	Soil particle distribution (%)		
								Sand	Silt	Clay
Khon Kaen	0–15	4.8	0.661	0.011	5.2	0.4	1.72	69.3	20.9	9.8
	15–30	4.7	0.375	0.018	11.2	0.8	1.70	73.3	17.9	8.8
	30–45	4.9	0.333	0.018	8.2	2.0	1.60	45.3	33.5	21.2
	45–60	5.0	0.249	0.011	11.1	12.1	1.61	37.1	36.6	26.3
	60–75	4.9	0.217	0.018	14.0	8.5	1.62	51.6	34.4	14.0
	75–90	4.9	0.180	0.005	12.3	8.5	1.57	42.6	35.3	22.1
	90–105	4.9	0.195	0.004	8.8	6.5	1.48	44.9	33.1	22.0
	105–120	6.6	0.225	0.002	13.8	14.8	1.90	33.6	37.3	29.2
	120–135	6.5	0.185	0.002	6.4	2.9	1.90	31.8	39.1	29.0
	135–150	6.1	0.128	0.001	12.8	4.5	1.86	31.8	41.2	27.0
	150–165	5.9	0.088	0.001	10.9	7.4	1.83	35.7	37.2	27.1
	165–180	5.8	0.056	0.002	12.3	12.1	1.90	33.9	39.1	27.0
	180–195	5.9	0.091	0.001	11.6	2.4	1.86	35.9	37.1	27.0
	195–210	5.5	0.120	0.001	14.8	4.5	1.89	35.9	37.1	27.0
Maha	0–15	5.0	0.665	0.014	4.0	7.0	1.51	74.4	17.8	7.8
Sarakham	15–30	4.8	0.596	0.018	2.5	5.3	1.66	70.4	19.8	9.8
	30–45	5.0	0.532	0.021	1.5	4.5	1.65	65.1	24.0	10.9
	45–60	4.7	0.480	0.023	2.7	5.5	1.63	62.2	22.9	14.9
	60–75	4.6	0.441	0.021	3.5	8.8	1.65	62.2	22.9	14.9
	75–90	4.6	0.387	0.024	3.3	6.6	1.60	60.1	24.0	15.9
	90–105	4.6	0.321	0.019	3.1	10.5	1.54	58.2	25.9	15.9
	105–120	4.5	0.190	0.005	7.4	5.9	1.94	50.4	32.8	16.8
	120–135	4.4	0.207	0.006	7.0	8.4	1.74	50.4	32.8	16.8
	135–150	4.5	0.190	0.005	8.0	17.6	1.89	50.4	32.8	16.8
	150–165	4.5	0.162	0.006	9.0	12.0	2.02	56.5	30.8	12.7
	165–180	4.5	0.164	0.007	11.5	7.6	1.89	56.3	30.9	12.8
	180–195	4.5	0.169	0.010	6.0	7.0	1.89	52.4	32.8	14.8
	195–210	4.5	0.144	0.006	9.9	6.2	1.91	48.3	32.9	18.8

Daily weather data (maximum and minimum temperatures, solar radiation, rainfall during the crop vegetation period) were recorded using an automatic weather station. In addition, crop management practices were recorded. At Khon Kaen, the minimum and maximum temperatures were in the ranges 9.5–30.0°C and 25–41.5°C, respectively and total rainfall and solar radiation were 634.4 mm and 5,805.2 MJ/m², respectively (Fig. 1). At Maha Sarakham, the minimum and maximum temperatures during the crop vegetation period were in the ranges 11.5–29.0°C and 26.0–41.0°C, respectively and the amounts of rainfall and solar radiation were 1,318.8 mm and 5,707.2 MJ/m², respectively (Fig. 1).

Model evaluation and application

For evaluation the CSM-MANIHOT-Cassava model requires four categories of data: characteristics of the soil

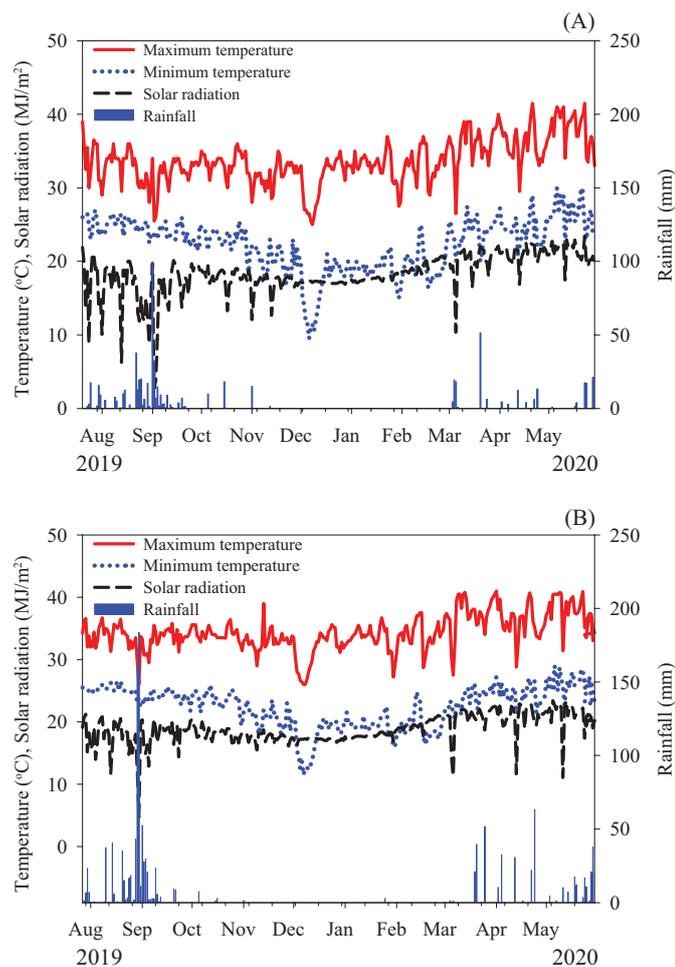


Fig. 1 Temperature, solar radiation and rainfall during crop vegetation period recorded at: (A) Khon Kaen province, Thailand; (B), Maha Sarakham province, Thailand

profile, daily weather parameters, management details and the genetic coefficients of each cassava cultivar (Hoogenboom et al., 2019a, b). The experimental data were input using the standard format of DSSAT. The genetics coefficients were obtained from Phoncharoen et al. (2021a). The index of agreement (d-index) and normalized root mean square error (*n*RMSE) were used to explain the capability of the model (Willmott, 1982; Yang et al., 2014; Li et al., 2015).

For application, the CSM-MANIHOT-Cassava model was run with historical daily weather data (1988–2018) for growth under rainfed and irrigated conditions and for different combinations (10 locations × 2 cultivars × 4 plant spacings) of crop management scenarios. The 10 selected locations were in important cassava production areas in Thailand (Table 2). The daily climatic data were taken from the Meteorological Department, Thailand and included the maximum and minimum temperatures and rainfall. The daily solar radiation was calculated based on the latitude, longitude, elevation and air temperature for all locations (Phakamas et al., 2013). The soil properties of each layer for the 10 locations were obtained from the Land Development Department, Thailand.

Results and Discussion

Model evaluation

The results for the model evaluation based on the accumulation of TW and SW for the cultivars KU50 and RY9 grown under the two different plant spacings for Khon Kaen indicated that the d-index and *n*RMSE varied in the ranges 0.82–0.93 (average = 0.88) and 26.3–47.8% (average = 38.6%), respectively (Fig. 2). For Maha Sarakham, the d-index and *n*RMSE varied in the ranges 0.90–0.98 (average = 0.93) and 13.5–47.2% (average = 29.7%), respectively (Fig. 3). The discrepancies between observed and simulated data could be explained by the effect of the interaction between the conditions of soil tillage, weeds and pests in the actual experiment that were not adequately described by the model (Hoogenboom et al., 2019b). The cassava red mite (*Tetranychus kanzawai*) was observed during the dry period before harvesting in Khon Kaen. This pest damaged leaves, which are a major source for photosynthesis of cassava in the field, ultimately decreasing TW and SW (El-Sharkawy, 2004).

Higher measured dry weights and better simulation results were obtained for Maha Sarakham than Khon Kaen (Figs. 2 and 3), perhaps due to Maha Sarakham having a higher soil water table during the dry period (October–March), that was more favorable for cassava growth compared to Khon Kaen. The soil moisture contents recorded for Maha Sarakham during Nov 2019 and Jan 2020 at depths of 0–15 cm, 15–30 cm and 30–45 cm varied in the range 3.50–9.14% (between the levels

of field capacity to permanent wilting point), whereas those recorded for Khon Kaen were in the range 2.46–5.11% (close to permanent wilting point). El-Sharkawy (2007) mentioned that a water deficit reduces the cassava canopy, leading to less photosynthesis and storage root yield. Orek et al. (2020) studied a selection of 37 cassava genotypes in Kenya and reported that drought stress decreased leaf retention and storage root yield by 50% and 59%, respectively.

Table 2 Soil types and the average values for 1988–2018 of daily maximum and minimum air temperatures (Max. and Min., respectively), amount of solar radiation and total rainfall for 20 July–20 May for 10 cassava growing sites in Thailand

Site	Latitude and longitude	Soil type	Solar radiation (MJ/m ²)	Max. (°C)	Min. (°C)	Rainfall (mm)
Buriram	14°24'N, 102°36'E	Rhodic Kandiuotox	5,359.8	32.3	21.6	970.4
Kalasin	16°32'N, 103°22'E	Paleustults	5,181.8	32.0	21.6	990.4
Khon Kaen	16°47'N, 102°41'E	Grossarenic Kandiuostalf	5,410.4	32.6	21.2	891.7
Loie	17°40'N, 101°26'E	Ultic Haplust	5,447.7	32.2	20.3	942.3
Maha Sarakham	16°05'N, 103°06'E	Grossarenic Kandiuostalf	5,574.2	33.8	22.1	990.8
Mukdahan	16°52'N, 104°09'E	Paleustults	5,345.5	32.6	21.8	1,023.6
Nakhon Ratchasima	15°17'N, 101°34'E	Kandiuostults	5,344.9	32.8	22.7	882.1
Sisaket	14°32'N, 104°13'E	Paleustults	5,342.0	32.7	22.1	1,037.0
Ubon Ratchathani	16°03'N, 105°09'E	Paleustults	5,529.1	33.2	22.0	1,121.4
Udon Thani	17°05'N, 103°24'E	Paleustults	5,352.8	32.5	21.5	1,003.4

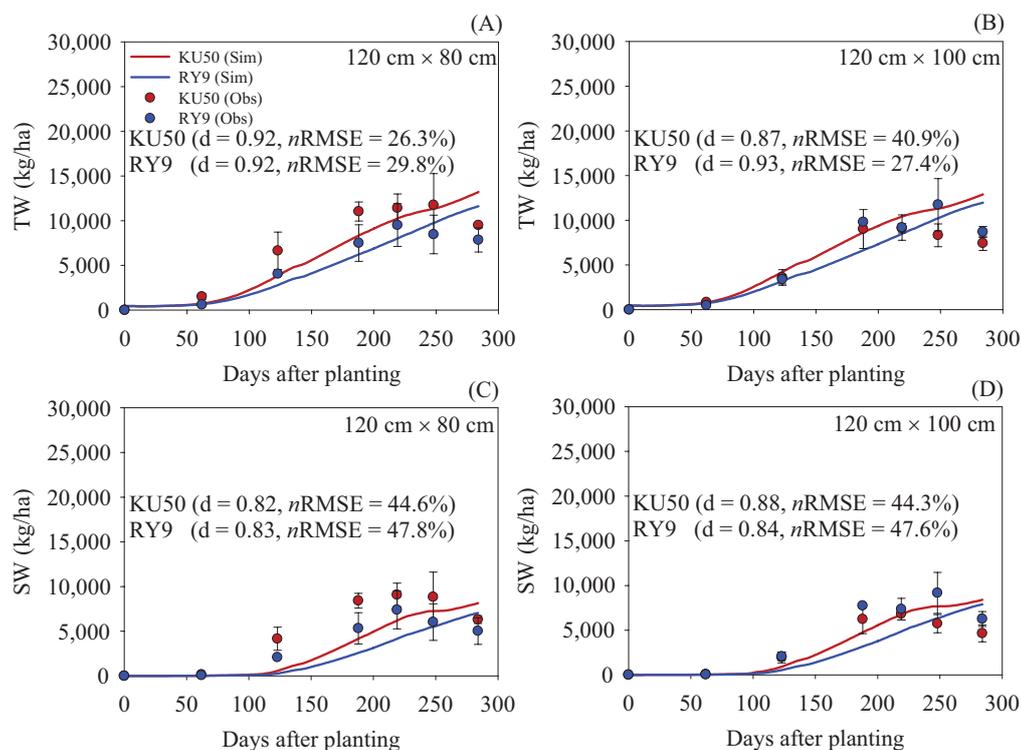


Fig. 2 Simulation line (Sim) and observation points (Obs) for Khon Kaen province for total crop and storage root dry weights (TW and SW, respectively) of Kasetsart 50 (KU50) and Rayong 9 (RY9) cultivars at different plant spacings of: (A, C) 120 cm x 80 cm; (B, D) 120 cm x 100 cm, where error bars indicate \pm SD, d = index of agreement and nRMSE = normalized root mean square error

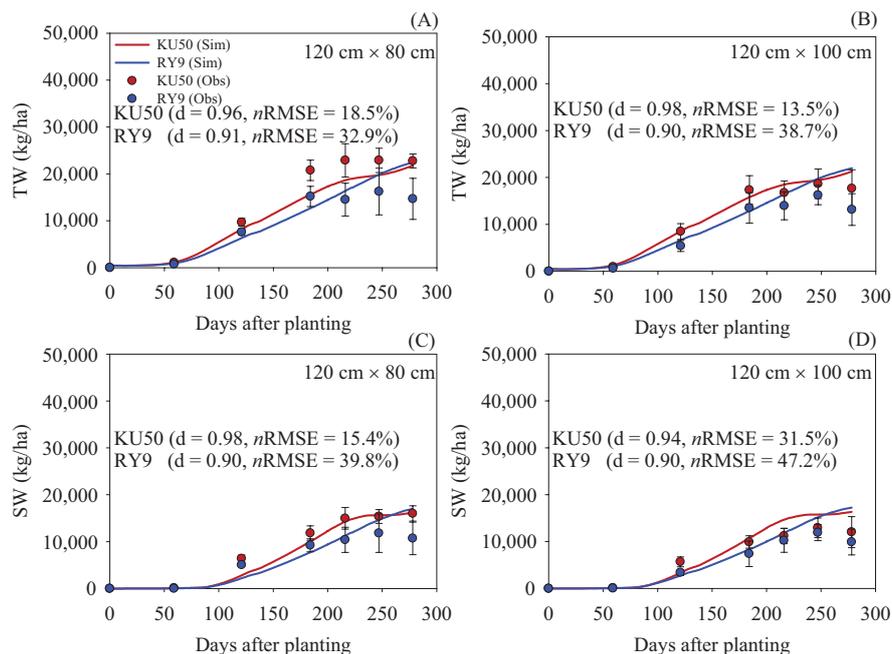


Fig. 3 Simulation lines (Sim) and observation points (Obs) for Maha Sarakham province for total crop and storage root dry weights (TW and SW, respectively) of Kasetsart 50 (KU50) and Rayong 9 (RY9) cultivars at different plant spacings of: (A, C) 120 cm × 80 cm; (B, D) 120 cm × 100 cm, where error bars indicate ± SD, d = index of agreement and nRMSE = normalized root mean square error

According to field observations at final harvest (300 DAP), the plant spacing of 120 cm × 80 cm for KU50 in Khon Kaen and for KU50 and RY9 in Maha Sarakham produced higher TW per area and SW per area than the plant spacing at 120 cm × 100 cm (Table 3), whereas, the opposite was observed for RY9 in Khon Kaen. Therefore, under the more favorable growing environment in Maha Sarakham, the experimental results indicated that increasing the plant spacing from 120 cm × 80 cm to 120 cm × 100 cm did not improve the productivity for both KU50 and RY9 cultivars. Although a wider plant spacing generally provides better growth and yield than a narrower plant spacing, the results indicated that the plant spacing of 120 cm × 100 cm had a slightly higher dry weight per crop than the plant spacing of 120 cm × 80 cm (data not shown). Therefore, the small differences in TW per crop and SW per crop among the two different plant spacings were the reason for the lower productivity with the wider plant spacing. However, under more severe water stress (Khon Kaen) increasing the plant spacing could increase the productivity but only for RY9, which was the reverse of the response to plant spacing for these two cassava cultivars.

There are various recommended plant spacings for cassava, mainly because of differences in cultivars and soil fertility (Howeler, 2014). For Thailand conditions, the general recommendation is a spacing of 100 cm × 100 cm, although

farmers may use ranges of 70–100 cm spacing between rows and 60–100 cm between plants. However, a spacing of 80 cm × 80 cm produced a higher yield and reduced soil erosion for growth in under low-fertility soils and on sloping land (Ratanawaraha et al., 2001). Akpan and Ikeh (2018) reported that the optimum spacing for growth in southeastern Nigeria was 100 cm × 80 cm for the TMS 30572 and TME 419 cultivars, but that 100 cm × 100 cm spacing was better for TMS 98/0505. In southwestern Nigeria, Onasanya et al. (2021) reported that the cultivar TME 419 at a plant density of 12,500 plant/ha had a higher yield than at 10,000 plants/ha. Streck et al. (2014) found that the cassava cultivar Fepagro-RS 13 planted in Brazil at a spacing of 80 cm × 80 cm had the highest storage root yield per area compared to spacings of 100 cm × 100 cm, 120 cm × 120 cm and 150 cm × 150 cm.

The data based on the field observations at final harvest also indicated that the cultivar KU50 at a plant spacing of 120 cm × 80 cm produced the highest values for observed TW and SW for Khon Kaen ($p < 0.01$). However, although the same trend was observed in Maha Sarakham but the difference was not supported by the statistical tests ($p > 0.05$), as shown in Table 3. KU50 is a branching cultivar, and it has larger plants than RY9. These results indicated that KU50 had better adaptability than RY9. The study of Wongnoi et al. (2020) in Thailand for cassava growing under rainfed conditions in a dry

environment during the high storage root accumulation stage also demonstrated that KU50 had a higher final crop biomass compared to RY9.

The *n*RMSE values between the simulated and observed data for final harvest varied in the range 5.8–76.6% (average = 31.0%), as shown in Table 3. The discrepancies between the simulated and observed data for final harvest were due to certain environmental factors that were not accounted for in the model, as mentioned previously. However, based on relative performance, the results from both the simulation and field observations indicated KU50 at a plant spacing of 120 cm × 80 cm was the best in terms of final TW for both Khon Kaen and Maha Sarakham. The small differences in the simulated SW among the different plant spacings and cultivars might have been due to differences in raking between the simulation and field observations. Further model evaluation based on large differences in plant spacings and cultivars would confirm the credibility of the model.

The overall model evaluation showed that the CSM-MANIHOT-Cassava model provided acceptable results in simulating the response of cultivars at certain plant spacings, indicating the potential of this model to help generate crop data for determining suitable plant spacing to increase land use efficiency. Other studies have demonstrated the ability of the CSM-MANIHOT-Cassava model to identify desirable cassava cultivars in terms of total crop biomass at harvest for different growing dates in particular upland conditions (Phoncharoen et al., 2021a, b) and in selecting a stable cassava cultivar based on the final crop biomass and storage root yield for different upper paddy fields during the rice off-season (Sawatraksa et al., 2021) for a tropical wet or savanna climate in Thailand. Therefore, the CSM-MANIHOT-Cassava model could be used to support

decision making to improve crop productivity in Thailand and in other similar production areas.

Model application

Long-term simulation (1988–2018) was carried out for different scenarios of growing conditions (10 locations × 2 cultivars × 4 plant spacings). Under the irrigated condition, there was a similar response of the cultivars to different plant spacings in terms of values for both the simulated TW and SW (Figs. 4 and 5). With increasing plant spacing under irrigated condition, the simulated TW per area decreased, whereas the simulated SW per area tended to increase, indicating that irrigation would support high partitioning to the storage root rather than to aboveground organs when the plant spacing was expanded. The plant spacing of 120 cm × 100 cm seemed to be more suitable for achieving high storage root productivity for both the KU50 and RY9 cultivars under irrigated conditions. To obtain high storage root yield per area, this simulation study suggested that a wider plant spacing could be an alternative strategy for growth in a favorable environment. However, this simulated result did not correspond to the experiment by Silva et al. (2013) who studied growing cassava with different plant densities under irrigated conditions in Brazil and showed that the wider plant spacing (plant densities lower than 7,000 plant/ha) tended to produce lower total root green matter per area than the narrower plant spacing (plant densities higher than 7,000 plant/ha). The differences in the cassava cultivars and other environmental factors between the current simulation and the previous experiment might have been the cause of these conflicting results.

Table 3 Simulated (Sim) and observed (Obs) data for storage root dry weight (SW) and total crop dry weight (TW) at 300 days after planting for Kasetsart 50 (KU50) and Rayong 9 (RY9) grown at plant spacing of 120 cm × 80 cm and 120 cm × 100 cm in Khon Kaen and Maha Sarakham provinces, Thailand

Location	Spacing (cm)	Cultivar	SW (kg/ha)			TW (kg/ha)		
			Sim	Obs (mean±SD)	<i>n</i> RMSE (%)	Sim	Obs (mean±SD)	<i>n</i> RMSE (%)
Khon Kaen	120 × 80	KU50	9,703	9,158±337 ^a	6.0	15,173	13,920±531 ^a	9.0
		RY9	7,837	4,709±207 ^c	66.4	12,517	7,765±438 ^c	61.2
	120 × 100	KU50	9,809	5,554±455 ^b	76.6	14,660	9,144±420 ^b	60.3
		RY9	8,540	5,767±268 ^b	48.1	12,707	8,192±119 ^{bc}	55.1
Maha Sarakham	120 × 80	KU50	18,207	23,742±1,618 ^a	23.3	25,580	34,473±1,096 ^a	25.8
		RY9	18,486	21,380±1,351 ^a	13.5	24,470	26,761±1,495 ^a	8.6
	120 × 100	KU50	18,310	21,395±824 ^a	14.4	24,731	29,688±1,869 ^a	16.7
		RY9	18,543	19,677±1,666 ^a	5.8	23,729	25,210±2,666 ^a	5.9

*n*RMSE = normalized root mean square error;

Mean±SD within each column and location superscripted with different lowercase letters are significantly ($p < 0.01$) different.

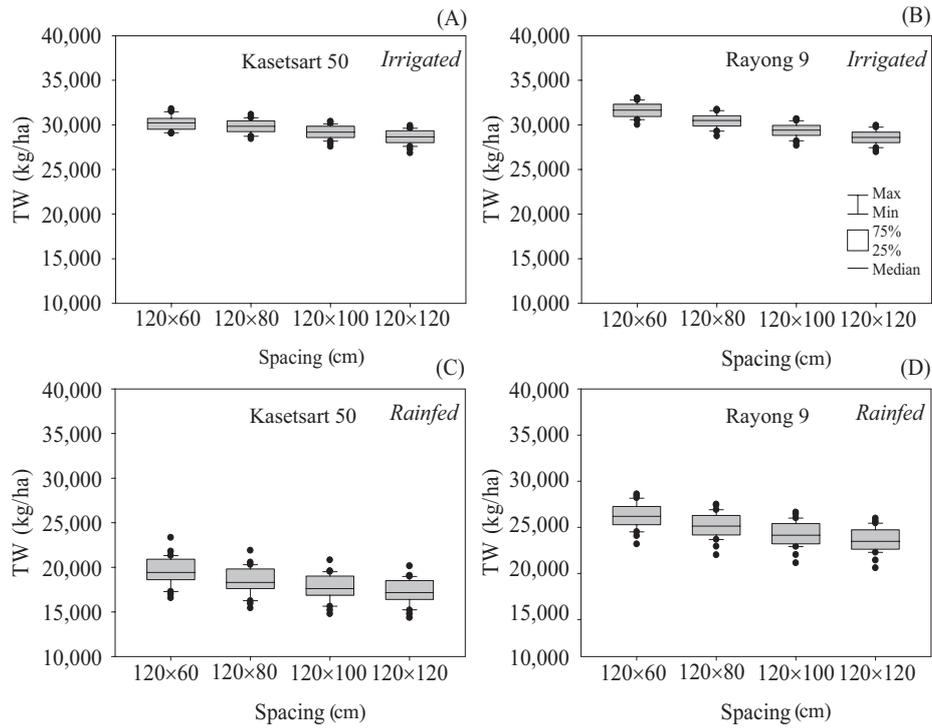


Fig. 4 Means over 10 locations and years (1988–2018) for simulated total dry weight (TW) for Kasetsart 50 (KU50) and Rayong 9 (RY9) at four different plant spacings under: (A, B) irrigated conditions; (C, D) rainfed conditions

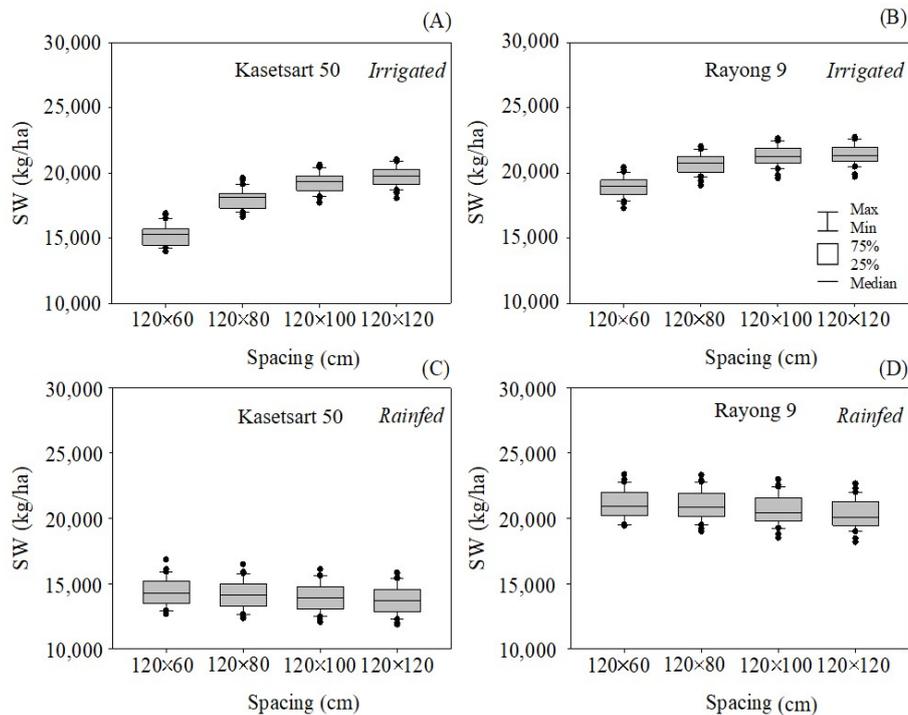


Fig. 5 Means over 10 locations and years (1988–2018) for simulated storage root dry weight (SW) for Kasetsart 50 (KU50) and Rayong 9 (RY9) at four different plant spacings under: (A, B) irrigated conditions; (C, D) rainfed conditions

Under rainfed conditions, the two cassava cultivars had similar responses to the four different plant spacings based on the simulated TW and SW (Figs. 4 and 5). There were small differences in the simulated TW and SW between the four plant spacings. However, the plant spacing of 120 cm × 60 cm seemed to produce the highest means for the simulated TW and SW compared to the other plant spacings. The limited rainfall during 150–300 DAP (the growth stage of storage root accumulation) caused decrease the simulated biomass for a single plant, and, therefore, the narrower plant spacing (120 cm × 60 cm) produced a higher simulated biomass per area than the wider plant spacings.

Another experiment in Thailand demonstrated that lower rainfall during the late growth stage resulted in low quantum yields of Photosystem II and cassava photosynthesis (Wongnoi et al., 2020). The quantum efficiency of Photosystem II is a key factor supporting crop photosynthesis and biomass (Murchie and Lawson, 2013; Sawatraksa et al., 2019). El-Sharkawy (2007) also reported that limited water availability during crop growth decreased cassava photosynthesis, with the lower photosynthesis of cassava being related to small plants and low yields. The current simulation study indicated that growing cassava in an unfavorable environment during the

late growth period (low rainfall) with a high plant density could help improve crop productivity. The results from the current simulation agreed with those of the field experiment for the rainfed conditions in Table 3. The average values for observed TW and SW for the plant spacing of 120 cm × 80 cm (20,730 kg/ha and 14,747 kg/ha, respectively) were higher than for the plant spacing of 120 cm × 100 cm (18,059 kg/ha and 13,098 kg/ha, respectively). The information based on the actual field experiment for cassava growing under rainfed condition of Streck et al. (2014) also demonstrated that a narrow plant spacing could increase the yield per area.

According to the simulated results based on harvest index (HI) under both irrigated and rainfed conditions, Fig. 6 indicates that a higher value of HI was recorded for the wider plant spacing for both the KU50 and RY9 cultivars. The HI value is defined as SW divided by TW; it can be used to demonstrate the partitioning of photosynthetic assimilates from the aboveground part (source) to the storage root organ (sink) (Kawano, 1990). Therefore, the current simulation results suggested that growing the two different cassava branching types under both irrigated and rainfed conditions with the wider plant spacing could enhance partitioning from the source to the sink. The results for the field experiment also indicated

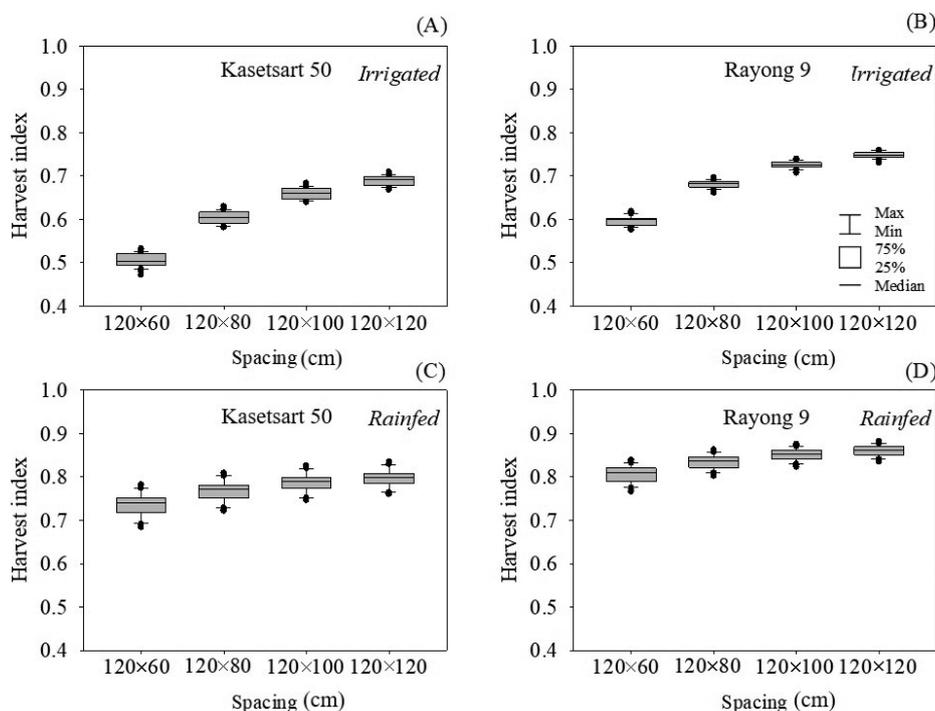


Fig. 6 Means over 10 locations and years (1988–2018) for simulated harvest index for Kasetsart 50 (KU50) and Rayong 9 (RY9) at four different plant spacings under: (A, B) irrigated conditions; (C, D) rainfed conditions, where harvest index is the ratio of storage root dry weight to total crop dry weight

that the plant spacing of 120 cm × 100 cm tended to produce a higher HI than the plant spacing of 120 cm × 80 cm (data not shown). In addition, Silva et al. (2013) reported that growing cassava at a lower plant density produced a larger harvest index compared to growing with a higher plant density.

Other studies have shown the potential of other models in DSSAT to help support determining management practices for tropical regions. For example, Banterng et al. (2010) used the CSM-CROPGRO-Soybean model to identify suitable management strategies for soybean in Thailand and found that the narrower plant spacing (plant density of 40 plants/m²) produced a higher simulated yield than the wider plant spacing (plant density of 20 plants/m²). Vilayvong et al. (2015) applied the CSM-CERES-Rice model to lowland rice in Laos and reported different responses among two cultivars at different plant densities. Growing with a plant population at 1 seedling/hill for the rice cultivar TDK8 produced a similar grain yield with 5 seedlings/hill. The current study has pioneered investigations to improve cassava productivity and land use efficiency by showing the potential of the CSM-MANIHOT-Cassava model to serve as an information technology tool for determining a suitable plant spacing for cassava in Thailand and other tropical areas.

It can be concluded that the agreement between the simulated and observed crop biomass varied from good to poor. However, both the simulation and experimental approaches identified the cultivar KU50 at a plant spacing of 120 cm × 80 cm as being superior in terms of TW. Model application for an irrigated scenario indicated that a wider plant spacing produced higher SW per area, whereas a narrower plant spacing was suitable for growing cassava under rainfed conditions with low rainfall during the late growth period. Overall, this study showed the capability of the model as an alternative approach to support determining the appropriate plant spacing to improve cassava productivity. This plant density study utilizing both experimental and simulation modeling is valid only for fully stocked fields. However, the missing plant during the crop vegetation period commonly occur in some fields. Therefore, the scenario of missing plants would be an interesting issue for further model application.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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