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Original Article

Performance of the DSSAT MANIHOT-Cassava model for cassava cultivation in the Recôncavo Baiano[1]

Performance do modelo DSSAT MANIHOT-Cassava para cultivo de mandioca no Recôncavo Baiano

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HIGHLIGHTS:

Calibration improved model performance for growth simulation of both varieties.
Calibration helps reduce uncertainties associated with simulations of the cultivation of varieties grown in the region.
The DSSAT MANIHOT-Cassava model can be used to support studies of agricultural planning, yield gap and climate risk zoning.

ABSTRACT: The aim of the present study was to calibrate the DSSAT MANIHOT-Cassava model with information from cassava varieties grown in the Recôncavo Baiano region, Bahia state, Brazil. The database used to calibrate the model was obtained in the dry sub-humid tropical climate in Cruz das Almas city, from 2019 to 2020. The model was calibrated with experimental data obtained under irrigated and rainfed conditions for the BRS Novo Horizonte and Eucalipto varieties. The calibration was carried out by adjusting parameters related to the characteristics of each variety. Model performance was evaluated with statistical indices that indicate the precision and accuracy of the simulations, such as the root mean square error and coefficients of determination, the Willmott index, and the performance index. The model, regardless of the variety, adequately simulated most of the variables studied during the calibration and validation stage, with reliability considered excellent or optimal and minor errors than the default variety for most of the variables simulated. An exception was simulation of the leaf area index, which did not properly represent the leaf senescence or regrowth phase 180 days after planting, showing overestimations for the BRS Novo Horizonte variety and underestimations for the Eucalipto variety. The model can be applied for reliably simulating performance of the cassava varieties under the sub-humid conditions of the Recôncavo Baiano.

Key words: *Manihot esculenta* Crantz, crop simulation models, biometrics, parametrization

RESUMO: O objetivo do presente estudo foi calibrar o modelo MANIHOT-Cassava com informações de variedades de mandioca cultivadas na região do Recôncavo Baiano, Bahia, Brasil. A base de dados utilizada para calibração do modelo foi obtida no clima tropical subúmido seco de Cruz das Almas, no período de 2019 a 2020. O modelo foi calibrado com dados experimentais obtidos em condições irrigadas e de sequeiro para as variedades BRS Novo Horizonte e Eucalipto. A calibração foi realizada ajustando parâmetros relacionados às características de cada genótipo. O desempenho do modelo foi avaliado a partir de índices estatísticos que indicam a precisão e acurácia das simulações, como a raiz do erro quadrático médio e coeficientes de determinação, o índice de Willmott e o índice de desempenho. O modelo, independente da variedade, simulou adequadamente a maioria das variáveis estudadas durante a etapa de calibração e validação, com confiabilidade considerada excelente ou ótima e menores erros que a variedade default para a maioria das variáveis. A exceção foi a simulação do índice de área foliar, que não representou adequadamente a fase de senescência ou rebrota foliar 180 dias após o plantio, apresentando superestimações para a variedade BRS Novo Horizonte e subestimações para a variedade Eucalipto. O modelo pode ser utilizado para simular de forma confiável o desempenho das variedades de mandioca nas condições subúmidas do Recôncavo Baiano.

Palavras-chave: *Manihot esculenta* Crantz, modelos de simulação de cultivos, biometria, parametrização

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Introduction

Cassava is commonly cultivated in the tropics and subtropics. It is a key agricultural activity for food security, since the crop does not have a specific harvest season and shows tolerance to adverse growing conditions (Amelework et al., 2021; Devi et al., 2022). In addition, it is an important source of carbohydrates accessible to the population and offers raw material for different industries (Parmar et al., 2017).

Under experimental cultivation conditions, the yield of cassava storage roots can exceed 80 Mg ha^{-1} (El-Sharkawy, 2003). Visses et al. (2018), when analyzing variations in cassava yield across different producing regions in Brazil through simulations, reported yields of up to 66.9 Mg ha^{-1} under optimal conditions, without water restrictions. However, official agricultural data from IBGE (2024) for the year 2022 indicated a national average yield of only 14.94 Mg ha^{-1}, with even lower values in some traditional producing regions, such as the Recôncavo of Bahia, where the average yield was 7.19 Mg ha^{-1}.

The discrepancy between cassava's production potential and the yields reported in official statistics can be attributed to multiple factors, which vary across producing regions. Among these factors, edaphoclimatic conditions, the genetic variability of cultivated varieties, and agronomic management strategies stand out (Oliveira et al., 2020; Phoncharoen et al., 2021a; Abrell et al., 2022; Devi et al., 2022; More et al., 2023; Zebalho et al., 2025).

When investigating the causes of yield decline in the Western Cerrado region of Brazil, Zebalho et al. (2025) identified yield reductions of up to 44.6 Mg ha^{-1}, mainly attributed to the production potential of the cultivated varieties, planting time, and potassium fertilization. Oliveira et al. (2020) reported a 44% difference in dry matter yield of cassava storage roots between the BRS Novo Horizonte variety, developed through a genetic improvement program, and varieties traditionally cultivated by farmers in the Recôncavo of Bahia. Similarly, Abrell et al. (2022), when analyzing data from traditional cassava-producing communities in the Amazon region operating under low-technology systems, observed high yield variability, associated with planting density and field preparation strategies, with yield losses of approximately 50%. More et al. (2023), in a review on the effects of water deficit on cassava, indicated that water scarcity can lead to yield reductions exceeding 80% when water stress occurs during the crop's most sensitive growth stages. These findings underscore the importance of selecting regionally adapted varieties, properly defining planting times, and implementing agronomic management strategies to mitigate yield losses, as demonstrated by Phoncharoen et al. (2021b) and reviewed by Devi et al. (2022).

To reduce the risk associated with yield gap, it is important to study the agroecosystem to prevent problems and choose more appropriate crop strategies. A tool that may assist agricultural planning and decision making is crop simulation models (Jones et al., 2017; Moreno-Cadena et al., 2021).

Crop simulation models are sets of mathematical equations normally associated with computational systems that simulate cultivation of agricultural crops (Corrêa et al., 2011). These models have been applied to simulate what happens to a crop when it is grown under certain growing conditions. The information obtained from the simulations can be applied for different purposes in areas such as education, applied research, and agricultural policies and planning (Boote et al., 1996).

Among the options of computational systems developed for simulating agricultural crops is the Decision Support System for Agrotechnology Transfer (DSSAT), a free and popular option containing models of different crops (Jones et al., 2003; Hoogenboom et al., 2019; Hoogenboom et al., 2024). One of these models, the DSSAT MANIHOT-Cassava, allows daily simulation of the development, growth, and yield of cassava plantations (Moreno-Cadena et al., 2020).

The model calculates the amount of photoassimilates produced daily by the plant from the product between intercepted solar radiation and solar radiation use efficiency. The photoassimilate distribution approach used in the model is the "spill-over" type, which considers that the aerial part and the fibrous roots of the plant have preference in energy consumption compared to plant reserve roots, which are left with the left-over energy, according to the description provided by Moreno-Cadena et al. (2021).

Just as for any model, one of the main limitations in using MANIHOT-Cassava is the need to carry out a calibration process when the simulations are sensitive to more specific growing conditions. This need can be exemplified by adjusting model parameters for the purpose of simulating cultivation of cassava varieties in other tropical or subtropical environments such as Cuba (Zayas-Infante et al., 2023), Jamaica (Rankine et al., 2021) and Thailand (Phoncharoen et al., 2021b).

In MANIHOT-Cassava model, the calibration is performed by adjusting around 16 parameters, related to development of the aerial part, leaf traits, phytomass distribution, and photosynthetic efficiency (Moreno-Cadena et al., 2020). During the calibration process, it is necessary to compare simulated results with results observed in the field for the purpose of adjusting the parameters, aiming to reduce errors, as exemplified by Phoncharoen et al. (2021a).

The calibration of MANIHOT-Cassava model for sweet and industrial cassava varieties grown in the dry sub-humid tropical climate has not yet been carried out in Brazil. The calibration of the model is important to reduce the uncertainties involving the simulation of cassava cultivation in regions of climate transition, closer to the coastal strip located in the extensive strip between the north and northeast of Brazil. This region is one of the most traditional in the cultivation of cassava and is responsible for supplying several urban centers, covering tens of millions of people.

This study aimed to calibrate the DSSAT MANIHOT-Cassava model for the varieties BRS Novo Horizonte and Eucalipto grown in the Recôncavo Baiano region, Bahia state, Brazil.

Material and Methods

The experiments were conducted in experimental fields of Embrapa Mandioca e Fruticultura, in Cruz das Almas (Bahia state, Brazil), which are at around 220 m altitude above mean sea level, near the geographic coordinates 12° 40' 31" S and 39° 05' 17" W. The climate in Cruz das Almas region is classified as humid or sub-humid tropical type (Am), according to Köppen's climate classification, with the meteorological norms described by Silva et al. (2016). The soil of the experimental fields was classified as Oxisol, according to Soil Survey Staff (2022), and the soil physical-hydraulic attributes were characterized by Souza & Souza (2001).

Experiments 1 and 2 were conducted from January 4, 2019 to December 20, 2019, and Experiments 3 and 4 from September 15, 2019 to September 15, 2020. Experiments 1 and 2 were planted 2.5 months before the rainy season, whereas Experiments 3 and 4 were planted around five months before the rainy season. The two planting times also showed differences regarding photoperiod, temperature, and solar radiation, especially in the first 180 days after planting (DAP), as shown in Figure 1.

The planted areas in Experiment 1 were cultivated without water restriction, with supplemental irrigation from planting to harvest. However, the planted areas in Experiments 2, 3, and 4 received supplemental irrigation only up to near 60, 140, and 45 DAP, respectively. Final harvest in Experiments 1 and 2 was carried out at 350 DAP, while final harvest in Experiments 3 and 4 was carried out at 363 DAP. The management system adopted to grow the cassava crop included conventional soil tillage, control of weeds and pests, correction of soil reaction, fertilization at planting, topdressing fertilization, and supplemental irrigation.

Two varieties were cultivated in these field experiments, BRS Novo Horizonte and Eucalipto. BRS Novo Horizonte is a high-yield-potential variety developed for industry and evaluated under the growing conditions of the Recôncavo Baiano (Oliveira et al., 2020). Eucalipto is a sweet cassava variety selected by local farmers and traditionally cultivated

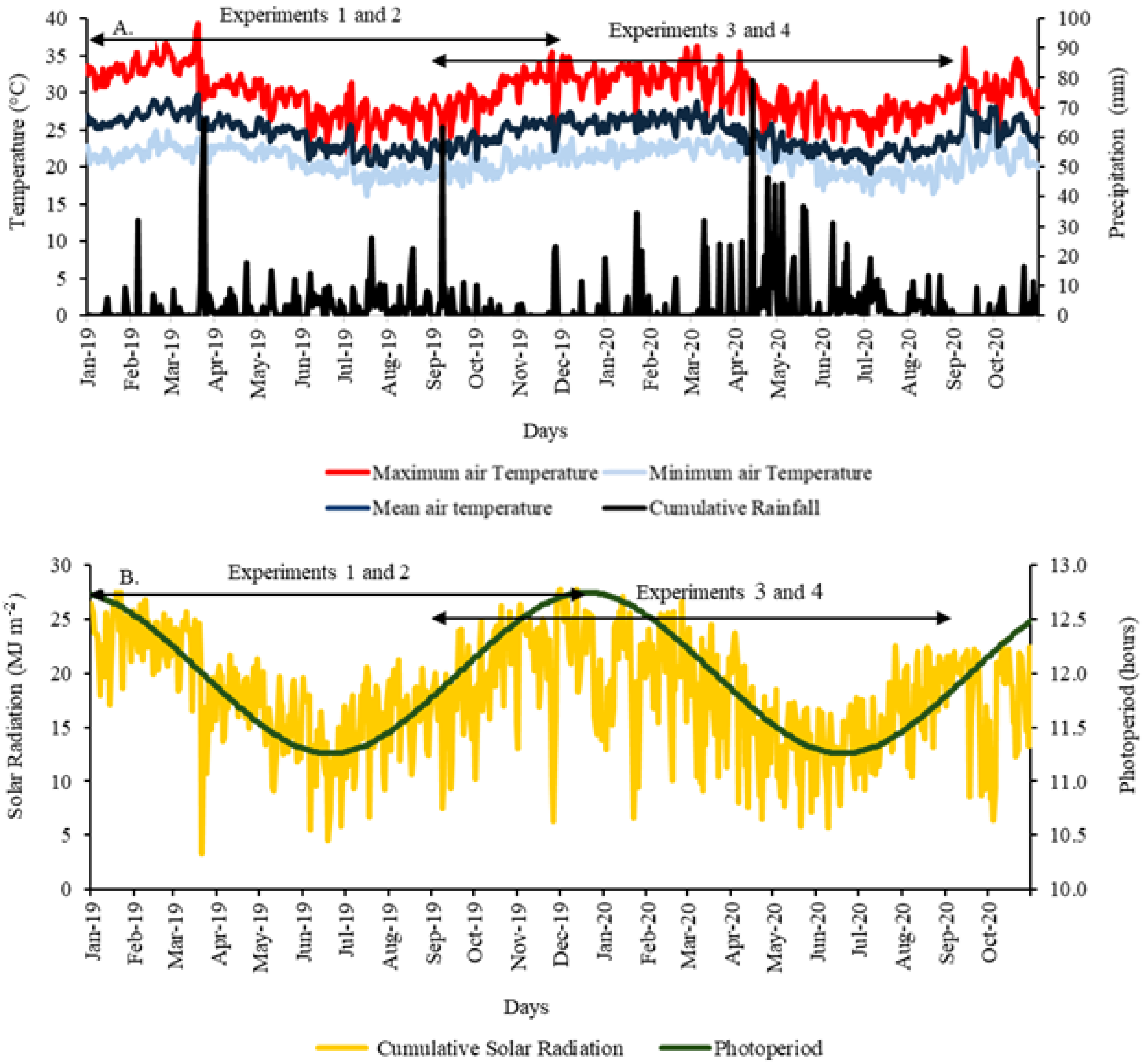


Figure 1. Daily record of rainfall, mean, maximum, and minimum air temperatures (A) and cumulative solar radiation and photoperiod (B), from January 2020 to October 2021 in Cruz das Almas, Bahia state, Brazil

in the Recôncavo Baiano region. The data for the model calibration for the varieties BRS Novo Horizonte and Eucalipto, as well as its validation, were collected in Experiments from 1 to 4. The experimental results from Experiment 1 were used to calibrate the model, while the results of Experiments 2, 3, and 4 were used to validate the calibration.

The simulations were conducted using the DSSAT MANIHOT-Cassava model (Hoogenboom et al., 2023, version 4.8.2). Detailed information on the processes involving simulation of the cassava crop in MANIHOT-Cassava model can be found in the studies of Moreno-Cadena et al. (2020; 2021). Digital files containing data on the growing conditions of each experiment were prepared according to the standard data files of DSSAT. The meteorological data was organized in DSSAT climate input files (.wth) and the soil data in soil input files (.sol); and the information on the growing conditions of each experiment was organized in experimental data files (.csx). The initial conditions of the crop environment were informed considering the beginning of the simulations in the year prior to the beginning of the experiments, to regulate the water balance. The experiments were conducted under optimal intensive management conditions, with fertilization and pest and disease control. Therefore, under simulated growing conditions, management was considered optimal, maintaining activated only the module that controls losses by water stress. Finally, the results observed in the experiments were organized in time series experimental result files (.cst).

The methods selected in the DSSAT experimental file (.csx) included the methods used as default by the system, except for the evapotranspiration and photosynthesis methods. The method used for evapotranspiration was the Priestley-Taylor/Ritchie on an hourly scale, while the photosynthesis method was the radiation use efficiency with modifications related to the vapor pressure deficit on an hourly scale. These options are not yet available in the version 4.8.2 of DSSAT interface. However, they can be selected directly in the experimental files (.csx), in the simulation control, in methods, replacing the current option with the letters "H" and "V", for the EVAPO and PHOTO options, respectively.

The MANIHOT-Cassava model calibration process was carried out based on adjustment of model parameters that define the characteristics of the variety, contained in the data files that define the characteristics of the cultivars CSYCA047.cul and CSYCA047.eco (Table 1).

Adjustment was made using the trial-and-error approach by checking the correlation between observed and simulated data evaluated using statistical indices. The calibration protocol used was based on the study carried out by Phoncharoen et al. (2021a). The comparison of observed and simulated results was made using the following variables: level of branching of the aerial part, leaf production per apex, leaf area index, dry phytomass production of the plant, and its distribution between the aerial part and the reserve roots. The statistical analysis was done based on statistical indices used in both calibration and validation phases of the model. The following statistical indices were used: coefficient of determination (R^2); agreement index (d) of Willmott (1982); reliability index (c) proposed by Camargo & Sentelhas (1997); root mean square error (RMSE); and relative root mean square error (RRMSE). These indices are obtained by Eqs. 1 to 5.

$$R^2 = 1 - \frac{\sum\left(E_i - \bar{O}\right)^2}{\sum\left(O_i - \bar{O}\right)^2} \quad (1)$$

$$d = 1 - \left[\frac{\sum\left(E_i - \bar{O}\right)^2}{\sum\left(\left|E_i - \bar{O}\right| + \left|O_i - \bar{O}\right|\right)^2}\right] \quad (2)$$

$$c = d \cdot \sqrt{R^2} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum\left(E_i - O_i\right)^2}{n}} \quad (4)$$

$$RRMSE = \frac{RMSE}{\bar{O}} \times 100 \quad (5)$$

where:

E_i - corresponds to the values estimated by the models;
O_i - is the observed values;
$\bar{O}$ - is the average of the observed values; and,
n - is the total number of observed or estimated values.

Table 1. Model parameters adjusted during the calibration process of the MANIHOT-Cassava model

Information file on the phenotypic characteristics of the cultivars (CSYCA048.cul)	
Parameter	**Definition**
BxyND	Thermal time 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 (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)
Information file on the ecophysiological response of the cultivars (CSYCA048.eco)	
Parameter	**Definition**
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 reliability index (c) is interpreted using the performance ranges - higher than 0.85: optimal; from 0.76 to 0.85: excellent; from 0.66 to 0.75: good; from 0.61 to 0.65: average; from 0.51 to 0.60: fair; from 0.41 to 0.50: poor; and less than 0.40: bad. In the present study, only the interpretation of the reliability index was presented, based on the classification ranges. As for the RRMSE, the closer to 0, the better. However, the mean deviation between the simulated and observed data can be evaluated according to interpretation ranges - below 10%: perfect, from 10 to 20%: good; from 20 to 30%: average, and above 30%: bad; as in the study for calibration of the MANIHOT-Cassava model presented by Phoncharoen et al. (2021b).

The calibrated parameters for each variety, as well as the statistical indices for the correlation between the simulated and observed data, were presented in the form of tables. Correlation between the observed and simulated data was also presented in graph form to allow visual assessment of the ability of the model to simulate the growth trends of the variables evaluated. In graph representation, the plotted line represented the evolution of the simulated data, and the highlighted points represented the results observed in the field. Furthermore, statistical indices related to the performance of the MANIHOT-Cassava default variety are presented, based on an experimental database for each variety, to illustrate the improvement associated with the calibration process of each variety.

Results and Discussion

The parameters of the MANIHOT-Cassava default variety and the calibrated parameters for simulation of growing in a sub-humid tropical environment of the BRS Novo Horizonte and Eucalipto varieties are shown in Table 2.

In the present study, the parameters BR1FX, BR2FX, BR3FX, LAXS, SLAS, LPEFR, NODWT, NODLT, and HMPC began to be adjusted based on information obtained in the field. The other parameters were adjusted according to standard values suggested in the DSSAT cultivar and ecophysiology information file for cassava varieties within the genetic information file of the MANIHOT-Cassava model.

The BRS Novo Horizonte variety had parameters BR3FX, LFPR, HMPC, and NODLT with adjusted values within or very near those of the range of values observed in the field, while the Eucalipto variety had adjusted values within or very near those of the range of values observed for the parameters BR1FX, BR2FX, BR3FX, SLAS, LFPR, HMPC, and NODLT. The LAXS and NODWT values were much higher than the values recorded in the field, for both varieties, and the adjusted values for the parameters BR1FX, BR2FX, and SLAS were above the range of values observed for the BRS Novo Horizonte variety.

Moreno-Cadena et al. (2021) explained that there is no way to be sure if the characteristics observed in the field of varieties grown under specific conditions will have good correlation with the parameters of the model, because the parameters of the model are developed from a large amount of information that considers the general response of the species in different environments. However, knowing the true range of values associated with the parameters can help direct the adjustment and help understand which variables are most important at the data collection level for purposes of calibration.

For the calibration of the BRS Novo Horizonte and Eucalipto varieties, simulating the growing conditions and database from Experiment 1, all the simulations of all the variables, except for the leaf area index (LAI), showed high precision and accuracy, with R^2 and d values near 1. The reliability level was classified as optimal for all the variables, except for LAI. A summary of the statistical indices recorded per variety and variable during the calibration is shown in Table 3.

Table 2. DSSAT MANIHOT-Cassava default variety parameters and calibrated parameters for the BRS Novo Horizonte and Eucalipto cassava varieties growing in a sub-humid tropical environment

Input file	Parameter	Unit	MANIHOT-Cassava default	BRS Novo Horizonte	Eucalipto
.cul	B01ND	°Cd	200	500.00	450.00
	B12ND		250	450.00	500.00
	B23ND		250	250.00	400.00
	B34ND		250	250.00	400.00
	BR1FX	Apex	2.2	4.50	2.00
	BR2FX		2.7	1.00	2.00
	BR3FX		2.0	2.00	2.00
	BR4FX		1.5	2.00	2.00
	LAXS	cm²	350.00	950.00	425.00
	SLAS	g cm^{-2}	220.00	250.00	185.00
	LLIFA	°Cd	1000.00	1600.00	1500.00
	LPEFR	-	0.33	0.25	0.25
	LNSLP	-	1.20	1.05	0.90
	NODWT	G	4.00	13.00	9.25
	NODLT	Cm	2.00	2.50	4.00
.eco	KCAN	-	0.65	0.65	0.75
	PARUE	g MJ^{-1}	2.80	2.45	1.70
	HMPC	%	30.00	39.00	31.00

BxyND - Thermal time interval between X and Y branching (°Cd); BRxFX - Number of apices that developed from X branching; LAXS - Leaf area of leaves developed without stress (cm²); SLAS - Specific leaf area (cm² 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 (%)

Table 3. Statistical indices and calibration performance of the DSSAT MANIHOT-Cassava Model using all experimental data from the BRS Novo Horizonte and Eucalipto varieties

Variety	Variable	RMSE	RRMSE (%)	R²	d	Reliability (c)
BRS Novo Horizonte	Apex branching level (ABL, level)	0.36	21.04	0.98	0.98	Optimal
	Cumulative number of leaves per apex (NLA, leaves)	15.01	15.45	0.97	0.97	Optimal
	Leaf area index (LAI, dimensionless)	0.98	31.56	0.59	0.83	Average
	Crop total dry matter yield (CTDMY, kg ha^{-1})	706.62	3.41	1.00	1.00	Optimal
	Aerial part dry matter yield (APDMY, kg ha^{-1})	1716.97	14.20	0.98	0.98	Optimal
	Reserve root dry matter yield (RRDMY, kg ha^{-1})	2392.69	30.80	0.98	0.97	Optimal
Eucalipto	Aerial part branching level (ABL, level)	0.06	4.00	1.00	1.00	Optimal
	Cumulative number of leaves per apex (NLA, leaves)	11.70	15.00	0.97	0.97	Optimal
	Leaf area index (LAI, dimensionless)	0.90	38.00	0.33	0.77	Fair
	Crop total dry matter yield (CTDMY, kg ha^{-1})	855.70	6.00	0.99	1.00	Optimal
	Aerial part dry matter yield (APDMY, kg ha^{-1})	1057.77	15.00	0.95	0.98	Optimal
	Reserve root dry matter yield (RRDMY, kg ha^{-1})	1304.74	22.00	0.94	0.97	Optimal

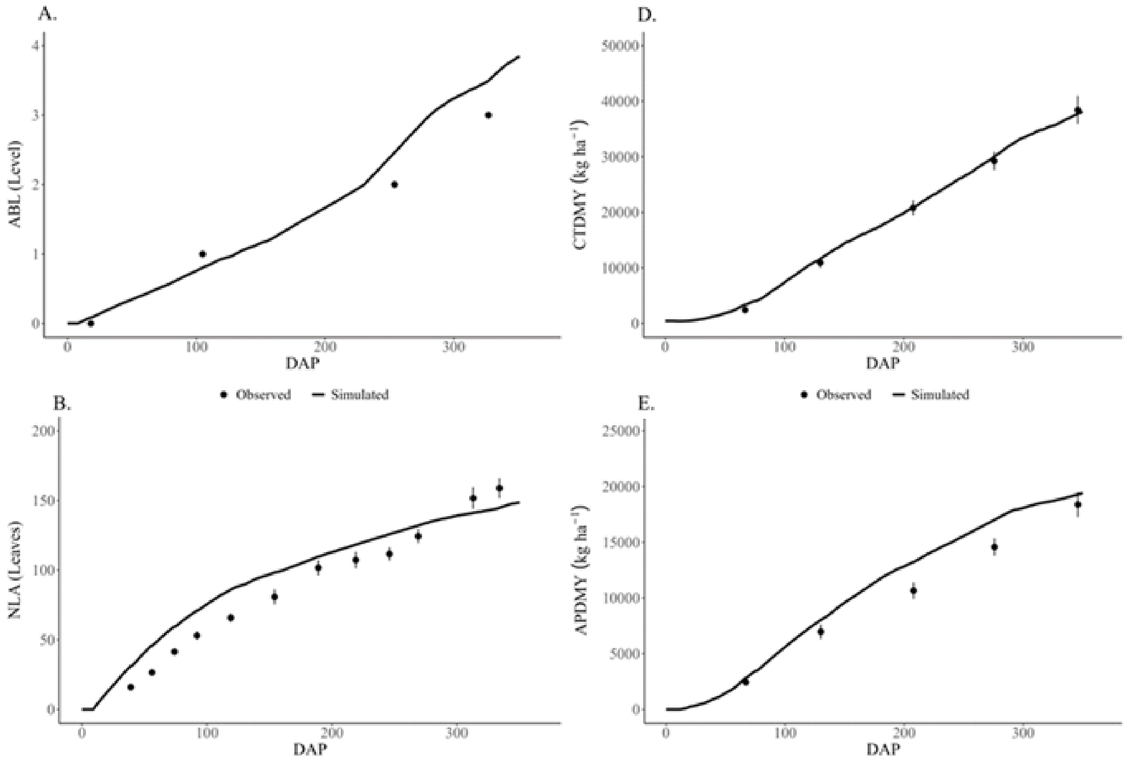
RMSE - Root mean square error; RRMSE - Relative root mean square error; R^2 - Coefficient of determination; d - Agreement index of Willmott

The LAI simulations for the BRS Novo Horizonte variety showed a R^2 value of 0.59 and d value of 0.83. The reliability index in the LAI simulations of the variety was classified as average. For LAI, the simulation for the Eucalipto variety exhibited a R^2 value of 0.33 and d value of 0.77, and the reliability index was classified as fair (Table 3).

According to the RRMSE index, for the BRS Novo Horizonte variety, the mean deviation of the simulated data from the observed data for the apex branching level (ABL) variable was classified as average, with RRMSE of 21.04% and RMSE of 0.36. The cumulative number of leaves of the apex (NLA) was classified as good, with RRMSE of 15.45% and RMSE of 15.01 leaves. The LAI variable was classified as bad, with RRMSE of 31.56% and RMSE of 0.98. The crop total dry matter yield (CTDMY) was classified as perfect, with RRMSE of 3.41% and RMSE of 706.62 kg ha^{-1}. The aerial part dry matter yield (APDMY) variable was classified as good, with RRMSE of 14.20% and RMSE of 1716.97 kg ha^{-1}. The reserve root dry matter yield (RRDMY) variable was classified as bad, with RRMSE of 30.80% and RMSE of 2392.69 kg ha^{-1} (Table 3).

For the Eucalipto variety, the mean deviation of the simulated data from the observed data was classified as perfect for the ABL variable, with RRMSE of 4% and RMSE of 0.06. NLA was classified as good, with RRMSE of 15.00% and RMSE of 11.70 leaves. LAI was classified as bad, with RRMSE of 38.00% and RMSE of 0.90. CTDMY was classified as perfect, with RRMSE of 6% and RMSE of 855.70 kg ha^{-1}. The APDMY variable was classified as good, with RRMSE of 15.00% and RMSE of 1057.77 kg ha^{-1}. RRDMY was classified as average, with RRMSE of 22.00% and RMSE of 1304.74 kg ha^{-1} (Table 3).

During the calibration phase, the trend lines simulated by the model were able to represent the pattern of evolution of the variables studied for both the varieties: BRS Novo Horizonte (Figure 2) and Eucalipto (Figure 3). The exception was the LAI variable; during the leaf senescence phase, after 180 DAP, it exhibited an overestimate for the BRS Novo Horizonte variety



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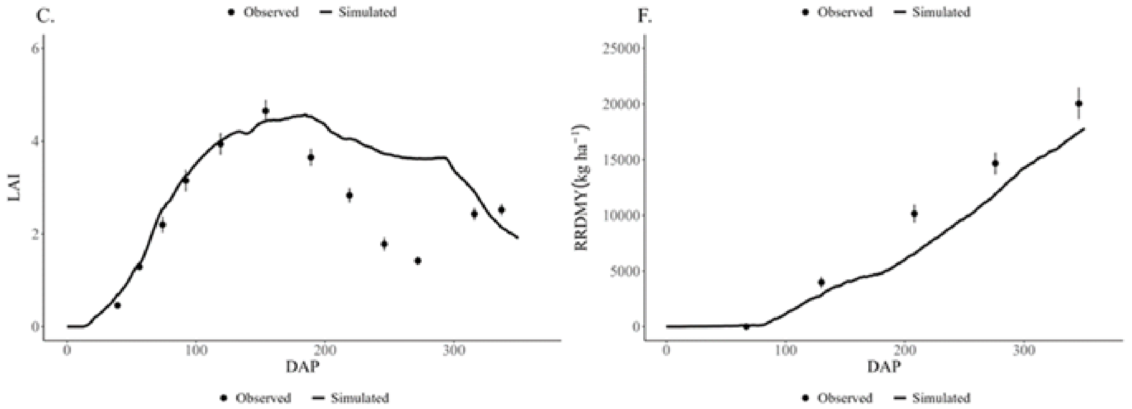
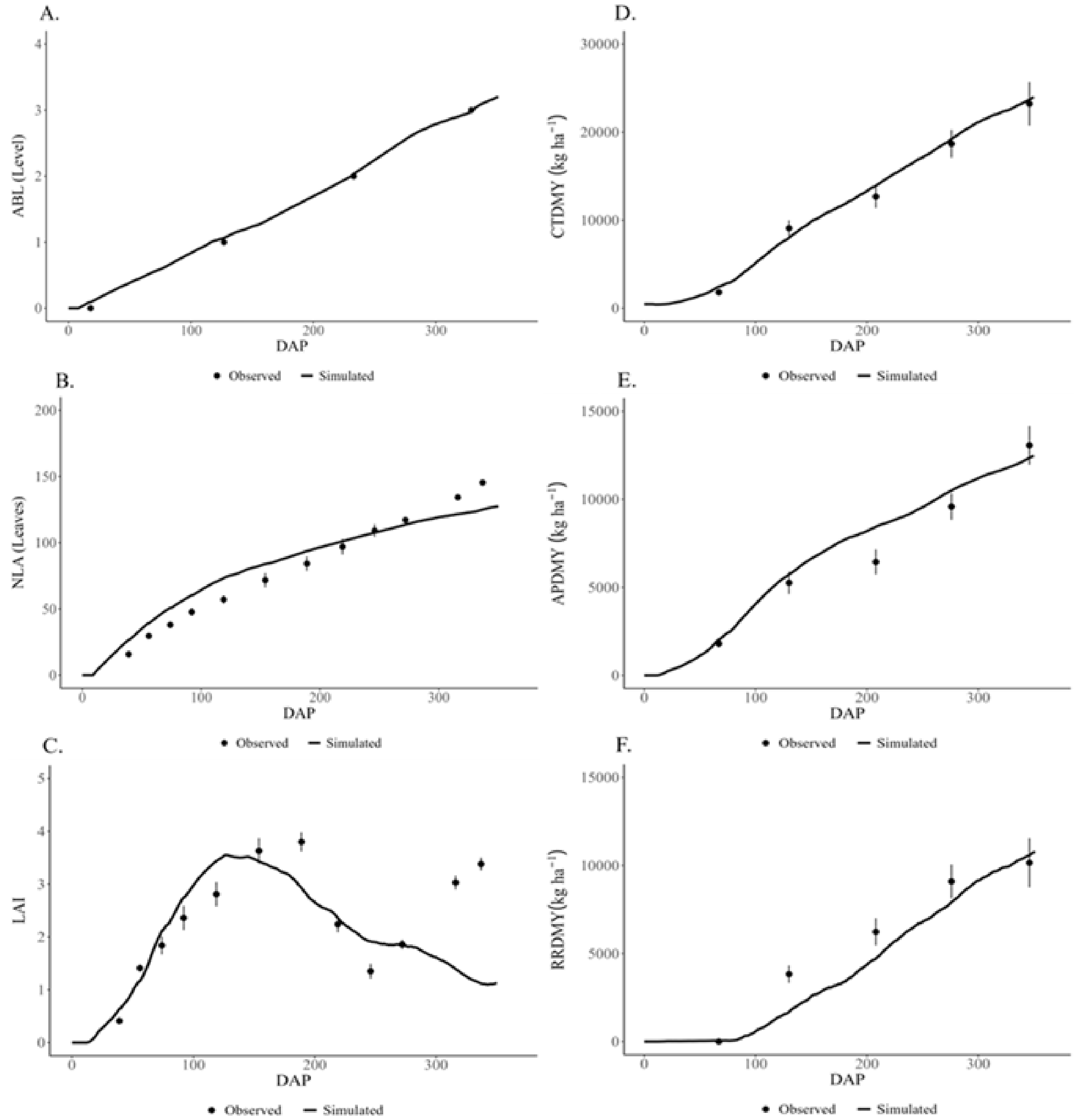


Error bars represent the mean standard error of the sample; DAP - Days after planting

Figure 2. Simulated growth trends for the BRS Novo Horizonte variety, with observed values plotted for (A) apex branching level (ABL); (B) number of leaves of the apex (NLA); (C) leaf area index (LAI); D) crop total dry matter yield (CTDMY); (E) aerial part dry matter yield (APDMY); (F) reserve root dry matter yield (RRDMY)



Error bars represent the mean standard error of the sample; DAP - Days after planting

Figure 3. Simulated growth trends for the Eucalipto variety, with observed values plotted for (A) apex branching level (ABL); (B) number of leaves of the apex (NLA); (C) leaf area index (LAI); (D) crop total dry matter yield (CTDMY); (E) aerial part dry matter yield (APDMY); (F) reserve root dry matter yield (RRDMY)

(Figure 2C), and the leaf senescence phase did not occur as it did in the field. For the Eucalipto variety, the model was not efficient in representing the leaf canopy regrowth phase, which occurred after 250 DAP (Figure 3C).

For RRDMY, underestimates were observed for both varieties during evolution of the variable (Figures 2F and 3F). Similarly, overestimates of APDMY were found (Figures 2E and 3E). Simulation of the CTDMY variable had few errors for both varieties (Figures 2D and 3D). This result means that, during the calibration phase, the model efficiently simulated plant biomass production. However, there were some errors in simulation of the plant biomass distribution between the aerial part and the reserve roots. This result explains the higher RMSE values and the classification attributed by the RRMSE index, which penalizes larger errors, that is, higher deviations of the simulated data from the observed data.

During the validation phase, the model demonstrated high accuracy and precision in representing the variables ABL, NLA, CTDMY, and APDMY, with R^2 and d values approaching 1 for both parameters, for all simulations. The reliability was classified as excellent based on the evaluation of simulations across the entire dataset from Experiments 2, 3, and 4 (Table 4).

Mean deviations of the simulated data from the observed data were recorded during validation of simulation of ABL. RRMSE was classified as bad, with values of 38 and 35%, and RMSE of 0.40 and 0.42 for the BRS Novo Horizonte and Eucalipto varieties, respectively. The NLA variable was classified as good for both varieties, with RRMSE of 20 and 16%, and RMSE of 17.47 and 12.69 leaves for the BRS Novo Horizonte and Eucalipto varieties, respectively. The CTDMY variable was classified as good for BRS Novo Horizonte and average for Eucalipto, with RRMSE of 15 and 25%, and RMSE of 3144.91 and 3081.30 kg ha^{-1}, respectively. The APDMY variable was classified as good for both varieties, with RRMSE of 13 and 11%, and RMSE of 1472.97 and 884.07 kg ha^{-1} for the BRS Novo Horizonte and Eucalipto varieties, respectively (Table 4).

For the validation of LAI, the BRS Novo Horizonte variety had a R^2 of 0.72 and a d index of 0.91. It had an excellent reliability index, and the mean deviations were classified as average, with RRMSE of 27% and RMSE of 0.85. For the Eucalipto variety, the trend simulated by the model was not able to explain well the variance of the data, with R^2 of 0.55 and d of 0.85. The reliability index was classified as average and the mean deviations were classified as bad, with RRMSE of 37% and RMSE of 0.87 (Table 4).

In relation to the RRDMY variable, the simulations of the BRS Novo Horizonte variety had precision and accuracy in evaluation of the dataset, with R^2 of 0.82 and d index of 0.95. The reliability index variable was classified as optimal. The Eucalipto variety had a R^2 value of 0.79 and d index of 0.91, and the reliability index variable was classified as excellent. The mean deviations for both varieties were classified as bad, with RMSE of 3140.69 and 2695.57 kg ha^{-1} and RRMSE of 37 and 55% for the BRS Novo Horizonte and Eucalipto varieties, respectively (Table 4).

Just as found in the calibration phase, during validation, the model was able to simulate the developmental trend of each variable and of each variety correctly, except for the LAI variable (Figures 4 and 5).

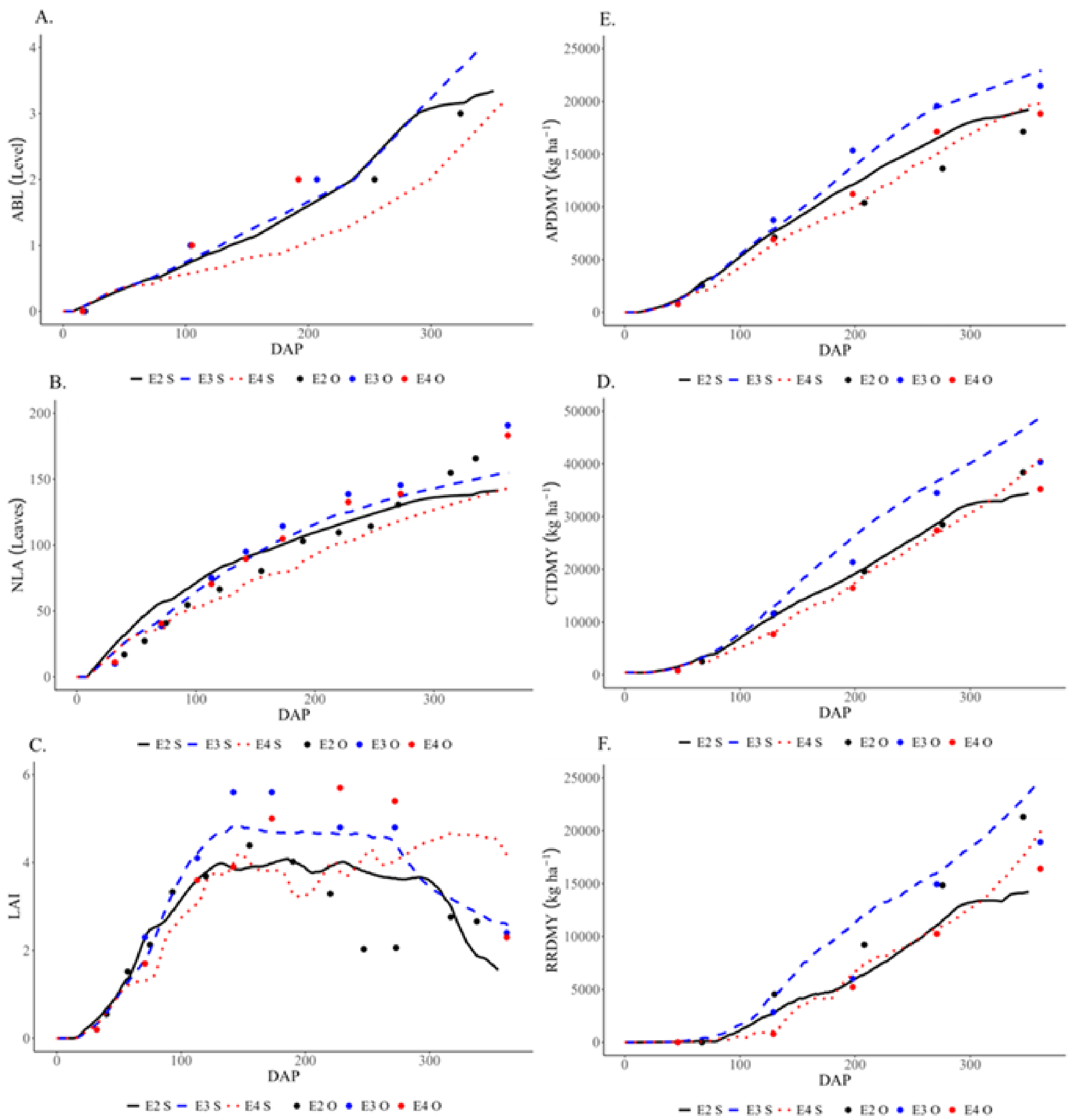
For both varieties, the model underestimated the growth of the crop leaf canopy, as observed in the ABL and NLA variables

Table 4. Statistical analysis of the performance of calibration of the MANIHOT-Cassava model for the BRS Novo Horizonte and Eucalipto varieties

Variable	Exp.	BRS Novo Horizonte					Eucalipto				
		RMSE	RRMSE (%)	R^2	D	Reliability (c)	RMSE	RRMSE (%)	R^2	D	Reliability (c)
ABL, level	2	0.23	15.00	0.98	0.99	Optimal	0.12	8.00	1.00	1.00	Optimal
	3	0.27	33.00	1.00	0.97	Optimal	0.39	39.00	0.96	0.92	Optimal
	4	0.63	115.00	1.00	0.76	Excellent	0.64	64.00	0.96	0.75	Good
	All	0.40	38.00	0.86	0.96	Optimal	0.42	35.00	0.87	0.95	Optimal
NLA, leaves	2	14.49	15.00	0.97	0.97	Optimal	9.62	12.00	0.98	0.98	Optimal
	3	15.11	16.00	0.99	0.98	Optimal	7.82	10.00	0.99	0.99	Optimal
	4	22.93	29.00	0.99	0.94	Optimal	19.06	23.00	0.99	0.95	Optimal
	All	17.47	20.00	0.93	0.96	Optimal	12.69	16.00	0.94	0.97	Optimal
LAI, dimensionless	2	0.78	27.00	0.58	0.87	Good	0.85	39.00	0.30	0.75	Fair
	3	0.49	14.00	0.96	0.98	Optimal	0.98	36.00	0.63	0.88	Good
	4	1.17	38.00	0.64	0.86	Good	0.79	34.00	0.66	0.88	Good
	All	0.85	27.00	0.72	0.91	Excellent	0.87	37.00	0.55	0.85	Average
CTDMY, kg ha^{-1}	2	2010.23	10.00	0.98	0.99	Optimal	946.67	7.00	0.98	1.00	Optimal
	3	4374.14	17.00	0.99	0.98	Optimal	4140.81	31.00	1.00	0.95	Optimal
	4	2548.98	14.00	0.98	0.99	Optimal	3231.21	29.00	0.98	0.96	Optimal
	All	3144.91	15.00	0.97	0.99	Optimal	3081.30	25.00	0.95	0.97	Optimal
APDMY, kg ha^{-1}	2	1967.80	17.00	0.99	0.97	Optimal	1319.24	17.00	0.95	0.96	Optimal
	3	1039.09	8.00	0.98	1.00	Optimal	493.98	6.00	0.99	1.00	Optimal
	4	1247.80	12.00	0.97	0.99	Optimal	600.27	8.00	0.98	0.99	Optimal
	All	1472.97	13.00	0.96	0.99	Optimal	884.07	11.00	0.96	0.99	Optimal
RRDMY, kg ha^{-1}	2	3841.05	55.00	0.98	0.91	Optimal	1591.45	26.00	0.97	0.96	Optimal
	3	3476.21	31.00	0.95	0.95	Optimal	3556.64	73.00	0.99	0.88	Optimal
	4	1659.53	22.00	0.99	0.98	Optimal	2572.15	67.00	1.00	0.91	Optimal
	All	3140.69	37.00	0.82	0.95	Optimal	2695.57	55.00	0.79	0.91	Excellent

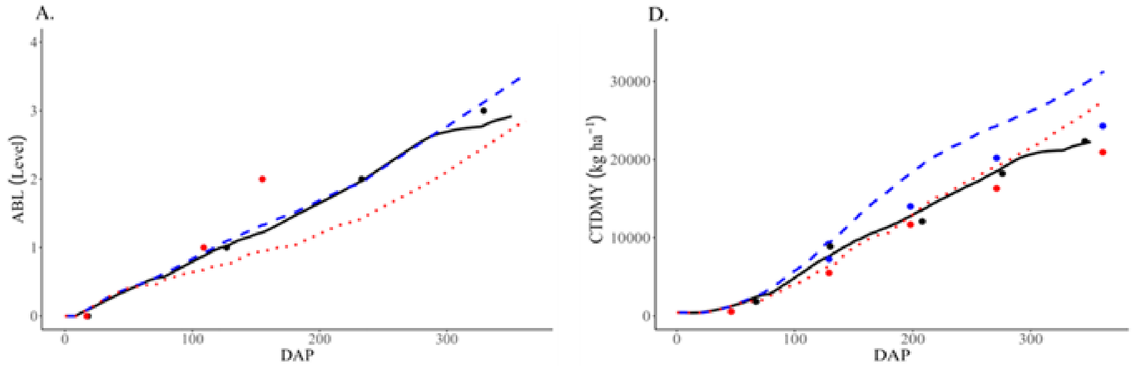
Exp - Experiment; All - Evaluation of the entire dataset of Experiments 2, 3, and 4; ABL - Apex branching level; NLA - Number of leaves of the apex; LAI - Leaf area index; CTDMY - Crop total dry matter yield; APDMY - Aerial part dry matter yield; RRDMY - Reserve root dry matter yield; RMSE - Root mean square error; RRMSE - Relative root mean square error; R^2 - Coefficient of determination; d - Agreement index of Willmott; c - Reliability index

(Figures 4A, B and 5A, B) in Experiment 4, where the water restriction condition was more severe than in Experiment 3, in which the plants were grown at the same time, but without water restriction. This result shows that the model may be excessively penalizing the development of the aerial part and the leaf production rate under the condition of more severe water restriction. This is something to be improved in future updating of calibration with a database that considers experiments with more severe water availability conditions, and in a hotter and drier environment.



E2 S - Experiment 2 simulation; E3 S - Experiment 3 simulation; E4 S - Experiment 4 simulation; E2 O - Experiment 2 observation; E3 O - Experiment 3 observation; E4 O - Experiment 4 observation; DAP - Days after planting

Figure 4. Simulated growth trends for the BRS Novo Horizonte variety, with observed values plotted for (A) apex branching level (ABL); (B) number of leaves of the apex (NLA); (C) leaf area index (LAI); (D) crop total dry matter yield (CTDMY); (E) aerial part dry matter yield (APDMY); (F) reserve root dry matter yield (RRDMY)



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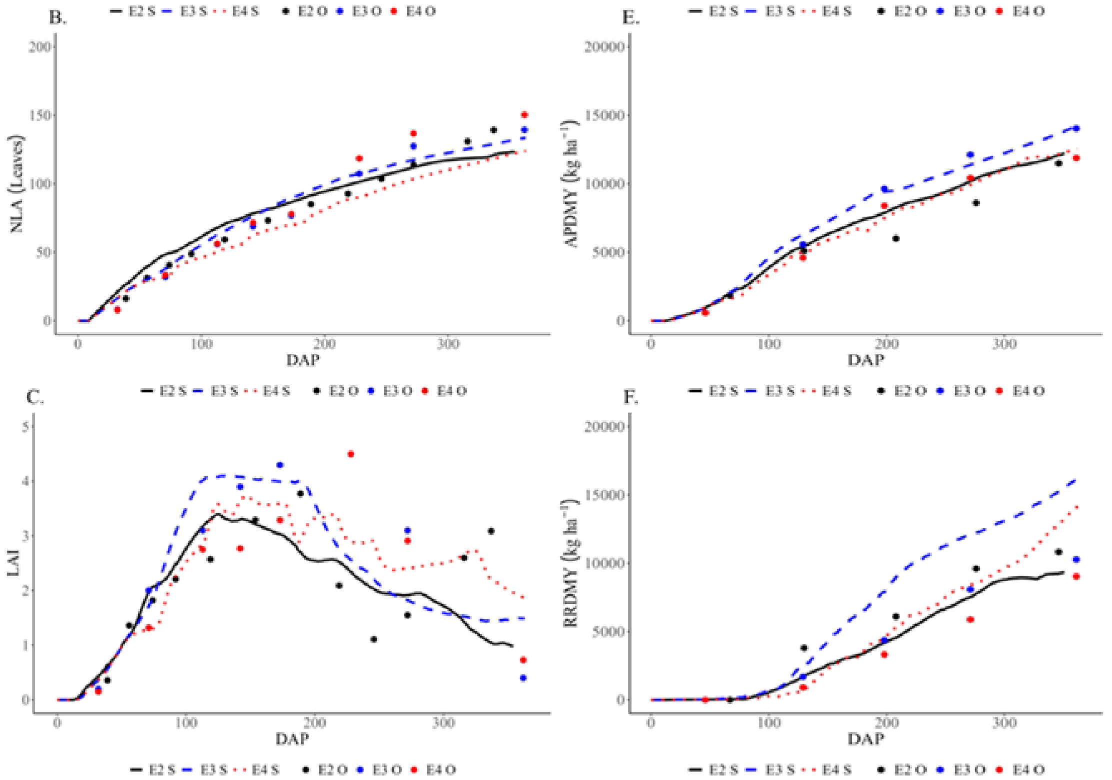


E2 S - Experiment 2 simulation; E3 S - Experiment 3 simulation; E4 S - Experiment 4 simulation; E2 O - Experiment 2 observation; E3 O - Experiment 3 observation; E4 O - Experiment 4 observation ; DAP - Days after planting

Figure 5. Simulated growth trends for the Eucalipto variety, with observed values plotted for (A) apex branching level (ABL); (B) number of leaves of the apex (NLA); (C) leaf area index (LAI); (D) crop total dry matter yield (CTDMY); (E) aerial part dry matter yield (APDMY); (F) reserve root dry matter yield (RRDMY)

Although considerable, the plant growth penalty imposed by the model under water restriction conditions is consistent. Cassava shows tolerance to lack of water due to morphophysiological mechanisms (El-Sharkawy, 2006). These stress-induced mechanisms tend to become more pronounced as the severity and duration of the stress increase. Examples include reduced leaf area, increased stomatal regulation to limit transpiration and conserve water, and, under more prolonged or intense stress, dormancy to preserve energy (Coelho Filho, 2020; Devi et al., 2022). However, despite its tolerance to lack of water, a substantial yield gap persists, when compared to optimal, stress-free conditions, storage root yield losses can exceed 50%, as reported by Devi et al. (2022) and More et al. (2023).

Moreno-Cadena et al. (2021) explain how the model works and mention that water deficit is based on the soil available water content, instead of the ratio between actual and potential transpiration used in other cassava models cited in their review. In the MANIHOT-Cassava model, the water stress factor increases germination time and the time between branching of the apices, reducing the leaf emergence rate, leaf size, and photosynthesis (Moreno-Cadena, 2020).

For LAI simulation, just as found in the calibration phase, errors concentrated after 180 DAP, with failures in simulation of both varieties during the leaf senescence and leaf canopy regrowth phases, leading at times to overestimates or underestimates (Figures 4C and 5C).

Phoncharoen et al. (2021a) calibrated the MANIHOT-Cassava model with information from cassava varieties in a tropical climate and recorded similar errors in part of the LAI simulations, with growth trends failing to reach the maximum LAI or failing to simulate the leaf senescence phase at times, a result very close to what was found in this study.

Among the variables simulated by the model, LAI is likely one of the most challenging. This is because most of the calibration parameters adjusted have some level of effect on LAI. Moreno-Cadena et al. (2020) studied the sensitivity of output data of the MANIHOT-Cassava model resulting from variations in the calibration parameters and recorded that 10 of the 16 parameters evaluated during sensitivity analysis interfered in simulation of the maximum LAI in environments with higher temperatures, such as the environments of the Recôncavo Baiano or Thailand (Phoncharoen et al., 2021a).

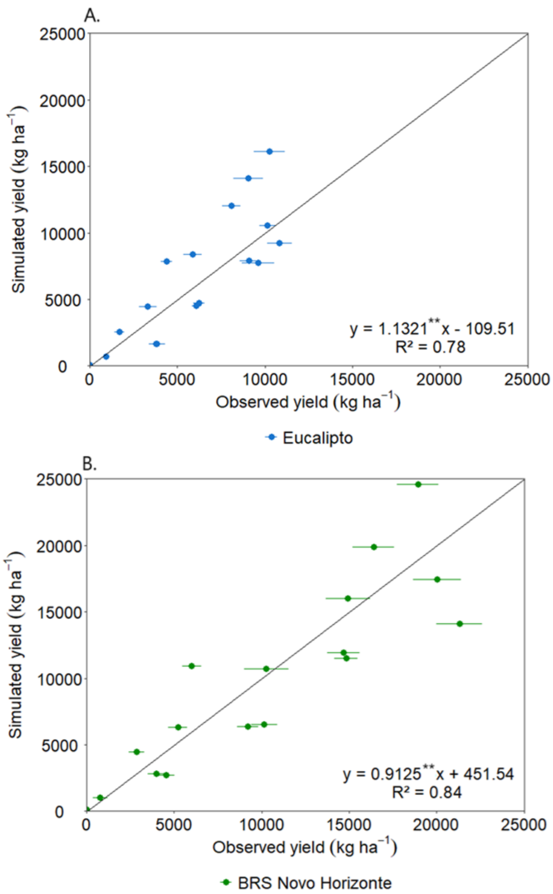
The model showed overestimation of CTDMY for both varieties in Experiments 3 and 4 (Figures 4D and 5D). In Experiment 2, in which the growing conditions are similar to those of Experiment 1, used in the calibration process, there were fewer errors for the variable. In relation to the distribution of the plant biomass between the aerial part and reserve roots, the model showed few errors in simulations of APDMY (Figures 4E and 5E), especially for the Eucalipto variety (Figure 5E). In the simulations of RRDMY, overestimations were recorded in the simulations of Experiments 3 and 4, and underestimates for Experiment 2, for both varieties (Figures 4F and 5F).

It can be seen based on differences between the growth trends of Experiments 3 and 4 that the model is right in penalizing the dry matter yield in Experiment 4, which had lower water availability, for the BRS Novo Horizonte variety (Figures 4D, E and F) and for the Eucalipto variety (Figures 5D, E, and F). It can also be seen that the model is able to capture the differences that occur between the planting times, with greater plant biomass yield at the time when there is greater energy availability in the agroecosystem, without water restriction - Experiment 3 (Figures 2D, 3D, 4D, and 5D).

Calibration improved the model's performance in simulating cassava cultivation in relation to the default cassava variety described in the MANIHOT-Cassava variety files, considering the same experimental database, for the Eucalipto and BRS Novo Horizonte varieties, for all variables (Table 5).

In general, the DSSAT MANIHOT-Cassava model was able to simulate the growth, development, and production of cassava under the growing conditions of the Recôncavo Baiano, with satisfactory statistical indices (Table 5, Figure 6), close to those reported in other studies that dealt with calibration of the model in other environments, sources of variation, and varieties (Phoncharoen et al., 2021b; Rankine et al., 2021; Photangtham et al., 2022).

In a potential update of the calibration of DSSAT MANIHOT-Cassava model, with information on the varieties studied here, it is important to better evaluate the differences that occur among the planting times and among the growing conditions associated with more limited water supply. When evaluating plant performance in environments undergoing climate transition, with a hotter and drier climate, it may also be useful and timely to check the limitations of the model under growing conditions with more severe abiotic stresses.



Error bars represent the mean standard error of the sample; ** - Significant at p ≤ 0.05 by F test

Figure 6. Relationship between cassava storage root final yields observed in experiments in the Recôncavo Baiano, Brazil, with standard errors, and those simulated by DSSAT MANIHOT-Cassava model in both calibration and evaluation phases, for Eucalipto (A) and BRS Novo Horizonte (B) cassava varieties

Table 5. Statistical analysis of the calibration and evaluation performance of the DSSAT MANIHOT-Cassava model for the varieties BRS Novo Horizonte, Eucalipto and default with the complete experimental database per variety

Variety	Variable	RMSE	RRMSE (%)	R^2	D	Reliability (c)
BRS Novo Horizonte	Apex branching level, levels	0.39	30.27	0.89	0.97	Optimal
	Cumulative number of leaves per apex, leaves	16.77	18.06	0.91	0.96	Optimal
	Leaf area index	0.89	29.61	0.66	0.89	Good
	Crop total dry matter yield, kg ha^{-1}	2746.40	13.77	0.97	0.99	Optimal
	Aerial part dry matter yield, kg ha^{-1}	1537.61	13.69	0.96	0.99	Optimal
	Reserve root dry matter yield, kg ha^{-1}	2745.71	31.62	0.84	0.96	Optimal
DSSAT Manihot-Cassava default variety/BRS Novo Horizonte variety experimental data	Apex branching level, levels	1.43	111.38	0.94	0.79	Excellent
	Cumulative number of leaves per apex, leaves	20.42	22.18	0.89	0.95	Optimal
	Leaf area index	2.03	58.76	0.27	0.60	Bad
	Crop total dry matter yield, kg ha^{-1}	3461.85	16.62	0.98	0.98	Optimal
	Aerial part dry matter yield, kg ha^{-1}	5046.27	44.92	0.73	0.84	Good
	Reserve root dry matter yield, kg ha^{-1}	4205.27	48.31	0.87	0.93	Optimal
Eucalipto	Apex branching level, levels	0.35	27.52	0.90	0.97	Optimal
	Cumulative number of leaves per apex, leaves	12.40	15.74	0.94	0.97	Optimal
	Leaf area index	0.88	37.46	0.50	0.83	Fair
	Crop total dry matter yield, kg ha^{-1}	2702.57	21.34	0.94	0.97	Optimal
	Aerial part dry matter yield, kg ha^{-1}	930.54	12.39	0.95	0.99	Optimal
	Reserve root dry matter yield, kg ha^{-1}	2423.87	46.99	0.78	0.92	Excellent
DSSAT Manihot-Cassava default variety/Eucalipto Variety experimental data	Apex branching level, levels	1.35	105.08	0.89	0.80	Excellent
	Cumulative number of leaves per apex, leaves	28.21	34.88	0.71	0.89	Good
	Leaf area index	2.00	73.10	0.40	0.65	Poor
	Crop total dry matter yield, kg ha^{-1}	11707.00	93.60	0.91	0.74	Good
	Aerial part dry matter yield, kg ha^{-1}	1375.00	19.04	0.92	0.97	Optimal
	Reserve root dry matter yield, kg ha^{-1}	10777.00	209.01	0.80	0.55	Poor

RMSE - Root mean square error; RRMSE - Relative root mean square error; R^2 - Coefficient of determination; d - Agreement index; c - Reliability Index

Conclusions

1. The DSSAT MANIHOT-Cassava model was efficiently calibrated, which was proved in the evaluation phase, and was able to properly simulate the development, growth, and production of the BRS Novo Horizonte and Eucalipto varieties in a sub-humid tropical climate, under the growing conditions of the Recôncavo Baiano.

2. The yield estimates with the calibrated varieties showed performance generally higher than the estimates obtained by the default variety available in the system, reinforcing the essentiality of the calibration phase with experimental data for improved simulations.

Contribution of authors: DMM participated in data collection and all stages involving data handling and manuscript writing. PBF, FLCS, and PMC contributed to data handling, analysis, literature review, translation, and manuscript writing. ABH and JRV were involved in methodological guidance. MACF contributed to the conceptualization of the study, coordination, manuscript revision, and funding acquisition.

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