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Sweet cassava yield gaps and key management factors in Brazil

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Abstract

The objective in this study was to identify yield gaps and management factors that limit the yield of cassava (*Manihot esculenta* Crantz) in tropical and subtropical regions of Brazil. A total of 303 cassava fields were analyzed, and the yield potential was estimated using the Food and Agriculture Organization of the United Nations (FAO) model for agroecological zones for tropical regions and the Simanihot model for subtropical regions. Yield-limiting management factors were identified using regression tree analysis, and the optimal values of the key variables were determined using threshold functions (boundary). The estimated yield gap was 34.2 Mg ha^{-1} in tropical regions and 27.7 Mg ha^{-1} in subtropical regions. In the tropical regions, the most limiting factors were planting density, planting date, land tenure, and irrigation. In the subtropical regions, planting density, planting date, row spacing, and desiccation were the most important constraints. Optimal values for planting density were 13,000 plants ha^{-1} for tropical and 11,000 plants ha^{-1} for subtropical regions. The recommended planting dates to achieve maximum yields were by November 15 in tropical areas and by September 27 in subtropical areas. These results show the importance of adapting cultivation practices to regional conditions in order to close yield gaps and improve cassava yields in Brazil.

Plain Language Summary

Cassava is an important food crop grown throughout Brazil, but farmers often achieve lower yields than what is possible. To find out why, researchers analyzed 303 cassava fields in tropical and subtropical regions. They found that using better cultivation practices, especially planting the right number of plants per area and planting earlier, can significantly increase cassava yields. In tropical areas, the best results came from planting 13,000 plants per hectare by mid-November. In the subtropical areas, the

Abbreviations: AHy, high-yielding tertile; ALy, low-yielding tertile; FAO, Food and Agriculture Organization of the United Nations; Hy, high-yield; Ly, low-yield; OPD, optimal planting density; YP, yield potential.

optimal practice was 11,000 plants per hectare planted by the end of September. Other helpful practices included using irrigation in the tropics. If more farmers adopted these key practices, Brazil could produce significantly more cassava without needing more land. This would help improve food security and increase farmers' incomes.

1 | INTRODUCTION

It is estimated that the world population will grow from 7.6 to 9.8 billion people by 2050, which will increase the demand for food by 50% (Nelson et al., 2010). This population growth presents modern agriculture with the major challenge of improving crop yields to meet the demand for food in a sustainable way (Cirera & Masset, 2010). To achieve this, higher production efficiency is required in agricultural areas (Grassini et al., 2011; Van Wart et al., 2013). It is therefore necessary to determine how high the yield potential (YP) is, by how much it can be increased (yield gaps), and which biophysical and management factors limit the yield at farm level (Grassini et al., 2011; Van Ittersum et al., 2013).

Cassava (*Manihot esculenta* Crantz) is considered a staple food for >1 billion people in 105 countries (Chetty et al., 2013). In 2023, Brazilian production is about 18.4 million t on an area of >1.2 million ha (Instituto Brasileiro de Geografia e Estatística [IBGE], 2023). Cassava is cultivated in all Brazilian regions as it is an adaptable, drought-tolerant crop with high nutritional value and low cultivation costs (Tironi et al., 2017). Although Brazil is the fifth largest producer of cassava in the world, the average yield is still low (15 Mg ha^{-1}) (Instituto Brasileiro de Geografia e Estatística [IBGE], 2023), compared to the yield of 33 Mg ha^{-1} in some experiments in Brazil (Tironi et al., 2015) and the YP determined by Visses et al. (2018), which ranged from 44.8 to 66.9 Mg ha^{-1} in Brazil.

In East Africa, yield gap of 26.2 and 21.6 Mg ha^{-1} was observed in Kenya and Uganda, respectively, which were mainly attributed to low soil fertility, low rainfall in the first 6 months after sowing, inadequate weed control, soil texture, and the socio-economic characteristics of the farmers (Fermont et al., 2009). Although cassava is grown nationwide in Brazil and is of great socio-economic importance, average yields remain far below their YP. Studies have shown that the yield gap of industrial cassava in the western Cerrado region of Brazil can reach up to 44.6 Mg ha^{-1}, mainly due to suboptimal management practices such as the use of traditional varieties, delayed sowing, insufficient potassium fertilization, and inadequate weed control (Zebalho et al., 2024). These results emphasize the urgent need to identify and apply regionally adapted management strategies to improve the yields and resource efficiency of cassava production. Visses et al. (2018) also found a cassava yield gap of 25–55 Mg ha^{-1} for Brazil, depending on regional and technological aspects.

In order to achieve higher production efficiency in cassava cultivation, the YP, the extent of yield gaps, and the biophysical and management factors that limit yield on farms must be determined (Grassini et al., 2011; Van Ittersum et al., 2013). Sustainable yield increases also depend on a clear understanding of the climatic, agronomic, and socio-economic conditions specific to each region. In this context, knowledge of the specificities of cassava cultivation in Brazil is crucial to guide efforts toward more efficient resource use and to prioritize investments in technologies and inputs. Therefore, the objective of the study was to identify yield gaps and the main crop management factors that affect sweet cassava yield in tropical and subtropical environments in Brazil.

2 | MATERIALS AND METHODS

2.1 | Study region and climate description

The study was conducted on 25% of the cassava cultivation area in the Central-West region (Federal District [DF], Goiás [GO], south-east of the state of Minas Gerais [MG]) and in the south of Brazil (state of Rio Grande do Sul—RS) (Figure 1a). The Central-West region is characterized by a tropical environment with dry winters and rainy summers, while the South region is characterized by a subtropical environment with clearly defined seasons (autumn, winter, spring, and summer), where frost occurs in winter, summer is extremely hot and rainfall is well distributed throughout the year.

The climatic characterization of the study area was obtained by analyzing the daily meteorological data of the "Instituto Brasileiro de Meteorologia—INMET" over an average of 5 years (2017–2021) (Figure 1b). In Luziânia/GO, São Simão/GO, Montes Claros/MG, and São João Del Rei/MG, the average air temperature between 2017 and 2021 was above 20°C, with an average range of 17°C–29°C. In addition, solar radiation was high, fluctuating between 15 and 26 MJ m^{-2} day^{-1} throughout the year. From May to September, there was a drastic decrease in rainfall (dry winter), while the average cumulative rainfall was 1255 mm per year. In the subtropical environment of Santa Maria/RS and Santo Augusto/RS, the average air temperature during the same period was below

18°C, with an average range of 14°C–25°C. The solar radiation had a greater amplitude than in the tropical environment, from 7 to 27 MJ m^{-2} day^{-1}. The average rainfall was 1660 mm and was well distributed over the years.

2.2 | YP modeling and field data collection

Two mathematical models were used to estimate the YP: the Food and Agriculture Organization of the United Nations (FAO) model for the tropical environment, where the YP was estimated by Visses et al. (2018), and the Simanihot model for the subtropical environment, where the YP was estimated by Borges et al. (2020). The FAO model is an empirical model that does not take into account the ecophysiological processes of plants. The Simanihot model is a dynamic, process-based ecophysiological model that takes into account the influence of the environment on the interaction of the growth, development, and yield processes of cassava crops in a subtropical environment (Gabriel et al., 2014; Tironi et al., 2017).

Ecophysiological models are the best means to capture plant-environment interactions when analyzing YP and yield gap. However, it is important that the ecophysiological models are calibrated to the study sites (Grassini et al., 2015). For cassava, this is a major challenge, as there are >4500 cultivars in Brazil, and many cultivars have lost their cultivar registration name, making it difficult to calibrate the models (Tironi et al., 2019). Therefore, calibrated models for each environment were used in this study, with the future possibility of calibrating the Simanihot model for the tropical environment and thus estimating the YP with a model based on ecophysiological processes.

For 4 years (2018–2021), information was collected through a survey from more than 200 cassava farms in Rio Grande do Sul, and from 2019 to 2020, from more than 150 cassava farms in the Distrito Federal, Goiás, and Minas Gerais with a harvest within 12 months of planting. This information was entered into a digital database using Microsoft Office Excel and subjected to triage to remove questionnaires with erroneous and/or incomplete data. Therefore, information from 86% of the analyzed crops was used, totaling 174 crops in Rio Grande do Sul and 129 crops in Distrito Federal, Goiás, and Minas Gerais (Figure 1). The information collected related to the farms, yield, planting, cultivars, fertilization, weed control, pests, and diseases. The cassava root yields recorded in the surveys were used as the average yield (Ya) for each environment.

2.3 | Statistical analysis and identification of yield-limiting factors

The dataset was divided into tertiles according to yield, with the top tertile categorized as high-yield (Hy) and the lowest tertile as low-yield (Ly). (Grassini, van Bussel, et al., 2015). This made it possible to determine the average yield of the high-yielding tertile (AHy) and the average yield of the low-yielding tertile (ALy). If you know the AHy, you can determine how much the AHy accounts for of the YP. Published studies assume that the achievable yield (Yat) or economic profitability is 70%–80% of the YP (Lobell et al., 2009; Monzon et al., 2021; Van Ittersum et al., 2013). Based on this analysis, it was possible to determine whether farmers in the Ya area had already reached the achievable yield (Yat). The average yield gap (Yga) was determined by the difference between YP and Ya.

The difference between the farms with Hy and Ly was analyzed for each variable using the *t*-test or Wilcoxon test (if the data were not normal) and the chi-square test for categorical variables, with significance at 1%, 5%, and 10% error probability. InfoStat software was used to statistically analyze the data. The variables with a number of observations (n) of <10 in the Hy or Ly tertile were not included in the statistical analysis due to the small sample size.

A regression tree analysis was used to determine the yield-limiting management factors in order of importance (Breiman et al., 1984). The packages "caret" and "na.rpart" in R were used for the regression tree. The dataset was used for calibration and validation, with 70% and 80% of the data used for calibration and 30% and 20% for validation in the subtropical and tropical environments, respectively. If missing values were found, they were ignored, and the predictions were calculated using the non-missing values of the respective factors (Venables & Ripley, 2002).

To determine the optimal value of an analyzed factor, the method proposed by French and Schultz (1984), the so-called frontier function, was used, which aims to quantify the

Core Ideas

- In the tropical and subtropical regions, yield gaps of 34.2 and 27.7 Mg ha^{-1} were found.
- The yield potential of cassava was estimated by applying the FAO and Simanihot models for each environment.
- The main limiting factors in the tropical areas include planting density, date, tenure, and irrigation.
- In the subtropics, yield was limited by planting density, planting date, row spacing, and desiccation methods.
- Optimal planting: 13,000 plants ha^{-1} (tropical) and 11,000 plants ha^{-1} (subtropical), with early sowing dates.

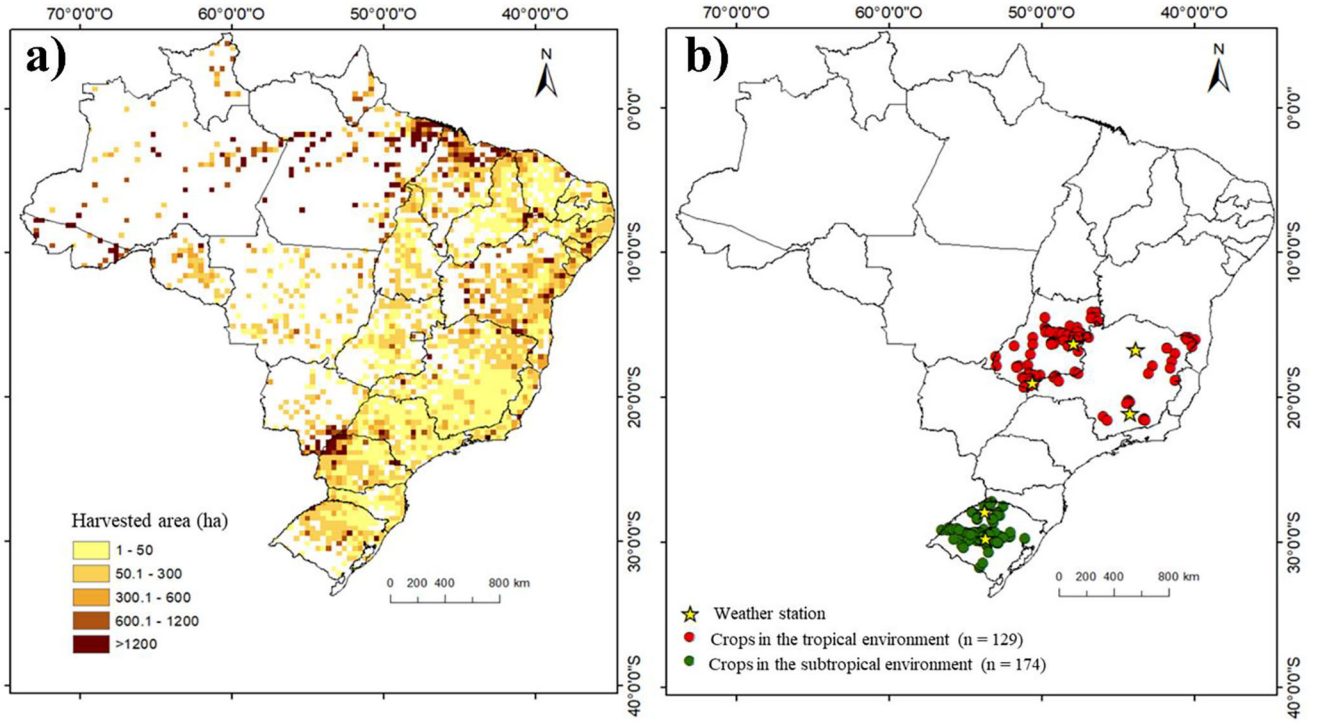

FIGURE 1 Map of cassava harvested area in Brazil, 5-year average (2017–2021) (a), geographical location of the assessed cassava crops in the tropical environment (red circles), in the subtropical environment (green circles), and the selected weather stations (yellow stars) in the study's coverage area (b).

influence of individual factors on yield. The optimal value was defined when the yield increase was <0.05%.

3 | RESULTS AND DISCUSSION

3.1 | YP and yield gap of sweet cassava

The YP for Rio Pardo de Minas/MG determined by Visses et al. (2018) using the FAO mathematical model was 66.9 Mg ha^{-1} and was used in this study as the YP for the tropical environment. For the subtropical environment, an average YP of 57.4 Mg ha^{-1} was used, with the YP values determined by Borges et al. (2020) using the Simanihot model being 64.6 Mg ha^{-1} for São Luiz Gonzaga/RS and 50.2 Mg ha^{-1} for Santa Maria/RS. Using the Simanihot model, Cardoso et al. (2022) found a YP value of 55.3 Mg ha^{-1} for Ibarama/RS, confirming the work of Borges et al. (2020). Cassava cultivars express YP under conditions with annual rainfall of more than 600 mm, high solar radiation, and optimal air temperature (El-Sharkawy, 2004).

The cardinal temperatures (minimum, optimum, and maximum) for cassava are 14°C, 30°C, and 42.5°C respectively (Matthews & Hunt, 1994). The higher YP value in a tropical environment is therefore due to the higher solar radiation, which averages 20 MJ m^{-2} day^{-1} per year, while in the subtropical environment it is only 16 MJ m^{-2} day^{-1} (Figure 2). During the photosynthesis process, solar radiation is the decisive component; therefore, high values lead to a higher daily growth rate of the plant (Fukai & Hammer, 1987). In addition, the average air temperature in the tropics varies between 25°C and 30°C, which is in the optimum temperature range that allows the highest photosynthetic rates for several cassava cultivars (Matthews & Hunt, 1994).

3.2 | Comparison between Hy and Ly crops

The average yield (Ya) of the cassava crops evaluated in the tropical environment was 32.7 Mg ha^{-1}, which represents an average yield gap (Yga) of 34.2 Mg ha^{-1} or 51% (Figure 3). The Ya of the cassava crop assessed in the subtropical environment was 30.0 Mg ha^{-1} and a Yga of 27.4 Mg ha^{-1} or 48%. In the United States, Lobell et al. (2009) found yield gaps ranging from 20% to 80% for different crops. Fermont et al. (2009) found yield gaps of 67%–79% for cassava in Uganda and Kenya, respectively. Visses et al. (2018) found cassava yield gaps of 55%–90% in some regions of Brazil, confirming the Yga found in this study. The large yield gap in cassava (over 50%) is mainly due to lack of investment in mechanization, lack of technology transfer from research to farmers, and access to investment and labor needed to improve the

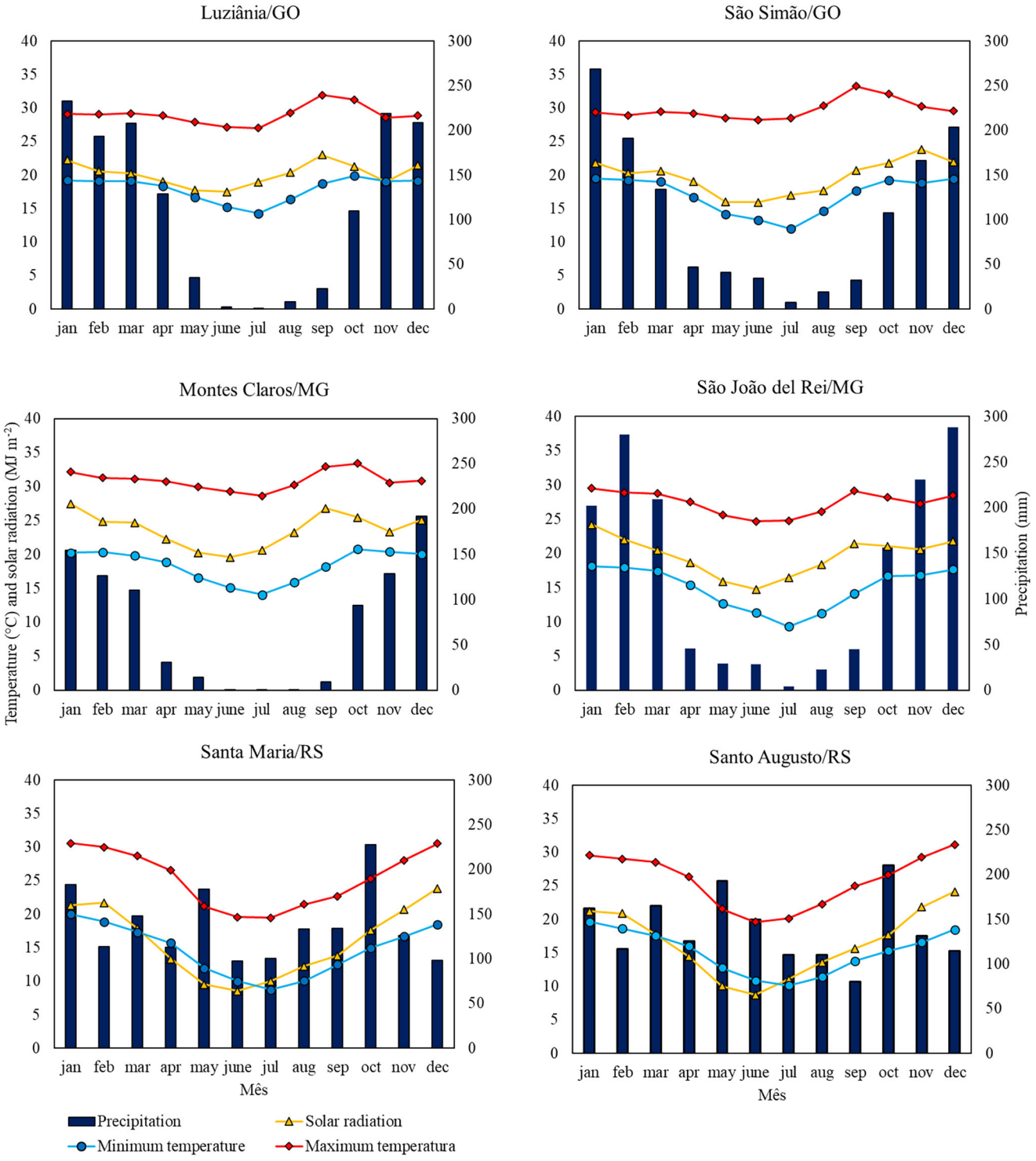

FIGURE 2 Five-year average (2017–2021) of solar radiation (MJ m^{-2} day^{-1}), maximum temperature (T_{max}), minimum temperature (T_{min}), and precipitation for the six weather stations that represent the scope area of the study.

technical efficiency of cassava production. The average crop yield in the AHy was 49.0 Mg ha^{-1} and in the ALy was 18.7 Mg ha^{-1} for the tropical environment (Figure 3).

For the subtropical environment, AHy and ALy were 42.3 and 18.2 Mg ha^{-1}, respectively (Figure 3). This indicates that the crops with the best yields are already using management factors that reduce Yga to 27%, and in other words, Hy crops have reached 73% of the YP of the tropical and subtropical environments. Published studies consider the attainable yield (Yat) as 70% of YP, and as long as there is adequate access to inputs, market, and technical information, this value can be between 70% and 80% of YP (Lobell et al., 2009; Monzon

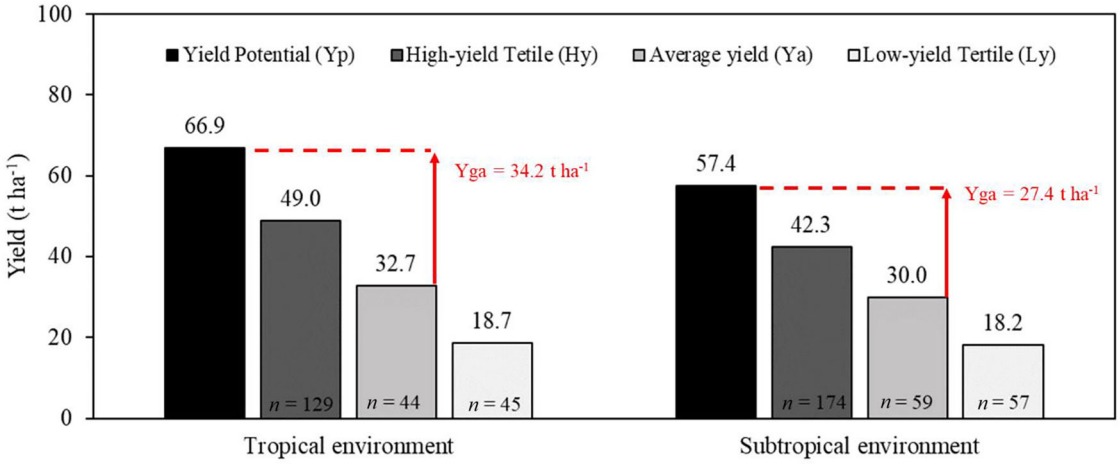

FIGURE 3 Yield potential (YP) of sweet cassava for the tropical environment determined by Visses et al. (2018) and for the subtropical environment according to Borges et al. (2020), Average yield of the tertile of high-yield (AHy) and low-yield (ALy), and the average yield (Ya) of the crops evaluated. The difference between YP and Ya is the average yield gap (Yga).

et al., 2021; Van Ittersum et al., 2013). Van Ittersum and Rabbinge (1997) consider 70% of YP as the point of maximum technical and economic efficiency of crops.

Hy crops produce 62% and 57% more than Ly crops in the tropical and subtropical environments, respectively (Figure 3). Similar to irrigated rice (*Oryza sativa* L.) crops in Rio Grande do Sul, where Hy crops yield 50% more than Ly crops (Ribas et al., 2021). The management factors that differed between Hy and Ly crops in the tropical environment were planting density, planting date, row spacing, plant spacing, nitrogen application, and cycle (Table 1). In the subtropics, they were planting density, planting date, row spacing, and interplant spacing. Among these management factors, we emphasize planting density and planting date, as together they explain >80% of cassava yield, both in tropical and subtropical environments.

3.3 | Limiting management factors in tropical environments

In the tropics, the first yield-limiting management factor was plant density, with the crops with the best yield having a plant density of ≥ 12,500 plants ha^{-1} (Figure 4). Plant density is the most important determinant of cassava yield, mainly due to the distance between rows and plants (Tironi et al., 2019). Spacing influences plant height, stem diameter, number of leaves, and root yield (Rojas et al., 2007). It is also directly related to the occurrence of weeds and competition for water and nutrients (Ayoola & Makinde, 2007; López-Bellido et al., 2005). The crops with a plant density ≥ 12,500 plants ha^{-1} and sown by November 16 had the highest yields (55.1 Mg ha^{-1}) (Figure 4).

Planting date has a major impact on YP as it is management that determines the availability of water, sunlight, and temperature during the development cycle in different environments, especially during critical periods of the crop (Lobell et al., 2009; Van Ittersum et al., 2013). In the tropics, sowing after the second half of November means that the crop's critical period due to water deficit coincides with the dry period that starts in mid-May or April (Figure 2), which reduces root yield. Although cassava is considered a drought-tolerant crop, a lack of water over long periods of time and at critical stages of development leads to yield losses (Alves, 2006). In cassava, the critical period for water deficits is 1–5 months after sowing, as this is the time when root nodule formation and rapid leaf growth take place. A deficit of at least 2 months during this period can reduce root yield by 32%–60% (Porto et al., 1989).

For crops with a plant density of 7600–12,400 plants ha^{-1}, the second yield-limiting factor was cultivation on leased land, as crops on owned land yielded 3.9 or 11.1 Mg ha^{-1} more than crops on leased land (27 Mg ha^{-1}), which is due to higher investment in cultivation on owned land, including irrigation (Figure 4). Irrigation enabled an increase of 7.2 Mg ha^{-1} compared to land without irrigation (30.9 Mg ha^{-1}). Of the crops evaluated in the tropical environment, 77% are grown on their own land and 42% use supplemental irrigation, indicating the possibility of expanding irrigated areas. In addition to increasing yields, the advantage of irrigation is the ability to plant and harvest cooking-quality roots throughout the year. This is an option for farmers aiming for early maturity and root quality for the market at different times (Tironi et al., 2017).

The lowest yields were obtained in crops with a planting density <7600 plants ha^{-1} (Figure 4). Planting density

TABLE 1 Averages of the variables evaluated in sweet cassava crops and average of the tertile of high yield (AP) and low yield (BP) in the tropical and subtropical environment of Brazil; the difference between high yield (Hy) and low yield (Ly) (Δ) was tested by *t*-test and Wilcoxon test (when the distribution deviated from normality), with significance of $*p < 0.1$, $**p < 0.05$, or $***p < 0.01$.

	Variable	Unit	Tropical environment					Subtropical environment				
			Total (*n*)	Hy tertile (*n*)	Ly tertile (*n*)	Δ		Total (*n*)	Hy tertile (*n*)	Ly tertile (*n*)	Δ	
Farm characterization	Farm land	ha	27.7 (126)	26.5 (42)	24.9 (45)	1.2		28.5 (22)	39.1 (9)	17.4 (8)	21.7	
	Agricultural land	ha	19.3 (120)	19.9 (43)	17.1 (41)	2.8		21.8 (22)	31.2 (9)	13.8 (8)	17.4	
	Leasing land	ha	15.1 (30)	14.5 (11)	15.0 (10)	−0.5		22.8 (6)	35.3 (3)	4.0 (3)	31.3	
	Land with cassava	ha	3.5 (97)	2.9 (39)	2.2 (31)	0.7		–	–	–	–	
	Evaluated farm land	ha	2.5 (120)	2.2 (42)	1.7 (42)	0.5		0.9 (174)	0.7 (59)	1.1 (57)	−0.4	
	Annual income from cassava farming	%	39.9 (106)	42.7 (37)	29.2 (35)	13.5		21.3 (13)	31.2 (4)	22.5 (6)	8.7	
Yield	Yield	Mg ha^{-1}	32.7 (129)	48.9 (44)	18.7 (45)	30.2	***	30.0 (174)	42.3 (59)	18.2 (57)	24.1	***
	Roots weight	kg $plant^{-1}$	3.5 (129)	4.2 (44)	2.5 (45)	1.7	***	2.6 (174)	3.3 (59)	2.0 (57)	1.3	***
Management	Cassava age that gave rise to the branches	month	12.0 (115)	12.2 (40)	11.5 (39)	0.7		–	–	–	–	
	Stem cutting lenght	cm	17.5 (113)	18.6 (37)	17.0 (40)	1.6		11.6 (16)	12.9 (7)	10.4 (5)	2.5	
	Buds per cutting	number	6.0 (116)	5.0 (40)	6.0 (39)	−1.0		5.0 (165)	5.0 (56)	5.0 (54)	0.00	
	Planting date with irrigation	dd/mm	19/08 (54)	12/08 (18)	26/07 (20)	17		–	–	–	–	
	Planting date without irrigation	dd/mm	13/10 (75)	23/10 (26)	25/10 (25)	−2.0	**	26/09 (174)	26/09 (59)	27/09 (57)	−1	
	Cutting density	1000 stem cutting ha^{-1}	11.5 (129)	13.8 (44)	10.6 (45)	3.2		13.7 (174)	15.7 (59)	11.9 (57)	3.8	
	Plant density	1000 plants ha^{-1}	9.8 (129)	12.7 (44)	8.2 (45)	4.5	***	11.8 (174)	13.7 (59)	9.7 (57)	4	***
	Plant establishment	%	86.0 (129)	91.0 (44)	81.0 (45)	10.0		86.0 (174)	88.0 (59)	83.0 (57)	5	
	Row spacing	m	1.1 (129)	1.0 (44)	1.2 (45)	−0.2	***	1.0 (174)	1.0 (59)	1.1 (57)	−0.1	***
	Plant spacing	m	0.9 (129)	0.8 (44)	0.9 (45)	−0.1	**	0.8 (174)	0.7 (59)	0.8 (57)	−0.1	***
	N (basal fertilization)	kg ha^{-1}	16.6 (54)	15.7 (14)	11.5 (21)	4.2		12.9 (38)	7.5 (9)	13.4 (16)	−5.9	
	P_2O_5 (basal fertilization)	kg ha^{-1}	76.8 (54)	59.6 (14)	63.6 (21)	−4.0		56.3 (38)	37.8 (9)	60.3 (16)	−23	
	K_2O (basal fertilization)	kg ha^{-1}	39.1 (54)	34.6 (14)	26.4 (21)	8.2		53.1 (38)	33.7 (9)	55.2 (16)	−22	
	N (topdressing)	kg ha^{-1}	33.4 (46)	27.8 (13)	38.6 (17)	−11	*	44.9 (30)	57.9 (7)	44.0 (9)	13.9	
	P_2O_5 (topdressing)	kg ha^{-1}	16.7 (8)	14.9 (4)	15.0 (1)	−0.1		34.1 (7)	51.2 (2)	40.0 (3)	11.2	
	K_2O (topdressing)	kg ha^{-1}	35.8 (32)	28.8 (10)	40.6 (8)	−18		37.1 (12)	66.2 (2)	23.1 (4)	43.1	
	Topdressing fertilization	days after planting	63.0 (44)	66.0 (13)	62.0 (17)	4.0		64.4 (18)	48.7 (4)	56.7 (6)	−8	
	Cycle	months	9.5 (129)	10.1 (44)	8.6 (45)	1.5	**	6.9 (174)	6.8 (59)	6.9 (57)	−0.1	

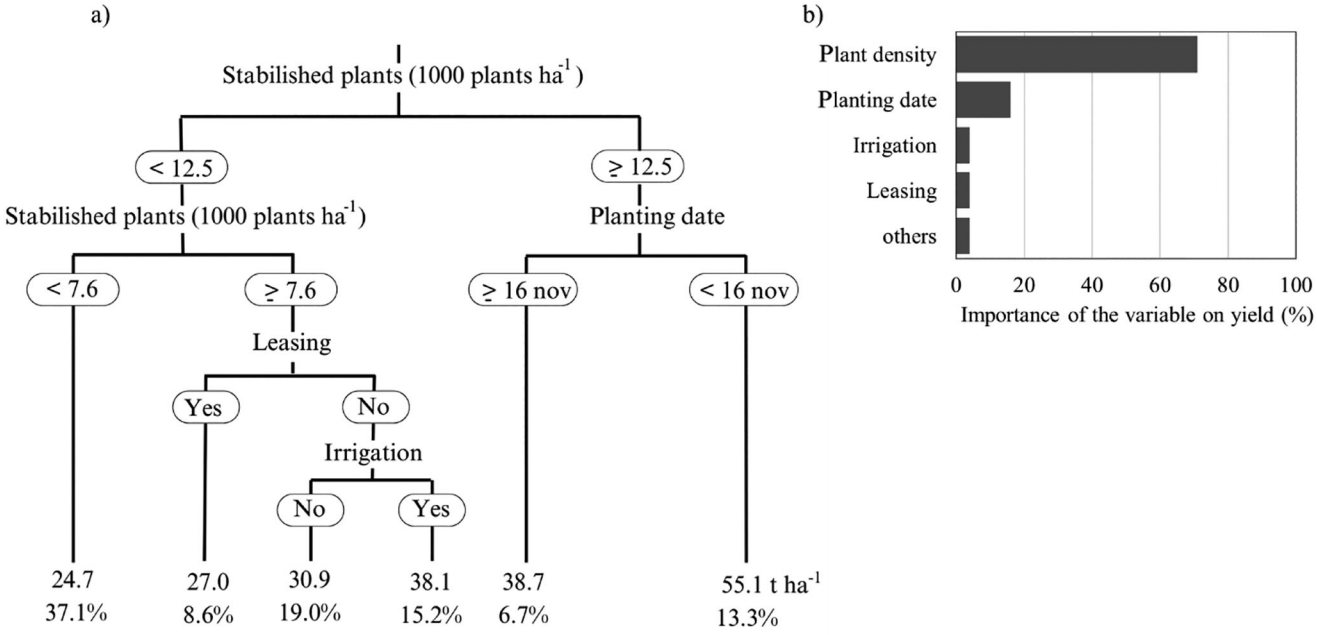

FIGURE 4 Regression tree showing variation in sweet cassava yield due to management practices in the tropical environment. The values below each node indicate the average root production (Mg ha^{-1}) and the percentage of observations at each node (a). Relative importance of each management practice on the yield of sweet cassava roots in the tropical environment (b).

(71%) and planting date (16%) are responsible for 87% of the yield and are management factors that do not incur high costs and can be implemented by farmers with Lys (Figure 4).

3.4 | Limiting management factors in subtropical environments

In the subtropical environment, the first yield-limiting factor was also plant density, with crops with a plant density ≥9100 plants ha^{-1} achieving the best yields (Figure 5). With a planting density of ≥15,300 plants ha^{-1} and planting by September 12, crops yielded 16% more than crops planted after September 12 (33.6 Mg ha^{-1}). Although yields are higher for crops with higher planting density and early planting, they account for only 5.7% of the crops studied in subtropical environments, due to the greater climatic risk and difficulties in establishing the crops at this time. According to El-Sharkawy (2004), cassava emergency is halted at soil temperatures below 17°C and promoted at soil temperatures around 28°C–30°C. Since soil temperature is related to air temperature, low temperatures in the first half of September in the subtropics can delay the cassava plant and expose it to attack by diseases and pests in the soil for a longer period of time, which affects the establishment of the plant. However, in the warmer regions of the subtropics, early sowing can be a good option if there are no problems with plant mortality.

3.5 | Optimal planting density and planting date

Crops with a planting density of 9100–15,300 plants ha^{-1}, with a row spacing <1.2 m and planted by September 28 yielded 33.8 Mg ha^{-1}, while crops with this row spacing and planted after September 28 showed a yield reduction of 3.5 Mg ha^{-1} (Figure 5). Planting in the second half of September allows the period with the highest solar radiation (December–January–February) (Figure 2) to coincide with the tuberization of the plant and to have the best temperatures during the development cycle. Cassava favors the shift of photoassimilates from photosynthesis to the leaves and stems and then to the roots. Therefore, this prioritization has a negative effect on root yield under more restrictive solar radiation conditions during tuber formation (Alves, 2006). Moreover, in the subtropics, with an average cycle of 7 months (Table 1), planting in the second half of September allows harvesting in April. If planted after this date, the harvest may coincide with the coldest months (May–June–July), with low temperatures (<17°C) and greater risks to yield and root quality. According to Cock and Rosas (1975), temperatures below 17°C reduce the production of cassava leaves and roots.

The lowest yields were obtained in crops with a plant density <9100 plants ha^{-1} (Figure 5). At lower plant density, the second factor affecting yield was desiccation, followed by planting date. The dried plants yielded 9 Mg ha^{-1} more than the non-dried plants planted by October 8 (17.7 Mg ha^{-1}).

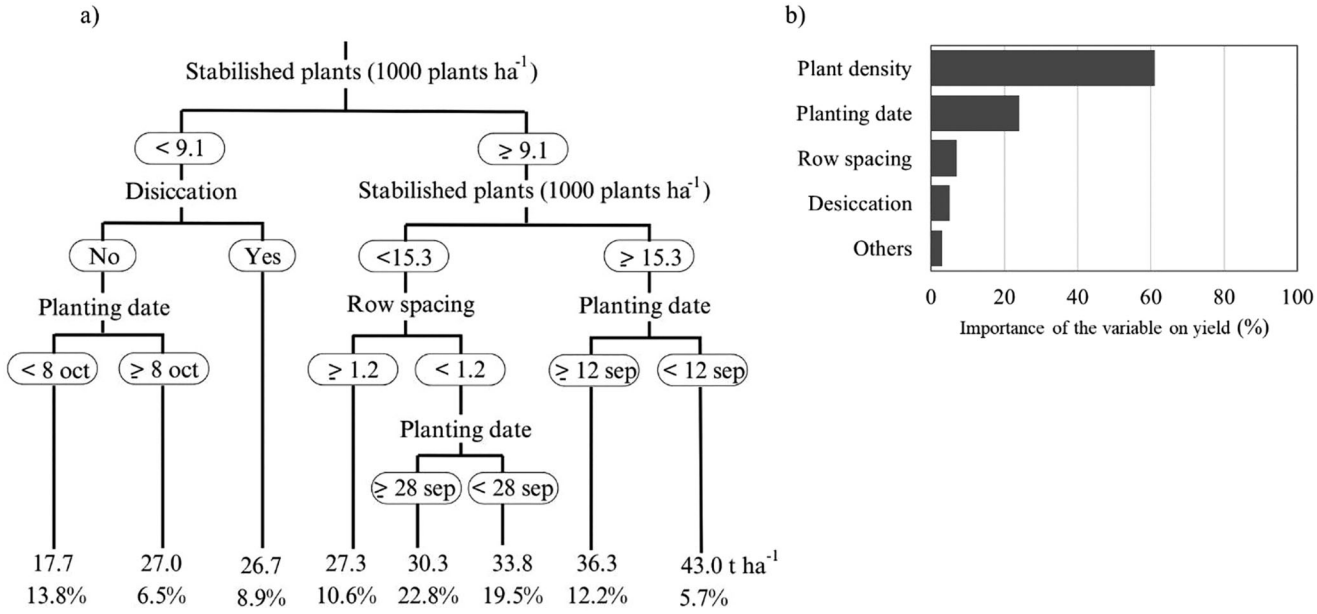

FIGURE 5 Regression tree showing variation in sweet cassava yield due to management practices in the subtropical environment. The values below each node indicate the average root production (Mg ha^{-1}) and the percentage of observations at each node (a). Relative importance of each management practice on the yield of sweet cassava roots in the subtropical environment (b).

The crops that were not dried achieved the best yields when planted after October 8 (27.0 Mg ha^{-1}), as the high air temperature favors germination, rapid plant establishment, and row closure, which is important for weed control, especially in crops with lower plant densities (Peressin et al., 2022).

At higher plant densities, crops have less competition from weeds, higher yield, less crop damage, and less post-harvest decay, which allows for a longer marketing period (Peressin et al., 2022). However, in crops with lower plant density, the roots not only develop faster but also more individually (weight per plant), which leads to a higher commercial quality (Aguiar et al., 2011). According to Schons et al. (2009), roots are considered commercial (CR) if they are longer than 10 cm and have a diameter of >2 cm, and non-commercial (NCR) if they are shorter than 10 cm and have a diameter between 1 and 2 cm. CRs are sold fresh or minimally processed (frozen or chilled), while NCRs are often discarded and can be used as animal feed and/or sold as an ingredient in culinary recipes. Planting density and planting date were the most important management factors limiting yield in both the tropics (87%) and subtropics (84%). In this way, optimal planting density (OPD), which allows for higher root weight per plant (an indicator of commercial quality), and optimal planting date, which allows for higher root yield, were determined, complementing the information from the regression trees for the tropical and subtropical environments.

For the tropical environment, the OPD was 13,000 plants ha^{-1} (Figure 6) and for the subtropical environment, 11,000 plants ha^{-1}, at which point the root weight per plant begins to decrease. Although higher densities provide the highest yield per area, the highest weight per plant was observed at OPD, a parameter that indicates the commercial quality of the roots, which is extremely important for sweet cassava. In the tropical environment, the optimum planting date for crops without irrigation is November 15, and from then on, there is a yield loss of 394 kg ha^{-1} day^{-1} due to the aforementioned water restrictions during the dry period. For the subtropical environment, the optimum planting date is 27 September, with a loss of 452 kg ha^{-1} day^{-1} due to the delay in planting. In this case, the climatic factor limiting the yield is the low temperature in autumn and winter (Figure 6D). Zebalho et al. (2024) found that the highest yields were obtained in fields that were planted by July 18. After that, the yield decreased at a rate of 0.132 Mg ha^{-1} day^{-1}.

3.6 | Implications for yield increase and land use

Applying the results found in this paper, an increase in average farmer yield by 73% of YP (average for Hy crops) results in a yield increase of 16.3 and 12.3 Mg ha^{-1} for the tropical and subtropical environments, respectively. In the subtropics, 47,600 ha were harvested, with an average yield of 17.2 Mg ha^{-1}, corresponding to a production of 843,000 t of cassava (Instituto Brasileiro de Geografia e Estatística [IBGE], 2023). If we consider the adoption of the previously discussed management, the average yield will increase to 29.5 Mg ha^{-1}. Considering the current cultivated area, it would be possible to produce 1.4 million t on the current cultivated area, which

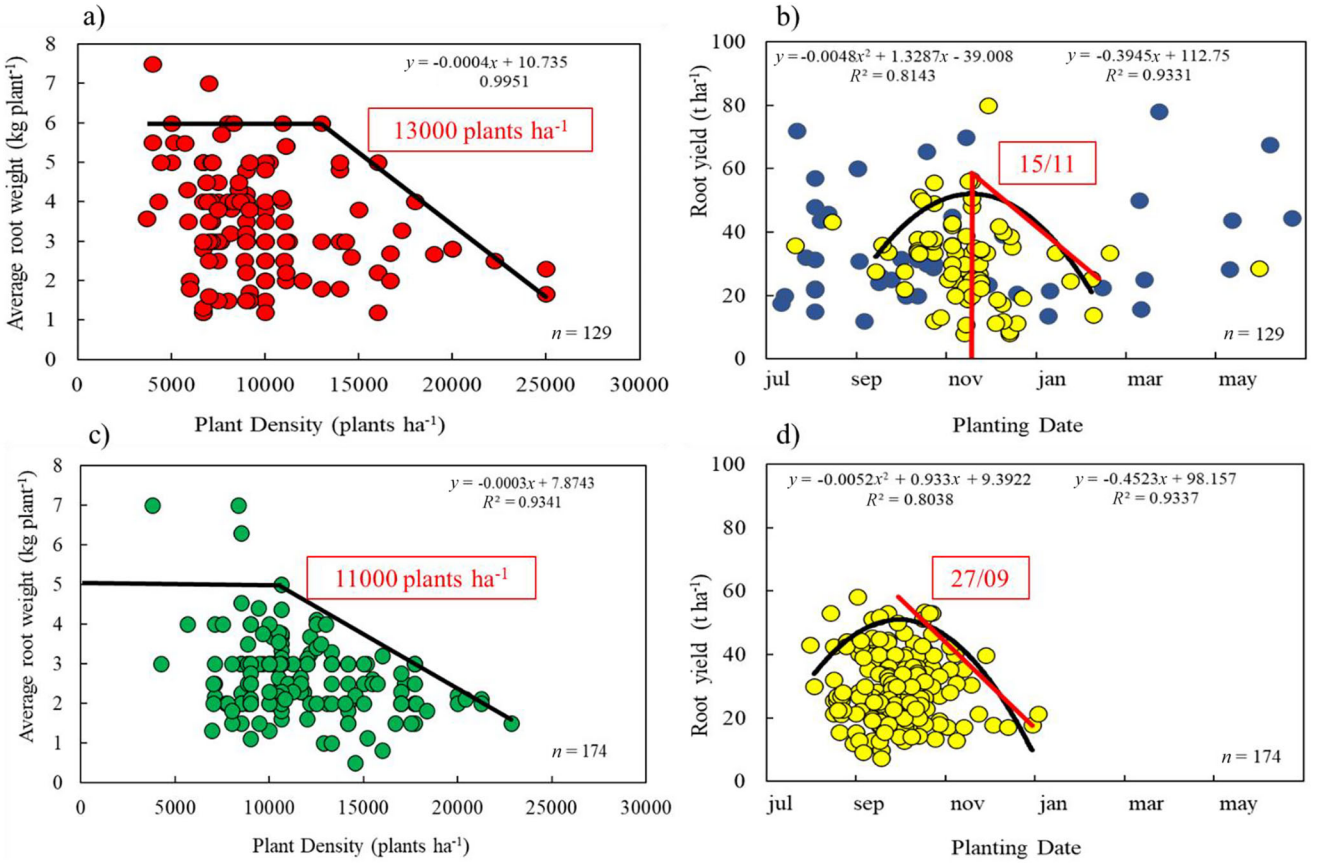

FIGURE 6 Root weight (kg plant^{-1}) in relation to plant density (plants ha^{-1}), where the red circles represent the crops evaluated in the tropical environment (a) and the green circles represent the crops in the subtropical environment (c). Root yield (Mg ha^{-1}) in relation to planting date, where yellow circles represent crops without irrigation and blue circles represent crops with irrigation in the tropical (b) and subtropical (d) environments. Black solid line represents the limit function, and the red line indicates the planting date of maximum root yield and the associated daily loss.

would mean a 40% increase in the production of sweet cassava in the tropics. On the other hand, if we consider the yield of 29.5 Mg ha^{-1} obtained with the implementation of the management discussed, the current production of 843,000 t could be obtained on an area of 28,600 ha, that is, 19,000 ha less that would be available for the cultivation of other food crops, which would mean a diversification of cultivation and income.

In the tropical environment (MG, DF, and GO), an average of 17,300 ha were harvested last year, with an average yield of 15.1 Mg ha^{-1}, which corresponds to a production of 251,300 t of cassava (Instituto Brasileiro de Geografia e Estatística [IBGE], 2023). With an increase of 16.3 Mg ha^{-1} through management, the average yield would increase to 31.4 Mg ha^{-1}, so that production on the current harvested area would be 543,200 t, an increase of 54%. If we maintain the current production of 251,300 t, with the increase in yield it would be possible to achieve this production of 8000 ha, leaving 9300 ha available for other crops. However, this yield increase would be even greater if Ya were increased to YP, eliminating the average yield gap by 100%.

In contrast to the pronounced response of industrial cassava to phosphate fertilization observed in tropical Brazilian Cerrado conditions by Zebalho et al. (2024), our study with sweet cassava in subtropical environments demonstrates limited or absent yield improvements from phosphorus application. The tropical study identified phosphate fertilization (74.8 kg ha^{-1} P_2O_5 in Hy fields) as a key factor increasing root yields by 9.4 Mg ha^{-1} compared to Ly fields, alongside significant starch content improvements through optimized planting dates and potassium management (Silveira et al., 2024; Zebalho et al., 2024). This discrepancy may be because of differences in soil phosphorus dynamics between ecosystems—tropical oxisols typically exhibit higher phosphorus fixation capacities than subtropical soils, potentially creating stronger crop responsiveness to fertilization in the former (Silveira et al., 2024). Additionally, the interaction between planting dates and nutrient uptake efficiency noted in tropical conditions (where early planting maximized starch synthesis) may be less relevant in subtropical photoperiod and temperature regimes (Borges et al., 2025; Zebalho et al., 2024). These findings highlight the critical importance of regional environmental factors in determining cassava's nutritional requirements, suggesting that generalized fertilization recommendations require careful adaptation to specific agroecological contexts.

The results in this study can be guidelines for decision makers, especially in the context of public policies that promote sweet cassava yield increase, viability of cassava cultivation, irrigation in the tropical environment for the production of cooking quality roots throughout the year, and consequently higher profitability. In the Table S1, you will find information on the farms that explain the profile of farmers and consumer demand. It also highlights trends and studies that can be carried out based on the information collected to improve cassava yields in tropical and subtropical areas of Brazil.

4 | CONCLUSIONS

1. The average yield gap for sweet cassava observed in this study was 34.2 Mg ha^{-1} in the tropical environment and 27.4 Mg ha^{-1} in the subtropical environment, corresponding to 51% and 48% of the YP, respectively.
2. The main management factors limiting sweet cassava yield in the tropical environment were plant density, planting date, land tenure (leasing), and irrigation. In the subtropical environment, the limiting factors included plant density, planting date, row spacing, and the use of desiccation practices.
3. The optimum planting density (OPD) to ensure both yield and commercial root quality was determined to be 13,000 plants ha^{-1} in the tropical environment and 11,000 plants ha^{-1} in the subtropical environment.
4. The optimal planting date for maximizing sweet cassava yield was identified as up to November 15 for rainfed crops in tropical regions and up to September 27 in subtropical regions.
5. Achieving an average yield equivalent to 73% of the YP would result in a production increase of 40% in the subtropical environment and 54% in the tropical environment, without the need for expanding the cultivated area.

AUTHOR CONTRIBUTIONS

Kelin Pribs Bexaira: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; validation; visualization; writing—original draft; writing—review and editing. **Mauricio Fornalski Soares**: Formal analysis; investigation; methodology; visualization; writing—review and editing. **Charles Patrick de Oliveira de Freitas**: Conceptualization; data curation; investigation; methodology; validation. **Luis Fernando Rodrigues de Oliveira**: Conceptualization; investigation; methodology; supervision; visualization. **Eduardo Alano Vieira**: Conceptualization; data curation; funding acquisition; validation; visualization; writing—original draft. **Camille Flores Soares**: Formal analysis; methodology; validation; visualization; writing—review and editing. **Alencar Junior Zanon**: Conceptualization; data curation; funding acquisition; methodology; project administration; resources; supervision; validation; visualization. **Nereu Augusto Streck**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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