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Optimizing spatial arrangements and planting schedules for cassava-watermelon intercropping in the Amazon Savannah

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Abstract
The intercropping system increases the productive potential of crops and improves land use efficiency. However, it is necessary to arrange the plants so that the spatial distribution and planting time are as favorable as possible. The objective of this study was to evaluate the agronomic performance of the intercropping of cassava with watermelon in different spatial arrangements and planting time. The experiment was conducted from December 2020 to August 2021 in a typical Amazonian savannah area, and the soil of the experimental area is classified as Typic Hapludox. The experimental design was randomized blocks, arranged in a split-plot scheme, with four replications. Four cassava planting times were tested in the plots: 0, 10, 20 and 30 days after watermelon sowing, and five arrangements were tested in the subplots; Cassava and watermelon were planted in various arrangements, including single and double rows, on the same or opposite sides of each other: I) cassava planted in a single row (4.0 m x 1.0 m), on the same side of the watermelon sowing furrow; II) cassava planted in a single row (3.5 x 1.0 m), on the opposite side of the watermelon sowing furrow; III) cassava planted in double rows (3.5 x 1.0 x 0.5 m), on both sides of the watermelon sowing furrow, IV) cassava planted in single rows, in double rows (3.5 x 1.0 x 0.5 m), on both sides of the furrow and V) watermelon sown in single rows (4.0 m x 1.0 m). The irrigation was carried out using furrows 40.0 m in length, with a slope of 1.0% and an average flow rate of 0.5 L s^{-1}. The spatial arrangements and planting times did not interfere with the watermelon crop and were capable of maintaining high productive yield and desirable fruit quality. Under the experimental conditions, watermelon recorded an average productivity among the treatments corresponding to 47,735.78 kg ha^{-1}. This value was 53.82% and 13.96% higher than the productivities of Roraima and Brazil, respectively. As for the cassava productivity, although the variations were statistically similar, we strongly recommend planting in a single row on the same side of the watermelon sowing furrow, with which we obtained a productivity of approximately 18,000 kg ha^{-1}.

Keywords: *Citrullus lanatus* L., *Manihot esculenta* Crantz., Single and double rows, Growing season, Plant distribution, Intercropping.
Abbreviations: NF_number of fruit; A_spatial arrangement; S_supplementary data; DAE_days after emergence; DAP_days after planting; AEI_area equivalence index; HI_harvest index; FCI_Falker chlorophyll index; CV1_coefficient of variation corresponding to the residues of blocks and plots (arrangements); CV2_coefficient of variation corresponding to the residues of plots (periods of implementation of the arrangements); PCAPW_Planting cassava after planting watermelon (days).

Introduction

Intercropping is the simultaneous cultivation of two or more crops in the same area. The advantages of this system, when compared to single cropping, include increased productivity per unit area, vegetative soil protection against erosion, weed control (Albuquerque et al., 2015), and a reduction in the incidence of pests and diseases. Additionally, it helps to diversify income sources and product offerings (Costa et al., 2024).

The watermelon (*Citrullus lanatus*) is a widely cultivated vegetable crop across all regions of Brazil; however, it is rarely used in intercropping systems (Oliveira et al., 2018). In the Northern region, particularly in Roraima, watermelon is the main commercially grown species among cucurbits. The crop has a great productive potential in the State, with average yields exceeding 40 t ha^{-1} (Monteiro Neto et al., 2016; Silva et al., 2017).

In Roraima, watermelon is mainly cultivated during the dry season (from October to March) in a sole cropping system, using spacing of 5.0 x 1.0; 5.0 x 0.8; 4.0 x 1.0; 3.5 x 1.0; or 3.0 x 1.0 meters, with irrigation predominantly by drip and, to a lesser extent, by furrows. Local producers typically grow one to two crops per year, and after harvest, the area is either used for cattle grazing or left fallow until the next cultivation. This practice encourages the occurrence of weeds, pests, and diseases in subsequent crops (Oliveira et al., 2018).

The cassava (*Manihot esculenta*) is one of the most traditional crops in Roraima, predominantly cultivated by small farmers and indigenous communities (Alves et al., 2009; Albuquerque et al., 2023). It is grown during the rainy season (from April to September), both in sole cropping and intercropping systems, using conventional soil preparation methods and, in many cases, without any soil preparation at all.

The most commonly reported crops intercropped with cassava are maize (*Zea mays*) and cowpea (*Vigna unguiculata*) (Albuquerque et al., 2015). However, other crops such as banana (*Musa spp*) (Silva et al., 2014), sunflower (*Helianthus annuus*) (Carvalho et al., 2018), pineapple (*Ananas comosus*) (Santos et al., 2024), and peanut (*Arachis hypogaea*) (Soares et al., 2024) have also been used. Watermelon cultivation is another option for intercropping. However, it is important to emphasizet that, so far, there are no reports of intercropping it with cassava.

The great challenge in achieving the peak of biological and economic productivity in intercropping systems lies mainly in adjusting the spatial arrangement and selecting the right planting time to minimize competition for water, light, and nutrients among the associated crops (Soares et al., 2024).

The appropriate time to plant cassava is when the necessary conditions for the sprouting and rooting of the mother stems are met. Regarding spatial arrangements, cassava can be grown with plants arranged in single rows and double rows (Fialho et al., 2017). The double-row arrangement has some advantages compared to single rows, such as greater ease of working with agricultural implements. However, there is no consensus among authors (Albuquerque et al., 2015; Santos et al., 2024).

Therefore, the objective of this study was to evaluate the agronomic performance of intercropping cassava with watermelon in different spatial arrangements and planting times in the Savannah of Roraima, Brazil.

Results and Discussion

Yield parameters assessment in watermelon

The average values of the number of fruits smaller than 5.0 kg per hectare, the number of fruits per hectare between 5.0 and 10.0 kg, the number of fruits larger than 10.0 kg per hectare, the total number of fruits per hectare, average mass, and watermelon fruit yield are shown in Table S1. These variables were determined from counting the fruits with their respective masses (kg). For example, fruits that had a mass of less than 5.0 kg were included in the variable NF < 5.0 kg ha^{-1} (Table S1). It was found that the spatial arrangements and planting times adopted did not interfere with these characteristics. The non-significant values for fruit yield obtained in this study are in agreement with Miller and Greene (2018).

The fruit yield values observed in watermelon cultivation, when grown in intercropping systems, were considerably higher than those obtained in sole cropping, though not statistically significant, especially in the state of Roraima. Studies conducted by Araújo et al. (2011) and Silva et al. (2017), in sole cropping watermelon cultivation in the Roraima savannah, revealed a lower number of fruits compared to the values reported in this study, with averages close to 5500 fruits per hectare.

The average fruit mass obtained (8.15 kg) meets the needs of the consumer market, not only in Roraima but throughout the Northern region, which demands fruit size considered medium to large, between 6 and 15 kg (Leão et al., 2008).

In terms of productivity, the observed averages (ranging from 37,037.50 to 54,005.00 kg ha^{-1}) were considerably higher than the yield of watermelon cultivation in Roraima, which is 22,045 kg ha^{-1} (Ibge, 2024), and are in agreement with the values achieved by Monteiro Neto et al. (2016), Silva et al. (2017), and Oliveira et al. (2018), with averages exceeding 40,000 kg ha^{-1} .

In the case of intercropping systems, the absence of a response for a particular crop implies that it has not suffered adverse effects caused by the other crop regarding competition for water, light, and nutrients. In this study, this occurred due to the favorable spatial arrangements and planting timings (Tambara et al., 2017).

The absence of response from the watermelon (shorter cycle) can be explained by the slow initial development of the cassava crop (longer cycle), given that, even when planted simultaneously (at day 0), the cassava did not cause a reduction in its yield. Almendra (2005) reported similar response by mentioning that cassava has a slow initial growth, causing the cassava stems to take up to fifteen days for the appearance of the first shoots, and sometimes up to thirty days, their growths depend on their reserves. As for watermelon, it has a faster initial development, being able to begin its reproductive phase around 40 DAP (days after planting) and reach the maximum dry mass accumulation at 75 DAP (Moreira et al., 2015). The absence of response is also due to the choice of species with different vegetative architectures, considering that they did not compete for the same light stratum (Albuquerque et al., 2015; Oliveira Filho et al., 2016).

In Table 1, the average values of pulp firmness, pH, soluble solids (SS), titratable acidity (TA), and SS/TA ratio of watermelon fruits are shown according to the planting time of cassava, which did not differ from each other and corroborated with Miller and Greene (2018), who did not find significant effects on the quality of watermelon fruits in intercropping cultivation. Although there was no statistical difference, the pulp firmness measurements (Table 1) were similar to those observed in single-cropping by Silva et al. (2017) and Silva et al. (2020), who detected values between 10.66 and 14.52 and between 10.30 and 14.90 N, respectively, and considered them to be high. This is an important characteristic because, according to Huang et al. (2016), high pulp firmness values are essential for the post-harvest shelf life of fruits, as they make them more resistant to injuries caused by transportation and commercialization.

The pH of the fruits was similar to that obtained by Carmo et al. (2015), with averages close to 5.5 (Table 1), and is in accordance with the pH range desired by the consumer market, which is from 5.0 to 6.0 (Alan et al., 2018). The observed soluble solids (SS) values were relatively high, always above 10° Brix (Table 1), corresponding to fruits of excellent internal quality (Kyriacou et al., 2018).

The titratable acidity (TA) ranged from 0.99% to 1.13% (Table 1), which, according to Silva et al. (2020), indicated increases in the flavor and aroma components of the studied fruits. As for the SS/TA ratio, according to Carvalho Júnior et al. (2019), it is one of the best ways to evaluate the fruit's flavor, as it provides a better understanding of the characteristics' behavior than isolated measurements of sugars or titratable acidity. According to the same author, high SS/TA ratios, such as those obtained in this study (between 9.26 and 12.72) (Table 1), suggests a better balance between sweet and sour, giving the fruits a more pleasant flavor and making them more attractive.

Yield parameters assessment in cassava

For plant height, stem diameter, and number of stems, only isolated effects of spatial arrangements and planting times were observed (Table S2). The highest values of height and diameter were obtained when cassava was cultivated in a single row, on the same side of the planting furrow of the watermelon (arrangement I) (2.12 m and 2.83 cm, respectively), and when the crops were planted simultaneously (time 0 days) (2.14 m and 2.92 cm, respectively).

As for the number of stems, the highest values were observed in double-row cultivation, either in the intercropping system (arrangement III), with 2.85, or single-row (arrangement IV), with 2.45, and during planting times closer to that of the watermelon crop, with 2.50; 2.79; and 2.68 stems at 0, 10, and 20 days, respectively.

Relating plant height and stem diameter to the number of stems, it was observed that planting cassava in a single row (arrangements I and II) tends to provide a lower number of stems, which allows the plants to express greater vigor in height and stem diameter. Morais et al. (2020) demonstrated this response by correlating the growth characteristics of cassava and obtaining greater plant height and stem diameter at the expense of a lower number of stems. The cultivation of cassava in a single row allowed the crop to avoid competition for light and take advantage of the availability of water and nutrients, which were previously provided to the watermelon crop, as observed by Silva et al. (2013) in a study on cassava planting density.

It was also noted that, regardless of the spatial arrangements adopted, there was a decrease in plant height, stem diameter, and the number of stems as the cassava planting was delayed (Table S2). This occurred due to the fewer number of days during which the cassava crop benefited from the cultural practices applied to the watermelon crop, especially fertilization, irrigation, and weed control. According to Phoncharoen et al. (2019) and Vitor et al. (2019), the anticipation of cassava planting promotes greater growth and dry mass accumulation in the plant. This happens because the crop's cycle is relatively long, and the rainy season in many regions is short.

The fresh mass and the dry mass of the aerial part were jointly affected by spatial arrangements and planting times (Table S2). In general, the planting time had an influence only when cassava was cultivated in double rows, either in the intercropping form (arrangement III) or alone (arrangement IV). In these arrangements, the highest values were obtained when cassava was planted simultaneously with watermelon (at 0 days), with 2.46 kg, and zero and ten days after sowing (at 0 and 10 days), with 2.35 kg, respectively.

Regarding the arrangements, in some of the evaluated attributes, cassava, when grown in a single row, on the opposite side of the planting furrow of watermelon (arrangement II), had lower fresh and dry mass (Table S2). This response was due to the lower availability of nutrients on that side of the furrow, especially nitrogen, considering that the side dressing fertilizations (55 kg ha^{-1} of N applied at 15 and 30 DAE) were only applied to the watermelon planting holes, on the opposite side. It was also observed that, even when cultivated in double rows, the dry mass of these arrangements did not exceed that obtained in a single row, on the same side of the watermelon planting (arrangement I).

The values of fresh mass of the aerial part and dry mass of the aerial part of cassava found here are close to those observed by Albuquerque et al. (2012) and Morais et al. (2020). However, it is noteworthy that these authors did not find significant differences in planting arrangements with single and double rows.

The levels of chlorophyll a and chlorophyll b were not influenced by the spatial arrangements and planting times used (Table S2). However, the observed values (between 24.92 and 29.08 for chlorophyll a and between 3.56 and 5.07 for chlorophyll b) are close to those obtained by Dethvongsa et al. (2021) in different cassava varieties. The absence of a response for chlorophyll levels indicates that there was no competition between the plants for the same luminous extract. Therefore, differences in chlorophyll accumulation will result from the amount of radiation available to the plant. According to the same authors, reduction in light intensity increased chlorophyll b levels, as this chlorophyll was degraded more slowly than chlorophyll a, a response not observed in the present study.

The harvest index (HI) is the distribution of dry matter to the economically useful parts of the plant. In cassava, this index represents the efficiency of root reserve production and must exceed 50% to be considered satisfactory. In the present study, although there was no significant difference, the observed HIs were relatively high, always above 50% (Table S3). Devide et al. (2009) found indices close to those reported, both for cassava in sole cropping and for intercropping, and similarly, no differences were observed between the arrangements. When intercropping cassava in single and double rows with common bean (*Phaseolus vulgaris*), Albuquerque et al. (2012) also did not observe differences in the HI between the arrangements.

In general, although not significant, the HI values decreased as the cassava planting was delayed in relation to the watermelon sowing (Table S3). A similar response was obtained by Phoncharoen et al. (2019), when evaluating growth rates and productivity of cassava at different planting times in a tropical savanna climate, and they found that the HI increases as planting is brought forward.

The total root number was influenced by the interaction between spatial arrangements and planting times adopted. A difference was observed between the times only when the cassava was planted in a single row, on the same side of the watermelon sowing furrow (arrangement I), particularly at the moment of 0 days (simultaneous planting of the crops), reaching an average value of 36,406.25 roots. Regarding the spatial arrangements, there was a difference between them only at the 0 and 10 days of planting time, with arrangement I again standing out (Table S3).

For the commercial root number, only isolated effects were observed, with the highest values obtained in arrangement I, however, not different from arrangement III and arrangement IV. For the time of planting, the highest measurements were observed at 0 and 10 days after the watermelon planting.

The highest number of roots observed at 0 and 10 days was due to the greater availability of water and nutrients for the crop at the beginning of its cycle, due to the anticipation of planting (Phoncharoen et al., 2019). As for the best arrangement being the one where cassava was cultivated in single rows, this occurs due to greater productivity per plant in less dense planting arrangements, such as single rows, with increases in the number of roots when the spacing between rows is increased. Streck et al. (2014) also reported that this response is due to the greater investment of the plant in the aerial part, allowing it to develop and support a larger number of tuberous roots in this arrangement.

Table 1. Average values of pulp firmness, pH, soluble solids (SS), titratable acidity (TA) and SS/TA ratio of watermelon fruits (*Citrullus lanatus*) grown in intercropping with cassava (*Manihot esculenta*) under different planting times, Boa Vista, Roraima, 2025.

PCAPW (days)	Firmness (N)	pH	Soluble Solids (SS) ºBrix	Titratable Acidity (TA) (% of citric acid)	Relationship SS/TA
0	11.50 a	4.94 a	11.17 a	0.91 a	12.72 a
10	10.50 a	4.87 a	10.53 a	1.13 a	9.26 a
20	10.66 a	5.10 a	11.62 a	0.99 a	11.79 a
30	10.14 a	5.04 a	11.35 a	1.00 a	11.60 a
CV%	16.90	2.31	7.76	12.53	14.40

Means followed by the same letters do not differ from each other using the Tukey test at 5% probability. PCAPW=Planting cassava after planting watermelon (days).

Table 2. Average Values of Root Dry Mass, Starch Content, and Cassava Flour Yield (*Manihot esculenta* Crantz.), Grown in Intercropping with Watermelon (*Citrullus lanatus* L.), Under Different Spatial Arrangements and Planting Times, Boa Vista, Roraima, 2025.

PCAPW (days)	Spatial arrangement (A)				Média
	I	II	III	IV	
	Root dry matter (%) (CV1% 2.86 & CV2% 2.80)				
0	34.13 bB	35.93 abAB	37.13 aA	36.83 aA	36.00 ab
10	36.45 aA	36.56 aA	36.42 abA	36.77 aA	36.55 a
20	35.53 abA	35.31 abA	36.06 abA	36.86 aA	35.94 ab
30	35.94 abA	34.06 bA	34.90 bA	35.66 aA	35.14 b
Mean	35.51 B	35.46 B	36.13 AB	36.52 A	
	Starch content (%) (CV1% 3.28 & CV2% 3.21)				
0	29.48 bB	31.28 abAB	32.48 aA	32.17 aA	31.35 ab
10	31.80 aA	31.91 aA	31.77 abA	32.12 aA	31.90 a
20	30.88 abA	30.66 abA	31.41 abA	32.21 aA	31.29 ab
30	31.29 abA	29.41 bA	30.25 bA	31.01 aA	30.49 b
Mean	30.86 B	30.81 B	31.48 AB	31.87 A	
	Flour yield (%) (CV1% 4.19 & CV2% 4.13)				
0	25.42 bB	27.47 abAB	28.81 aA	28.47 aA	27.54 ab
10	28.06 aA	28.18 aA	28.02 abA	28.42 aA	28.17 a
20	27.02 abA	26.78 abA	27.62 abA	28.50 aA	27.48 ab
30	27.49 abA	25.34 bA	26.30 bA	27.15 aA	26.57 b
Mean	26.99 B	26.94 B	27.69 AB	28.13 A	

Mean followed by the same letters, lowercase in the columns and uppercase in the rows, do not differ from each other by the Tukey test at a 5% probability level. I = cassava planted in a single row (4.0 m x 1.0 m) on the same side of the watermelon planting furrow; II = cassava planted in a single row (3.5 m x 1.0 m) on the opposite side of the watermelon planting furrow; III = cassava planted in a double row (3.5 m x 1.0 x 0.5 m) on both sides of the watermelon planting furrow; and IV = cassava planted in a single cultivation in a double row (3.5 m x 1.0 x 0.5 m) on both sides of the furrow. CV1=coefficient of variation corresponding to the residues of blocks and plots (arrangements); CV2=coefficient of variation corresponding to the residues of plots (periods of implementation of the arrangements); PCAPW=Planting cassava after planting watermelon (days).

Table 3. Area equivalence index (AEI) of the cassava (*Manihot esculenta* Crantz.) consortium with watermelon (*Citrullus lanatus* L.), under different spatial arrangements and planting times, Boa Vista, Roraima, 2025.

PCAPW (days)	Spatial arrangement			Mean
	I	II	III	
	IEA			
0	2.67	2.19	2.04	2.30
10	2.38	1.80	2.61	2.26
20	2.03	1.67	2.14	1.95
30	2.56	1.65	2.44	2.22
Mean	2.41	1.83	2.31	

I = cassava planted in a single row (4.0 m x 1.0 m) on the same side as the watermelon planting furrow; II = cassava planted in a single row (3.5 m x 1.0 m) on the opposite side of the watermelon planting furrow; III = cassava planted in a double row (3.5 m x 1.0 m x 0.5 m) on both sides of the watermelon planting furrow. PCAPW=Planting cassava after planting watermelon (days).

The average root masses, both total and commercial, responded similarly, where only the planting time influenced these characteristics. It was found that planting cassava closer to the watermelon sowing (planting time 0, 10, and 20 days) were responsible for the highest root mass values, with 0.61, 0.50, and 0.50 kg, respectively, for total mass, and 0.78, 0.65, and 0.69 kg, respectively, for commercial mass (Table S3). According to Oliveira et al. (2019), these average mass results are important because cassava is marketed based on its size, a characteristic that is directly related to its mass.

The total root productivity ranged from 4432.81 kg ha^{-1} in arrangement II, planting time 30, to 21346.87 kg ha^{-1} (79.23% more), in arrangement I, planting time 0 (Table S3). A difference was observed between the spatial arrangements only at planting time 0 and 10 days, where at these times, the highest productivities were obtained in arrangements I, II, III, and IV, respectively. Considering the planting times, it was observed that arrangements I and II stood out at time 0, while arrangements III and IV were superior at times 0, 10, and 20 days. The lowest productivity, regardless of the arrangements, occurred when the cassava was planted 30 days after the watermelon sowing, that is, when the planting was delayed. In general, the highest total root productivity was achieved with the simultaneous planting of the crops (time 0) and when the cassava was arranged in a single row, on the same side of the watermelon sowing furrow (arrangement I), with 21,346.87 kg ha^{-1}.

Morais et al. (2020), when evaluating biometric and productive characteristics of cassava in different arrangements, found greater root productivity in a single row. Albuquerque et al. (2012) also found higher cassava root productivity in a single row, which can be explained by the larger coverage area of the root system due to the greater space available for its growth. As for the timing, Phoncharoen et al. (2019) reported that early plantings tend to increase crop yield due to providing greater accumulation of dry mass in the tuberous roots.

The commercial productivity, considering roots with a diameter greater than 40.0 mm in equatorial diameter, was influenced only by the isolated effects of spatial arrangements and planting times. The highest values were obtained at time 0 and in arrangements I, III, and IV, which did not differ from each other (Table S3).

The highest productivity obtained in this study, both total (21,346.87 kg ha^{-1}) and commercial (14,090.23 kg ha^{-1}), were considerably higher than those reported in the national territory (14,500 kg ha^{-1}), in the state of Roraima (13,800 kg ha^{-1}) (Ibge, 2024), and in some research evaluating intercropping systems with cassava, especially when arranged in a single row, such as in Albuquerque et al. (2015), with 15,250.0 kg ha^{-1}. It should also be emphasized that the spacing adopted in the arrangements (4.0 x 1.0 m, in single rows, and 3.5 x 1.0 x 0.5 m, in double rows) is much less dense than what is commonly practiced, and therefore, has a lower number of plants.

The dry root mass, starch content, and flour yield behaved similarly, all of which were influenced by the interaction between the spatial arrangements and the planting times adopted (Table 2). For arrangement I, the highest values were obtained at 10, 20, and 30 days (when the cassava planting was delayed relative to the watermelon). For arrangements II and III, higher values were observed at days 0, 10, and 20 (when cassava planting was anticipated in relation to watermelon). For arrangement IV, the single crop, no difference was observed. Regarding the time points, a difference was noted only when cassava was planted simultaneously with watermelon (at time point 0), with emphasis on arrangements II, III, and IV, supporting the findings of Phoncharoen et al. (2019) who reported that the highest accumulation of root mass occurs in earlier plantings.

The arrangements that recorded the highest root dry mass, starch content, and flour yield were those consisting of a double row, whether in intercropping or single cropping. This response is possibly due to these arrangements tending to present a higher fresh mass of the aerial part (numerically) (Table S2). Aaccording to Oliveira et al. (2019), there is a greater accumulation of root dry mass and, consequently, higher starch content and flour yield, in plants with a larger canopy volume, due to the transfer of a greater amount of assimilates accumulated in the aerial part. However, in studies with intercropping systems of cassava arranged in single and double rows, Albuquerque et al. (2012) and Albuquerque et al. (2015) did not observe differences regarding the industrial characteristics of the roots.

Fukuda et al. (2006) stated that the main characteristic that defines the quality of cassava yield for the industry is the dry matter content of its roots, and that these typically present, on average, 30%, in agreement with the results obtained in the present study. The other measurements of starch content and flour yield corroborate with Cereda and Vipoux (2003), who reported values ranging from 20% to 30% for starch and from 25% to 35% for flour yield.

It is desirable that the spatial arrangements responsible for the highest root productivity are also those that present the highest dry matter content, starch content, and flour yield, which would maximize the final yield, especially from an industrial point of view. However, this was not observed in the present study, as the highest root productivity was found in arrangement I, while dry matter, starch content, and flour yield were higher in arrangements II, III, and IV.

Intercropping is considered efficiently productive when the AEI value is higher than 1.0, and the higher this value, the greater the efficiency (Vieira, 1999), as long as the commercial standard of the crops is met, a fact observed in the present study. Based on the productivity values of watermelon and commercial productivity of cassava (Table S1 and Table S3, respectively), obtained in the intercropping system, in different spatial arrangements and planting times, the AEI were calculated, all of which were above 1.0 and therefore considered efficient (Table 3).

The maximum AEI reached was 2.67, in arrangement I (Single row), at moment 0 days. This means that a 167% increase in planted area (physical space) would be necessary to achieve, with single cropping (of watermelon and cassava), the productivity equivalent to that reached in the intercropping. The second highest AEI was 2.61, however, in arrangement III (Double row) and at time 10 days. The lowest IEAs, in turn, were observed in arrangement II, at times 20 and 30 days, with averages of 1.67 and 1.65, respectively (Table 3).

The results obtained here are considerably higher than those achieved by Albuquerque et al. (2012), who obtained a maximum AEI of 1.54 in the cassava and common bean intercropped. It is worth noting that, unlike this study, the authors obtained a higher AEI value in a double-row arrangement, which highlights that the effectiveness of planting arrangements for cassava is closely linked to the cultivation pattern of another crop grown in the intercropping.

In intercroppings, there is usually a reduction in crop productivity, which highlights the need for studies aimed at better understanding the specific ecological mechanisms involved. However, in the present study, considering that the cassava crop did not interfere with the watermelon and still achieved excellent root yields, it is evident that the cultivation system was advantageous.

Materials and Methods

Experimental site description

The experiment was conducted from December 2020 to August 2021 in a typical Amazonian savannah area at the Água Boa Experimental Field, owned by Embrapa Roraima, in Boa Vista, Roraima, Brazil. The site is located at 02° 39' 00'' N and 60° 49' 28.40'' W, at an altitude of 90 meters above sea level. The local climate, according to the Köppen classification, is of the Am type (Tropical rainy with a short dry period), with two defined rainfall periods, one rainy (April to August) and the other dry (September to March) (Araújo et al., 2024). The soil of the experimental area is classified as Typic Hapludox, with a medium texture, and with the following physicochemical properties in the 0 to 15 cm layer: pH = 5.9; P = 52.0 mg dm^{-3}; K^{+} = 0.05 cmolc dm^{-3}; Ca^{2+} = 1.66 cmolc dm^{-3}; Mg^{2+} = 0.470 cmolc dm^{-3}; Al^{3+} = 0.03 cmolc dm^{-3}; H + Al^{3+} = 1.93 cmolc dm^{-3}; OM = 12.98 g kg^{-1}; CTCt = 1.86 cmolc dm^{-3}; V(%) = 49.0; m(%) = 2.0; sand(%) = 67.2; silt(%) = 8.4; clay(%) = 24.4.

Plant material, growth conditions and experimental design

The experimental design was randomized blocks, arranged in a split-plot scheme, with four repetitions and six plants per experimental unit. The main plots tested four planting times for cassava: 0, 10, 20, and 30 days after the watermelon sowing, and the subplots tested five spatial arrangements: I) cassava planted in a single row (4.0 m x 1.0 m), on the same side of the watermelon sowing furrow; II)

cassava planted in a single row (3.5 m x 1.0 m), on the opposite side of the watermelon sowing furrow; III) cassava planted in a double row (3.5 x 1.0 x 0.5 m), on both sides of the watermelon planting furrow, IV) cassava planted in single crop in a double row (3.5 x 1.0 x 0.5 m), on both sides of the furrow, and V) watermelon seeded in single crop (4.0 m x 1.0 m). The cassava plant populations for each arrangement were, respectively, 2500, 2857, 8888, and 8888 plants per hectare, while for watermelon it was 2500 plants per hectare.
Each plot was made up of three rows from the intercropping, with a length of 40.0 m, spaced 4.0 m apart, totaling 480.0 m² (40 x 12 m). The subplots, on the other hand, had an area of 32.0 m², derived from a central row of 8.0 m (8 x 4 m), containing six productive watermelon plants and six cassava plants. It is important to highlight that the only crop that underwent variations in spatial arrangements and planting times was cassava, while a single cultivation standard was adopted for watermelon.
The soil preparation consisted of plowing to a depth of 20 cm, two leveling harrowings, and the opening of planting furrows with a depth of 20 cm. At the time of planting, liming was carried out by applying 450 kg ha^{-1} of dolomitic limestone (PRNT 90%), aiming to meet the desired 70% base saturation (V%) for watermelon cultivation.
The foundation fertilization was carried out in the planting furrow, following the recommendations for watermelon cultivation in Roraima (Medeiros and Halfeld-Vieira, 2007). A total of 120 kg ha^{-1} of P_2O_5, 160 kg ha^{-1} of K_2O, and 25 kg ha^{-1} of micronutrients in the form of single superphosphate, potassium chloride, and FTE BR 12, respectively, were applied, in addition to 10 m^3 ha^{-1} of sheep manure. Nitrogen fertilization was applied as topdressing in the watermelon holes, consisting of 110 kg ha^{-1} of N in the form of urea, split into two equal applications, at 15 and 30 days after emergence (DAE).
The watermelon cultivar used was Santa Amélia, sown with a spacing of 4.0 meters between rows (furrows) and 1.0 meter between plants. Two seeds were used per hole, and twelve days after the emergence of the seedlings, thinning was performed, leaving only one plant per hole.
The irrigation was carried out using furrows 40.0 m in length, with a slope of 1.0% and an average flow rate of 0.5 L s^{-1}. Irrigation monitoring was conducted using the tensiometer method, as recommended for watermelon cultivation in Roraima. At 16 DAE (days after emergence), irrigation was performed when the tensiometers reached readings of 30 to 45 kPa (every three to four days). From 17 days until fruit formation, irrigation was applied when the tensiometers recorded a tension of 20 to 30 kPa (every two to three days). During the fruit maturation phase, irrigation was carried out when the tensiometers registered readings of 30 to 45 kPa (every three to four days). At the time of watermelon harvest, irrigation for cassava was suspended and remained so until the end of its cycle (Medeiros and Halfeld-Vieira, 2007).
The cultural practices in watermelon cultivation consisted of regular manual weeding with a hoe between the rows, vine training, and pest and disease control. The watermelon harvest took place 75 days after sowing (DAS), based on the observation of the dried tendril closest to the fruit, the change in color of the ground spot on the fruit, and the measurement of the fruit's soluble solids (SS), with a minimum of 10 ºBrix, using a handheld refractometer (model Q767-1) on two fruits in the border area (Araújo et al. 2011).
The cassava cultivar used was Aciolina, an early-cycle variety (10-12 months) from the germplasm bank collection of Embrapa Roraima. This cultivar stands out as one of the most widely grown in the state, mainly due to its superior characteristics for both fresh consumption and industrial use (Alves et al., 2009; Albuquerque et al., 2015). The planting of cassava was carried out in the pre-established spatial arrangements and time periods as treatments. Stem cuttings, 20.0 cm in length, obtained from the middle third of the stems, were manually planted in a horizontal position at a depth of 10.0 cm in holes opened along the planting furrows.
The cultural practices in cassava cultivation, when intercropped, were the same as those applied in watermelon cultivation. After the watermelon harvest, two manual weeding were carried out at 150 and 200 days after planting to control weeds. The harvest was performed manually, with the aid of a hoe, at 270 days (9 months) after planting, always maintaining a ten-day interval between each harvest, depending on the planting schedule adopted.

Watermelon Evaluation
For the assessment of yield characteristics, all fruits from the useful area of each plot were counted and weighed in the field to determine the number of fruits smaller than 5.0 kg per hectare, the number of fruits per hectare between 5.0 and 10.0 kg, the number of fruits larger than 10.0 kg per hectare, the total number of fruits per hectare, the average fruit mass, and fruit productivity. The average fruit mass was obtained by dividing the total number of fruits by the productivity. Productivity was determined by estimating the total fruit mass from the useful area to one hectare.
After evaluating the yield characteristics, four fruits were randomly selected, each corresponding to a specific cassava planting time, and sent to the Post-Harvest Laboratory of Embrapa Roraima for the determination of physicochemical characteristics: pulp firmness, pH, soluble solids content (SS), titratable acidity (TA), and SS/TA ratio.
The firmness of the pulp was determined using a manual penetrometer, model CAT 729-20, with an 8.0 mm diameter tip. Each fruit was longitudinally divided into two parts, and three readings were taken at equidistant points in the equatorial region of the pulp. The values were expressed in Newtons (N). The pH was measured in samples consisting of 10 g of pulp diluted in 100 mL of distilled water, using a pH meter. The results were expressed in pH units, based on the method established by the Adolfo Lutz Institute (Ial, 2008). The soluble solids content (SS) was obtained from the pulp using refractometry with temperature correction (Ial, 2008), with the results expressed in °Brix. The titratable acidity (TA) was determined by titration with a sodium hydroxide solution (0.1 M), and the results were expressed as a percentage of citric acid (Ial, 2008). The SS/TA ratio was calculated by dividing the absolute values of SS by the absolute values of TA.

Cassava Assessment
The characteristics assessed were plant height, stem diameter, number of stems, fresh biomass of the aerial part, dry biomass of the aerial part, chlorophyll a, chlorophyll b, harvest index, total number of roots, number of commercial roots, average total root mass, average commercial root mass, total productivity, commercial productivity, dry root mass, starch content, and flour yield.
The height of the plant was obtained with the help of a tape measure, measuring from the point of insertion of the stump to the upper top of the plants. The stem diameter was measured using a digital caliper, with measurements taken at the base of the main stem. The number of stems was obtained by counting the total number of stems from the mother manivas (stumps) of each hole. The fresh mass of the aerial part was obtained by cutting and weighing the plants from the usable area, while the dry mass was obtained after drying the plants in a forced circulation oven at 65°C until a constant mass was reached.

The readings of the Falker chlorophyll index (FCI) a and b were always carried out at 08:00 AM, measuring the third fully developed compound leaf, counted from the apex to the base of each plant, on the lateral part of the leaf blade, avoiding the central vein. Two readings were taken (apex and base of each lobe) on each compound leaf, totaling 12. The readings were taken using the chlorophyll meter, model CFL 1030, operated according to the manufacturer's specifications.

The Harvest Index (%) was obtained through the ratio between the total fresh root mass, excluding the mother cuttings (stems), and the total fresh plant mass, multiplied by 100. The total and commercial root count was obtained by counting the number of root units harvested per plant. The average total and commercial root mass was obtained by dividing the productivity by the number of roots. The total and commercial root productivity was determined by weighing the tuberous roots and estimating them per hectare.

The classification into commercial and non-commercial roots followed the standard in place at the Companhia de Entrepostos e Armazéns Gerais de São Paulo-CEAGESP, which considers roots with a diameter above 40.0 mm as commercial. The dry mass of the root was obtained using the hydrostatic balance method, determined by the formula: dry root mass (%) = 158.3 x specific mass - 142. Where specific mass = mass in air / (mass in air - mass in water) (Kawano et al., 1987). The starch content was obtained by subtracting the constant 4.65 from the dry mass content of the root (Grossmann and Freitas, 1950). The flour yield was obtained using the equation $Y = 2.56576 + 0.0752613564X$, where: Y represents the percentage of flour, X is the weight of 3.0 kg of roots in water, obtained using the hydrostatic balance method (Fukuda and Caldas, 1987).

The assessment of the productive efficiency of the intercropping system was carried out using the area equivalence index (AEI), taking into account the arrangements within each planting period, through the formula: AEI = (total cassava productivity in the intercropping ÷ total cassava productivity in sole cropping) + (total watermelon productivity in the intercropping ÷ total watermelon productivity in sole cropping), where the intercropping is considered efficient when the IEA is greater than 1.0, and the higher the AEI, the greater the efficiency (Vieira, 1999).

Statistical snalysis

The statistical analysis was conducted separately for each crop. The data were subjected to normality tests (Lilliefors) and homogeneity of variance tests (Cochran). When normal and homogeneous, analysis of variance was performed with the application of the F-test ($p \leq 0.05$), and the means were compared using the Tukey test at a 5% probability level, using the R software (R Development Core Team, 2018).

Conclusion

Spatial arrangements and planting times do not interfere with watermelon cultivation and are capable of maintaining high productive yield and desirable fruit quality. Arrangements in double rows promote desirable industrial characteristics for cassava roots. Cassava cultivated in a single row, simultaneously with watermelon, on the same side of the planting furrow, provides better productive and economic performance in the intercropping.

Statement of author contributions

Edgley Soares Silva: Conception of the experiment, data collection, scientific writing and statistical analysis; Roberto Dantas de Medeiros: Orientation; José de Anchieta Alves de Albuquerque: Co-supervision, revision and adjustments; Admar Bezerra Alves: Data collection; João Luiz Lopes Monteiro Neto: Statistical analysis and writing review; Musibau Oyeleke Azeez: Translation, manuscript review and submission; José Maria Arcanjo Alves: Review of scientific writing; Valdinar Ferreira Melo: Scientific writing review; Maria Beatriz Bernades Soares: Statistical analysis; Everton Luis Finoto: Manuscript review for submission.

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