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Phytomass input and nutrient cycling under different management systems in dwarf cashew cultivation

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ABSTRACT: Rational management of spontaneous plants is an alternative for increasing productivity in tree crops. This study aimed to evaluate the impact of management systems between rows and under the canopy of early dwarf cashew trees on the soil chemical properties and light-fraction organic matter and cashew root systems; we also evaluated the nutrient inputs from the spontaneous plants phytomass and cashew leaves deposited on an Arenic Kandiustults. The management systems under study were disc harrowing (DH) and mechanical mowing (MM) between rows, both with clearing under the cashew canopy (crowning), and herbicide (HERB) between the rows and under the canopy (without crowning). Soil and plant samples (leaves, stems, and roots) were collected at three points: under the canopy, at the canopy projected limit, and between the rows of cashew plants, all after seven years of conducting the experiment. Soil samples collected at the layers of 0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.30 m were evaluated for total organic carbon, light-fraction organic matter, and chemical attributes. Dry matter, Na, Ca, Mg, N, P, and K were determined in the spontaneous-plant phytomass from under the canopy, at the canopy projected limit, and between the rows. Results showed that between rows of cashew trees there are higher phytomass input and increases in the light fraction of organic matter, pH and Mg^{2+} in the soil in the treatment MM. Not removing crop residues or spontaneous plants by crowning promoted accumulation of organic material and higher contents of nutrients under the canopy. The management of spontaneous plants and also soil surface under the canopy of the cashew plants had a great influence on productivity. The crowning, used in MM and DH, led to lower productivity, 1,171.87 and 594.97 kg ha^{-1}, respectively, when compared with the absence of crowning (HERB), which resulted in productivity of 1,363.80 kg ha^{-1}. The practice of crowning is not recommended for soil management systems in dwarf cashew crops.

Keywords: nutrient cycling, perennial crops, spontaneous plants.

INTRODUCTION

Cashew (*Anacardium occidentale* L.) is a tropical fruit crop native of Brazil and grown in many tropical regions, where the nuts and peduncles are extracted, processed, and sold (Alencar et al., 2018). Cashew production has high socio-economic importance for the Brazilian semi-arid region, especially in the states of Ceará, Rio Grande do Norte, and Piauí, which are responsible for 64.2, 13.7, and 13.5 % of the planted area of the country, respectively (IBGE, 2019).

The average production in Brazil in 2018 was only 131 kg ha^{-1} cashew nuts (IBGE, 2019), while the average production worldwide was 694 kg ha^{-1} (FAO, 2018). This productivity is very low, considering that proper management can lead to more than 3,000 kg ha^{-1} (Oliveira, 2002). Low productivity can be attributed to unsuitable plant and soil management practices, inadequate control of pests and disease, low soil fertility, low genetic potential of the plants, and the irregular rainfall in the northeast of Brazil (Xavier et al., 2013; Alencar et al., 2018). With the development of early cashew varieties, substantial increases in productivity became possible, but it is still necessary to adopt practices that minimize the causes of low productivity

In the northeast of Brazil, soil management in cashew crops depends on the available mechanization, which usually varies between the use of a disc harrow, mechanical or manual clearing, and herbicides (Xavier et al., 2013). The use of legumes as cover crops is highly recommended due to the potential benefits to the soil, such as supplying organic matter and N, favoring soil structure, reducing erosion, and helping to suppress competing plants (Silva et al., 2011; Plaza-Bonilla et al., 2016; Couëdel et al., 2018; Veloso et al., 2018), but this practice is little applied in commercial areas of cashew (Xavier et al., 2013). Maia et al. (2004) found that the management of spontaneous plants is a good option for green manure, since these plants act as natural cover and promote the accumulation of K, Ca, and Mg in the soil.

Besides controlling spontaneous plants between rows, usually with tractor and disc harrow, it is also common to clean under the tree canopy, a practice locally known as 'crowning', which aims to facilitate the harvest (Oliveira, 2007; Xavier et al., 2013). This practice tends to remove all organic residue from the surface, as it is usually carried out with manual implements (hoes) for dwarf cashew, or by tractor and disc harrow when the trees are larger. In both cases, damage occurs to the root system of the plants, especially to the fine and surface roots in the upper layers of the soil. Thus, the effects of maintaining or not the residue and not disturbing the surface layers under the canopy of cashew trees still need to be better understood. Previous studies have already indicated that the maintenance of cover plants between rows of cashew trees (spontaneous vegetation and leguminous species) contributed to increase the organic matter content and nutrient cycling in the soil (Xavier et al., 2013) and cashew nut productivity (Ribeiro et al., 2007), but no studies are focusing on the crowning and its influence on soil fertility and productivity of cashew trees in the study area.

It is known that reduced soil turning, together with the maintenance and supply of organic residue, increases the organic matter compartments and nutrient contents of the soil (Bayer et al., 2016; Veloso et al., 2019), progressively favoring its productive potential (Lenka et al., 2012; Bayer et al., 2016; Veloso et al., 2018, 2019; Maia et al., 2019). Few studies associate soil management practices with cashew cultivation in soils of the semi-arid region of the northeast (Ribeiro et al., 2007; Xavier et al., 2013).

This study aimed to assess the consequences of cleaning the surface of a Arenic Kandiustults under the cultivation of cashew plants, by evaluating the chemical properties of the soil, the deposited plant material (spontaneous plants and cashew leaves), and the root system of the cashew tree. The hypothesis under test is that the removal of residue from the surface and soil tillage reduce the supply of organic matter, the availability of nutrients, and the number of roots, affecting the development and productivity of the cashew plant.

MATERIALS AND METHODS

Description of the experimental area

The study was conducted in the Pacajus Experimental Area of the National Research Centre for Tropical Agro-industry of the Brazilian Agricultural Research Corporation (CNPTA-EMBRAPA), in the municipality of Pacajus in the state of Ceará, located at 4° 10' S and 38° 27' W, at an altitude of 60 m. The mean temperature in the region varies from 26 to 28 °C and the annual precipitation is 930 mm, with a dry season of 4-5 months (August-December) and a rainy season from January to July (Aguiar et al., 2001). The average rainfall and temperature during the study period are shown in figure 1. According to Ribeiro et al. (2007), the soil on which the experiment was conducted is an *Argissolo Acinzentado distrófico arênico*, which corresponds to a sandy loam Arenic Kandiustults (Soil Survey Staff, 2014). The area is located in flat relief and belongs to a coastal Caatinga transition. Selected soil chemical and physical properties are presented in table 1.

The experiment was started in 1997 in an area of two hectares. Seedlings of the CCP 76 clone of the dwarf cashew (*A. occidentale*) were planted at a spacing of 7 × 7 m. Each experimental plot comprised 16 plants and an area of 441 m^2. Soil fertilization was carried out annually, always applied within the canopy projection, and incorporated to a depth of 0.05 m. The applied doses were based on the requirements of the growth stage of the cashew crop (Crisóstomo et al., 2001; Oliveira, 2002). When setting up the experiment, the holes were prepared by mixing 350 g P_2O_5 and 50 g K_2O with the surface layer. From the second to the fourth year of the experiment, 178 g N, 300 g P_2O_5, and 100 g K_2O were applied, while in the fifth year, 140 g N, 100 g P_2O_5, and 120 g K_2O were applied. Finally, in the sixth year, the quantities were changed to 200 g N, 300 g P_2O_5,

Table 1. Selected soil physical and chemical properties of an Arenic Kandiustults cultivated with early dwarf cashew in the experimental station in the municipality of Pacajus, Ceará, Brazil

Soil properties	0.00-0.23 m layer
pH(H_2O)	4.70
Ca^{2+} ($cmol_c$ kg^{-1})	0.40
Mg^{2+} ($cmol_c$ kg^{-1})	0.40
Na^{2+} ($cmol_c$ kg^{-1})	0.05
K^+ ($cmol_c$ kg^{-1})	0.06
P (mg kg^{-1})	3.00
H^++Al^{3+} ($cmol_c$ kg^{-1})	0.99
Al^{3+} ($cmol_c$ kg^{-1})	0.20
CEC ($cmol_c$ kg^{-1})	1.90
Total organic C (g kg^{-1})	3.60
Base saturation (%)	48
Aluminum saturation (%)	18
Fine sand (g kg^{-1})	300
Coarse sand (g kg^{-1})	630
Silt (g kg^{-1})	40
Clay (g kg^{-1})	30

pH in water at a 1:2.5 ratio of soil:solution; P, K^+, and Na^+ were extracted with Mehlich-1 (H_2SO_4 0.05 mol L^{-1} + HCl 0.125 mol L^{-1}) (Teixeira et al., 2017); Ca^{2+}, Mg^{2+}, and Al^{3+} were extracted by KCl 1 mol L^{-1} (Teixeira et al., 2017); H+Al (calcium acetate extractant at 0.5 mol L^{-1} and pH 7.0); soil CEC is the sum of the concentrations of H+Al, K^+, Ca^{2+}, Mg^{2+}, and Na^+ cations; total organic carbon (determinated according to Walkley-Black method) (Walkley and Black, 1934). Soil texture (determinated according to pipette method) (Bouyoucos, 1926).

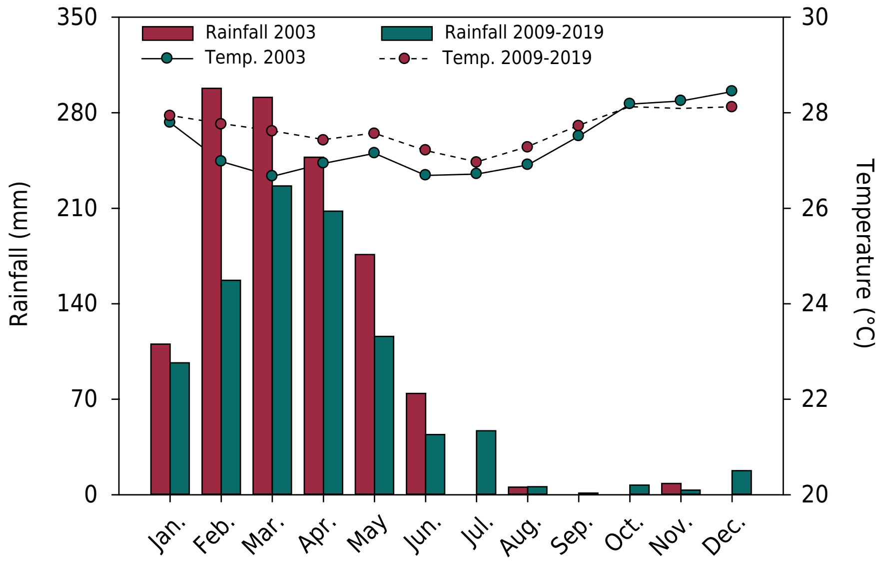

Figure 1. Climatic data throughout the year of data collection (2003 and series of average monthly rainfall and temperature in the last 10 years - 2009-2019) in the municipality of Pacajus, Ceará, Brazil. Temperature data is from the Fortaleza station, where the climate is similar to Pacajus.

and 180 g K_2O. Fertilization was generally carried out in February and March, or at the start of the rainy season.

The treatments have been carried out since 1997 and are described in more detail in Ribeiro et al. (2007) and Xavier et al. (2013), consisting of disc harrowing + crowning; mechanical mowing + crowning; mowing clearing + crowning; plant cover + crowning; plant cover + mulch and herbicide. The studies mentioned above reported that the use of harrows to eliminate weeds (between cashew rows) favored intense soil disturbance and resulted in a loss of soil organic matter and nutrients. However, when mechanical mowing or herbicide was used to eliminate weeds, the opposite was true. Besides that, the absence of crowning in herbicide treatment resulted in increased productivity. However, in both studies, soil collections for analysis were performed only in between cashew rows, hence not directly evaluating the crowning effect. Therefore, for the present study, the following treatments were selected: disc harrowing + crowning (DH), mechanical mowing + crowning (MM) and herbicide (HERB), considering the following criteria: (i) crowning (DH and MM) or no crowning (HERB); (ii) the usual practice, adopted in commercial areas for eliminating spontaneous plants between rows (DH and MM); and (iii) productivity, considering the highest, intermediate and lowest production of cashew nuts, according to Ribeiro et al. (2007), which were obtained in the DH, MM, and HERB treatments, respectively. In the treatment DH, crowning was performed under the canopy of the cashew tree and a declumping harrow with 10 discs, 0.60 m in diameter, coupled to a wheeled tractor, was used between cashew rows, crushing and incorporating spontaneous plants to a depth of 0.15-0.20 m. For the treatment MM, crowning was performed under the canopy of the cashew tree and a mechanical brush cutter, coupled to an agricultural wheeled tractor, was used between cashew rows, whereby spontaneous plants were mowed and left under the soil surface. The HERB treatment consisted of the application of the systemic herbicide glyphosate at a dose of 3 L ha^{-1}, diluted in 400 L of water. The herbicide was applied under the canopy and between rows of the cashew plants, and the organic material from the spontaneous plants or the cashew trees was left on the soil. Each practice included in the treatments was applied when the spontaneous plants between rows reached a height of 0.40 m, giving an average of three times a year, with crowning carried out once a year only in the DH and MM treatments. For each treatment, the phytomass and soil samples were collected at three different sampling points: (i) under the canopy of the trees and therefore subject to the effects of crowning (e.g., the DH and MM treatments) or not subject to the effects of crowning (e.g., the HERB treatment); (ii) within the canopy projection limit, i.e., in the intermediate area, and potentially susceptible to the effects of crowning; and (iii) between the rows, where there were no effects of crowning.

Sampling the soil and phytomass and chemical analysis

Composite and disturbed soil samples were collected at the layers of 0.00-0.05, 0.05-0.10, and 0.20-0.30 m in each management system (DH, MM, and HERB) at three different sampling points: under the canopy (UC), at the limit of the canopy projection (CP), and between the crop rows (BR) (Figure 1). Samples of cashew leaves, spontaneous plants, and roots were collected from the same places as the soil samples between May and July, the rainy season in the region. For these samples, a frame with an area of 0.25 m^2 was randomly thrown three times to make up a composite sample. The phytomass of the cashew leaves, spontaneous plants, and roots were prepared for analysis by washing, drying in an oven at 60 °C until reaching constant weight and grinding in a mill; they were then stored in paper bags at room temperature. Composite samples were made from this material for chemical analysis.

Soil chemical analysis was performed as described by Teixeira et al. (2017): exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} were extracted with KCl 1 mol L^{-1}; Ca^{2+} and Mg^{2+} were quantified by atomic absorption spectrophotometry and Al^{3+} by titrimetry; available P and K^+ were extracted with Mehlich-1, with P being determined by colorimetry and K by photometry. The soil total organic carbon was quantified by wet oxidation in the presence of $K_2Cr_2O_7$ in sulfuric acid medium, with an external heat source (Teixeira et al., 2017). The light-fraction soil organic matter extracted from 0.00-0.05 m soil layer was obtained by flotation, using NaI at a density of 1.8 g cm^{-3} (Sohi et al., 2001).

The plant material collected in the different situations was subjected to nitric-perchloric digestion and the levels of Ca and Mg were determined by atomic absorption spectrophotometry; K and Na by flame emission photometry, and P by colorimetry (Malavolta et al., 1997). The total N was obtained by digesting the material in sulfuric acid medium followed by Kjeldahl distillation and quantified by titration with H_2SO_4 0.005 mol L^{-1} (Teixeira et al., 2017).

A specific sampling of the cashew roots from the MM and HERB treatments was carried following the procedure described by Smit et al. (2000) and Flores-Sanchez et al. (2016). The choice of the evaluated treatments was carried out aiming to compare the effects of the existence of crowning or not under the canopy of the cashew tree, not considering the need to evaluate more than one treatment with crowning. Soil monoliths

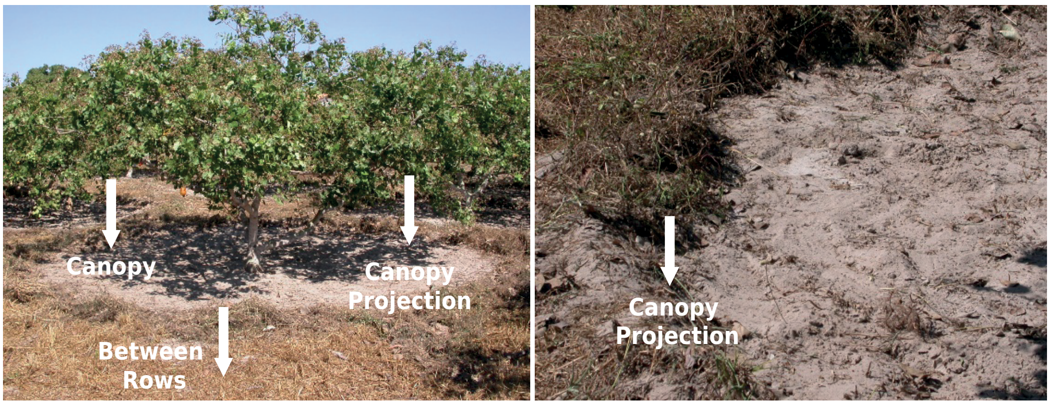

Figure 2. Collection sites of the soil and cashew and spontaneous-plant phytomass in an Arenic Kandiustults cultivated with early dwarf cashew under different management systems in the municipality of Pacajus, Ceará, Brazil.

of 0.2 × 0.2 m were collected at the layers of 0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.30 m. The monoliths were placed in containers with water, and the roots were collected and separated by flotation with a sieve. The roots were dried in an oven at 65 °C and weighed. Digitized images were then generated and analyzed by the SIARCS software (Integrated System for the Analysis of Roots and Soil Cover), developed by EMBRAPA, to determine the root area.

Statistical analysis

The data obtained were subjected to analysis of variance (ANOVA) and the means were compared by orthogonal contrasts, with significance evaluated by the F test at 10, 5, or 1 % probability levels, considering the collection layers as an independent effect. The first two contrasts considered the comparisons between the means of treatments of the management systems, but only for the data obtained under the canopy of the cashew tree: C1 - herbicide *vs* (mechanical mowing + disc harrowing) and C2 - mechanical mowing *vs* disc harrowing. The means referring to the data obtained at the limit of the cashew canopy projection were evaluated by C3 - herbicide *vs* (mechanical mowing + disc harrowing) and C4 - mechanical mowing *vs* disc harrowing. The comparisons of the means referring to data obtained between the rows of cashew in the management systems were performed by C5 - herbicide vs (mechanical mowing + disc harrowing and C6 - mechanical mowing vs disc harrowing. The other set of contrasts complementary to those performed previously compared the means obtained under the canopy of the cashew tree *vs* other situations (limit of the cashew canopy projection and between the rows of cashew), C7, and, lastly, the means of the data obtained from the limit of the cashew canopy projection *vs* between the rows of cashew by C8. Root density was evaluated only for MM and HERB treatments and the means were compared using the F test with up to 5 % probability level using Sisvar 5.6 software (Ferreira, 2014).

RESULTS

Soil chemical properties and light-fraction organic matter

Figure 3 shows the mean values of the chemical properties, total organic carbon (TOC), and light-fraction organic matter (LF) in the soil for the different management systems and collection sites. The contrasts, as well as the magnitude of their means (positive or negative), are shown in table 2. In the comparison made between management systems (HERB *vs* MM + DH) under the canopy of the cashew tree (C1), it was found that there were significant differences for TOC, LF, P, K^+, and Ca^{2+} in the 0.00-0.05 m layer; TOC, K^+, and Ca^{2+} in the 0.05-0.10 m layer; and P, K^+, Ca^{2+}, Mg^{2+}, and Na^+ in the 0.20-0.30 m layer (Table 2). The highest values obtained (TOC, P, K^+, Ca^{2+}, Mg^{2+}, and Na^+) occurred in HERB treatment. In contrast to LF, the highest means were observed in MM + DH (Figure 3).

When comparing MM *vs* DH under the cashew canopy (C2), significant differences were found ($p<0.10$) for pH in the surface layer, as well as Ca^{2+} in each layer under evaluation (Table 2). In DH, the pH increased (5.53-5.93), as did the levels of Ca^{2+} in the soil (10.1-17.1; 7.08-11.9; and 4.07-6.97 in the layers of 0.00-0.05, 0.05-0.10, and 0.20-0.30 m, respectively) compared to MM.

The Mg content in the surface layer was greater ($p<0.10$) at the limit of the cashew canopy projection in HERB (6.53 $mmol_c$ dm^{-3}) when compared to MM + DH (4.47 $mmol_c$ dm^{-3}). For LF and pH in the 0.00-0.05 m layer, and available P in the 0.05-0.10 m layer, the highest mean values were seen in MM + DH (Figure 3). When comparing MM *vs* DH in the canopy projection (C4), significant differences were seen in the contrasts ($p<0.10$) for the variables TOC, LF, and available P in the 0.00-0.05 and 0.05-0.10 m layers, respectively, and pH in both layers. Except for available P, the highest mean values ($p<0.10$) were obtained in the soil under MM. The management under the cashew canopy (crowning)

Table 2. Mean squares and significance by F-test of the orthogonal contrasts tested for the chemical properties, total organic carbon (TOC), and light-fraction organic matter (LF) of an Arenic Kandiustults cultivated with early dwarf cashew under different management systems in the municipality of Pacajus, Ceará, Brazil

System	TOC	LF	pH(H_2O)	P	K^+	Ca^{2+}	Mg^{2+}	Na^+
	g kg^{-1}			mg dm^{3}	mmol$_c$ dm^{-3}			
				0.00-0.05 m				
C1	14.2*	-0.33**	-0.20^{ns}	148**	2.32**	13.7**	0.64^{ns}	-0.01^{ns}
C2	-4.08^{ns}	0.97^{ns}	-0.40^{+}	-24.6^{ns}	-0.33^{ns}	-7.04^{+}	-0.68^{ns}	-0.68^{ns}
C3	6.72^{ns}	-4.17**	-0.64**	-21.7^{ns}	0.29^{ns}	5.42^{ns}	2.06^{+}	-0.15^{ns}
C4	11.3^{+}	7.13**	0.55*	7.30^{ns}	0.58^{ns}	5.25^{ns}	1.73^{ns}	0.17^{ns}
C5	-2.11^{ns}	-1.57*	-0.56**	4.20^{ns}	0.23^{ns}	5.23^{ns}	0.87^{ns}	0.33^{ns}
C6	10.3^{ns}	2.32*	0.71**	-1.67^{ns}	0.95^{ns}	4.35^{ns}	3.34*	-0.32^{ns}
C7	-10.9**	-1.95**	-0.11^{ns}	72.5**	-0.18^{ns}	-1.76^{ns}	-4.25**	-0.24^{ns}
C8	1.62^{ns}	1.03*	0.10^{ns}	15.9^{ns}	0.71^{ns}	1.32^{ns}	-1.13^{ns}	0.47^{ns}
				0.05-0.10 m				
C1	17.6**	-	-0.30^{ns}	8.47^{ns}	0.64^{+}	7.03**	0.58^{ns}	-0.17^{ns}
C2	-2.34^{ns}	-	-0.58^{ns}	1.60^{ns}	-0.58^{ns}	-4.82*	-0.30^{ns}	0.17^{ns}
C3	0.59^{ns}	-	-0.91^{ns}	-18.4**	-0.66*	-0.72^{ns}	-0.26^{ns}	0.43^{ns}
C4	1.68^{ns}	-	0.31^{+}	-6.80^{ns}	-0.25^{ns}	3.29^{ns}	0.54^{ns}	0.33^{ns}
C5	-1.36^{ns}	-	-0.93^{ns}	1.95^{ns}	-0.22^{ns}	0.34^{ns}	-1.21^{ns}	0.18^{ns}
C6	2.57^{ns}	-	0.70^{ns}	-2.03^{ns}	0.50^{ns}	1.23^{ns}	2.43*	0.03^{ns}
C7	-10.2*	-	-0.32^{ns}	0.01^{ns}	-0.39^{ns}	-3.76*	-3.25*	-0.23^{ns}
C8	-0.74^{ns}	-	0.17^{ns}	11.5*	0.19^{ns}	2.65^{ns}	-0.51^{ns}	0.50^{ns}
				0.20-0.30 m				
C1	3.03^{ns}	-	-0.03^{ns}	3.15*	0.34*	2.49^{+}	0.54^{+}	0.80*
C2	-2.42^{ns}	-	-0.20^{ns}	-1.50^{ns}	-0.28^{ns}	-2.91^{+}	-0.34^{ns}	-0.47^{ns}
C3	-2.02^{ns}	-	-0.22^{ns}	0.38^{ns}	0.19^{ns}	0.97^{ns}	0.22^{ns}	0.48^{ns}
C4	-3.13^{ns}	-	0.09^{ns}	-2.10^{ns}	0.12^{ns}	-1.92^{ns}	0.37^{ns}	-0.30^{ns}
C5	-3.89^{ns}	-	-0.37^{ns}	0.32^{ns}	-0.08^{ns}	0.47^{ns}	-0.50^{+}	0.73^{+}
C6	-9.59^{+}	-	0.23^{+}	-2.37^{ns}	0.07^{ns}	-2.27^{ns}	1.13**	-0.27^{ns}
C7	-3.40^{ns}	-	-0.43^{ns}	1.18**	-0.05^{ns}	-1.46^{+}	-1.47**	0.14^{ns}
C8	-0.36^{ns}	-	-0.15^{ns}	1.12*	0.10^{ns}	-0.10^{ns}	-0.11^{ns}	0.00^{ns}

^{ns}, *, **, $^{+}$: not significant, significant at 5, 1, and 10 %, respectively by F-test. C1: Herbicide *vs* (Mechanical mowing + Disc harrowing) under the cashew canopy; C2: mechanical mowing *vs* Disc harrowing, under the cashew canopy; C3: herbicide *vs* (Mechanical mowing + Disc harrowing) at the limit of the cashew canopy projection; C4: mechanical mowing *vs* Disc harrowing, at the limit of the cashew canopy projection; C5: Herbicide *vs* (Mechanical mowing + Disc harrowing) between the rows of cashew; C6: mechanical mowing *vs* Disc harrowing, between the rows of cashew; C7: Canopy *vs* Canopy projection + Between rows; C8: canopy projection *vs* Between rows.

in DH and MM favored the accumulation of organic material and nutrients within the canopy projection.

In comparing the HERB *vs* (MM + DH) contrast between the rows of cashew (C5), it was found that LF (0.00-0.05 m) and pH in the surface layer (0.00-0.10 m) and Mg^{2+} and Na^+ in the 0.20-0.30 m layer showed significant differences ($p<0.10$). Except for Na^+, the other variables obtained higher mean values in the areas of MM + DH. Significant differences were found in the comparison of mean values by contrast C6 (MM *vs* DH, between the rows of cashew), ($p<0.10$) for pH and LF in the 0.00-0.05 and 0.20-0.30 m layers, TOC in the 0.20-0.30 m layer, and Mg^{2+} in each layer under study. For significant cases, the highest mean values were found in MM, except for TOC.

When the comparison was made only between the cashew canopy and CP + BR (C7), significant differences in contrast were seen ($p<0.10$) for most of the variables, especially

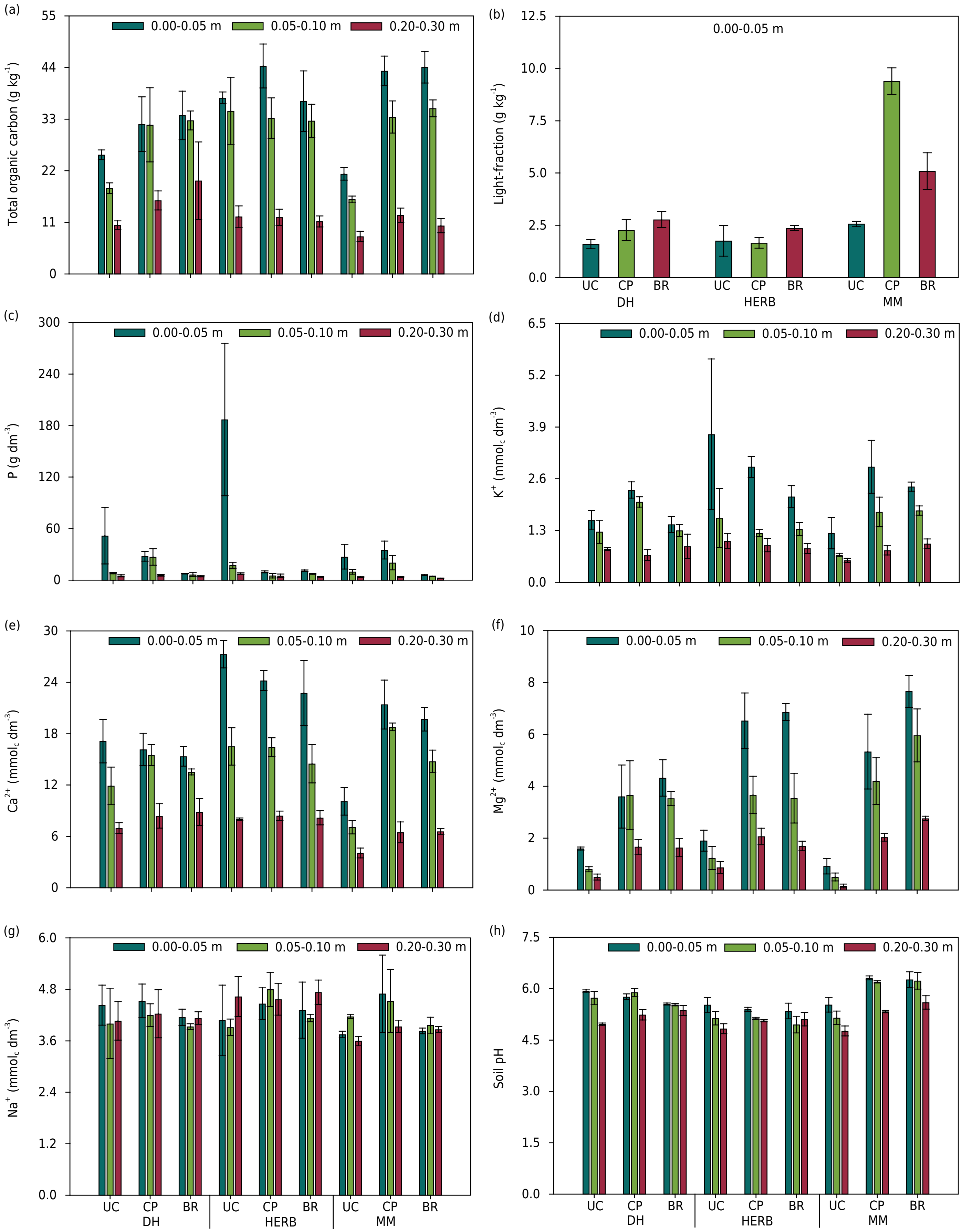

Figure 3. Chemical properties, total organic carbon, and light-fraction organic matter of an Arenic Kandiustults cultivated with early dwarf cashew under different management systems in the municipality of Pacajus, Ceará, Brazil. Error bars represent the standard error of the mean (n = 3). HERB: herbicide; DH: disc harrowing + crowning; MM: mechanical mowing + crowning; UC: under the canopy; CP: limit of the canopy projection; and BR: between the crop rows.

for TOC, LF, P, and Mg^{2+} in the 0.00-0.05 m layer; TOC, Ca^{+}, and Mg^{2+} in the 0.05-0.10 m layer; and P, Ca^{2+}, and Mg^{2+} in the 0.20-0.30 m layer. In each case, the highest mean values were obtained for CP + BR. The CP *vs* BR contrast (C8) showed significant differences ($p<0.10$) for LF (4.44-3.41 kg^{-1}) in the surface layer and available P in the 0.05-0.10 m (17.4-5.93 mg dm^{-3}) and 0.20-0.30 m (4.68-3.56 mg dm^{-3}) layers, with the mean values obtained in the cashew canopy projection always being greater.

Nutrient content in shoot phytomass and cashew roots

In the comparison between management systems (HERB *vs* MM + DH) under the cashew canopy (C1), significant differences were seen ($p<0.10$) for phytomass and the accumulation of N and Ca (Table 3). In general, HERB showed a greater amount of phytomass, N and Ca (5.074, 64.0, and 9.3 kg ha^{-1}, respectively) compared to MM + DH (3.659, 38.6, and 3.4 kg ha^{-1}, respectively) (Table 3). When MM was compared with DH in the cashew canopy (C2), significant differences were found for phytomass and Mg accumulation, with higher mean values in DH (Table 3).

The contrast HERB *vs* MM + DH, when evaluated between the rows of cashew (C5), showed significant differences ($p<0.10$) for the accumulation of K and Na. In both cases, the highest mean values were obtained in areas of MM + DH (Table 3). The comparisons between MM and DH between the rows of cashew (C6) identified the effect of these managements on all variables, except Ca accumulation. In cases where there was a

Table 3. Mean values and significance by F-test of the orthogonal contrasts tested for phytomass production and macronutrient accumulation in the total biomass (cashew leaves + roots and shoots of spontaneous plants) under the canopy, in the canopy projection, and between the rows of a Arenic Kandiustults cultivated with early dwarf cashew under different management systems in the municipality of Pacajus, Ceará, Brazil

System	Phytomass	N	P	K	Ca	Mg	Na
	kg ha^{-1}						
DH_{UC}	3702	37.7	0.80	1.50	4.14	2.49	0.92
DH_{CP}	3646	39.8	1.91	3.05	3.60	2.25	0.62
DH_{BR}	2008	22.0	1.41	2.44	1.55	1.34	0.34
$HERB_{UC}$	7539	97.6	2.16	2.95	16.00	3.95	0.97
$HERB_{CP}$	3940	49.6	1.28	2.15	6.45	2.42	0.59
$HERB_{BR}$	3357	44.8	1.25	2.29	5.10	2.11	0.42
MM_{UC}	1148	15.8	0.95	1.21	1.72	0.67	0.47
MM_{CP}	4662	46.4	2.83	5.35	3.95	2.43	1.51
MM_{BR}	6750	67.2	3.01	7.55	5.54	3.55	2.27
Contrasts							
C1	5114^{+}	70.8^{*}	1.28^{ns}	1.60^{ns}	13.1^{**}	2.37^{ns}	0.27^{ns}
C2	-2553^{+}	-21.8^{ns}	0.16^{ns}	-0.29^{ns}	-2.42^{ns}	-1.82^{+}	-0.45^{ns}
C3	-214^{ns}	6.45^{ns}	-1.09^{ns}	-2.05^{ns}	2.68^{ns}	0.08^{ns}	-0.47^{ns}
C4	1017^{ns}	6.66^{ns}	0.92^{ns}	2.31^{ns}	0.36^{ns}	0.17^{ns}	0.88^{ns}
C5	-1022^{ns}	0.44^{ns}	-0.96^{ns}	-2.71^{+}	1.56^{ns}	-0.34^{ns}	-0.89^{+}
C6	4742^{**}	45.6^{*}	1.60^{+}	5.12^{**}	3.99^{ns}	2.21^{*}	1.93^{**}
C7	68.6^{ns}	5.49^{ns}	-0.65^{ns}	-1.91^{*}	2.93^{*}	0.02^{ns}	-0.17^{ns}
C8	44.4^{ns}	0.75^{ns}	0.12^{ns}	-0.57^{ns}	0.60^{ns}	0.03^{ns}	-0.10^{ns}

^{ns}, *, **, $^{+}$: not significant, significant at 5, 1, and 10 % respectively by F-test. C1: herbicide *vs* (Mechanical mowing + Disc harrowing) under the cashew canopy; C2: mechanical mowing *vs* Disc harrowing, under the cashew canopy; C3: herbicide *vs* (Mechanical mowing + Disc harrowing) at the limit of the cashew canopy projection; C4: mechanical mowing *vs* Disc harrowing, at the limit of the cashew canopy projection; C5: herbicide *vs* (Mechanical mowing + Disc harrowing) between the rows of cashew; C6: mechanical mowing *vs* Disc harrowing, between the rows of cashew; C7: Canopy *vs* Canopy projection + Between rows; C8: canopy projection *vs* Between rows.

significant difference (phytomass, and N, P, K, Mg, and Na accumulation), it was found that the highest mean values occurred in the management system with MM. When comparing UC with CP + BR (C7), significant differences ($p<0.10$) were found only for the accumulation of K and Ca (Table 3). In the case of K, the highest mean value was obtained for CP + BR, while Ca achieved the highest mean value in UC.

The results of cashew root density in the treatments with crowning (MM) and with no crowning (HERB) clearly showed that the areas where crowning was adopted had a lower root density (Figure 4). The mass/volume ratio at the layer of 0.10-0.20 m and area/volume ratio at the layers of 0.05-0.10 and 0.10-0.20 m, as well as in the complete layer 0.00-0.30 m in HERB, were significantly ($p<0.05$) greater than those seen in MM.

DISCUSSION

Soil chemical properties and light-fraction organic matter

The TOC content found in the surface layer (0.00-0.10 m) was the highest, regardless of the management system; among these, HERB had the highest TOC content compared to the other treatments, in this case under the cashew canopy. This can be attributed to the organic residue not being removed by crowning. Although crowning can facilitate the harvesting of cashew nuts, the results showed that leaving plant residue on the soil can increase the TOC content under the cashew canopy, as seen in HERB, where this practice was not adopted. Furthermore, the use of herbicide helps maintain the organic material and soil surface in a less disturbed condition, with a positive impact on the maintenance of nutrients. On the other hand, the crowning process favored the accumulation of TOC under CP + BR in the cashew.

Thus, it can be inferred that soil organic matter is one of the factors that govern the dynamics of soil nutrients under the canopy of the trees and between the rows (discussed below), determining the accumulation, mineralization, or immobilization of nutrients, especially in soils of sandy texture (Gomes et al., 2018) like that of the present study. In addition, soil organic matter plays an important role in water retention and maintenance of soil structure (Verchot et al., 2011; Chaplot and Cooper, 2015; Rosolem et al., 2016), providing more favorable conditions for the development and performance of soil microbial biomass (Xavier et al., 2009, 2013; Kaschuk et al., 2011).

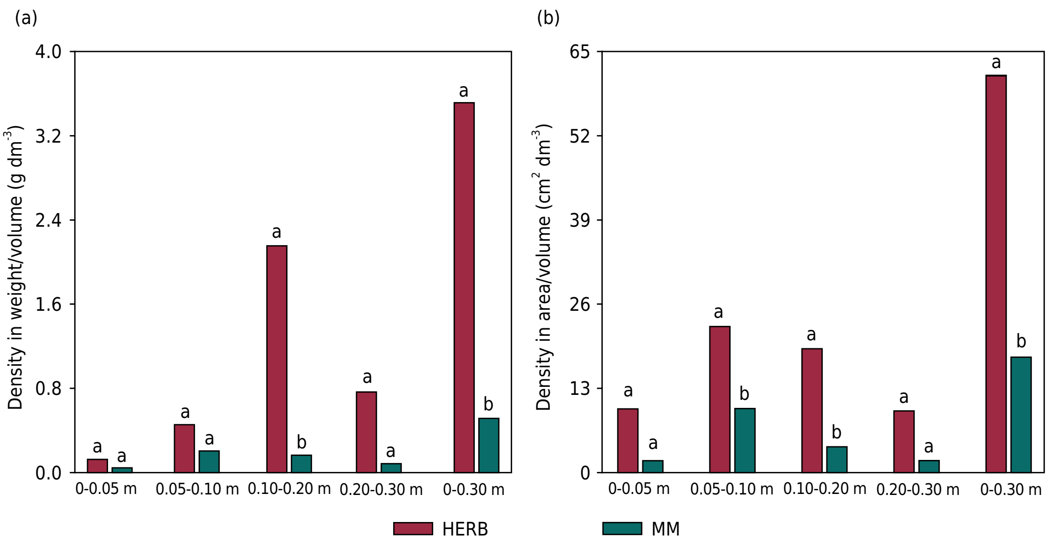

Figure 4. Density in weight/volume (a) and density in area/volume (b) for the roots of early dwarf cashew under different management systems in an area cultivated with early dwarf cashew in Pacajus, Ceará, Brazil. DH: disc harrowing; MM: mechanical mowing + crowning; HERB: Herbicide. Mean values followed by the same letter in the soil layers do not differ by F-test.

It is therefore expected that the addition of organic matter, and its consequences, will also affect the levels of light-fraction soil organic matter (LF). This compartment has a recycling time of 1 to 5 years (Chan et al., 2002; Louis et al., 2016) and is a dynamic reservoir of soil organic matter, transitory between litter and mineral-associated C, composed of partially decomposed plant and animal residues and not associated with the mineral matrix of the soil (Bu et al., 2012; Xavier et al., 2013). Among the systems under evaluation, MM obtained the highest LF content in the canopy projection limit and between the rows, as compared to the DH treatment (Figure 3). Higher levels of LF in the MM system compared to DH between the rows in the study area were also seen by Xavier et al. (2013). According to these authors, MM crushes the organic residue, producing fractions of organic matter of a similar size to that of the LF. In the case of the canopy projection limit and between the rows, it is understandable that the levels are higher in the MM treatment compared to HERB and DH. The shoots of spontaneous plants being crushed and continuously deposited on the surface may be causing this behavior. However, further studies are necessary to know the reasons that led to the higher LF content under the cashew canopy in the MM+DH treatment when compared to HERB treatment, since in these treatments (MM and DH) there is the practice of crowning, and therefore, the LF comes from the soil surface.

Between the rows of cashew trees, it is expected that the soil disturbance promoted by the use of disc harrowing and crushing of spontaneous plants in DH and MM treatments, respectively, tend to promote the natural selection of materials more resistant to decomposition. In the case of MM, there would be an accumulation over time, since the crushed material is deposited under the soil surface, while for DH, the organic material produced by the spontaneous plants and cashew leaves is incorporated into the soil.

Concerning the soil chemical propertiesl, more-detailed observations should be made regarding the levels of exchangeable Ca^{2+} and Mg^{2+} and available K^{+} and P. The levels of available P under the canopy exceeded those found between the rows in the 0.00-0.05 m layer in all the management systems under study (Figure 3), especially HERB. These results may be attributed to the accumulation of available P under the cashew canopy in the surface layer, together with its low mobility in the soil (Turner and Engelbrecht, 2011; Rodrigues et al., 2016; Lustosa Filho et al., 2019). This situation is even more marked due to the maintenance fertilization of the crop, which was always carried out within the canopy projection. With the growth of the cashew plants and change in fertilization site due to the natural expansion of the canopy projection, the addition of fertilizers was carried out almost throughout the whole area under the canopy. Even though thin layers of soil were removed by using hand implements (hoes) when crowning, the incorporation of fertilizers into the surface and even the movement of P in soils of sandy texture (Rashmi et al., 2020) determine only partial removal of the remaining fertilizer. In addition, the practice of crowning favored an increase in available P in the canopy projection, which becomes obvious from the higher values in the DH and MM treatments. The removal of organic residue derived from spontaneous plants or cashew leaves and the removal of part of the surface layer of the soil resulted in this increase in available P in the canopy projection.

As for the higher levels of available P under cashew canopy, obtained when the herbicide was applied, it should be considered that the above-mentioned effect was even more marked due to the lack of crowning. In this case, this favors accumulation, since non-removal of the top centimeters of soil and the annual applications of fertilizer can result in a greater accumulation of available P over time. The input of organic material from the cashew leaves and spontaneous plants should also be considered, evidenced by the data shown in table 3, where there is a greater supply of phytomass under canopy in the HERB treatment. In addition, another important aspect to be considered is the increase in cation exchange capacity and the possible blocking of P adsorption sites by organic acids (Jiang et al., 2015) produced by the decomposition of the deposited plant material, which must also have contributed to the greater availability of P. The effect of blocking the P adsorption sites in soil by organic acids is more pronounced in soils of sandy texture (Rashmi et al., 2020), as in the present study.

The process for P described above is even more pronounced in the case of exchangeable Ca^{2+} and Mg^{2+}, since these elements are not accumulated over the years, as is the case with the available P and K^{+}. The differences between management systems are exclusively due to the contribution of the phytomass through its decomposition and mineralization. The phytomass input from the spontaneous plants and cashew leaves under the canopy in the HERB system was greater than in the other treatments (Table 3). Certainly, with the favorable conditions of moisture and nutrients resulting from residue being left on the surface and from the maintenance fertilization, in addition to the other aspects discussed above, nutrient cycling tends to increase. Carvalho et al. (2004), when evaluating nutrient release behavior with the mineralization of cashew leaves over 12 months, found that only Mg^{2+} showed an increase in the soil, while Ca^{2+} did not change, and the available P and K^{+} showed a tendency to decrease, probably due to P being immobilized by microorganisms (Bünemann, 2015) and the K leaching (Silva et al., 2013).

The changes caused by the addition of organic residue also had a positive effect on the pH and Mg^{2+} of the soil. The MM system resulted in an increase both in soil pH and in the exchangeable Mg^{2+} content between crop rows when compared to HERB. This behavior may be related to the greater input of phytomass in MM between the crop rows (6,764 kg ha^{-1}) compared to 2,008 and 3,359 kg ha^{-1} in DH and HERB, respectively (Table 2). The increase in soil pH is probably associated with the greater availability of exchangeable bases. In the case of this experiment, decomposition of the residue is dependent on the lignin content of the leaves, and in the case of the cashew leaves, the lignin content was around 13.3 % with a C/N ratio of 34.1 (data not shown). Such results indicate a tendency towards the slow and continuous release of nutrients.

Phytomass and nutrient content of the roots

The HERB treatment (where no crowning was carried out) showed a greater input of plant phytomass during the evaluation period, affecting the nutrient content of the analyzed phytomass. When compared with the cashew canopy only, in this case (HERB) the effect of crowning is obvious, as the supply of phytomass was 7,862 kg ha^{-1}, compared with 3,727 and 1,148 kg^{-1} in DH and MM, respectively. Such behavior is also reflected in the nutrient content of the phytomass, especially N and Ca, results that agree with Soares et al. (2008), who evaluated nutrient cycling in the early dwarf cashew-based on litter production. According to those authors, the potential for nutrient recycling in the cashew, in decreasing order, was: N>Ca>Mg>Na>K>S>P. Therefore, leaving spontaneous plants and cashew leaves under the canopy helps to increase nutrient cycling, with a positive effect on crop development.

Between the rows of cashew, MM increased the supply of phytomass and its nutrient content, with the exception of Ca. The amounts of phytomass were reduced on average by 50 and 80 % in HERB and DH, respectively. As such, this reduction in the phytomass input in DH can be attributed to the elimination and periodic incorporation of plant residue and harrowing of the soil. Under such conditions, the renewal of natural vegetation is very slow, resulting in low organic-matter production between rows (Xavier et al., 2013). Similar behavior may be associated with HERB, where cover crops are often eliminated by herbicides (Xavier et al., 2013).

The practice of crowning under the conditions of the present study contributed to the reduced development of the root system in the cashew plants, with negative effects on phytomass input (Table 3) and the levels of TOC and nutrients (Figure 3), observed

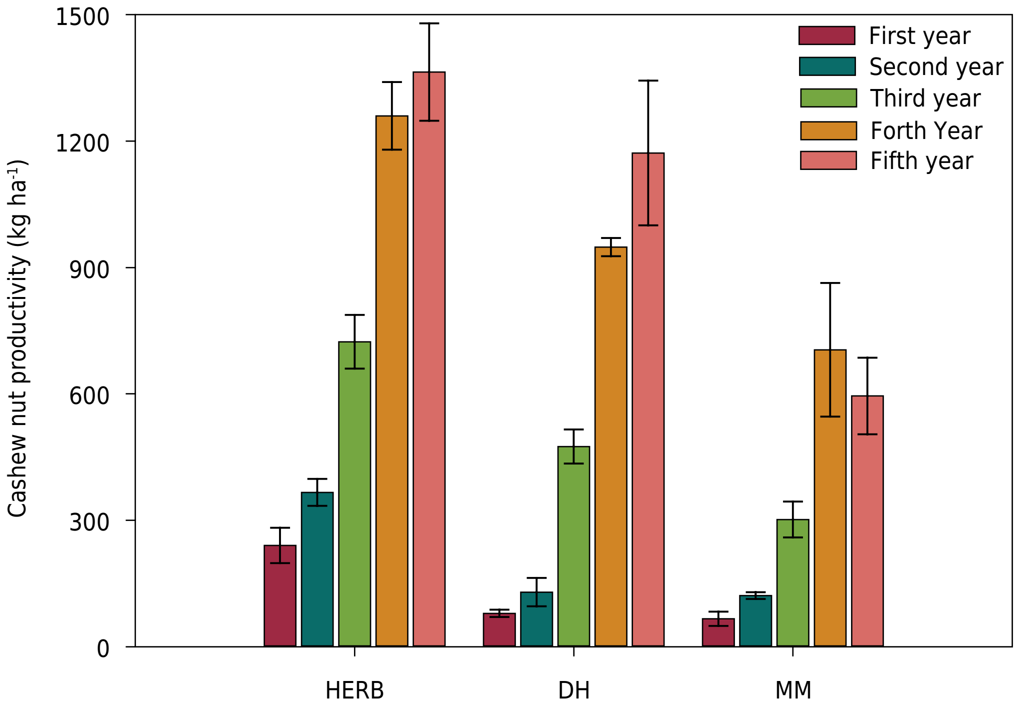

Figure 5. Cashew nut productivity under different management systems in an area cultivated with early dwarf cashew in Pacajús, Ceará, Brazil. Data from the first four years of cultivation were adapted from Ribeiro et al. (2007). Error bars represent the standard error of the mean (n = 3). HERB: herbicide; DH: disc harrowing + crowning; and MM: mechanical mowing + crowning.

in DH and MM treatments. It is important to note that around 82 % of the absorbent roots of the cashew are found in the first 0.30 m of soil (Wahid et al., 1989). Therefore, the use of practices or implements that contribute to damaging the root system of the plant should be avoided.

For production, the soil management systems under test resulted in different levels of cashew-nut productivity. For example, after five years, the HERB treatment achieved mean productivity of 1,363.80 kg ha^{-1}, while the DH and MM treatments achieved yields of 1,171.87 and 594.97 kg ha^{-1}, respectively (Figure 5). These results indicate that, although the MM treatment resulted in greater soil cover, and phytomass and nutrient input between crop rows, this situation did not result in increased productivity. There is probably greater competition for nutrients and water with the spontaneous plants between the rows under MM than in the other treatments, where the plants are systematically controlled by harrowing or the use of herbicides.

Therefore, the results showed that treatments that resulted in no soil disturbance, associated with maintenance of organic residue under the soil surface (MM and HERB), were more effective in storing carbon in the soil and nutrient cycling. Although the removal of organic residue from the soil surface under the canopy of the cashew tree (crowning) can facilitate harvesting of the cashew nuts, the results obtained in this study showed that maintaining this material on the soil surface can be an effective strategy for increasing soil fertility and improving plant yield in sandy and poor soils, where the cashew orchards are cultivated in the northeast of Brazil.

CONCLUSIONS

There are significant differences between what occurs under the canopy of the plants and between the crop rows in cashew cultivation. Between the rows, mechanical mowing led to higher phytomass input, soil organic matter, and nutrients in the soil. However, this did not result in high cashew-nut productivity.

The absence of crowning under the canopy of the cashew trees in the management of the herbicide treatment favored the maintenance accumulation of organic residues on the soil surface, favoring a better soil fertility. Consequently, this was the treatment with the highest level of crop productivity. Therefore, our results indicate that management under the canopy (no crowning) has the greatest influence on productivity in the cashew.

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