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Root Morphological Responses of Arabica Coffee to Stem Density Under Programmed Cycle Pruning

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Abstract

Programmed Cycle Pruning of Arabica Coffee (PPCA) promotes periodic canopy renewal, but its effects on the root system remain poorly understood. This study evaluated root morphology of *Coffea arabica* 'Catuaí Vermelho IAC 81' under PPCA with 4000, 8000, 12,000, or 16,000 stems ha^{-1} and annual or biennial plagiotropic branch removal, compared with traditional management. Roots were sampled before and 90 days after the corresponding management periods in 2016 and 2017. Mean root diameter, volume, length, and surface area were evaluated, with the latter three traits separated into <1, 1–<2, 2–<3, and ≥3 mm diameter classes. PPCA showed no detectable differences from traditional management in root volume or mean root diameter. Differences were concentrated in the length of roots < 2 mm in diameter and the surface area of roots < 1 mm in diameter. Responses varied among sampling times, and higher stem densities were associated with greater length and surface area of smaller-diameter roots at the final sampling time. At the final sampling time, increasing stem density from 4000 to 16,000 stems ha^{-1} increased the estimated root surface area (<1 mm) from 71.3 to 160.1 cm^2, representing an increase of approximately 125%. Annual and biennial branch removal produced no consistently divergent responses. These findings indicate that root morphological responses to PPCA depended on stem density, sampling time, and root-diameter class, with the greatest variation observed in smaller-diameter roots.

Keywords: fine roots; root architecture; orthotropic stems; plagiotropic branch removal; canopy renewal; coffee management

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1. Introduction

Coffee is one of the most important perennial crops in tropical agriculture and has major economic and social relevance in several producing countries. Brazil occupies a prominent position in global coffee production, with *Coffea arabica* L. accounting for a substantial proportion of the national crop. Because coffee plantations remain productive for many years, maintaining their productive capacity requires management practices that

promote the renewal of vegetative and reproductive structures. Plant architecture therefore becomes an important component of crop longevity as stems and productive branches age over successive harvests [1].

Coffee plants exhibit continuous growth and characteristic dimorphism, with orthotropic stems responsible for vertical growth and plagiotropic branches associated with lateral and reproductive development. As these structures age, their vigor and productive contribution may decline, increasing the need for periodic canopy renewal. Pruning is consequently an important management practice in Arabica coffee because it allows the renewal of plant structures and correction of canopy architecture [2].

Canopy-renewal practices used in Arabica coffee differ substantially in the proportion and position of the aerial structure removed. Conventional practices, such as stumping and skeleton pruning, involve extensive removal of orthotropic stems or plagiotropic branches, whereas topping primarily reduces plant height. Changes imposed on the shoot may also be accompanied by belowground responses. Alves et al. [3] demonstrated that manipulation of the aerial portion of *C. arabica* modifies root growth, indicating that the consequences of canopy management are not restricted to the aboveground portion of the plant.

The coffee root system is morphologically heterogeneous, and its development is influenced by cultivation conditions and plant arrangement. In Arabica coffee, changes in spatial arrangement modify root morphology and distribution [4]. Consequently, responses to management may not be expressed uniformly throughout the root system, particularly when roots with contrasting diameters are considered.

Programmed Cycle Pruning represents a different approach to coffee canopy renewal. In *Coffea canephora*, the management of orthotropic stem number and planting density has been shown to influence crop productivity [5]. It was subsequently adapted to Arabica coffee as Programmed Cycle Pruning of Arabica Coffee (PPCA), combining cyclic stem renewal with periodic management of plagiotropic branches [6]. The renewal cycle involves removing approximately 75% of the older orthotropic stems after harvest, selecting new shoots to maintain the target stem density, and removing the remaining older stems after the following harvest. Unlike conventional stumping and skeleton pruning, this approach allows canopy renewal while retaining productive stems during the transition. The economic viability of alternative pruning strategies in Arabica coffee has also been investigated, including different skeleton pruning-based management approaches [7]. Under PPCA, stem density and branch-removal frequency are central components of management. Stem density is regulated by the number of orthotropic stems retained per plant, whereas branch-removal frequency determines whether plagiotropic branches that have completed most of their productive cycle are removed annually or biennially. Baitelle et al. [8] demonstrated that grain yield of Arabica coffee responds to stem density under PPCA and that plagiotropic branches that have already expressed most of their productive capacity can be removed annually or biennially without reducing yield. Subsequent research also showed that PPCA modifies agronomic and physiological characteristics of Arabica coffee [9].

Despite the increasing knowledge of the aboveground responses to PPCA, considerably less is known about its effects on the root system. This gap is relevant because root responses to canopy renovation may vary according to both the type of intervention and the time elapsed after management [10]. Furthermore, changes in total root volume or mean root diameter may not reveal responses concentrated within particular root-diameter fractions. In particular, root length and surface area within smaller-diameter classes may provide additional information about morphological responses to stem density and branch-removal frequency.

Root diameter provides a useful morphological criterion for separating components of the root system, although diameter alone should not be interpreted as a direct indicator of

physiological function [11]. Therefore, evaluating root length, volume, and surface area within distinct diameter classes can provide a more detailed description of the belowground response to pruning than considering the root system as a single compartment.

The temporal dimension is also important because PPCA combines progressive stem renewal with periodic removal of plagiotropic branches. Root responses observed shortly after management may differ from those expressed later in the production cycle, and their magnitude may depend on the number of stems maintained per hectare. Based on the structural heterogeneity of the coffee root system and its responsiveness to changes in plant architecture, greater temporal variation is expected in the smaller root-diameter classes. Higher stem densities may also favor root length and surface area in these classes, particularly during later evaluation periods. Therefore, this study aimed to evaluate mean root diameter, root volume, root length, and root surface area of *Coffea arabica* 'Catuaí Vermelho IAC 81' subjected to programmed cycle pruning under four stem densities and annual or biennial removal of plagiotropic branches, with evaluations performed before and 90 days after management in 2016 and 2017.

2. Materials and Methods

2.1. Experimental Site and Plant Material

The experiment was conducted under field conditions in Alto Mutum Preto, municipality of Baixo Guandu, northwestern Espírito Santo State, Brazil, at 634 m above sea level and at the geographic coordinates 19°21′44.32″ S and 40°50′31.95″ W. According to the Köppen climate classification, the region has an Aw-type tropical climate [12]. The experimental plantation consisted of 12-year-old *Coffea arabica* L. 'Catuaí Vermelho IAC 81' plants grown at a spacing of 2.5 m × 1.0 m under rainfed conditions. The region has an average annual temperature of 21.4 °C, an average annual precipitation of 1260 mm, and undulating to rugged topography.

2.2. Experimental Design and Treatments

The experiment was conducted in a randomized complete block design with four replicates. Each experimental plot consisted of nine plants. The factorial treatments consisted of four stem densities (4000, 8000, 12,000, and 16,000 stems ha^{-1}), corresponding to one, two, three, and four orthotropic stems per plant, respectively, two plagiotropic branch-removal frequencies (annual and biennial), and four sampling times, resulting in a 4 × 2 × 4 factorial arrangement. An additional treatment represented traditional coffee management.

Plagiotropic branch management consisted of removing branches that had already produced at least 70% of their total yield. The four sampling times were defined as T1, before management in 2016; T2, 90 days after management in 2016; T3, before management in 2017; and T4, 90 days after the corresponding management period in 2017. The additional treatment represented the traditional management system used for the crop, characterized predominantly by one orthotropic stem per plant, absence of periodic removal of plagiotropic branches, and stumping when plant vigor declined.

2.3. Implementation of Programmed Cycle Pruning in the Field

Programmed Cycle Pruning of Arabica Coffee was established in 2013 after the fruit harvest. At establishment, approximately 75% of the old orthotropic stems were removed. The first desuckering was performed 50 days after pruning, when the number of shoots corresponding to the stem density assigned to each treatment was selected. Considering the planting density of 4000 plants ha^{-1}, one, two, three, or four orthotropic stems per plant were retained to establish the respective treatments. Additional shoots emerging after this selection were periodically removed.

After the 2014 harvest, the remaining old stems from the 2013 pruning were removed, and the plants were maintained only with the previously selected shoots. The first harvest from the renewed stems occurred in 2015.

2.4. Root Sampling

Roots were sampled in 2016 and 2017 using a steel soil auger 100 mm in diameter and 60 cm long. Samples were collected 30 cm from the plant stem at two soil depths, 0–10 and 10–20 cm, in each of the four plant quadrants, resulting in eight subsamples per sampled plant. One plant per treatment was sampled in each of the four blocks.

Within each year, the first sampling was performed before management and the second was performed 90 days after the corresponding management period. The same sampling procedure was followed at all evaluation times.

2.5. Root Processing and Image Analysis

Each subsample was individually identified and placed in a plastic bag in the field. The sampled material was immersed in water for approximately 3 min to facilitate separation of the roots from the soil. Roots were subsequently washed over a 20-mesh sieve, transferred to 15 × 20 cm plastic bags containing 70% ethanol, and stored at −6 °C until image analysis.

Root samples were analyzed at Northern Fluminense State University Darcy Ribeiro. Roots were scanned using an Epson 11000 XL scanner (Seiko Epson Corporation, Suwa, Nagano, Japan) at a resolution of 400 dpi. For image acquisition, roots were distributed in 15 × 20 cm acrylic trays containing an approximately 15-mm layer of water. Images were processed using WinRHIZO Pro 2007a software (Régent Instruments Inc.).

Mean root diameter (mm), root volume (cm^3), root length (cm), and root surface area (cm^2) were determined. Root volume, root length, and root surface area were separated into four root-diameter classes: <1, 1–<2, 2–<3, and ≥3 mm. Mean root diameter was analyzed without separation into diameter classes.

2.6. Statistical Analysis

Data were evaluated for normality and homogeneity of variances and subsequently subjected to analysis of variance. The factorial analysis considered stem density, branch-removal frequency, sampling time, and their interactions. The four sampling times were analyzed as independent observations, without a repeated-measures structure. Means associated with branch-removal frequency and sampling time were compared using Tukey's test at $p \leq 0.05$.

Stem density was treated as a quantitative factor and analyzed by regression. When no effect of stem density was detected, the response was represented by the overall mean across the four densities. The additional traditional-management treatment was compared with the factorial PPCA treatments by partitioning the treatment sum of squares into orthogonal contrasts and testing the contrast between traditional management and the factorial treatments. Statistical analyses were performed using SAEG version 9.1.

3. Results

3.1. Root Volume and Mean Root Diameter

Root volume was affected by sampling time and stem density in all root-diameter classes (Table 1). Branch-removal frequency did not show a main effect on root volume. For roots < 1 mm, there was a three-way interaction among sampling time, stem density, and branch-removal frequency. Interactions between sampling time and branch-removal frequency were detected for the 1–<2 and 2–<3 mm classes. No effect of the contrast between

the factorial treatments under programmed cycle pruning and traditional management was detected for root volume in any diameter class.

Table 1. Mean squares from the analysis of variance for root volume of *Coffea arabica* L. 'Catuaí Vermelho IAC 81' subjected to programmed cycle pruning with four stem densities (4000, 8000, 12,000, and 16,000 stems ha^{-1}), annual or biennial removal of plagiotropic branches, and four sampling times. Root volume was evaluated separately for the diameter classes <1, 1–<2, 2–<3, and ≥3 mm. The additional treatment corresponded to traditional management.

Source of Variation	df	<1 mm	1–<2 mm	2–<3 mm	≥3 mm
Block	3	0.056	0.065	0.012	1.861
Sampling time (T)	3	4.254 **	3.701 **	3.440 **	33.918 **
Stem density (SD)	3	1.471 **	1.535 **	0.569 **	6.266 **
Branch removal (BR)	1	0.310	0.195	0.106	0.025
T × SD	9	0.420	0.304	0.100	1.155
T × BR	3	0.499	0.744 **	0.338 **	1.805
SD × BR	3	0.020	0.023	0.037	1.638
T × SD × BR	9	0.525 *	0.288	0.116	0.699
Factorial vs. traditional management	1	0.670	0.537	0.193	0.834
Residual	93	0.250	0.178	0.068	1.270
Overall mean	–	1.16	1.05	0.66	1.59
CV (%)	–	42.81	39.94	39.56	70.80

Root volume is expressed in cm^3. T, sampling time; SD, stem density; BR, branch-removal frequency; CV, coefficient of variation. * $p \leq 0.05$; ** $p \leq 0.01$ by the F test.

Mean root diameter was affected by sampling time, whereas stem density and branch-removal frequency did not show main effects. No effect of the contrast between programmed cycle pruning and traditional management was detected for mean root diameter (Table 2). The overall mean root diameter was 1.171 mm, with a coefficient of variation of 10.67%.

Table 2. Mean squares from the analysis of variance for mean root diameter and root length of *Coffea arabica* L. 'Catuaí Vermelho IAC 81' subjected to programmed cycle pruning with four stem densities (4000, 8000, 12,000, and 16,000 stems ha^{-1}), annual or biennial removal of plagiotropic branches, and four sampling times. Root length was evaluated separately for the diameter classes <1, 1–<2, 2–<3, and ≥3 mm. The additional treatment corresponded to traditional management.

Source of Variation	df	Mean Root Diameter (mm)	Root Length (cm)			
			<1 mm	1–<2 mm	2–<3 mm	≥3 mm
Block	3	0.037	41,560.5	146.9	10.7	23.9
Sampling time (T)	3	0.474 **	924,655.3 **	16,268.5 **	1621.7 **	3320.2 **
Stem density (SD)	3	0.005	867,970.9 **	5536.2 **	275.8 **	104.3
Branch removal (BR)	1	0.011	1967.2	434.4	26.4	144.5
T × SD	9	0.015	238,047.8	1573.0 **	36.7	203.0
T × BR	3	0.015	158,502.6	2430.1 **	135.7 **	284.1
SD × BR	3	0.003	83,051.3	191.5	21.9	567.0 **
T × SD × BR	9	0.004	100,832.3 **	895.0 *	48.2	389.9 **
Factorial vs. traditional management	1	0.002	420,722.8 **	3027.6 **	110.3	0.1
Residual	93	0.015	29,815.8	413.09	27.8	109.6
Overall mean	–	1.171	785.6	66.9	14.1	12.9
CV (%)	–	10.67	21.9	30.4	37.5	80.6

Mean root diameter is expressed in mm, and root length in cm. T, sampling time; SD, stem density; BR, branch-removal frequency; CV, coefficient of variation. * $p \leq 0.05$; ** $p \leq 0.01$ by the F test.

3.2. Root Length

Root length responded differently among root-diameter classes (Table 2). For roots < 1 mm, the three-way interaction among sampling time, stem density, and branch-removal frequency was significant. The contrast between the factorial treatments under

programmed cycle pruning and traditional management was also significant for this diameter class.

For roots 1–<2 mm, root length was affected by sampling time and stem density, with significant interactions between sampling time and stem density, sampling time and branch-removal frequency, and among the three experimental factors. The contrast between programmed cycle pruning and traditional management was also significant for this class. For roots 2–<3 mm, sampling time, stem density, and the interaction between sampling time and branch-removal frequency affected root length. For roots ≥ 3 mm, effects were detected for sampling time, the interaction between stem density and branch-removal frequency, and the three-way interaction. No effect of the contrast between programmed cycle pruning and traditional management was detected for either of the two larger root-diameter classes (Table 2).

Thus, differences between programmed cycle pruning and traditional management for root length were restricted to roots with diameters <2 mm.

3.3. Root Length in the <1 mm Diameter Class

The response of root length in the <1 mm diameter class to stem density depended on sampling time and branch-removal frequency (Table 3, Figure 1). Before management in 2016 (T1), stem density did not affect root length under either annual or biennial branch removal, with mean values of 757.10 and 841.08 cm, respectively.

Table 3. Regression equations for root length in the <1 mm diameter class of *Coffea arabica* L. 'Catuaí Vermelho IAC 81' as a function of stem density under annual and biennial plagiotropic branch-removal management at four sampling times. T1, before management in 2016; T2, 90 days after management in 2016; T3, before management in 2017; and T4, 90 days after the corresponding management period in 2017. Stem densities were 4000, 8000, 12,000, and 16,000 stems ha^{-1}.

Branch-Removal Management	Sampling Time	Regression Equation	R^2
Annual	T1	$\overline{Y} = 757.10$	–
Annual	T2	$\hat{Y} = 0.0333x + 283.34$	0.90 **
Annual	T3	$\hat{Y} = -1 \times 10^{-5}x^2 + 0.2225x - 45.042$	0.72 *
Annual	T4	$\hat{Y} = 0.0581x + 320.46$	0.79 **
Biennial	T1	$\overline{Y} = 841.08$	–
Biennial	T2	$\hat{Y} = -6 \times 10^{-6}x^2 + 0.1363x - 151.66$	0.56 *
Biennial	T3	$\overline{Y} = 753.03$	–
Biennial	T4	$\hat{Y} = 0.0912x + 122.4$	0.80 **

* $p \leq 0.05$; ** $p \leq 0.01$, according to the F-test. Root length is expressed in cm, and x represents stem density (stems ha^{-1}). $\hat{Y}$ indicates the fitted regression estimate. When no effect of stem density was detected, $\overline{Y}$ represents the mean root length across the four stem densities. R^2, coefficient of determination.

At 90 days after management in 2016 (T2), root length increased linearly with stem density under annual branch removal, whereas a quadratic response was observed under biennial branch removal. Under annual removal, estimated root length increased from approximately 417 cm at 4000 stems ha^{-1} to 816 cm at 16,000 stems ha^{-1}. Under biennial removal, the quadratic response reached its highest estimated value at approximately 11,360 stems ha^{-1}. These responses occurred after the reduction in root length reported between T1 and T2 for most treatment combinations.

Before management in 2017 (T3), stem density produced a quadratic response under annual branch removal, whereas no response to stem density was detected under biennial removal, for which the mean root length was 753.03 cm. Under annual removal, the fitted

model indicated increasing root length up to an intermediate stem density, followed by a reduction at the highest density.

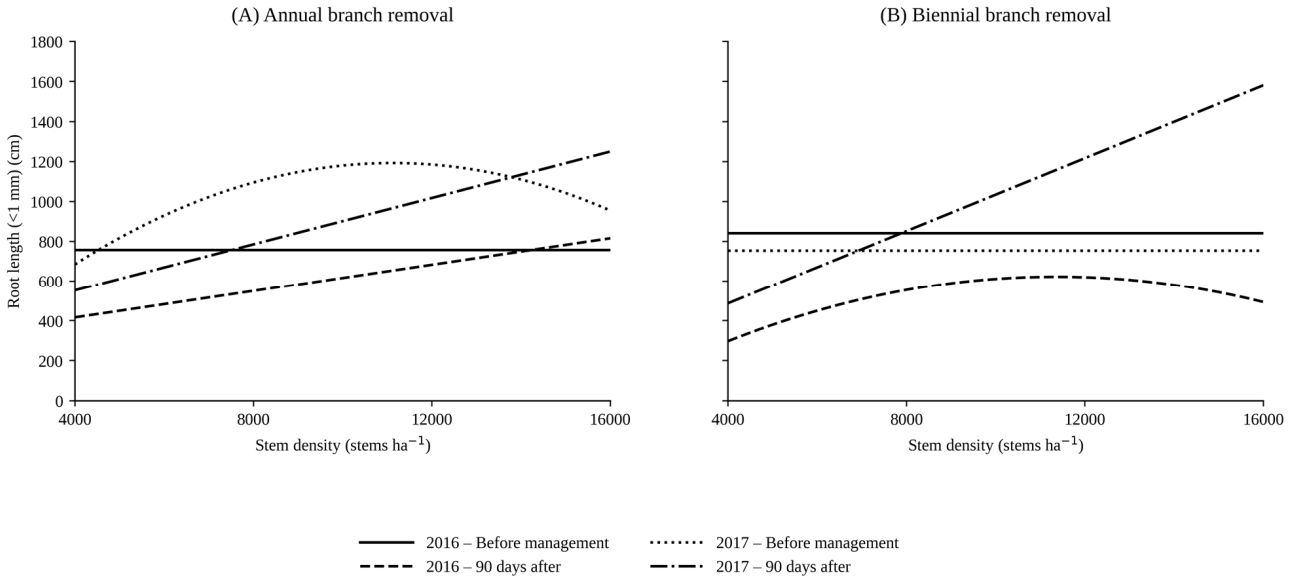

Figure 1. Root length in the <1 mm diameter class of *Coffea arabica* 'Catuaí Vermelho IAC 81' as a function of stem density under (**A**) annual and (**B**) biennial removal of plagiotropic branches. Lines represent the fitted regressions or treatment means for sampling before management and 90 days after management in 2016 and 2017. Regression equations and coefficients of determination are presented in Table 3.

At the fourth sampling time (T4), root length increased linearly with stem density under both branch-removal frequencies. Under annual removal, the fitted equation estimated approximately 553 and 1250 cm at 4000 and 16,000 stems ha^{-1}, respectively. The increase with stem density was more pronounced under biennial management, reaching approximately 1580 cm at 16,000 stems ha^{-1}. Relative to T3, root length increased at 12,000 and 16,000 stems ha^{-1} under annual branch removal and at most stem densities under biennial management, except at 4000 stems ha^{-1}.

3.4. Root Length in the 1–<2 mm Diameter Class

The response of root length in the 1–<2 mm diameter class also depended on sampling time, stem density, and branch-removal frequency (Table 4, Figure 2). Before management in 2016 (T1), stem density did not affect root length under either annual or biennial branch removal, with mean values of 83.38 and 93.42 cm, respectively.

Table 4. Regression equations for root length in the 1–<2 mm diameter class of *Coffea arabica* L. 'Catuaí Vermelho IAC 81' as a function of stem density under annual and biennial plagiotropic branch-removal management at four sampling times. T1, before management in 2016; T2, 90 days after management in 2016; T3, before management in 2017; and T4, 90 days after the corresponding management period in 2017. Stem densities were 4000, 8000, 12,000, and 16,000 stems ha^{-1}.

Branch-Removal Management	Sampling Time	Regression Equation	R^2
Annual	T1	$\overline{Y} = 83.38$	–
Annual	T2	$\hat{Y} = 0.0026x + 23.615$	0.97 **
Annual	T3	$\hat{Y} = 0.0028x + 34.45$	0.96 **
Annual	T4	$\hat{Y} = 0.0032x + 47.955$	0.93 **

Table 4. *Cont.*

Branch-Removal Management	Sampling Time	Regression Equation	R^2
Biennial	T1	$\overline{Y} = 93.42$	–
Biennial	T2	$\overline{Y} = 42.11$	–
Biennial	T3	$\overline{Y} = 35.75$	–
Biennial	T4	$\hat{Y} = 0.0090x - 0.72$	0.95 **

** $p \leq 0.01$, according to the F-test. Root length is expressed in cm, and x represents stem density (stems ha^{-1}). $\hat{Y}$ indicates the fitted regression estimate. When no effect of stem density was detected, $\overline{Y}$ represents the mean root length across the four stem densities. R^2, coefficient of determination.

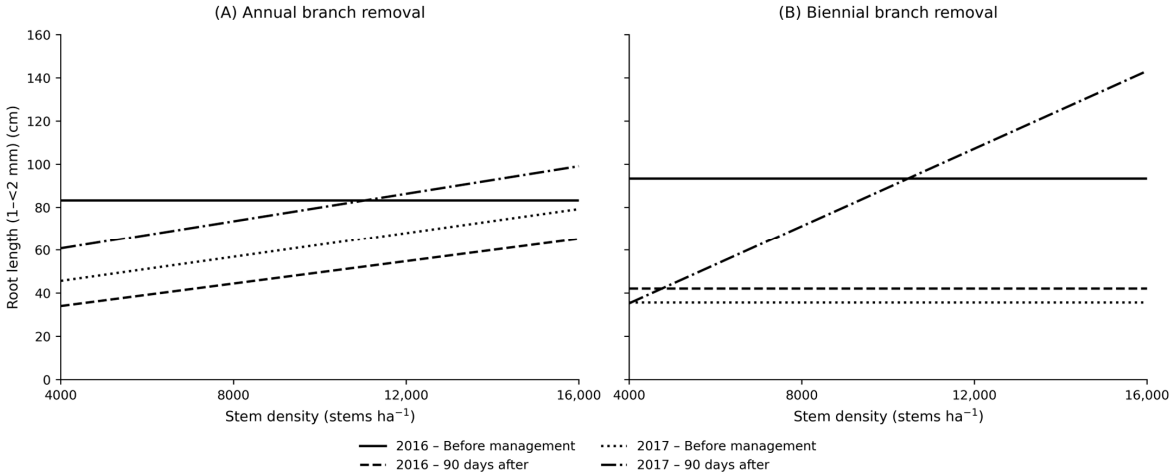

Figure 2. Root length in the 1–<2 mm diameter class of *Coffea arabica* 'Catuaí Vermelho IAC 81' as a function of stem density under (**A**) annual and (**B**) biennial removal of plagiotropic branches. Lines represent the fitted regressions or treatment means for sampling before management and 90 days after management in 2016 and 2017. Regression equations and coefficients of determination are presented in Table 4.

At 90 days after management in 2016 (T2), root length was lower than at T1 under both branch-removal frequencies. Under annual removal, root length increased linearly with stem density, from an estimated 34.0 cm at 4000 stems ha^{-1} to 65.2 cm at 16,000 stems ha^{-1}. Under biennial removal, no effect of stem density was detected, and the mean root length was 42.11 cm. Relative to T1, root length was lower at T2 across all evaluated stem densities.

Before management in 2017 (T3), root length increased linearly with stem density under annual branch removal, reaching estimated values of approximately 45.7 and 79.3 cm at 4000 and 16,000 stems ha^{-1}, respectively. Under biennial removal, stem density had no effect, and the mean root length was 35.75 cm. Thus, relative to T2, root length increased under annual removal but decreased under biennial removal.

At T4, root length increased linearly with stem density under both annual and biennial branch-removal management. Under annual removal, the fitted equation estimated approximately 60.8 cm at 4000 stems ha^{-1} and 99.2 cm at 16,000 stems ha^{-1}. The response was more pronounced under biennial management, increasing from approximately 35.3 cm at 4000 stems ha^{-1} to 143.3 cm at 16,000 stems ha^{-1}. Relative to T3, root length increased at T4 across all stem densities under both branch-removal frequencies.

3.5. Root Surface Area

Root surface area was affected by sampling time and stem density in all root-diameter classes (Table 5). Branch-removal frequency did not show a main effect. Interactions between sampling time and stem density were detected for the <1 and 1–<2 mm classes,

whereas interactions between sampling time and branch-removal frequency occurred for the <1, 1–<2, and 2–<3 mm classes. The contrast between the factorial treatments under programmed cycle pruning and traditional management was significant only for roots < 1 mm. No effect of this contrast was detected for the 1–<2, 2–<3, or ≥3 mm classes.

Table 5. Mean squares from the analysis of variance for root surface area of *Coffea arabica* L. 'Catuaí Vermelho IAC 81' subjected to programmed cycle pruning at four stem densities (4000, 8000, 12,000, and 16,000 stems ha^{-1}), annual or biennial plagiotropic branch removal, and four sampling times. Root surface area was evaluated separately for the diameter classes <1, 1–<2, 2–<3, and ≥3 mm. The additional treatment corresponded to traditional management. T, sampling time; SD, stem density; BR, branch-removal frequency; CV, coefficient of variation.

Source of Variation	df	<1 mm	1–<2 mm	2–<3 mm	≥3 mm
Block	3	65.4	10.5	4.4	89.0
Sampling time (T)	3	17,542.8 **	2563.5 **	917.0 **	2835.7 **
Stem density (SD)	3	10,170.9 **	1084.0 **	144.9 **	294.9 **
Branch removal (BR)	1	1449.9	132.6	29.7	0.0
T × SD	9	2264.6 *	307.7 **	22.6	40.0
T × BR	3	3183.4 *	617.8 **	75.6 **	53.3
SD × BR	3	572.9	15.2	11.5	59.5
T × SD × BR	9	1326.0	205.7	23.4	61.6
Factorial vs. traditional management	1	6146.6 **	379.0	52.2	24.8
Residual	93	1326.0	116.5	15.8	50.5
Overall mean	–	84.0	30.1	10.8	13.0
CV (%)	–	35.2	35.9	36.7	54.5

Root surface area is expressed in cm^2. T, sampling time; SD, stem density; BR, branch-removal frequency; CV, coefficient of variation. * $p \leq 0.05$; ** $p \leq 0.01$ by the F test.

Because the interaction between sampling time and stem density was significant for the <1 mm class, this fraction was examined separately (Figure 3). Before management in 2016 (T1), stem density did not affect root surface area, with a mean of 86.38 cm^2. At 90 days after management in 2016 (T2), root surface area increased linearly with stem density, from an estimated 46.2 cm^2 at 4000 stems ha^{-1} to 79.8 cm^2 at 16,000 stems ha^{-1}. Nevertheless, root surface area at T2 was lower than at T1 across the evaluated stem densities.

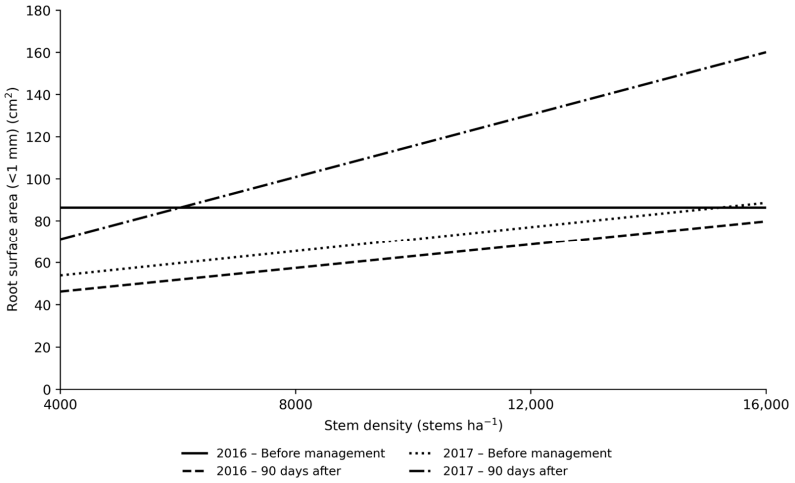

Figure 3. Root surface area in the <1 mm diameter class of *Coffea arabica* 'Catuaí Vermelho IAC 81' as a function of stem density at four sampling times: before management and 90 days after management in 2016 and 2017. Lines represent fitted regressions or the overall mean across stem densities. Regression equations and coefficients of determination are presented in Table 6.

Table 6. Regression equations for root surface area in the <1 mm diameter class of *Coffea arabica* L. 'Catuaí Vermelho IAC 81' as a function of stem density at four sampling times under programmed cycle pruning. T1, before management in 2016; T2, 90 days after management in 2016; T3, before management in 2017; and T4, 90 days after the corresponding management period in 2017. Stem densities were 4000, 8000, 12,000, and 16,000 stems ha^{-1}.

Sampling Time	Regression Equation	R^2
T1	$\overline{Y} = 86.38$	–
T2	$\hat{Y} = 0.0028x + 35.005$	0.65 *
T3	$\hat{Y} = 0.0029x + 42.24$	0.92 **
T4	$\hat{Y} = 0.0074x + 41.68$	0.95 **

Root surface area is expressed in cm^2, and x represents stem density (stems ha^{-1}). $\hat{Y}$ indicates the fitted regression estimate. When no effect of stem density was detected, $\bar{Y}$ represents the mean root surface area across the four stem densities. R^2, coefficient of determination. * $p \leq 0.05$; ** $p \leq 0.01$ by the F test.

Before management in 2017 (T3), root surface area also increased linearly with stem density, with estimated values of approximately 53.8 and 88.6 cm^2 at 4000 and 16,000 stems ha^{-1}, respectively. At T4, the linear response became considerably steeper, with estimated surface area increasing from approximately 71.3 cm^2 at 4000 stems ha^{-1} to 160.1 cm^2 at 16,000 stems ha^{-1}. Relative to T3, root surface area increased at T4 across all evaluated stem densities.

3.6. Branch-Removal Frequency and Root Surface Area in the <1 mm Diameter Class

The interaction between sampling time and branch-removal frequency affected root surface area in the <1 mm diameter class (Table 7). Under annual branch removal, root surface area did not differ among T1, T2, and T3, whereas T4 showed a higher value than the previous sampling times. Under biennial management, root surface area decreased from T1 to T2 and remained low at T3, followed by a marked increase at T4.

Table 7. Root surface area of the <1 mm diameter class of *Coffea arabica* L. 'Catuaí Vermelho IAC 81' under annual and biennial plagiotropic branch-removal management at four sampling times, with traditional management included as an additional treatment. T1, before management in 2016; T2, 90 days after management in 2016; T3, before management in 2017; and T4, 90 days after the corresponding management period in 2017.

Management	T1	T2	T3	T4
Annual branch removal	82.06 Ba	69.15 Ba	87.35 Ba	111.10 Aa
Biennial branch removal	90.70 Aa	56.11 Ba	55.15 Bb	120.77 Aa
Traditional management	71.81	72.60	69.38	213.17
Overall mean	86.38	62.63	71.25	115.94

Root surface area is expressed in cm^2. Means followed by the same lowercase letter within a column and uppercase letter within a row do not differ by Tukey's test at $p \leq 0.05$. The traditional-management treatment was included as an additional treatment and was not part of the mean comparison between annual and biennial branch-removal frequencies. CV = 35.19%.

Comparison between branch-removal frequencies showed a difference only at T3, when annual management resulted in a greater root surface area than biennial management. No difference between annual and biennial branch removal was detected at T1, T2, or T4.

The traditional-management treatment showed root surface areas of 71.81, 72.60, 69.38, and 213.17 cm^2 at T1, T2, T3, and T4, respectively. These values are presented as the additional treatment and were not included in the Tukey comparison between annual and biennial branch-removal frequencies.

4. Discussion

4.1. Differential Response of Root Diameter Classes

The main belowground response to PPCA was concentrated in the smaller root-diameter fractions rather than in the root system as a whole. Root volume and mean root diameter showed no detectable differences between PPCA and traditional management, whereas differences in root length and surface area were primarily associated with roots < 2 mm (Tables 1, 2 and 5). Smaller-diameter roots can show greater morphological variation than larger structural roots, although diameter alone cannot be used to assign physiological function [11].

The greater morphological variation observed in smaller-diameter roots is consistent with the functional heterogeneity of fine-root systems described by McCormack et al. [11]. These authors emphasize that root diameter alone does not determine physiological function, although root morphology provides relevant information about belowground responses. Therefore, the variation in root length and surface area observed in the present study indicates morphological adjustments to management rather than direct evidence of changes in water or nutrient uptake.

In coffee, root morphology is also strongly influenced by cultivation arrangement and growing conditions [4,13,14], reinforcing that changes in root length or surface area may occur without parallel changes in total root volume or mean diameter.

The higher coefficients of variation observed for root volume and length in the larger-diameter classes may be associated with the heterogeneous spatial distribution of coffee roots. Ronchi et al. [4] and Partelli et al. [14] demonstrated that root morphological characteristics and distribution vary according to sampling position and soil depth. Such spatial heterogeneity may contribute to variability among experimental units, particularly when evaluating specific root-diameter classes.

The absence of a generalized decline in root volume under PPCA is particularly relevant when considered against evidence that modifications of the aerial portion and renovation practices can alter coffee root growth and biomass. Alves et al. [3] demonstrated changes in root growth following manipulation of the aerial portion of *Coffea arabica*, while Rendón et al. [10] showed that root biomass responses depend on the renovation method and the time elapsed after intervention. Root growth can also respond substantially to direct disturbance of the root system itself [15]. In contrast, the present results indicate that PPCA altered specific root fractions, while no differences from traditional management were detected for root volume or mean root diameter.

This distinction also limits the interpretation of PPCA simply as a "non-drastic" pruning system. The present experiment did not directly compare PPCA with stumping or skeleton pruning; therefore, pruning severity cannot be ranked directly. What the data demonstrate is that, under PPCA, the effects on the root system were selective rather than generalized.

4.2. Temporal Root Dynamics Under PPCA

The temporal pattern of root response is equally important. Reductions observed shortly after management were followed by increases in root length and surface area at subsequent sampling times in specific combinations of stem density, branch-removal frequency, and root-diameter class. This temporal pattern is particularly relevant in perennial coffee because the responses observed shortly after management differed from those recorded at later sampling times.

Somarriba and Quesada [16] showed that responses to pruning in Arabica coffee are strongly dependent on tissue age and time since renewal. Although their work focused on yield dynamics, the same temporal framework is useful for interpreting the present root responses. Likewise, Filla et al. [17] reported that Arabica coffee cultivars show different

responses in successive years following skeleton pruning, confirming that the consequences of canopy renewal change with time.

The later increase in the smaller-diameter fractions, particularly under higher stem densities, shows that root responses differed according to the stage of the PPCA cycle. This interpretation is consistent with the temporal nature of canopy restructuring previously described for Arabica coffee under PPCA [8,9], although direct causal relationships between canopy development and root growth cannot be established from the variables measured here.

The fact that the strongest density-related responses occurred during the later evaluation also indicates that early post-pruning assessments may not represent the root responses observed at later stages of the PPCA cycle. This is particularly relevant for perennial crops, in which vegetative renewal and reproductive development overlap over several seasons.

The present study evaluated roots within the upper 20 cm of soil, where previous research has reported a greater concentration of smaller-diameter coffee roots [14]. Nevertheless, the results are restricted to the sampled soil layer and do not represent the entire root system.

4.3. Stem Density and Branch-Removal Management

Stem density was a central component of the belowground response. Higher densities did not produce a progressive reduction in the measured root system; instead, the responses of the smaller-diameter fractions became more pronounced later in the cycle. At T4, root length and surface area increased with stem density, particularly at 12,000 and 16,000 stems ha^{-1} (Tables 3, 4 and 6). This pattern shows that higher stem densities were associated with greater root length and surface area in the smaller-diameter fractions at T4.

This finding is consistent with the morphological plasticity of the coffee root system described under different crop arrangements [4]. Although plant density and stem density are distinct management factors, both alter the spatial organization of the crop. The response observed here is consistent with previous evidence that coffee root morphology varies with crop spatial arrangement [4].

The greater root length and surface area observed at higher stem densities, particularly at 12,000 and 16,000 stems ha^{-1}, indicate that stem density influences the morphological development of smaller-diameter roots during the later stages of the pruning cycle. Under comparable growing conditions, Baitelle et al. [8] reported maximum estimated grain yield at approximately 12,531 stems ha^{-1}. Together, these findings suggest that higher stem densities may be agronomically promising under the evaluated conditions, although root morphological responses alone do not establish an optimal stem density.

Branch-removal frequency, in contrast, exerted a more limited and temporally dependent influence. Annual and biennial removal did not produce consistently divergent root responses, and differences were restricted to particular sampling times and traits (Table 7). For root surface area in the <1 mm diameter class, annual branch removal resulted in a higher value than biennial removal only at T3. This agrees with previous PPCA studies showing that annual or biennial removal of plagiotropic branches can be adopted without consistent reductions in yield [8]. The present findings indicate that this management flexibility was also compatible with maintenance of the measured root traits over the evaluated cycle.

4.4. Implications of PPCA for Belowground Management of Arabica Coffee

Research on PPCA in Arabica coffee has progressively expanded from crop architecture and yield to physiological traits and nutrient cycling. Baitelle et al. [8] demonstrated that stem density modifies vegetative characteristics and grain yield, while Baitelle et al. [9]

further characterized agronomic and physiological responses to PPCA. Araújo et al. [18] subsequently showed that plant material removed during programmed pruning contributes to biomass input and nutrient cycling in Arabica coffee plantations.

The present study adds a complementary belowground component to this framework. The results indicate that PPCA does not simply reduce or increase the root system as a whole. Instead, the response is selective, temporally dynamic, and strongly dependent on root-diameter class and stem density. This provides a more integrated view of the management system, showing that belowground responses vary among root-diameter classes and sampling times rather than occurring uniformly across the root system.

Under the conditions evaluated here, PPCA showed no detectable differences from traditional management in root volume, root length in classes ≥ 2 mm, or root surface area in classes ≥ 1 mm, while the smaller-diameter fractions showed the greatest variation among sampling times.

Under traditional management, root surface area in the <1 mm diameter class increased numerically from 69.38 cm^2 at T3 to 213.17 cm^2 at T4 (Table 7). This variation highlights the importance of sampling time when describing root morphology. However, this temporal difference was not evaluated through the mean comparisons applied to the factorial treatments.

The results also reinforce the importance of evaluating root responses over multiple stages of the pruning cycle. A single assessment shortly after management would have emphasized the initial reduction observed in some root fractions and would not have captured the subsequent increases observed at the later stage. For perennial crops such as coffee, the biological meaning of pruning therefore depends not only on the type of intervention but also on when the root system is evaluated after management.

Taken together, these findings indicate that the belowground response to PPCA is characterized by responses concentrated in specific root-diameter fractions rather than by a generalized decline across the measured root system. This expands the current understanding of programmed cycle pruning by showing that its effects extend beyond canopy architecture, physiological performance, yield, and nutrient cycling [8,9,18] to include dynamic changes in the root system over the pruning cycle.

5. Conclusions

Programmed Cycle Pruning of Arabica Coffee showed no detectable differences from traditional management in root volume, mean root diameter, root length in classes ≥ 2 mm, or root surface area in classes ≥ 1 mm of *Coffea arabica* 'Catuaí Vermelho IAC 81', whereas the main responses were concentrated in the length of roots < 2 mm in diameter and the surface area of roots < 1 mm in diameter.

These responses depended on sampling time and stem density. Reductions in the smaller root-diameter fractions observed after management were followed by increases at subsequent evaluations, particularly at stem densities of 12,000 and 16,000 stems ha^{-1} during the later stage of the PPCA cycle. Annual and biennial removal of plagiotropic branches did not produce consistently divergent root responses. Differences between these management frequencies were restricted to specific traits and sampling times.

These findings expand the understanding of PPCA by demonstrating that its effects on Arabica coffee extend to root morphology and vary over the pruning cycle.

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