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Detection of the fruit-ripeness stage in the pre-harvest of *Coffea arabica*

Abstract – The objective of this work was to determine the optimal number of plants to be sampled and which method best represents the green-maturation stage of the Catuaí Vermelho IAC 144 and Mundo Novo IAC 376-4 *Coffea arabica* cultivars. The experimental design consisted of four treatments: harvest of the fruits located in the central bud of 12 plagiotropic branches; harvest of the fruits located in the first bud, central bud, and last bud of 12 plagiotropic branches; harvest of all fruits of 12 plagiotropic branches; and harvest of all fruits of the plant. Both coffee cultivars were subjected to all treatments, with the respective evaluation of the percentage of green fruits. For the two cultivars, the first, second, and fourth treatments adequately represent the percentage of green fruits of the crop. It is recommended to use the collection of fruits from the central bud of the plagiotropic branches to determine the percentage of green fruits of both cultivars. For the Catuaí Vermelho IAC 144 and Mundo Novo IAC 376-4 cultivars, the optimal number of plants to be sampled to quantify the green phenological stage is 13 and 14, respectively.

Index terms: *Coffea arabica*, central bud, joint analysis, cane-green fruit.

Detecção do estádio de maturação de frutos na pré-colheita de *Coffea arabica*

Resumo – O objetivo deste trabalho foi determinar o número ideal de plantas a serem amostradas e qual método melhor representa o estádio de maturação verde das cultivares Catuaí Vermelho IAC 144 e Mundo Novo IAC 376-4 de *Coffea arabica*. O delineamento experimental consistiu em quatro tratamentos: colheita dos frutos localizados na gema central de 12 ramos plagiotrópicos; colheita dos frutos localizados na primeira gema, na gema central e na última gema de 12 ramos plagiotrópicos; colheita de todos os frutos de 12 ramos plagiotrópicos; e colheita de todos os frutos da planta. Ambas as cultivares de café foram submetidas a todos os tratamentos, com a respectiva avaliação do percentual de frutos verdes. Para as duas cultivares, o primeiro, o segundo e o quarto tratamento representam de maneira adequada o percentual de frutos verdes da lavoura. Recomenda-se a utilização da coleta de frutos da gema central dos ramos plagiotrópicos para determinação do percentual de frutos verdes em ambas cultivares. Para as cultivares Catuaí Vermelho IAC 144 e Mundo Novo IAC 376-4, o número ideal de plantas a serem amostradas para quantificar o estádio fenológico verde é de 13 e 14, respectivamente.

Termos para indexação: *Coffea arabica*, gema central, análise conjunta, frutos verde-cana.

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Introduction

In recent years, there have been profound transformations in the coffee chain with changes in the aspects of production, processing, marketing, and the way in which high-quality *Coffea arabica* L. beans are prepared and consumed. As a result, there was an increase of the Brazilian production of specialty coffee that reached eight million bags in 2023, representing 20% of this production, with 15% growth of per year (Giomo et al., 2024).

To obtain specialty coffees, harvesting ripe fruit is crucial. The occurrence of sporadic rains around the spring season causes several flowerings in the coffee plant, resulting in uneven maturation (Bongase, 2017). As most of the time the harvest is carried out with fruit at different stages of maturation, the coffee bean produced ends up being of inferior quality.

In order to reduce these problems, sampling should be performed before harvesting, to determine the percentage of maturation (Ramos et al., 2018). In addition, the harvest time should be decided when samples indicate the highest possible percentage of ripe fruit, prioritizing the production of coffee beans graded as specialty coffees (Marcilio et al., 2023).

When the sampling process to determine fruit ripeness is still in its early stages, the accuracy of the results will be uncertain. According to Zhang & Ni (2021), sampling data accuracy is affected by the methodology used.

Current available methodologies are laborious for a more accurately quantification of coffee maturation percentage, since they require the random harvest of entire plants to determine the maturation stage (Martins et al., 2021; Rosas et al., 2022; Tamayo-Monsalve et al., 2022). Therefore, as a practical result for the coffee farmer, a large volume of fruit is accumulated for the analysis, as well as an increased demand of labor and time, which is not viable to carry out in some situations (Marcilio et al., 2023).

As reported by Rodríguez et al. (2020), there are several weaknesses, such as errors in quantification during sampling, insufficient samples of coffee fruit, and increased costs, making them unfeasible.

There is a recent method to quantify the percentage of green fruit, which consists of the random harvest of 13 to 14 plants per plot, and the fruit for sampling is collected close to the buds of the plagiotropic branches of the coffee tree. This methodology was tested as accurately quantifying the coffee tree maturation stage, in comparison with the method of entire plant harvest (Castro et al., 2023; Marcilio et al., 2023).

The objective of this work was to determine the optimal number of plants to be sampled and which method best represents the green-maturation stage of the Catuaí Vermelho IAC 144 and Mundo Novo IAC 376-4 *Coffea arabica* cultivars.

Materials and Methods

The experiment was carried out in São José farm, in the rural area of the municipality Inconfidentes (22º20'07"S, 46º19'13"W, at 1,118 m altitude), in the state of Minas Gerais, Brazil.

The soil classification in the study area is a dystrophic Latossolo Vermelho-Amarelo – LVAd, according to the Brazilian Soil System Classification (Santos et al., 2018), i.e., Ferralsol. The Köppen-Geiger's climate classification for the region is Cwa, subtropical type with hot summer and dry winter, with two well-defined seasons− the rainy one from October through March, and the dry one from April through September. The precipitation and temperature annual averages are respectively 1,800 mm and 19 ºC (Pereira et al., 2011).

A randomized complete block experimental design was used with four treatments (T) and six replicates from each treatment, in each experimental area. Each block was composed of 12 plants, divided in four experimental units (EU) with three plants each, totaling 24 EU, and each plant within the EU received one of the four treatments. The plots were independently prepared for the Mundo Novo IAC 376-4 and Catuaí Vermelho IAC 144 cultivars in 1.0 ha and 0.8 ha areas of 20 and 25 years, respectively. And, equal treatments were applied to both cultivars, to validate the methodology used by Marcilio et al. (2023).

Before harvesting, plants were identified in the experimental units, and the 12 plagiotropic branches to be evaluated in treatments T1, T2, and T3 were marked. The sampling process occurred at the four cardinal points in the three insertion heights of the productive branches on the plant (lower third, middle third, and upper third). Coffee fruit were harvested as follows: T1, at the central bud; T2, all fruit at the central bud, and at the first and the last buds in a branch; T3,

harvest of all buds in a branch; T4, harvest of all fruit from all branches of the plant (control treatment).

This procedure was carried out for the four EUs, from which the average of each maturation stage was obtained for each treatment.

The harvest for the experiment began 270 days after the main flowering, which took place on October 14, 2021. During the harvest of all treatments, the soil under the plants was covered with a common harvest cloth, aiming to avoid the loss of fruit that could fall. A sieve was used to collect treatments T1, T2, and T3. As treatment 4 consisted of a greater volume of fruit, the cloth was used to facilitate harvesting.

A unidirectional analysis of variance was performed, and the Tukey's test, at 5% probability, was performed to compare the mean fruit quantities at different maturation stages (green, cane-green, ripe, raisin, and dry colors). An individual statistical analysis was performed, and an analysis of variance of both crops was performed, when the homogeneity of residual variances verified by the quotient between the largest and smallest mean squared error was less than seven (Pimentel-Gomes & Garcia, 2002).

To quantify the minimum number of plants representing the maturation stage, we used the simulation method described by Silva et al. (2011), which consists of the analysis of the arithmetic mean of the percentage of green fruit from 2 to 24 EUs.

The mean estimates for each sample size were plotted on a graph for analysis and visualization of the stabilization of each estimate, according to the number of EUs of each subsample simulated for each treatment. Data stabilized when subsample sizes began to adequately represent the reference sample, which occurred when there was no simulated value outside the confidence interval (95% CI) for this sample with 95% probability (Marcilio et al., 2023).

The minimum EU was determined with the subsampling of two EUs, with the increase of an EU from one analysis to the following. The number of EUs increased significantly until the total of 24 samples (Marcilio et al., 2023). The simulation and analysis of variance were performed using the GENES software (Cruz, 2016).

Results and discussion

A joint analysis was performed for both environments (cultivars), given that the mean squared error was less than seven (Table 1). There was no significant difference between green and ripe stages, in the treatment x cultivars interaction (T x C). Therefore, the use of any methodology would not be influenced by the evaluated cultivars, which also highlights that 80% of Brazilian coffee production is made up of cultivars from the Mundo Novo and Catuaí groups in their different lineages (Sera et al., 2022). However, the cana-green and raisin/dry maturity stages showed a significant difference for the interaction between treatments and cultivars (Table 1), highlighting the influence of the treatments among the cultivars.

In a research with the same treatments, but with other environment and cultivars, Marcilio et al. (2023) found that for the cane-green and raisin stages the cultivars showed no significant interaction with the treatments. Certainly, this distinction between the research by Marcilio et al. (2023) and the present work is related to the temporal environmental factors and microclimate of each crop under study.

Table 1. Analysis of variance of treatments of *Coffea arabica* cultivars, in the municipality of Inconfidentes, in the state of Minas Gerais, Brazil.

Source of variation	DF	F ($p \leq 0.05$)			
		Sugarcane-green	Green	Raisin	Ripe
Treatment (T)	3	0.00	0.00	0.00	0.00
Cultivar (C)	1	0.93	0.49	0.00	0.00
T x C interaction	3	0.00	0.68	0.00	0.06
Replicate (environment)	10	0.00	0.00	0.00	0.00
Coefficient of variation (%)	-	11.09	14.24	10.85	6.48
>MSE/<MSE	-	1.22	1.38	2.38	1.38

DF, degrees of freedom. MSE, mean squared error.

For the analysis of the cane-green maturation stage for Catuaí Vermelho IAC 144 cultivar, the decoupling of treatments T1 and T2 was similar to that of the T4 (control), making it possible to use them to determine these maturation stages. However, T3 differed from the control, which shows that the T3 methodology is not recommended for quantifying the cana-green fruit of this cultivar (Table 2). For the Mundo Novo IAC 376-4 cultivar, treatments T1, T2, and T3 differed from T4 (Table 2), and these methodologies are not recommended for quantifying the cane-green maturation stage of this cultivar.

The raisin stage in the decomposition of the treatment resulted that the behavior between the cultivars was similar, since T1, T2, and T3 did not differ from each other, but they differed from the control (Table 2), which does not allow of the recommendation of these treatments to determine the raisin stage of the Catuaí Vermelho IAC 144 and Mundo Novo IAC 376-4 cultivars.

In the analysis of the cultivars within the cane-green fruit treatment, a significant interaction was observed (Table 1), as such, the methodology for determining the maturation stage was influenced by the environment and the cultivars. When comparing cultivars, there was a difference in maturation between treatments T1 and T4, while treatments T2 and T3 were similar for cane-green fruit. In the raisin stage, a difference was observed only for treatment 4 (Table 2). The difference of cultivars maturation can be explained by the later maturation of Catuaí Vermelho IAC 144 than that of Mundo Novo IAC 376-4.

For the cane-green and raisin ripening stages, only Mundo Novo IAC 376-4 cultivar showed no treatment results similar to the control (Table 2). This cultivar used in the experiment was over 3 m high, showing a limited sunlight access in the lower-middle third, which leaves its fruit with a maturation stage very different from those observed in the upper-middle third.

Marcilio et al. (2023) also found that the tall Icatu cultivar did not show similar results between the control and the other treatments used to evaluate the green fruit maturation stage. This great unevenness of maturation, in the same plant, may have limited the finding of satisfactory results in both experiments, indicating that the proposed methodologies can be used only with smaller plants.

At the green and ripe stage, there was a difference among the treatments (Table 3). For fruit at the green stage, there was no significant difference between treatments T1, T2, and T4 (control), which leads to the inference that T1 and T2 are efficient to determine this maturation stage. The treatment T3 differed from T1 and T4, therefore, it is not recommended. For the ripe stage, treatments T1, T2, and T3 (Table 3) showed no difference from the T4, hence, any methodology can be used to determine the ripe stage.

Similar results to those for green fruit of the present study were found by Marcilio et al. (2023) for Catuaí Vermelho IAC 144 cultivar, in treatments that consisted of harvesting fruit from the first bud and the last bud (T2) and the harvesting of all fruit from the plagiotropic branch (T3). These authors found results equivalent to those of the control (harvesting all fruit

Table 2. Uncoupling of the maturation percentage of the treatments within cultivar (Ts:C) and cultivars inside treatments (Cs:T) for cane-green and raisin stage of *Coffea arabica*, in the municipality of Inconfidentes, in the state of Minas Gerais, Brazil[1].

Treatment[2]	Sugarcane-green		Raisin	
	Catuaí Vermelho IAC 144	Mundo Novo IAC 376 − 4	Catuaí Vermelho IAC 144	Mundo Novo IAC 376 - 4
T1	25.28Bb	29.40Aa	24.43Ba	27.61Ba
T2	25.65ABa	27.10Aa	23.78Ba	26.94Ba
T3	29.83Aa	29.40Aa	21.55Ba	24.43Ba
T4	22.42Ba	16.65Bb	34.76Ab	46.25Aa

[1]Means followed by equal letters, uppercase in the columns and lowercase in the lines, do not differ between themselves, by Tukey's test, at 5% probability. [2]T1, fruit harvesting from the central bud in the plagiotropic branch, at the high-, mid- and lower-thirds of the plant; T2 fruit harvesting from the first, central, and last buds in a plagiotropic branch, at the high-, mid- and lower-thirds of the plant; T3, harvesting of all fruit in a plagiotropic branch at the high-, mid- and lower-thirds of the plant; T4, control, harvesting of the all fruit from the plant.

from the plant); also, they considered the methodology of harvesting all fruit from a plagiotropic branch to be the most feasible.

In a project with alternative methodologies to quantify the percentage of green fruit in coffee plants, Castro et al. (2023) found that, for Catucaí 2 SL cultivar, the harvesting of fruit from the first, central, and last buds (T2), and the harvesting of all fruit from the plagiotropic branch (T3) were effective to quantify the maturation of green fruit, while harvesting fruit from the central bud (T1) differed from the control (T4). In smaller plants, the harvesting of fruit from buds located at the extremities is more efficient for classifying the maturation stage of the coffee plant, as described by Castro et al. (2023) and Marcilio et al. (2023).

Table 3. Maturation percentage means of the treatments at the green and ripe stages of the Mundo Novo IAC 376-4 and Catuaí Vermelho IAC 144 *Coffea arabica* cultivars, in the municipality of Inconfidentes, in the state of Minas Gerais, Brazil[1].

Treatment[2]	Green	Ripe
T1	7.42b	39.20ab
T2	8.25ab	40.00ab
T3	9.03a	38.16ab
T4	7.71b	32.24b

[1]Means followed by equal letters, uppercase in the columns and lowercase in the lines, do not differ between themselves, by Tukey's test, at 5% probability. [2]T1, fruit harvesting from the central bud the plagiotropic branch, at the high-, mid-, and lower-thirds of the plant; T2, fruit harvesting from the first, central, and last buds, in a plagiotropic branch, at the high-, mid-, and lower-thirds of the plant; T3, harvest of all fruit in a plagiotropic branch, at the high-, mid-, and lower-thirds of the plant; T4, control, harvest of the all fruit from the plant.

Table 4. Maturation percentage of the Mundo Novo IAC 376-4 and Catuaí Vermelho IAC 144 *Coffea arabica* cultivars for green and ripe stages, in the municipality of Inconfidentes, in the state of Minas Gerais, Brazil[1].

Treatment	Green	Ripe
Catuaí Vermelho IAC 144	7.99a	40.07a
Mundo Novo IAC 376 − 4	8.22a	34.73b

[1]Means followed by equal letters, in the columns, do not differ between themselves, by the Tukey's test, at 5% probability.

In the evaluation of green fruit in the different cultivars, the fruit phenological stages were statistically equal; however, the ripe stage showed a significant discrepancy between the cultivars (Table 4).

One of the greatest advantages for the implementation of the methodologies under study is their cost reduction, accessibility to any class of coffee farmer, and speed of execution. Several researches have been carried out using remote images, however, with less expressive results.

When applied to medium and smaller plants, the methodology used in the present study does not show the drawbacks of light availability, energy, solar radiation, spacing, plant density, fruit, leaves and branches, which can affect the use of digital cameras. For the harvesting of fruit from buds, at the end of a plagiotropic branch of a coffee plant, the methodology shows several advantages, considering its applicability and immediate return to the small farmer. The coffee farmer himself can use it and – based on the results – decide on the right time to harvest. There is a tendency among coffee farmers to plant smaller coffee cultivars, increasing the applicability of this methodology. These low-sized cultivars, due to the shorter distance between the plant buds (Carvalho, 2008) and greater leaf density, can limit the reading and quantification of the maturation stage when the work is performed with digital cameras.

When evaluating the number of plants representing the green stage of the coffee plant, it was observed that for Catuaí Vermelho IAC 144 cultivar, the treatments require the following numbers of EU: T1, at least 13 EU (Figure 1 A); T2, 14 EU (Figure 1 B); T3, 11 UE (Figure 1 C), and T4 requires 14 UE (Figure 1 D).

When evaluating the number of plants representing the green stage of the coffee plant, it was observed that, for Mundo Novo IAC 376-4 cultivar, the treatments require the following numbers of EU: T1, 11 EU (Figure 2 A); T2, 13 EU (Figure 2 B); T3, 11 EU (Figure 2 C); and T4, 14 EU (Figure 2 D).

Therefore, considering the most efficient methodologies, the harvesting of at least 13 EUs is necessary to adopt the central bud harvest; besides, 14 EUs are required, using the other buds (the first, central, and the last ones) of a plagiotropic branch, to quantify the percentage of the green maturation stage..

The minimum number of coffee plants to be sampled to represent the plot is 13 EUs, to the Icatu

cultivar, and 14 EUs to the Catuaí Vermelho IAC 144 cultivar, using the harvest from the central bud (Marcilio et al., 2023). For the harvesting of the central buds, 11 EUs are the minimum number required for Catucaí 2 SL cultivar, according to Castro et al. (2023).

For the cultivation of dense coffee, with high density of plants and different heights, further studies are

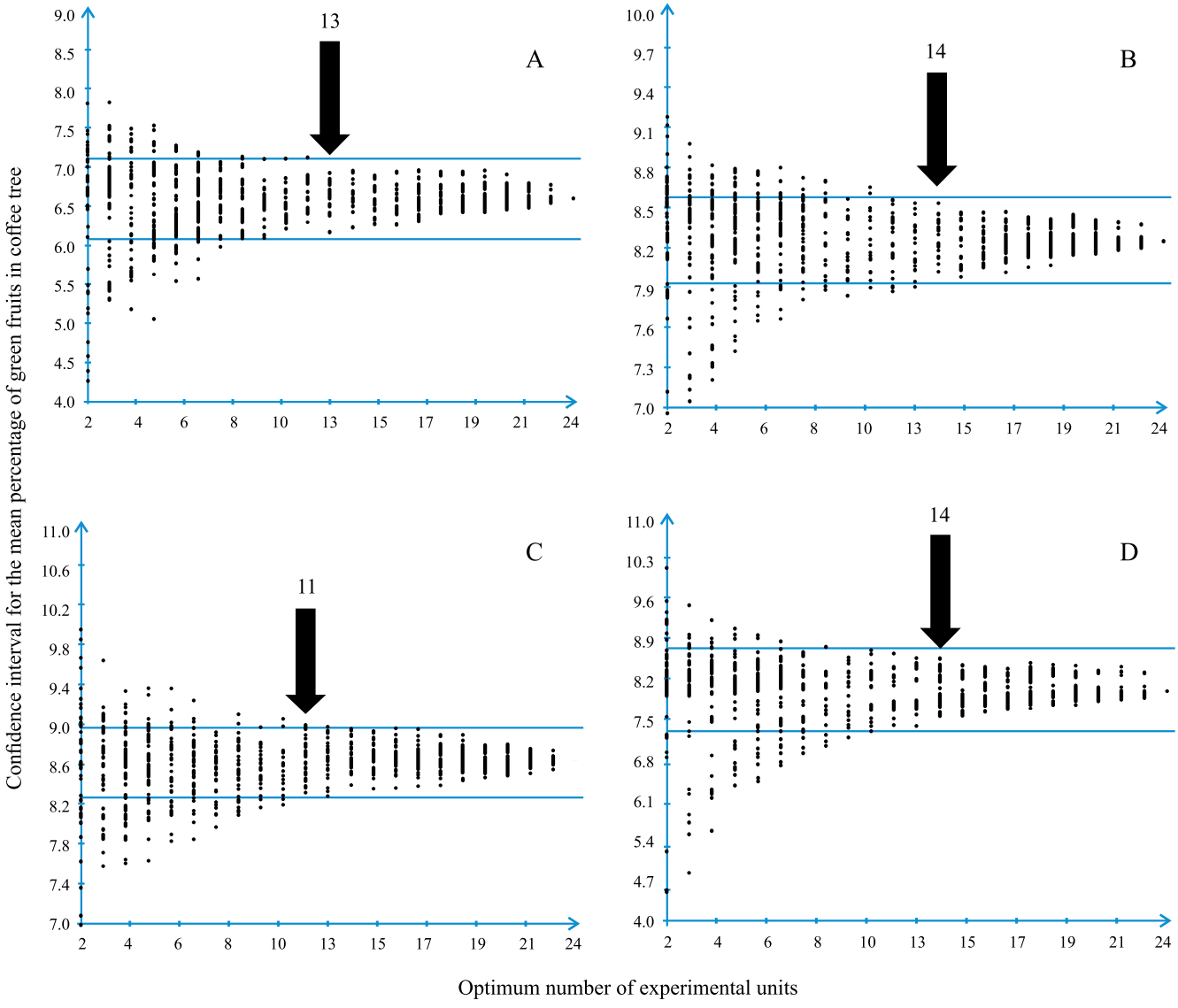

Figure 1. Minimum number of experimental units (EU) within treatments 1, 2, 3, 4, respectively represented by the capital letters A, B, C, and D, for the mean estimates of green fruit mean percentage for the Catuaí IAC 144 *Coffea arabica* cultivar, in the municipality of Inconfidentes, in the state of Minas Gerais, Brazil. Treatments: T1, fruit harvesting from the central bud in the plagiotropic branch, at the high-, mid-, and lower-thirds of the plant; T2, fruit harvesting from the first, central, and last buds, in a plagiotropic branch, at the high-, mid- and lower-thirds of the plant; T3, harvest of all fruit in a plagiotropic branch, at the high-, mid- and lower-thirds of the plant; T4, control, harvest of all fruit from the plant. Means followed by equal uppercase letters, in the columns, and lowercase letters, in the lines, do not differ between themselves, by the Tukey's test, at 5% probability.

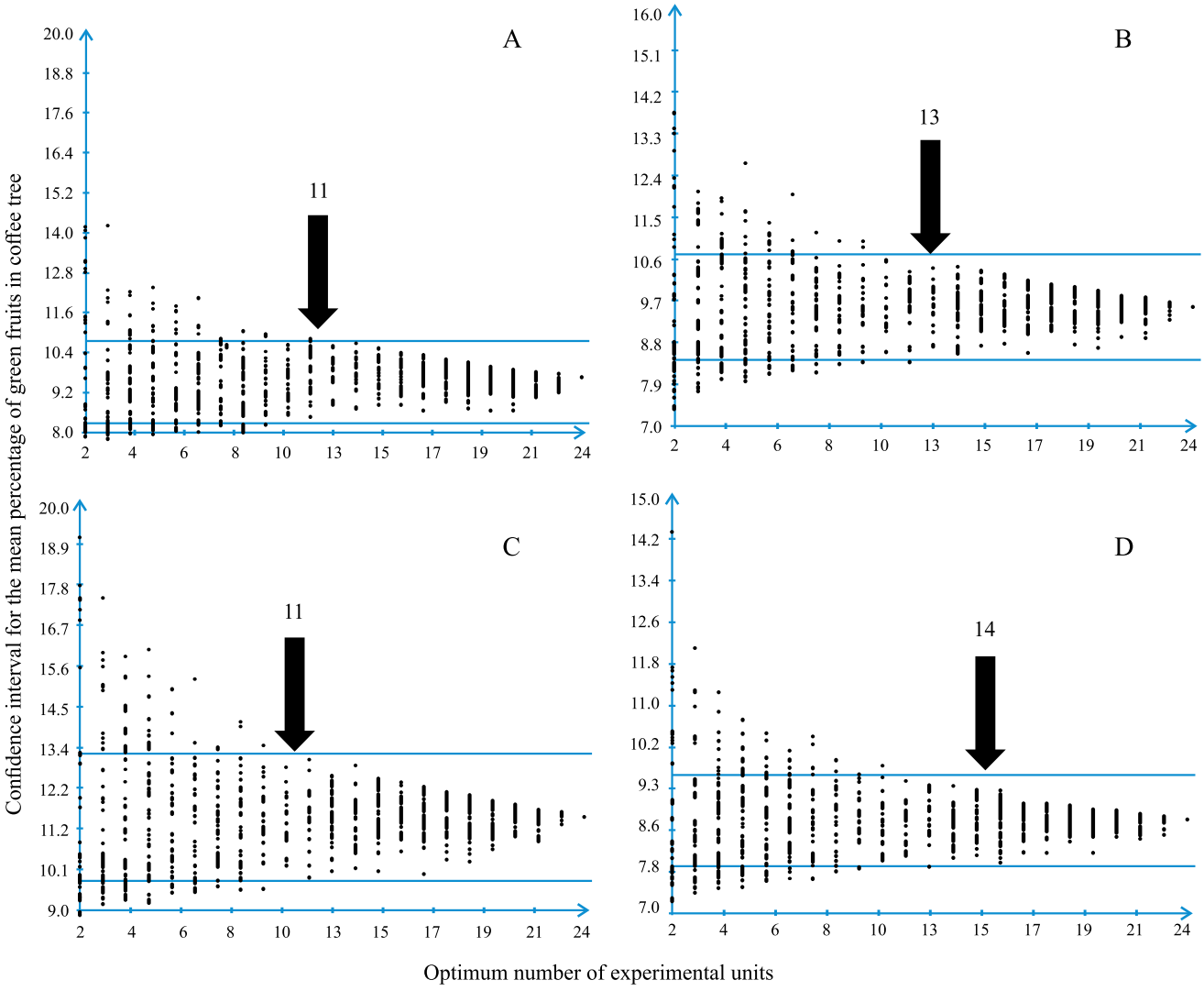

Figure 2. Minimum number of experimental units (EU) within the treatments 1, 2, 3, 4, respectively represented by the capital letters A, B, C, and D, for the mean estimates of green fruit mean percentage of the Mundo Novo IAC 376-4 *Coffea arabica* cultivar, in the municipality of Inconfidentes, in the state of Minas Gerais, Brazil. Treatments: T1, fruit harvesting from the central bud in the plagiotropic branch, at the high-, mid-, and lower-thirds of the plant; T2, fruit harvesting from the first, central, and last buds, in a plagiotropic branch, at the high-, mid- and lower-thirds of the plant; T3, harvest of all fruit in a plagiotropic branch, at the high-, mid- and lower-thirds of the plant; T4, control, harvest of all fruit from the plant. Means followed by equal uppercase letters, in the columns, and lowercase letters, in the lines, do not differ between themselves, by the Tukey's test, at 5% probability.

necessary to identify the most appropriate methodology to characterize the green maturation stage.

Conclusions

1. For the Catuaí Vermelho IAC 144 and Mundo Novo IAC 376-4 *Coffea arabica* cultivars, the optimal number of plants to be sampled, in order to quantify the green fruit phenological stage is 13 and 14, respectively.

2. Fruit harvest from the central bud of plagiotropic branches is the method recommended to determine the percentage of green fruit in both cultivars.

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Flávia de Souza Veronezzi Bastos: formal analysis (equal), investigation (equal); **Inara Almeida Pereira**: formal analysis (equal), investigation (equal); **Bruno Manoel Rezende de Melo**: conceptualization (equal), data curation (equal), formal analysis (equal), funding acquisition (equal), investigation (equal), methodology (equal), project administration (equal), resources (equal), supervision (equal), visualization (equal), writing - original draft (equal), writing - review & editing (equal); **Deilen Sotelo Moreno**: conceptualization, data curation, investigation, methodology, validation, writing – original draft, writing – review & editing; **Sindynara Ferreira**: conceptualization (equal), formal analysis (equal), methodology (equal), writing - original draft (equal), writing - review & editing (equal); **Rodrigo Barbosa Kloss**: writing - review & editing (equal); **Telma Miranda dos Santos**: formal analysis (equal), investigation (equal).

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Data available upon request: research data are only available upon reasonable request to the corresponding author.

Declaration of use of AI technologies

No generative artificial intelligence (AI) was used in this study.

Conflict of interest statement

The authors declare no conflicts of interest.

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