*Agronomy Research* **24**(S1), 192–206, 2026
https://doi.org/10.15159/AR.26.031

# Economic viability of different skeleton pruning-based management approaches in coffee (*Coffea arabica* L)

F.C. Silva[1,*], V.R. Paula[2], G.B. Sabino[3], A.L. Belem[1], J.P.B. Cunha[4] and M.M. Barros[4]

[1]Federal Fluminense University, Agricultural and Environmental Engineering Department, 156 Rua Passos da Pátria 156, bloco D, sala 235, 24210-240, Niterói, Brasil
[2]Instituto Federal de Educação, Ciência e Tecnologia do Sul de Minas, Rodovia Machado - Paraguaçu, KM 03 - Santo Antônio, 37750-000, Machado, Brasil
[3]Universidade Federal de Lavras, Departamento de Engenharia Agrícola
[4]Federal Rural University of Rio de Janeiro, Engineering Department, Rodovia BR 465, Km 07, s/n Zona Rural, 23890-000, Seropédica, Brasil
[*]Correspondence: flaviocastro@id.uff.br

Received: January 31st, 2026; Accepted: May 7th, 2026; Published: May 21st, 2026

**Abstract.** Coffee is one of the most valuable commodities on the international market, and its cultivation is among the most important agricultural activities in Brazil. Skeleton pruning is used in coffee crops to maintain production capacity by promoting the recovery of weakened plants and correcting problems related to plant architecture. This study evaluated the effects of different coffee skeleton-pruning management approaches on operating cost, productivity, and profitability. The experiment was conducted in a 22-year-old field of the cultivar Catuaí Vermelho IAC 144, spaced at 2.8×1.0 m. The treatments were obtained by combining two types of skeletonization and four types of regrowth management, totaling eight treatments plus a control without skeletonization. The experiment was arranged in a randomized block design with six replications, totaling 54 experimental plots. Operational cost was estimated from the time required for each management practice and the corresponding fuel consumption. The results showed that skeletonization restricted to branches between rows stimulated the growth of plagiotropic branches between plants, whereas total skeletonization promoted the greatest vegetative recovery and the highest productivity. Although total skeletonization resulted in higher crop cost, the treatment combining total skeletonization with sprout control showed the best economic performance, with an increase in profitability of up to USD 6,300.00 $ha^{-1}$ compared with the control.

**Key words:** *Coffea arabica* L, skeleton, semi-mechanized, operating cost, profitability.

## INTRODUCTION

In recent decades, global coffee production has increased substantially, making this crop stand out as the second most relevant commercial product worldwide. With an increasingly frequent demand, its production and commercialization have proven essential to the economies of many developing countries (Utrilla-Catalan et al., 2022). Consequently, coffee cultivation currently requires increasingly optimized production processes, mainly due to the still low level of technological adoption, resulting from the difficulties many producers face in accessing modern technologies (Rhiney et al., 2021).

One of the technologies adopted by coffee producers to enhance the sustainability and productivity of coffee plantations is crop management through pruning. The adoption of pruning in coffee plants aims to promote the development of productive branches; this practice allows greater and more continuous direct sunlight incidence (Cerda et al., 2017). Thus, pruning stimulates nutrient translocation to productive branches, resulting not only in greater vegetative growth but also in increased flowering and, consequently, higher productivity (Karim et al., 2021), reflecting improved plant growth and flowering, and enabling greater yield and bean quality.

Traditionally, the systems employed for coffee pruning include skeleton pruning, which renews lateral branches while maintaining the main structure; stumping, used to rejuvenate older or weakened plants aiming at a more advantageous biennial production cycle for plantation renewal; and topping, which stimulates branching and standardizes plant height (Pereira et al., 2013; Silva et al., 2016).

However, when these techniques are applied without proper criteria, they may cause drastic effects on the plants, resulting in reduced productivity, root system reduction, and plant death due to excessive removal of vegetative biomass (Gonçalves et al., 2014).

Especially in mechanically harvested areas, pruning can lead to disorganization of plant architecture, with increased branch density in the lower part of the plant and limited leaf growth in the middle third, altering plant size and geometry. This condition results in losses in the collection mechanisms of harvesting machines currently available on the market (Cunha et al., 2016).

Given this context, several studies have been conducted addressing challenges related to the variability of plant responses, aiming to integrate pruning into crop management strategies while considering physiological aspects (Filho et al., 2016; Pereira et al., 2016), the increased occurrence of abiotic stresses such as water deficit and rising temperatures (Custódio et al., 2013; Nascimento et al., 2014), and improvements in techniques associated with nutritional management, aiming to maximize productive efficiency and the longevity of coffee plantations under irrigated conditions (Souza et al., 2024).

Therefore, given the complexity of adopting pruning practices and the coffee plant's response to them, deepening the understanding of different pruning techniques becomes essential to support more precise technical recommendations. The novelty of this study lies in the integrated assessment of vegetative recovery, crop productivity, operating costs, and profitability under different skeleton pruning-based management strategies in mature coffee plantations, in which pruning decisions must reconcile vegetative recovery, productive performance, and economic return. We hypothesized that more intensive skeleton pruning strategies would promote greater vegetative recovery, higher productivity, and superior economic return than lateral skeletonization or the control treatment. Thus, the objective of the present study was to evaluate the effect of different coffee skeleton-pruning management strategies on production costs, their impact on crop productivity, and the differences in profitability resulting from the adopted management practices.

## MATERIAL AND METHODS

### Study area and pruning management

The study was conducted in the municipality of Poço Fundo in the southern region of the state of Minas Gerais, Brazil. The site is located at an elevation of 1,038 meters and has geographical coordinates of 21°42' S and 46°00' W. The region has a hot and temperate climate, with an average annual rainfall of 1,508 mm and low rainfall during the winter. According to Koeppen (1948), the climate is classified as Cwa, i.e., a humid subtropical climate with dry winters and hot summers. The experimental crop consisted of 20-year-old Catuaí Vermelho IAC 144 cultivar, with a spacing of 2.8×1.0 m, totaling 3,572 plants per hectare. The soil of the experimental area is classified as a dystrophic Red-Yellow Latosol (Latossolo Vermelho-Amarelo Distrófico, LVAd), a deep, well-drained, and highly weathered tropical soil with low natural fertility and generally medium to clayey texture, which is suitable for agricultural mechanization

The management practices adopted in this experiment were total pruning, in which all the plagiotropic branches were skeletonized and the top was cut 1.80 m from the ground, lateral thinning, in which only the plagiotropic branches that protruded between the crop rows were skeletonized, thinning, in which only two shoots were kept on each orthotropic branch, and removal of all shoots originating from the orthotropic branch above the first two pairs of plagiotropic branches.

The experiment was set up in a randomized block design according to Banzatto & Kronka (2013), with six replications and nine treatments (eight pruning-based management approaches plus the control), totaling 54 experimental plots. Each plot consisted of six plants, of which the two plants at the ends were used as borders and the four central plants were considered for evaluation. Different treatments were obtained by combining 2 types of skeletonization (total and lateral) and 4 types of regrowth management, totaling 8 combinations plus the control, as shown in Table 1 below.

**Table 1.** Skeletonization and regrowth management adopted in the experiment

| Treatment | Skeleton Management | Management of Sprouting |
|---|---|---|
| 1 | Only plagiotropic branches between rows | With saplings |
| 2 | All plagiotropic branches | With saplings |
| 3 | Only plagiotropic branches between rows | With thinning + capping |
| 4 | All plagiotropic branches | With thinning + capping |
| 5 | Only plagiotropic branches between rows | With capping |
| 6 | All plagiotropic branches | With capping |
| 7 | Only plagiotropic branches between rows | No pruning |
| 8 | All plagiotropic branches | No pruning |
| 9 | No skeletonization | No pruning |

Management of the crop began after harvest in October 2019 to allow light to enter the crops and create space for vigorous shoots. The treatments were differentiated into total skeletonization (T2, T4, T6 and T8), lateral skeletonization (T1, T3, T5 and T7) and the control. In all the treatments, the apex of the orthotropic branches were cut using the same methodology. The second intervention occurred 37 days after skeletonization and consisted of cutting the shoots to preserve the apical dominance of the orthotropic branch while the plagiotropic branches sprouted their first shoots, with the objective of facilitating management and reducing the incidence of shoots from the orthotropic branches as described above (Thomaziello & Pereira, 2008).

Beginning in January 2020, quarterly evaluations of shoot growth were performed on plagiotropic branches, followed by thinning management in treatments T1, T2, T3 and T4. The first thinning occurred in January, followed by harvesting in February for treatments T3, T4, T5 and T6, and the second thinning occurred in late March. There was no harvest in any of the plots, including the control, during the 2020 harvest due to the adoption of the 'zero harvest' system, which was a strategy to eliminate the need for harvesting in years of low productivity. In January 2021, when potentially productive branches for the next crop were developed, the last measurement of the new plagiotropic branches was performed.

**Statistical analysis**

The data were analyzed by analysis of variance (ANOVA) to evaluate the effects of treatment, branch position, evaluation time, and their interactions on plagiotropic branch length, and treatment means were compared using Tukey's test at the 5% probability level, using the SISVAR software in accordance with Ferreira (2019) Because branch growth was evaluated repeatedly over the study period, evaluation time was explicitly incorporated into the ANOVA model as an explanatory factor, together with its interactions with treatment and branch position. In order to ensure the robustness and interpretability of the statistical results, the ANOVA model was first fitted and its residual structure was examined, allowing the identification of possible deviations from the assumptions required for valid inference. More specifically, the residuals obtained from the fitted model were extracted and inspected, and the main assumptions underlying ANOVA were formally assessed by testing residual normality and homogeneity of variances among groups. These procedures were included to verify whether the data reasonably satisfied the statistical requirements of the model, thereby providing greater transparency in the analytical workflow and supporting the reliability of the comparisons among the different skeleton pruning management approaches evaluated in this study. The study did not analyze the treatments as a formal full-factorial design; instead, it compared combined management approaches generated by the association between skeletonization type and regrowth management. The Python-based assumption checks, implemented using statsmodels together with supporting statistical libraries, are available in the repository cited in the Data Availability section.

**Operating and total costs**

In this study, the economic indicator used was net profitability, calculated as gross revenue minus production cost, where production cost included labour and fuel associated with the evaluated operations. The data regarding operating costs were collected considering the operating time and fuel spent to perform the skeletonization of the plagiotropic branches, cut the orthotropic branches and remove the shoot apex of the orthotropic branch, in addition to the time spent thinning the crops. The calculation of the operating cost was based on the time spent managing the crops, converted into work days $ha^{-1}$; the daily value of an operator was set at US$ 19.42 $day^{-1}$ plus the fuel cost for each operation. Depreciation of the equipment was not considered due to its low value. As the study was conducted in Brazil, monetary values were originally calculated in Brazilian reais (BRL) and then converted to U.S. dollars (USD) using an exchange rate of 4.12 BRL per USD, consistent with the study period (2019–2021)

The 4 central plants of each plot were harvested separately in a semi mechanized and nonselective manner. The beans from each plot were weighed and transferred to a terrace, where they were conventionally dried in the sun before being sent to a processing plant with an average moisture content close to 11.5% (Borém et al., 2008). After processing, they were weighed again, and the weight was then transformed into productivity per hectare.

## RESULTS AND DISCUSSION

### Development of plagiotropic branches under different skeletonization management practices

Table 2 shows that there is a significant difference between the treatments, verified by analysis of variance (ANOVA) and the Tukey test at a significance level of 5%. In addition to the treatments, other sources of variation (FV) as well as the interactions between them also showed significant differences. Additionally, the coefficient of variation (CV) had a relatively low value (9.22%), suggesting a low variability in the data collected.

**Table 2.** Analysis of Variance (ANOVA)

| Source of variation | GL | SQ | QM | Fc | Pr>Fc |
|---|---|---|---|---|---|
| Treatment | 8 | 45,082.09 | 5,635.26 | 855.20 | 0.00** |
| Position | 1 | 31,110.65 | 31,110.65 | 4,721.35 | 0.00** |
| Time | 4 | 138,167.27 | 34,541.82 | 5,242.07 | 0.00** |
| Treatment * Position | 8 | 7,453.57 | 931.69 | 141.39 | 0.00** |
| Treatment * Time | 32 | 2,415.38 | 75.48 | 11.45 | 0.00** |
| Position*Time | 4 | 1,432.74 | 358.18 | 54.35 | 0.00** |
| error | 2,102 | 13,850.80 | 6.58 | | |
| Corrected total | 2,159 | 239,512.52 | | | |
| CV (%) | 9.22 | | | | |
| Overall average | 27.83 | | No. of observations | | 2,160 |

Legend: GL = degrees of freedom; SQ = sum of squares; QM = mean square; Fc = F calculated; Pr = power; **Significant.

Analysis of the fluctuations in the lengths of the plagiotropic branches in different treatments applied to the coffee plants (Fig. 1) showed that there was greater growth of the skeletonized branches in the lateral direction. This indicates that during the evaluation period, the branches showed greater development in this direction than between plants.

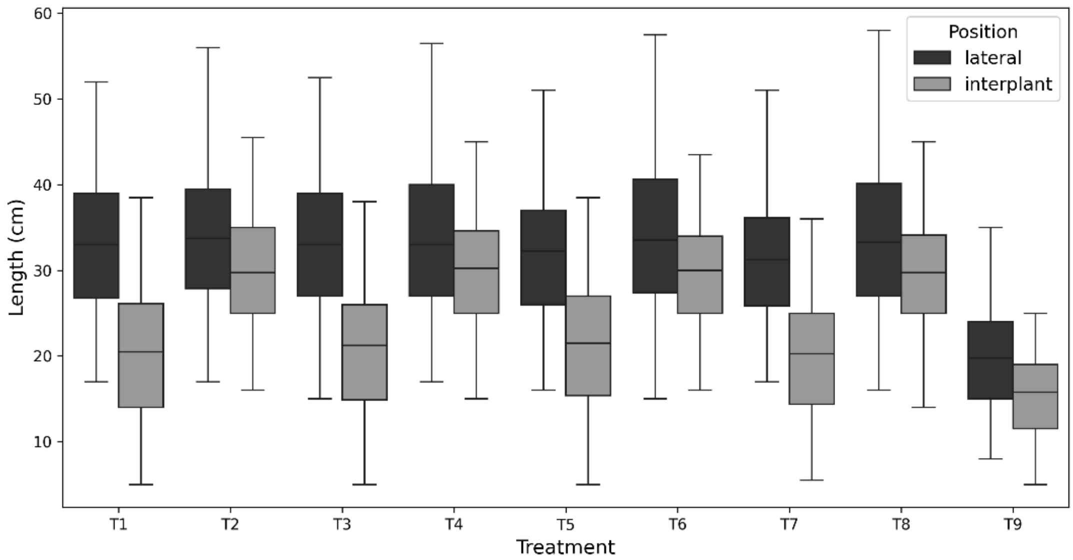


**Figure 1.** Variation in the observed mean lengths (cm) of plagiotropic branches in each treatment.

Regarding the variation in the average length (cm) of the plagiotropic branches for each treatment throughout the evaluation period (Fig. 2), treatments T2, T4, T6 and T8 stood out compared to the others, for example, although the plants showed greater changes in the lengths of the plagiotropic branches, there was also a lower variation in their size throughout the evaluation period.

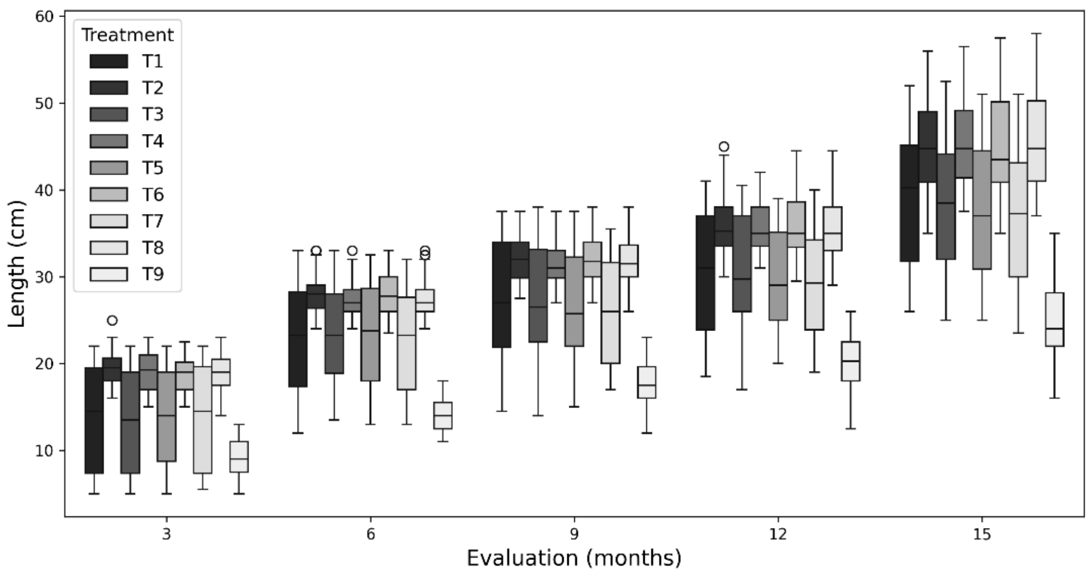


**Figure 2.** Variation in the mean lengths (cm) of plagiotropic branches in each treatment throughout the evaluation period.

Regarding the variation in the average length (cm) of the plagiotropic branches that underwent lateral skeletonization in each treatment throughout the evaluation period (Fig. 3), treatments T2, T4, T6 and T8 stood out relative to the remaining treatments, i.e., the plants in these treatments had greater changes in plagiotropic branch length throughout the evaluation period. It is noteworthy that the greatest variation in branch length occurred from 12 to 15 months of evaluation. Comparing the treatments with the control (T9), the importance of skeletonization in the renewal and growth of coffee branches is evident.

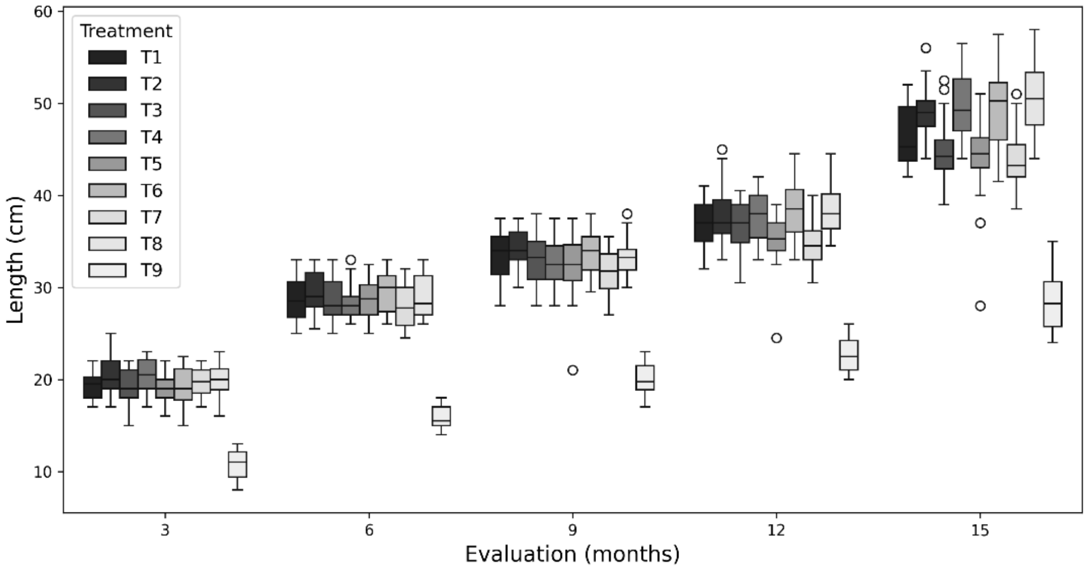


**Figure 3.** Variation in the mean lengths (cm) of lateral plagiotropic branches in each treatment throughout the evaluation period.

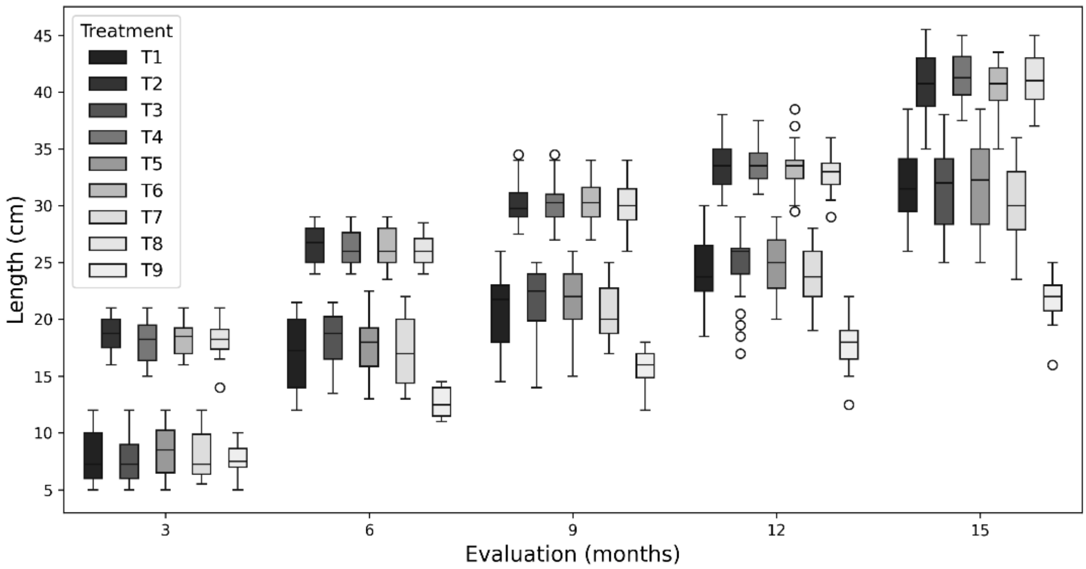


**Figure 4.** Variation in the mean lengths (cm) of the plagiotropic branches between plants in each treatment throughout the evaluation period.

Regarding the variation in the average length (cm) of the plagiotropic branches between plants that underwent skeletonization in each treatment throughout the evaluation period (Fig. 4), treatments T2, T4, T6 and T8 stood out compared to the others, i.e., the plants in these treatments exhibited greater changes in plagiotropic branch length throughout the evaluation period as well as lower variations in length (minimum and maximum). It is noteworthy that the variations in length among treatments T2, T4, T6 and T8 were higher than those among treatments T1, T3, T5 and T7 when compared with the lengths of branches in the treatments with lateral thinning. This can be verified by comparing the lower and upper limits of branch length in the two skeletonization management approaches for each treatment.

Regarding the average lengths (cm) of the plagiotropic branches in each treatment and with different skeletonization management approaches (Table 3), treatments T2, T4, T6 and T8 presented higher lateral growth rates and were significantly different from the other treatments considering the entire evaluation period. Treatments T2, T4, T6 and T8 showed the highest growth of plagiotropic shoots between plants, with significant differences from the other treatments. There was no significant difference among the other treatments, except for the control, and the lowest values of growth of the plagiotropic branches was observed.

**Table 3.** Mean lengths (cm) of the plagiotropic branches in each treatment with the different skeletonization management approaches

| Treatment | Skeletonization | |
|---|---|---|
| | Side | Between plants |
| T1 | 32.96 CDb | 20.34 Ba |
| T2 | 34.21 Eb | 29.97 Ca |
| T3 | 32.40 BCb | 20.66 Ba |
| T4 | 33.70 DEb | 29.92 Ca |
| T5 | 31.85 Bb | 20.97 Ba |
| T6 | 34.17 Eb | 29.77 Ca |
| T7 | 31.57 Bb | 19.97 Ba |
| T8 | 34.28 Eb | 29.63 Ca |
| T9 | 19.53 Ab | 15.12 Aa |

Means followed by the same uppercase letter within a column and the same lowercase letter within a row are not significantly different according to Tukey's test at the 5% probability level ($P \leq 0.05$). Uppercase letters compare treatments within each column, whereas lowercase letters compare skeletonization positions within each row.

When comparing lateral shoot growth between rows, for all the treatments, there was greater growth of the branches in the lateral direction, which differed significantly from growth between plants.

When analysing the average lengths (cm) of the plagiotropic branches throughout the evaluation period (Table 4), it was observed that there was an increase in the average branch length and that this increase was significant for all evaluations. It is noteworthy that the greatest variations occurred between 3 and 6 months (8.6 and 8.2 cm for lateral skeletonization and between plants, respectively) and between 12 and 15 months (9.7 and 6.9 cm for lateral skeletonization and between plants, respectively).

**Table 4.** Mean lengths (cm) of plagiotropic branches throughout the evaluation period in the different skeletonization management treatments

| Evaluation | Skeletonization | |
|---|---|---|
| | Lateral | Between plants |
| 3 months | 18.71 Ab | 12.62 Aa |
| 6 months | 27.33 Bb | 20.87 Ba |
| 9 months | 31.55 Cb | 24.59 Ca |
| 12 months | 35.38 Db | 27.59 Da |
| 15 months | 45.17 Eb | 34.53 Ea |

Means followed by the same letter (capital letters in columns and lowercase letters in the rows), did not differ from each other according to Tukey's test at the 5% probability level ($P \leq 0.05$).

When comparing the shoot growth in the lateral skeletonized branches between plants throughout the evaluation period, for all evaluations, there was greater growth of the branches in the lateral direction, which differed significantly from that between plants.

When evaluating the average lengths (cm) of the lateral plagiotropic branches across the different treatments (Table 5), a relatively small growth variation was observed in the control (T9), corresponding to 11.6 cm, which differed significantly from that in the other treatments at all evaluations, except for the 3-month evaluation. In this evaluation, none of the treatments showed a significant difference in branch growth due to weather conditions (low rainfall) and because it was within the initial recovery phase after the branches were cut.

Among the other treatments, the largest increase in the growth of plagiotropic branches was observed in treatments T6 and T8. Based on the data obtained, the importance of lateral skeletonization of coffee plants to support higher productivity among the plagiotropic branches is evident. This practice allows the development of new more productive floral buds. It is important to note the significant difference in the average lengths of the branches between plants that underwent skeletonization and the control plants that did not undergo skeletonization.

**Table 5.** Average lengths (cm) of lateral plagiotropic branches throughout the evaluation period in the different treatments

| Treatment | Evaluation period (months) | | | | |
|---|---|---|---|---|---|
| | 3 | 6 | 9 | 12 | 15 |
| T1 | 19.56 Aa | 28.21 ABb | 32.61 Bbc | 36.75 Bc | 45.75 BCd |
| T2 | 18.59 Aa | 29.92 Bb | 35.44 Bbc | 39.00 Bc | 50.25 BCd |
| T3 | 20.14 Aa | 29.61 Bb | 34.22 Bbc | 37.41 Bc | 46.41 BCd |
| T4 | 19.77 Aa | 27.96 ABb | 31.50 ABbc | 36.66 Bc | 46.91 BCd |
| T5 | 19.13 Aa | 29.07 ABb | 33.16 Bbc | 36.83 Bc | 45.41 BCd |
| T6 | 17.18 Aa | 28.92 ABb | 34.88 Bbc | 40.50 Bc | 51.83 Cd |
| T7 | 20.47 Aa | 27.23 ABb | 31.11 ABbc | 33.66 Bc | 42.00 Bd |
| T8 | 17.22 Aa | 23.71 Ab | 29.50 ABbc | 39.75 Bc | 51.08 Cd |
| T9 | 16.95 Aa | 23.50 Ab | 24.66 Ab | 23.00 Aab | 28.58 Ab |

Means followed by the same letter (capital letters in the columns and lowercase letters in the rows) did not differ from each other according to Tukey's test at the 5% probability level ($P \leq 0.05$).

When evaluating the average lengths (cm) of plagiotropic branches growing between plants in different treatments (Table 6), a relatively small growth variation was observed in the control (T9), corresponding to 14.0 cm, differing significantly from the other treatments in all the evaluations. Among the other treatments, the largest increase in the growth of the plagiotropic branches was observed for treatments T2, T4, T6 and T8, with values that differed significantly from those for the other treatments. Based on the data obtained, the importance of skeletonization both laterally and between coffee plants is evident, as this approach ensures the renewal of all plagiotropic branches, allowing more productive branches and more productive new floral buds.

There was higher growth of the plagiotropic branches in all the treatments in which thinning between plants was applied than in the other treatments. In addition, the results obtained in the control (T9) indicate that the thinning of only the branches located between the rows somehow stimulated the growth of the plagiotropic branches located between plants.

**Table 6.** Average lengths (cm) of plagiotropic branches growing between plants throughout the evaluation period in the different treatments

| Treatment | Evaluation period (months) | | | | |
|---|---|---|---|---|---|
| | 3 | 6 | 9 | 12 | 15 |
| T1 | 8.02 Aa | 17.00 Bb | 20.85 Bc | 24.00 Bd | 31.85 Be |
| T2 | 18.68 Ba | 26.54 Cb | 30.29 Cc | 33.62 Cd | 40.73 Ce |
| T3 | 7.70 Aa | 18.04 Bb | 21.45 Bc | 24.66 Bd | 31.45 Be |
| T4 | 18.12 Ba | 26.29 Cb | 30.27 Cc | 33.60 Cd | 41.33 Ce |
| T5 | 8.56 Aa | 17.77 Bb | 21.72 Bc | 24.85 Bd | 31.93 Be |
| T6 | 18.33 Ba | 26.35 Cb | 30.35 Cc | 33.29 Cd | 40.54 Ce |
| T7 | 8.16 Aa | 17.16 Bb | 20.64 Bc | 23.75 Bd | 30.12 Be |
| T8 | 18.27 Ba | 26.08 Cb | 29.95 Cc | 32.85 Cd | 41.02 Ce |
| T9 | 7.72 Aa | 12.62 Ab | 15.77 Ac | 17.68 Ad | 21.81 Ae |

Means followed by the same letter (capital letters in the columns and lowercase letters in the rows) did not differ from each other according to Tukey's test at the 5% probability level ($P \leq 0.05$).

### Productivity in the different treatments

Assessment of the average productivity (sacks $ha^{-1}$) of processed coffee in each treatment (Fig. 5) revealed that the treatments in which there was total skeletonization (lateral and between plants, here called T2, T4, T8 and T6) were 30.56%, 20.83%, 19.27% and 8.71% more productive than the control (T9), respectively. These treatments were 20.25%, 11.28%, 9.85% and 0.12% more productive than the treatment with the best performance among those in which only lateral skeletonization was applied. Therefore, total skeletonization, despite requiring more time and having a higher cost, demonstrates great agronomic viability in terms of renewing the vegetative and reproductive vigour of the crop.

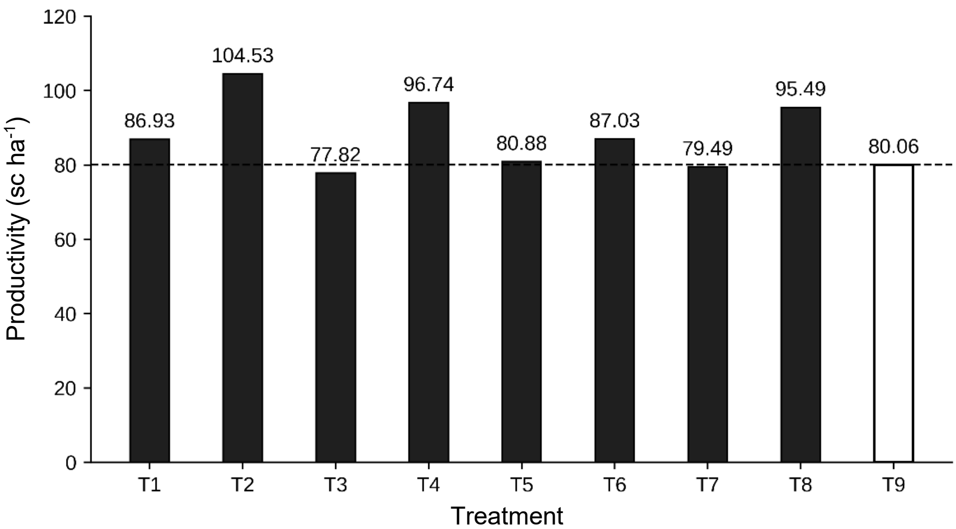


**Figure 5.** Average productivity of processed coffee (60 kg sacks $ha^{-1}$) in each treatment, calculated from dry coffee in husk at commercial moisture content using an approximate 2.6:1 conversion from coffee in husk to processed coffee.

Evaluating the vegetative and reproductive recovery capacity of different commercial Arabica coffee cultivars after skeleton pruning in a four-and-a-half-year-old plantation, Silva et al. (2016) observed good recovery capacity following pruning at a young stage, with emphasis on the cultivars Catiguá MG3, Topázio MG1190, and Sabiá 398, which proved to be the most productive and vigorous, presenting a low percentage of empty beans and a high percentage of large-sized beans in the first biennium after pruning.

Additionally, Carvalho et al. (2013), in a study aimed at selecting resistant progenies from the cross between the cultivars Catuaí Amarelo IAC 2077 and Mundo Novo IAC 515-20, verified low percentages of empty and peaberry beans in all evaluated coffee plants, with a high proportion of beans retained on sieve 16 and above. Furthermore, the studied genotypes showed a satisfactory response to pruning.

In contrast, studies demonstrate the complexity of pruning management and the need to adapt pruning practices to different field conditions. Evaluating the 'Zero Yield' system in Arabica coffee plantations, Japiassú et al. (2010) concluded that the use of different pruning cycles did not result in yield gains compared to the unpruned control. Likewise, Reis et al. (2018) reported that the cultivar Catucaí Vermelho 785/15 was not responsive to skeleton pruning, as it exhibited lower productivity, high incidence of coffee leaf rust, and reduced vegetative growth. According to the authors, however, the cultivars Catucaí Amarelo 20/15 cv. 479, Araponga MG1, and Tupi IAC 1669-33 were highly responsive to pruning, showing high productivity associated with high photosynthetic rates.

It is worth noting that, as with Arabica coffee, pruning can also be applied to *Coffea canephora* with the aim of increasing productivity. According to Verdin Filho et al. (2014), seeking to improve existing management recommendations for Conilon coffee cultivation, they concluded that reduced plant spacing combined with an increased number of orthotropic stems per plant has a positive effect on Conilon coffee yield.

The results obtained in the present study are corroborated by Rahman et al. (2024), who, in a study evaluating different pruning methods in *Coffea canephora* plants aimed at controlling plant size and assessing their effects on productivity and quality, reported productivity increases ranging from 34.8% to 49.7%, demonstrating that pruning is an efficient practice to enhance the productive potential of coffee plantations, especially older ones. This pattern is consistent with recent studies showing that pruning can improve vegetative recovery, source-sink balance, branching, and subsequent productive performance, although the magnitude of the response depends on cultivar, pruning intensity, and local growing conditions. This response may be explained by the fact that, after pruning, part of the foliage remains active, allowing the interception of photosynthetically active radiation and the production of photoassimilates required for vegetative recovery and branch renewal. In addition, skeleton pruning may improve source–sink relationships, stimulate branching and leaf development, and modify canopy microclimate, thereby favoring subsequent productive performance.

**Production costs, revenue and profit from the applied management practices**

Considering the costs involved in each treatment (Fig. 6) and taking into account that in each treatment, there was a different pruning management approach that resulted in a different production cost and yield, the main indicator was the difference in profit (in USD \$ $ha^{-1}$) compared to that for the control treatment (T9). Treatments T7, T5 and

T6 presented the lowest production costs. When net profitability (gross revenue - production cost) was compared, treatments T2, T8, T4 and T6 showed the highest values. Analysis of the difference in profit (net profitability of the treatment - net profitability of the control) among treatments showed that T2, T4 and T8 had the best results, resulting in an increase in profit of US $ 6,222.71, US $ 4,063.26 and US $ 4,011.17 per hectare, respectively. All the treatments that involved the skeletonization of all the plagiotropic branches resulted in a significant increase in profit compared to the control treatment.

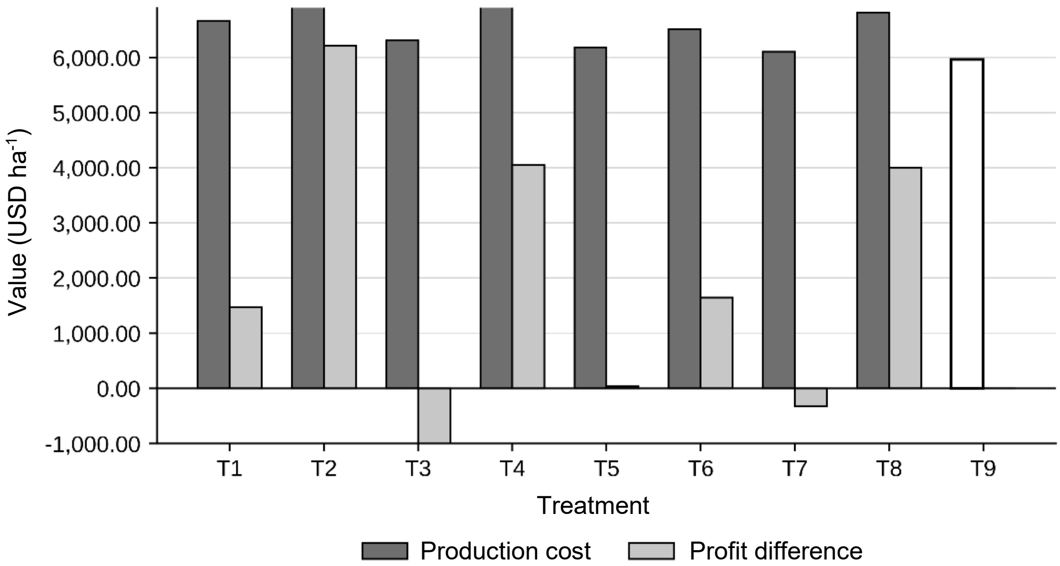


**Figure 6.** Production cost, net profitability, and profit difference in relation to the control treatment (T9) for each evaluated management approach (USD $ha^{-1}$).

The results obtained in this study indicate that the use of strategies aimed at management during cultivation and application of appropriate pruning techniques in coffee crops can result in significantly increasing the productivity and profitability of the crop. Similar results were observed in studies by (Viteri Salazar et al., 2018; Dufour et al., 2019). Unlike the observations of (Reis et al., 2018; Dufour et al., 2019), the Catuaí Vermelho IAC 144 variety used in this study responded positively to thinning and pruning management, resulting in gains in productivity and increased profitability.

The thinning and pruning methods used in this study were technically and economically feasible in addition to having great benefits for coffee plants, especially total plant skeletonization. In addition, the modified pruning methods facilitated the vertical growth of coffee plants and thus provided a large margin for the high-density planting system without compromising yield.

Therefore, modified pruning methods may be an option to improve productivity relative to labour in coffee production as well as to facilitate the application of fertilizers, corrective amendments and crop protection products. In addition, the material resulting from skeletonization and pruning can be used to improve soil parameters, as observed by (Musa et al., 2020).

According to (Parreiras Pereira et al., 2007) and (Musa et al., 2020), the best time to prune coffee trees is soon after harvest. Additionally, according to these authors, a reduction in spacing both between rows and between plants in a row increased crop productivity in the first harvest after pruning. It is important to note that higher plant density per area can result in greater shading, especially in the middle and lower thirds of the coffee plants, which can affect both crop quality and productivity, as discussed by Sarmiento-Soler et al. (2020) and Somarriba & Quesada, 2022.

It is also noteworthy that the increase in income due to management practices improves the sustainability of crops and increases market gain, as reported by (Campos et al., 2021) and (Turreira-García, 2022). In this study, it was evident that although there was a higher cost associated with total skeletonization, reflected in the production cost of the crop, this management approach resulted in a much higher profitability compared to treatments in which there was no pruning or only lateral skeletonization, which was performed with tractor-mounted machines.

From a technical-economic perspective, treatments T2 and T8 represented the most advantageous strategies, whereas T3 was not economically justified under the evaluated conditions because its additional management cost was not compensated by gains in productivity or net return. These profitability outcomes should be interpreted in light of the local production conditions and the assumptions adopted in the present study, since formal risk assessment and price-variability analyses were beyond its scope.

Taken together, these results highlight the novelty of the study by showing that the evaluation of skeleton pruning strategies becomes more informative when agronomic performance is interpreted jointly with operational cost and profitability.

## CONCLUSIONS

The laterally skeletonized plagiotropic branches developed faster than the skeletonized plagiotropic branches between coffee plants, indicating a stronger vegetative response in the lateral direction during the evaluation period. At the same time, the results showed that skeletonizing only the branches located between rows stimulated the growth of plagiotropic branches between plants, suggesting that partial pruning can also influence branch renewal beyond the directly managed portion of the canopy.

Among the evaluated treatments, total plant skeletonization consistently promoted greater branch development and higher productivity than the treatments based only on lateral skeletonization or the control without skeletonization. This demonstrates that more intensive pruning management can be effective in renewing the vegetative and reproductive vigor of older coffee plantations.

From an economic perspective, although total skeletonization resulted in higher production costs, this additional investment was offset by superior productivity and greater net return. In particular, the treatment combining total plant skeletonization with sprouting control showed the best economic performance, surpassing the treatment without skeletonization and reaching an increase in profitability of up to USD 6,000.00 per hectare. Overall, the results indicate that total skeletonization, especially when associated with adequate sprout management, is both agronomically and economically advantageous under the conditions of this study.

Overall, the results indicate that total skeletonization, especially when associated with adequate sprout management, is both agronomically and economically advantageous under the conditions of this study. In practical terms, this management approach provided the best balance between productivity gains and economic return, making it the most promising strategy among the treatments evaluated.

**Data availability:** The datasets, analysis notebooks, figures, and tables supporting this study are stored in the GitHub repository https://github.com/andrebelem/coffee-pruning-economics. The repository is currently private for peer-review purposes and will be made publicly available upon acceptance of the manuscript.

## REFERENCES


Augusto, A., Custódio, D.P., Lemos, L.B., Luiz, F., Mingotte, C., Pagan, T., Carlos, A., Carmeis de Almeida, A., Barbosa, J.C. & Pierre, C. 2013. Coffee productive and vegetative traits characteristics under different deletions of irrigation and side exposure to sun. *Coffee Science* **8**(4), 411–422.

Banzatto, D.A. & Kronka, S.D. Agricultural Experimentation. 4th ed. Jaboticabal, SP: Funep, 2013 (in Portuguese).

Borém, F.M., Coradi, P.C., Saath, R. & Oliveira, J.A. 2008. Quality of natural and washed coffee after drying on ground and with high temperature. *Ciênc. Agrotecnol.* **32**(5), 1609–1615. doi: 10.1590/S1413-70542008000500038 (in Portuguese).

Campos, A.D.S.N., Satolo, E.G., Mac-Lean, P.A.B. & Júnior, S.S.B. 2021. Economic sustainability analysis of the specialty coffee farmers in Garça/SP. *Coffee Science* 16. doi: 10.25186/.V16I.1993

Carvalho, G.R., Botelho, C.E., Rezende, J.C., Ferreira, A.D., Luz, R. & Pedro, F.C. 2013. Performance of F4 arabic coffee progenies before and after framework pruning. *Coffee Science* **8**(1), 33–42.

Cerda, R., Allinne, C., Gary, C., Tixier, P., Harvey, C., Krolczyk, L., Mathiot, C., Clément, E., Aubertot, J.-N. & Avelino, J. 2017. Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. *Eur. J. Agron.* **82**, 308–319.

Cunha, J.P.B., Silva, F.M., Dias, R.E.B., Lisboa, C.F. & Machado, T.A. 2016. conomic viability for different coffee harvest systems. *Coffee Science* **11**, 416–425 (in Portuguese).

Dufour, B.P., Kerana, I.W. & Ribeyre, F. 2019. Effect of coffee tree pruning on berry production and coffee berry borer infestation in the Toba Highlands (North Sumatra). *Crop Prot.* **122**, 151–158. doi: 10.1016/j.cropro.2019.05.003

Ferreira, D.F. 2019. SISVAR: a computer analysis system to fixed effects split plot type designs. *Rev. Bras. Biometria* **37**(4), 529–535. doi: 10.28951/rbb.v37i4.450

Filho, A.C.V., Tomaz, M.A., Ferrão, R.G., Ferrão, M.A.G., da Fonseca, A.F.A. & Rodrigues, W.N. 2014. Conilon coffee yield using the programmed pruning cycle and different cultivation densities. *Coffee Science* **9**(4), 489–494 (in Portuguese).

Filho, V., Carlos, A., Volpi, P.S., Amélia, M., Ferrão, G., Ferrão, R.G., Mauri, A.L., Almeida da Fonseca, F., Tristão, F.A., de Saul, S. & Júnior, A. 2016. New management technology for arabica coffee: the cyclic pruning program for Arabica coffee. *Coffee Science* **11**(4), 475–483.

Gonçalves, M.A., Cocco, C., Vignolo, G.K., Picolotto, L. & Corrêa Antunes, L.E. 2014. The effect of pruning intensity in the production and quality of peach fruits. *Rev. Bras. Frutic.* **36**(3), 742–747. doi: 10.1590/0100-2945-225/13 (in Portuguese).

Japiassú, L.B., Garcia, A.L.A., Guimarães, R.J., Padilha, L. & Carvalho, C.H.S. 2010. Pruning cycles and nitrogen fertilization of coffee fields conducted in the 'safra zero' system. *Coffee Science* **5**(1), 28–37 (in Portuguese).

Karim, A., Hifnalisa & Manfarizah. 2021. Analysis of arabica coffee productivity due to shading, pruning, and coffee pulp-husk organic fertilizers treatments. *Coffee Science* **16**, e161903. doi: 10.25186/.v16i.1903

Koeppen, W. 1948. Climatology: with a study of the Earth's climates. Fondo de Cultura Econômica, México, 479 pp. (in Spanish).

Musa, Y., Bahrun, A.H. & Rini, A. 2020. Farmers understanding and practices on shading and pruning for Arabica coffee: a survey and analysis on the effects to the yields. IOP Conf. Ser.: *Earth Environ. Sci*. **575**, 012158. doi: 10.1088/1755-1315/575/1/012158

Nascimento, L.M. do, Spehar, C.R. & Sandri, D. 2014. Produtivity of organic coffee orchard in the brazilian savannah after prunning and grown under different water regimes. *Coffee Science* **9**(3), 354–365 (in Portuguese).

Parreiras Pereira, S., Guimarães, R.J., Ferreira Bartholó, G., Tácito, P., Guimarães, G. & Alves, J.D. 2007. Vegetative growth and yield of coffee plants (Coffea arabica L.) in two different pruning times, conducted at different spacings. *Ciênc. Agrotecnol*. **31**(3), 643–649.

Pereira, A.A., de Morais, A.R., Scalco, M.S. & Fernandes, T.J. 2016. Modeling of the diameter of the canopy pruned coffee tree cultivated in different densities and water regimes. *Coffee Science* **11**(4), 495–501 (in Portuguese).

Pereira, S.P., Baliza, D.P. & Santos, M.O. 2013. Influence of cultivation spacing and two pruning times on stem carbohydrate levels in coffee. *Coffee Science* **8**(4), 460–468.

Rahman, G., Malek, A.A., Houssain, A. & Islam, S. 2024. Effect of pruning on growth, yield and quality of coffee. *East Afr. Sch. J. Agric. Life Sci*. **7**(2), 26–30. doi: 10.36349/easjals.2024.v07i02.002

Reis, E.A.C., Freitas, T., Carvalho, M.A.F., Mendes, A.N.G., Rezende, T.T. & Carvalho, J.P.F. 2018. Characterization of coffee cultivars leaf rust-resistant subjected to framework pruning. *Coffee Science* **13**(1), 63–70.

Rhiney, K., Guido, Z., Knudson, C., Avelino, J., Bacon, C.M., Leclerc, G., Aime, C. & Bebber, D.P. 2021. Epidemics and the future of coffee production. *Proc. Natl. Acad. Sci*. **118**, e2023212118. doi: 10.1073/pnas.2023212118

Sarmiento-Soler, A., Vaast, P., Hoffmann, M.P., Jassogne, L., van Asten, P., Graefe, S. & Rötter, R.P. 2020. Effect of cropping system, shade cover and altitudinal gradient on coffee yield components at Mt. Elgon, Uganda. *Agric. Ecosyst. Environ*. **295**, 106887. doi: 10.1016/j.agee.2020.106887

Silva, V.A., de Rezende, J.C., de Carvalho, A.M., Carvalho, G.R., Rezende, T.T. & Ferreira, A.D. 2016. Recovery of coffee cultivars under the ‘skeleton cut’ pruning after 4.5 years of age. *Coffee Science* **11**(1), 55–64.

Somarriba, E. & Quesada, F. 2022. Modeling age and yield dynamics in Coffea arabica pruning systems. *Agric. Syst*. **201**, 103450. doi: 10.1016/j.agsy.2022.103450

Souza, V.H.S., Carvalho, A.M., Teramoto, É.T., Silva, M.C.S. & Guimarães, R.J. 2024. Yield after intensive pruning of fertigated coffee plants subjected to different macronutrient rates. *Semina: Ciênc. Agrár*. **45**(1), 23–36.

Thomaziello, R.A. & Pereira, S.P. 2008. Pruning and training of Arabica coffee plants. Instituto Agronômico, Campinas, 39 pp. (Série Tecnologia APTA, Boletim Técnico IAC, 203). (in Portuguese).

Turreira-García, N. 2022. Farmers’ perceptions and adoption of Coffea arabica F1 hybrids in Central America. *World Dev. Sustain*. 1, 100007. doi: 10.1016/j.wds.2022.100007

Utrilla-Catalan, R., Rodríguez-Rivero, R., Narvaez, V., Díaz-Barcos, V., Blanco, M. & Galeano, J. 2022. Growing inequality in the coffee global value chain: a complex network assessment. *Sustainability* **14**, 672. doi: 10.3390/su14020672

Viteri Salazar, O., Ramos-Martín, J. & Lomas, P.L. 2018. Livelihood sustainability assessment of coffee and cocoa producers in the Amazon region of Ecuador using household types. *J. Rural Stud*. **62**, 1–9. doi: 10.1016/j.jrurstud.2018.06.004