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Maturation and detachment force for mechanized harvesting of irrigated Conilon coffee in the Brazilian Cerrado

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Abstract – The objective of this work was to determine the force required to detach fruits of Conilon coffee (*Coffea canephora*) genotypes in five maturation stages, to determinate the best stage for mechanized harvest, and to verify the possibility of future selections of genotypes adapted to mechanized harvesting. Harvests were carried out in the 2013/2014 crop season, and the detachment force was determined based for six fruits from each side of the crop row, collected randomly from the middle third of the plants. The detachment force curve was obtained for each cycle through logistic regression, using the R software. According to the duration of their cycle, the genotypes were divided into super early, early, medium, and semilate; the values of the coefficients of the detachment force curve equation were also obtained. There is genetic variability regarding fruit detachment force throughout the maturation cycle, which indicates the possibility of selecting genotypes adapted to mechanized harvesting. Fruit detachment force shows a considerable drop in the final stages of maturation. The raisin stage is the best for the mechanized harvest of irrigated Conilon coffee in the Cerrado.
Index terms: *Coffea canephora*, mechanized harvest, pre-breeding, ripening cycle, 'Robusta Tropical'.

Maturação e força de desprendimento para colheita mecanizada de café conilon irrigado no Cerrado brasileiro

Resumo – O objetivo deste trabalho foi determinar a força requerida para o desprendimento de frutos de genótipos de café conilon (*Coffea canephora*) em cinco estádios de maturação, determinar o melhor estádio para a colheita mecanizada e verificar a possibilidade de futuras seleções de genótipos adaptados à colheita mecanizada. As colheitas foram realizadas na safra de 2013/2014, e a força de desprendimento foi determinada para seis frutos de cada lado da linha de cultivo, colhidos aleatoriamente no terço médio das plantas. A curva de força de desprendimento foi obtida para cada ciclo, por meio de regressão logística, tendo-se utilizado o programa R. De acordo com a duração de seu ciclo, os genótipos foram divididos em superprecoces, precoces, médios e semitardios; também foram obtidos os valores dos coeficientes da equação da curva de força de desprendimento. Há variabilidade genética quanto à força de desprendimento dos frutos ao longo do ciclo de maturação, o que indica a possibilidade de seleção de genótipos adaptados à colheita mecanizada. A força de desprendimento dos frutos apresenta queda considerável nos estádios finais de maturação. A fase passa é a melhor para a colheita mecanizada do café conilon irrigado no Cerrado.

Termos para indexação: *Coffea canephora*, ciclo de maturação, colheita mecanizada, pré-melhoramento, 'Robusta Tropical'.

Introduction

The cultivation of *Coffea canephora* Pierre ex A.Froehner in the Brazilian Cerrado (Brazilian savanna) requires the selection of genotypes with longer cycles than *Coffea arabica* L., adapted to the climate and cultivation system of the region. Researches carried out in this biome in an irrigated production system show the potential of quality Conilon coffees (Brige et al., 2019; Santin et al., 2019).

Coffee production in the Cerrado has been increasing in recent years, mainly in the states of Minas Gerais and Bahia. The Arabic coffee growing system in the Cerrado is based on large areas and high investment in technology, with irrigation (mainly via central pivot) and mechanization of operations, especially harvesting, which differs from the growing system of traditional Conilon coffee producing regions. Cunha et al. (2016) reported that mechanized harvesting provided a cost reduction of 34% to over 61% when compared to manual coffee harvesting.

The objective of the machine's work is the detachment of the fruits and should be evaluated in different stages of maturation of the fruits, cultivars, coffee plants, and local conditions of the culture. The greater or lesser ease with which the beans are removed is associated, among other factors, with the ripening stage of the fruits. In the initial phase of harvest, for *C. arabica*, when most of the fruits are in the "green" and "cherry" stages, the machine will be less efficient at removing the beans. Rena et al. (1994) reported that the fruits of Conilon coffee are more strongly attached to the plant than those of Arabic coffee, and do not fall easily when ripe, a characteristic that can interfere with harvesting.

According to Souza et al. (2020), the force required to detach Conilon coffee fruits is significantly different when considering both stages of maturation and different genetic materials. The same authors observed that the force necessary to remove the green fruits from the plant was approximately twice that of applied to harvest the cherry fruits. For Silva et al. (2013), also, the detachment force varies between Arabic coffee cultivars and according to maturity stage. These authors mention this variation as an important factor for the management of mechanized harvesting.

The objective of this work was to determine the force required to detach fruits of Conilon coffee genotypes in five maturation stages, to determinate the best stage for mechanized harvest, and to verify the possibility of future selections of genotypes adapted to mechanized harvesting.

Materials and methods

The study was conducted in the 2013/2014 crop season in the experimental field of Embrapa Cerrados, located in Planaltina, Distrito Federal, Brazil (15º35'30"S, 47º42'30"W, at 1,007 m altitude).

The irrigation method used was sprinkler irrigation, and the system adopted was a central pivot. The irrigation management criteria were based on climate monitoring, and the moment of irrigation occurred every five days, according to the Cerrado irrigation monitoring program – Monitoramento de Irrigação no Cerrado (Rocha et al., 2006). For bloom uniformity, irrigation suspension was used in the period between the end of June and the beginning of September, aiming for uniformity of the bloom and greater production of coffee in the cherry stage (Guerra et al., 2005).

In the experimental field, there were about 3,500 different genotypes from natural crossbreeding of the Emcaper 8151 – Robusta Tropical cultivar, from the Empresa Capixaba de Pesquisa e Extensão Rural (Encaper), planted via seedling without repetition and, therefore, without experimental design. Preliminary observations, especially those made by Carneiro et al. (2013), allowed to pre-select some materials. After that, 220 plants (genotypes) were selected for this work. The plants were identified by their geographical position at the experimental field – line and number of position in the line.

The evaluations of fruit detachment force were performed at five stages of maturation: green, cane-green, cherry, raisin, and coco. The measurements were made using a dynamometer, model DD 300 (Instrutherm Instrumentos de Medição Ltda, São Paulo, SP, Brazil). In each evaluation, six fruits were harvested from the middle third of plagiotropic branches on each side of the cultivation line, totaling 12 fruits per plant in all 220 genotypes in each stage of maturation. The interval between measurements was variable, which made it possible to establish the maturation cycle of each material and the duration interval of each phase of the cycle for each genotype. With these data, it was possible to determine the fruit detachment force curve in relation to the maturation cycle, analogously to that obtained by Ferreira Júnior et al. (2018) for Arabic coffee.

The maturation cycles were determined by weekly observation of the 220 genotypes of the whole plants, following the scale developed and adapted from Pezzopane et al. (2003), so that a change of level was considered only when at least 80% of the fruits were in the same maturation stage. Thus, considering the cherry stage as the ideal point for harvesting, the time, in days, for each genotype to reach this stage was determined, counting from flowering, which occurred on average on September 18, approximately two weeks after the return of irrigation, usually occurring on September 4. To reach the cherry stage, the difference, in days, between the earliest (243 days) and the latest (293 days) was 50 days. Thus, three cuts were made in the medians (13, 25, and 38 days, approximately), forming four maturity groups, which were named super early (243–255 days), early (256–267), medium (268–280), and semilate (281–293).

The division of the genotypes into cycles was performed according to the medians, first dividing them into two larger groups and, from these, the four groups mentioned above. The detachment force data at each stage were used to determine the detachment force curve of each material, by means of non-linear regression, and the parameters b0 and b1 of the logistic curve formed, which are related, respectively, to the intercept of the regression curve on the Y-axis and the slope of the lowest part of the curve. This procedure was performed using the software R (R Core Team, 2016), which also allowed verifying the significance of the model fit.

With the variation of the fruit detachment force throughout the ripening cycle, the following polynomial regression model was drawn:

$$\text{Force (N)} = \frac{\Delta D}{1 + e^{-[(b0+b1)(\text{Days})]}} + \text{Min}$$

in which: ΔD, difference between the maximum and minimum force, in N; Min, minimum force reached throughout the maturation cycle; b0 and b1, coefficients of the logistic equation; Days, days between the first evaluation (in the green stage, 207 days after flowering) and the date when calculating the strength is intended.

Results and Discussion

Fruit detachment force varied between genotypes and between stages throughout the ripening cycle, showing variability between genotypes, which was also observed by Brige et al. (2019), when evaluating the quality of Conilon coffee beans in an irrigated production system in this same environment.

The used model considers the difference between maximum and minimum forces, which, from the point of view of mechanized harvesting, may favor selective harvesting, as long as the maximum force occurs during the initial stages and the minimum force, preferably, in the cherry or raisin stage.

Coefficient b0 is related to the intercept of the curve on the Y-axis, which provides information about the starting point of the detachment force. For mechanized harvesting, this is not an important parameter, except in cases of great disuniformity of fruits during ripening, which was not observed in the present study, mainly due to the uniformity of flowering resulting from drought stress.

Coefficient b1, however, is very important because of its direct relationship with the decrease in fruit detachment force: the higher its absolute value, the steeper the regression curve, i.e., the greater the reduction in the detachment force as the fruit ripening stages advance. This parameter is also closely related to the length of the cycle, meaning that, ideally, materials with an earlier cycle should present a curve with a greater slope, since their harvest time is more adequate. For these reason, the results for each maturation group will be discussed here separately.

Regarding the super early cycle, the five genotypes under this classifications were evaluated for fruit detachment force, whose polynomial regression curve was constructed using the obtained equation, which showed highly significant coefficients (Figure 1).

From the analysis of the graph, a vertiginous fall in the detachment force of the fruits could be noticed 43 days after observations of the green stage, the average period in which the genotypes of this ripening group reached the cherry stage. This drop reached the raisin stage, observed for this maturity group at 63 days, when the average detachment force had already decreased, showing a tendency for easier harvesting at this stage. Furthermore, an important point to be emphasized is a tendency of stabilization of the detachment force at the end of the ripening cycle. This observation is in agreement with that of Silva et al. (2013), who concluded that Conilon coffee fruits are more strongly attached to the plant even at the end of the ripening cycle. This factor can be considered advantageous in the sense that there is less spontaneous fall of dried fruits, reducing losses, the incidence of borers (Hollingsworth et al., 2020; Lemma & Abewoy, 2021), and the germination of seeds below the skirt of the coffee trees.

The transition from cherry to raisin takes an average of 20 days (Figure 1). The raisin stage, however, is shorter, reaching the coco in a little over two weeks. This information is important in the planning of the activity, because it represents the harvesting window (Barros et al., 2018). Thus, the longer the cherry and raisin stages are, especially the latter, in which the quality of the fruits is high (Martinez et al., 2013; Bastian et al., 2021) and the detachment force is low, the longer the adequate harvest period will be. Similarly, the shorter a stage is or the faster its passage to the next stage, the less time there will be for harvesting.

Regarding the early cycle, the equation obtained for the 151 genotypes under this classification was used to construct the polynomial regression curve for fruit detachment force and showed coefficients of variation that were highly significant for the model (Figure 2).

Analyzing the curve, a decrease in the detachment force of the fruit can be clearly seen, especially from day 59, when the majority of the genotypes in this maturity group reached the cherry stage. From then on, the detachment force continued to decrease, reaching the lowest values at the raisin stage, as had occurred with the genotypes of the super early group. Here, this occurred around 73 days after the first evaluation. Thereafter, a slight tendency of increase in the detachment force at the coco stage is perceptible, which leads to the conclusion that the fruits of these materials should not fall spontaneously, a factor, as commented, that is advantageous and in agreement with Rena et al. (1994).

Regarding the medium cycle, the equation obtained for the 53 genotypes under this classification, i.e., that took from 268 to 280 days from flowering to the cherry stage, expresses fruit detachment force as a function of the maturity stage (Figure 3).

Although the minimum force found in this case is a relatively high value (greater than 2 N), it is noted that the difference between the highest and lowest detachment forces (1.843 N) has almost the same value, which leads to the understanding that the highest force is almost twice that of the lowest. This leads to infer the possibility of selective mechanized harvesting (Santinato et al., 2015; Silva et al., 2016). Figure 3

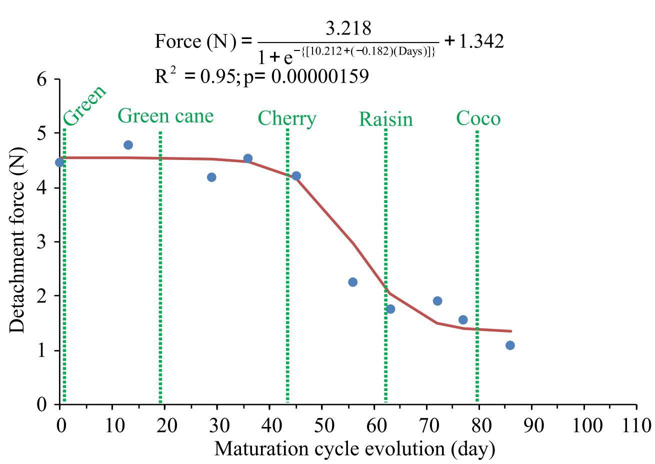

Figure 1. Average detachment force for Conilon coffee (*Coffea canephora*) fruits of super early genotypes observed and calculated using the regression model as a function of the evolution of the maturation cycle (green, green cane, cherry, raisin, and coco) in the 2013/2014 crop year, in the region of Planaltina, in Distrito Federal, Brazil.

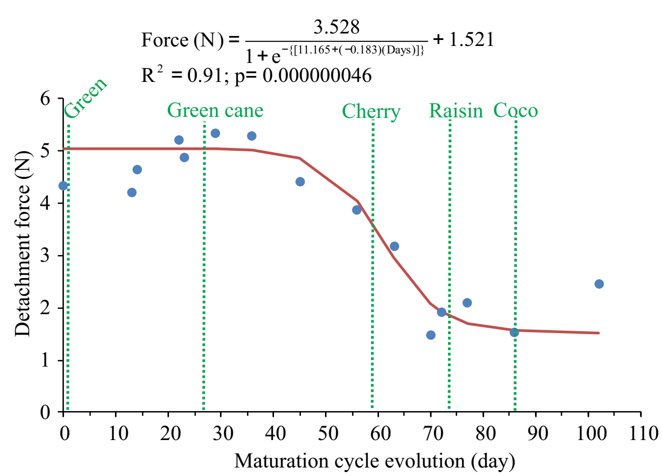

Figure 2. Average detachment force for Conilon coffee (*Coffea canephora*) fruits of early genotypes observed and calculated using the regression model as a function of the evolution of the maturation cycle (green, green cane, cherry, raisin, and coco) in the 2013/2014 crop year, in the region of Planaltina, in Distrito Federal, Brazil.

shows the regression curve of the fruit detachment force along the medium cycle.

It can be seen, by analyzing the graph, that the drop in fruit detachment force is not as sharp (less inclined curve) as those of the previous groups. This is evidenced by the value of parameter b1 of the equation generated for the detachment force, which has an absolute value (0.059) considerably lower than the previous ones (0.182 and 0.183 for the super early and early, respectively). However, the fact that the curve has a lower slope, which would be a disadvantage from the point of view of mechanized harvesting, can be mitigated by the longer cycle length, which makes the curve longer, reaching lower detachment force values when compared to those obtained by Silva et al. (2013).

The force required to detach the green fruits has a magnitude greater than twice that required for fruits in the raisin stage. Therefore, from the point of view of fruit detachment force as a parameter to determine the moment of mechanized harvest, the raisin stage is the most adequate. Still with respect to the magnitude of the force, the results found here are much lower than those found by Silva et al. (2013), when evaluating Arabic coffees in the cherry stage.

Regarding the semilate cycle, the equation obtained for the 11 genotypes under this classification showed highly significant coefficients (Figure 4).

Again, as occurred with the medium cycle genotypes, the minimum detachment force was close to 2.0 N. However, in this case, the coefficient b0 of the equation showed a slightly higher result, in absolute value, than in the previous maturity group. This caused the drop in fruit detachment force to be more abrupt with the evolution of the maturity cycle, resulting in a steeper polynomial regression curve (Figure 4).

As mentioned above, a more abrupt drop in the fruit detachment force was observed, especially from day 77 after the first evaluation, when the first materials of this maturation group reached the cherry stage. From then on, the drop became more pronounced until around day 100, when most genotypes had already passed the raisin stage. In this case, there was a slight increase in strength at the end of the cycle, making the detachment force of the nuts higher than in the raisin stage. It is worth remembering that this factor is important in the sense that it reduces the drop of nuts, which causes an increase in production costs due to the higher incidence of pests in the plantation, besides greatly reducing the quality of the beverage produced.

The semilate cycle materials showed a behavior slightly different from the others, characterized by a clear increase in detachment force in the green cane stage when compared to the green one, besides having shown a higher detachment force in the cherry stage

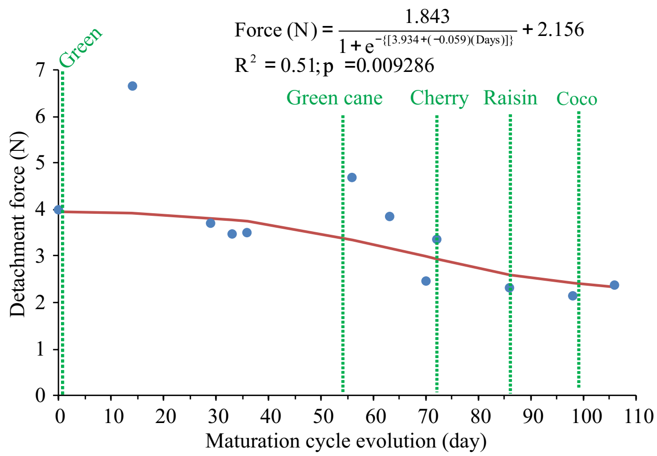

Figure 3. Average detachment force for Conilon coffee (*Coffea canephora*) fruits of medium cycle genotypes observed and calculated using the regression model as a function of the evolution of the maturation cycle (green, green cane, cherry, raisin, and coco) in the 2013/2014 crop year, in the region of Planaltina, in Distrito Federal, Brazil.

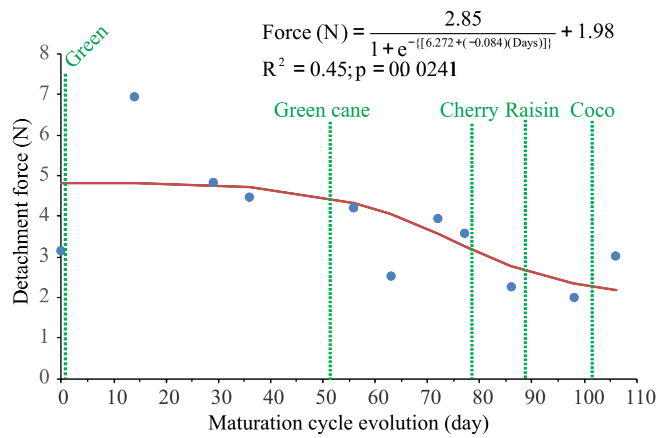

Figure 4. Average detachment force for Conilon coffee (*Coffea canephora*) fruits of semilate cycle genotypes observed and calculated using the regression model as a function of the evolution of the maturation cycle (green, green cane, cherry, raisin, and coco) in the 2013/2014 crop year, in the region of Planaltina, in Distrito Federal, Brazil.

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than in the green one. Regarding the raisin stage, the same rule was followed as for the other groups, showing the greatest difference in relation to the initial stages of maturation.

The behavior of the materials throughout the maturation cycle followed the logic already reported by Silva et al. (2013), in a study with Arabic coffee hybrids, who made a comparison between the green and cherry stages. It is important to emphasize that, as observed in this trial, the raisin stage showed a considerably lower detachment force than the cherry stage, a fact that was also observed by Ferreira Júnior et al. (2018), possibly showing that this is the ideal time to harvest Conilon coffee from the point of view of mechanized activity. This is because, besides the presence of low values in the raisin stage, the greatest differences in strength were also observed in relation to the green and green cane fruit stages, in which the quality of the beverage produced is much lower.

This becomes even clearer when considering that, in the trials conducted with Arabic coffee by Silva et al. (2013), the stripping efficiency increased greatly in the second pass in relation to the first (difference of 28 days), when even the cherry stage fruits were already in a more advanced stage of maturation within the stage itself, which can be understood as the raisin point.

It is of great relevance to emphasize that, regardless of the detachment force in the cherry stage, an important factor in harvest mechanization is the difference in force between the stages. Considering the raisin stage as the ideal for mechanized harvesting, it can be noted that the difference between this and the cherry stage was 2.5 N for the super early, 2.4 N for the early, 1.7 N for the medium and 0.83 N for the semilate. With a difference of 3.5 N between the cherry and green stages, Silva et al. (2013) obtained 77% of cherry fruit in relation to the total fruit harvested, clearly demonstrating the possibility of selective mechanized harvesting. This may prove to be an excellent alternative for harvesting in situations of maturity disuniformity.

Also, although the differences observed were smaller, the fact that the absolute force was also considerably lower leads to the inference that the regulation of the vibration of the harvester, in this case, may be different, with fewer cycles per minute, which would provide less damage to the plants during the harvest process, especially considering the possibility of physical damage to floral buds, a factor that generates concern especially in situations of late harvest. This conclusion corroborates Souza et al. (2020), who observed that the increase in the machine speed decreased the efficiency of harvesting and peeling of coffee fruits, caused by the shorter time of contact of the plants with the vibrating rods.

Considering especially the semilate cycle materials studied here, in which the raisin stage was observed in the second fortnight of July, a harvest that caused less damage would certainly accelerate the process of recovery of the plant after harvest, even for the possibility of causing less defoliation. The maturation cycle can be different between clonal groups and cultivars, because each stage of fruit formation has its own physiological and metabolic functions that are essential for the complete formation of the coffee bean (Bragança et al., 2001; Ságio et al., 2013).

Conclusions

1. There is genetic variability within the Conilon coffee (*Coffea canephora*) population studied regarding the fruit detachment force along the maturation cycle, which indicates the possibility of selecting genotypes adapted to mechanized harvesting.
2. The detachment force of the fruits presents a considerable drop in the final stages of maturation.
3. From the point of view of fruit detachment force, the raisin fruit stage is the ideal for the mechanized harvest of irrigated Conilon coffee in the Cerrado.

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