Effect of coffee tree pruning on berry production and Coffee Berry Borer infestation in the Toba Highlands (North Sumatra)

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Abstract

The productivity of Arabica coffee trees in the Toba Highlands (North Sumatra) suffers from inadequate agricultural practices and virtually non-existent protection against the coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari) (Coleoptera: Curculionidae : Scolytinae). While awaiting the development of a CBB control programme, this study proposed to achieve a rapid gain in productivity through coffee tree pruning. A comparison between the average production of ripe berries on pruned and unpruned coffee trees showed that pruning resulted in significantly higher yields over a two-year period. Within this increased production, the quantity of infested berries remained similar in the two treatments, due to the inherent dispersion behaviour of CBB, which seemed to occur throughout the fruiting period. Proper coffee tree pruning did not lead to any harvest losses in the first year, but affected the dynamics of production with a significant increase in the second year. As that improvement

did not cause any increase in the number of infested berries in the pruned coffee trees, infestation rates fell. However, towards the end of the second harvest in year two, infestation levels of those coffee trees tended to reach those of unpruned coffee trees. In the Toba Highlands, pruning is probably the first step needed to improve yields and help to reduce CBB infestations, by bolstering the generally recommended sanitation harvesting.

Introduction

North Sumatra province produces one third of Indonesia's total output of Arabica coffee, which accounts for about 9.7% of Indonesian coffee export volumes (Susila, 2005). On the international specialty coffee markets, this coffee, which is appreciated for its sensory characteristics, is known as Mandheling or Lintong Coffee (Susila, 2005; Saragih, 2013). The most representative variety is Sigara Utang, grown in North Sumatra, particularly in the different districts surrounding Lake Toba. The fundamental problem with Arabica coffee cultivation in North Sumatra is poor quality agricultural management due to the insufficient training of coffee farmers (Saragih, 2017). The lack of good agricultural practices, such as fertilization and periodic tree pruning, explains why productivity remains low (1139 kg green coffee/ha/year) compared to that of Aceh province (1568 kg green coffee/ha/year) (Saragih, 2013). It should be added that the Toba region enjoys a high-altitude equatorial climate, which influences the duration of coffee fruiting throughout most of the year. In this context, which is favourable to the development of the coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari) (Arcila *et al*., 1993), the deficiency of protection against this pest contributes to increasing numbers of infested beans, the degree of premature berry fall and the cost of post-harvest sorting (Decazy, 1990; IndoCafCo, personal communication). As a result, it causes considerable economic losses (Decazy, 1990; Baker, 1999; Damon, 2000; Bustillo Pardey, 2006).

Pruning is a practice used in various countries to rejuvenate coffee trees and boost berry production, but it can have different effects on CBB infestations depending on the technique used. For example, in Colombia, it is common practice to cut back, known as "zoqueo", every 5 or 6 years, but the harvest is non-existent in the first year and it takes another one to two years to return to normal production (Aristizábal *et al.*, 2016). On the other hand, CBB emerging from residual berries on the ground will disappear from the cut-back plots, but will be abundantly dispersing to neighbouring plots for more than 60 days (Castaño *et al.*, 2005). In Hawaii, pruning of the "Beaumont-Fukunaga" type is a new method that, unlike the traditional "Kona style" method, applies to an entire row or block, so that all the vertical branches present at any time in a tree are of the same age, making it easier to manage. However, alternating rows with different age branches can accelerate rather than limit the dispersion of CBB (Aristizábal et al., 2016).

Pending the establishment of a general control programme against CBB in the Toba area, and in order to immediately improve coffee bean production, we considered the hypothesis that periodic pruning of unproductive branches, combined with regular sucker removal adapted to the variety being grown, would lead to significantly better production, though without modifying CBB infestation intensity. In the agricultural context of the Toba area, we set up a two-year comparative trial focusing on berry production and CBB infestation levels, for pruned and unpruned trees. Pruning is known to have positive effects on coffee tree regeneration and vigour (Coste, 1989), but we did not know when the production gain after pruning would be detectable, and what its actual effects would be on CBB infestation.

Materials and methods

Experimental conditions

The study was undertaken in three coffee plots (*Coffea arabica*, Var. Sigara Utang) belonging to different owners near the village of Manik Saribu, in Simalungun province, North Sumatra, Indonesia. The six to eight-year-old coffee trees were cultivated in free growth without pruning, but with a similar architecture. The plots were flat, located at an altitude of about 1,200 m, ranging in area from 0.6 to 0.8 ha, with a density of 1666 plants/ha (2 m spacing between rows and 3 m between plants in the rows), and exposed to the sunlight with rare and scattered shade tree. Fertilization was organic and applied once a year. Manual weeding was carried out four times a year. The State-Owned Enterprise PT. Perkebunan Nusantara (PTPN) IV provided local climate data.

Trial design

In each of the three unpruned plots, considered as replications, 32 trees were chosen randomly on fixed rows (Fig. 1). Sixteen selected trees were pruned and sixteen others remained unpruned.

Pruning method

The pruning system proposed was basic-shaped pruning that consisted in selecting and keeping one to two vertical branches per coffee tree and cutting the others, and also cutting the top of the coffee tree (topping) at approximately 1.5 m in height, according to the traditional principles of pruning applied in Java (Bally, 1932). Pruning of plagiotropic side shoots (Jürgen Pohlan and Janssens, 2010) or maintenance pruning (Gaie and Flémal, 1988) consisted in removing all the primary branches up to around 80 cm from the ground that were dead, or living branches that were unproductive (Mestre-Mestre & Ospina-Ospina, 1994; Atrisiandy, 2015; Baker, 1999) (Table 1). Above this level, unproductive branches were also removed. All the cut branches were removed from the plot to leave the plot clean, taking care that the berries borne by the branches resulting from topping had been properly harvested. Pruning of orthotropic stems (Jürgen Pohlan and Janssens, 2010) or production pruning (Gaie and Flémal, 1988) is an operation that consists in removing suckers (suckering) growing from dormant buds on the trunk, to promote fruit-bearing, plagiotropic branches.

Sampling after pruning

The berry counts were carried out every two weeks from January 2015 to November 2016 on all selected pruned and unpruned coffee trees. After counting, infested and uninfested ripe berries, identified by their red colour, were removed from the coffee trees and returned to producers so that they would not be counted at the next counting (Fig. 1). We summed four successive ripe berry counts to obtain the quantity produced in eight weeks, this until the end of the trial.

Analysis methods

Effect of pruning on annual coffee production

Annual coffee production is decisive for producer incomes. Ripe berries represented the harvest, and infested ripe berries represented the damaged share of the harvest caused by CBB, resulting in an economic loss. Firstly, we explored its distribution between trees using density plots. Secondly, we analysed the effect of pruning on components of annual coffee production (ripe berries, infested ripe berries and ratio of infested berries to berries produced). We modelled berry production using generalized linear models (GLM) (Zuur *et al.*, 2013). Due to overdispersion of the data, the models used negative binomial distributions with a log-link function. These models are commonly adopted for counting data (Roman, 2019). We used the following three models:

Model 1: ripe berries

Model 1 analysed the effect of pruning on the number of harvested berries per tree. As the effect of pruning was expected to depend on the year (first and second year after pruning of plagiotropic side shoots), we created a combined variable "YT" from the year and the treatment.

Ripe ~ NB(μ, k) where μ = E(Ripe) and k the dispersion parameter of negative binomial distribution.

(Model 1) $\text{Log}(\mu) = \beta_1 + \beta_2 \text{ x } YT_{-} + \beta_3 \text{ x Replication}$

Model 2: infested ripe berries

The quantity of infested berries on a tree was considered as a proxy of the CBB population. Model 2 analysed the number of infested berries without the production term.

Infested ~ NB(μ, k) where μ = E(Infested) and k the dispersion parameter of negative binomial distribution.

(Model 2) $\text{Log}(\mu\text{-}) = \beta_1 + \beta_2 \text{ x } YT_{-} + \beta_3 \text{ x Replication}$

Model 3: ratio of infested ripe berries to ripe berries produced

Model 3 analysed the effect of pruning on the amount of infested berries per tree compared to tree production.

Infested ~ NB(μ, k) where μ = E(Infested) and k the dispersion parameter of negative binomial distribution.

(Model 3) $\text{Log}(\mu\text{-}) = \beta_1 + \beta\ 2\text{x Year} + \beta_3 \text{ x Treatment} + \beta_4 \text{ x Replication} + \beta_5 \text{ x Production}$

Effect of pruning on coffee production dynamics

The dynamics of ripe and infested berries were expected to have complex nonlinear relationships with time. To model them, we used generalized additive models with mixed effects (GAMM), which can incorporate nonlinear dependence. We used them with a Poisson distribution, because the production variables are counting data.

Model 4: dynamics of ripe berries

The dynamics of ripe berry production were modelled using the treatment effect and two smooth terms. Both were based on the number of days (time) considered as a continuous variable. Its effect was analysed as a smooth term using a thin plate spline, allowing dependence on the treatment to take into account the general production dynamics and the differential due to pruning. A random effect was included to take into consideration the correlation between different days on the same coffee tree.

Ripe ~ P(μ) where μ = E(Ripe)

(Model 4) Log(μ) ~ $\alpha_1 + \alpha_2$ x Treatment + f(Time) + f(Time / Treatment) + Coffee tree

Coffee tree was used as a random effect.

Model 5: dynamic of infested berries

The dynamics of infested ripe berries were modelled using the time, treatment and production effects. Smooth terms using a thin plate spline were used first to model the complex relationship between infestation and time (days), and then between infestation and production. The smooth terms allowed dependence on the treatment. A random tree effect was included.

Infestation ~ P (μ) where μ = E (Infestation)

(Model 5) Log (μ) ~ $\alpha_1 + \alpha_2$ x Treatment + f(Time) + f(Time /Treatment) + f(Ripe) + f(Ripe /Treatment) + Coffee tree.

All analyses were carried out using R v3.5.0 (R Core Team, 2018). For data management and visualization, the plyr (Wickham, 2009) and ggplot2 (Wickham, 2011) packages were used. For GLM and post hoc tests, the MASS (Venables & Ripley, 2002) and emmeans (Lenth, 2018) packages were used. For GAMM, the mgcv (Wood, 2017) and itsadug (van Rij *et al.*, 2017) packages were used.

Results

Climatic conditions and staggering of flowering and fruiting

The climate of the Toba region is an equatorial climate with uniform temperatures averaging around 21°C (Fig. 2) and a daily amplitude rarely exceeding 10°C. Relative humidity averages around 81% with variations that barely drop below 50% during the day. The annual distribution of rainfall was regular, with two periods of reduced rainfall in January or February and in July or September in 2015 and 2016. During those two years, the region received 2676 mm and 2200 mm of rain, respectively. Under these climatic conditions, four annual blooms occurred every three months: two large blooms in February and August and two small in May and November, resulting in overlapping fruiting bodies.

Effect of pruning on annual coffee production

The annual production of ripe berries per coffee tree varied from 20 to 2,813 berries with an overdispersed distribution. In year 1, the average number of ripe berries was 693 per pruned coffee tree and 691 per unpruned coffee tree, and in year 2 the average number of ripe berries was 1506 per pruned coffee tree and 744 per unpruned coffee tree. To go further in terms of variability, we studied density modes. In year 1, the density modes (most represented values) for pruned and unpruned coffee trees were superimposed around yields of about 500 ripe berries in year 1. The density modes were around 700 ripe berries for unpruned coffee trees and around 1,300 ripe berries for pruned coffee trees, in year 2, with a more widely dispersed distribution indicating high variability between trees (Fig. 3).

Model 1 explained 40% of the initial deviance of ripe berry production. Term significance in the negative binomial GLM (Model 1) established that replications and years combined with treatments (i.e. control or pruning) had a significant effect on production (Table 2). Annual production of ripe berry per coffee tree varied according to year and treatment (Fig. 4), with production of coffee tree pruned in year 2 being significantly higher than the three others (Table 3).

Effect of pruning on CBB infestation

Annual CBB damage on ripe berries ranged from 8 to 792 infested berries per tree, i.e. 6.2% to 66.4% of ripe berries infested (Fig. 5). The annual number of infested ripe berries per coffee tree was modelled using replications and years combined with treatments (Model 2). This model explained 68% of initial deviance. Replications and years combined with treatments had a significant effect on production (Table 2). All levels of year/treatment combinations were different, except for the control and pruning in year 2 (Table 3). The number of infested berries was significantly higher in year 2 than in year 1. In year 1 it was significantly higher for pruning than for the control.

To take into account the effect of variations in ripe berries on infested ripe berries, a model including replication, year, treatment and number of ripe berries as a covariable was fitted (Model 3). This model explained 83% of deviance. Model 3 showed that production had a positive, significant, linear effect on the log of mean CBB infestation (Table 2), meaning that there was an exponential relationship between production and CBB infestation. As the relation between the number of infested ripe berries and the number of ripe berries was taken into account in the model, the other variables were analysed with regard to the infested/ripe ratio. The infestation ratios were high in year 1 and year 2 (Table 3) and the pruning effect was reflected in a reduction in the infestation ratios compared to the control plots, over the same two years (Table 3).

The plotting of Model 3 predictions highlighted the differences between pruning and control treatments in relation to the ripe berries produced (Fig. 5). In year 1, the quantities of ripe berries produced per tree ranged within similar values for both treatments. The gap between the prediction lines for control and pruning treatments (Fig. 5) was small, but significant (Table 3). In year 2, the quantities of berries produced per pruned coffee tree reached a higher range, with a much higher maximum value. The gap between the prediction lines for control and pruning treatments was significant and higher than in year 1. This was due to the "sum of the differences between treatments" effect, and difference in berry production (Table 3).

Effect of pruning on coffee production dynamics

Term significance in GAMM (Model 4) confirmed that pruning had a favourable effect on production (Table 4) and that this effect was modulated over time. This model explained more than 61% of deviance.

The smooth representation of ripe berry dynamics based on predictions from Model 4 showed a main peak at the beginning of each year and a secondary peak at the end of the year, with low intensity in year 1 and greater intensity in year 2. Pruning induced an increase in production, growing over time and becoming significant after around 200 days (Fig. 6).

Effect of pruning on CBB infestation dynamics

Term significance in GAMM (Model 5) established that pruning had an adverse effect on CBB infestation (Table 5). Infestation depended on time and production in a nonlinear form modulated over time. This model explained more than 86% of deviance.

The smooth representation of infested ripe berry dynamics, based on GAMM predictions (Model 5), showed one peak at the beginning of each year (Fig. 7). Pruning induced a decrease in CBB infestation, which became significant after around 50 days and lasted until the end of the second year.

The smooth representation of infested ripe berries depending on ripe berry production showed a strong, linear relationship up to around 100 ripe berries per tree, but after that the slope decreased, with a significant difference between treatments (Fig. 8). For instance, on days 122 and 412, shortly after the infestation peaks of 2015 and 2016, the decrease in infestation was greater when the number of ripe berries was larger.

Discussion

Effect of pruning on annual coffee production

The results of this study on free-growing, high-altitude Arabica coffee trees revealed that basic- shaped pruning mainly consisting of topping, combined with the elimination of dead and unproductive branches, led to an increase in berry production, as was also found by Coste (1999) and Atrisiandy (2015). However, production varied little in year 1 and only increased significantly the following year (Figs. 3 and 4). In some plants, pruning seemed to lead to compensatory growth resulting from a weakening of internal competition for nutrients. In the case of the coffee tree, our results led us to ask whether pruning old, unproductive branches might not induce a compensatory increase in berry production. Such a hypothesis could be tested using a mathematical architecture model, such as GreenLab, which enables the simulation of interactions between plant structures and functions (Yan *et al.*, 2004). From a purely agronomic viewpoint, formation pruning offers the advantage of keeping coffee trees at accessible heights for all the harvesters, thereby facilitating harvesting work. In addition, suckering helps to reduce foliage volume at the base of coffee trees, thereby simplifying routine agricultural operations, such as weeding and fertilization, thus contributing to more efficient collection of ripe, over-ripe and dry berries on the ground during various harvesting operations (Baker, 1999).

Effect of pruning on CBB infestation

Despite some differences seen in the first year between the number of infested berries on pruned and unpruned coffee trees, the quantities of infested berries became equivalent in the two treatments the following year (Table 3), meaning that pruning did not seem to have a direct effect on CBB populations. However, as the total number of berries increased on the pruned coffee trees, the relative number of infested berries decreased on the pruned trees (Table 3).

The homogenization of the infestations seen in the two treatments might be explained by the fact that at no time did the total number of berries constitute a trophic obstacle to CBB population development. In addition, according to Román-Ruiz *et al.* (2018), female CBB emergence extends as time goes on throughout the fruiting period, and their migration is limited to short distances within each coffee tree, which becomes the spatial entity of their dispersion. Thus, despite any disturbances caused by harvesting operations that might modify that behaviour, the populations appeared to develop at the same rate under the two sets of agricultural conditions studied.

Pruning by topping led to temporary changes in the microclimate within the coffee tree, moving from a self-shaded status to a status more exposed to sunlight. That change may have been adverse to the development of CBB present in residual or ripening fruits (Bergamin, 1945; Decazy, 1990; Barrera, 1994; Dufour *et al.*, 1999; Wegbe *et al.*, 2007; Bosselmann *et al.*, 2009). In the Toba region, harvesting is carried out regularly (every two weeks) and residual berries on the ground or on branches are few in number (pers. com.). They therefore have little to do with the infestation process. However, in the branches, high temperatures combined with greater exposure of infested berries to light might help to slow down infestation dynamics. However, it needs to be pointed out that pruning does not have any durable effect on the microclimate, as the foliage soon grows back. It is doubtless for that reason that pruning is not considered as a true component of CBB population control in some countries, such as Colombia: it plays more of a facilitating role for the development of other components, such as sanitation harvesting (Baker, 1999; Bustillo Pardey, 2002; Bustillo *et al.*, 1998).

Effect of pruning on coffee production dynamics

The analysis of production dynamics showed that differences between the two treatments occurred and evolved slowly over the first year, increased in the second year and tended to decrease before the end of the second year. In physiological terms, these dynamics seem to back up the hypothesis of a redistribution of the coffee trees' nutrient resources, leading to a larger number of fruiting nodes and higher berry production. In economic terms, the absence of any reduction in harvest levels in the first year is a considerable advantage for producers, as it means that there will be no drop in income at any time. This is doubtless one of the main factors that might encourage the decision to adopt pruning as a measure that is complementary to the other agricultural activities inherent to coffee growing.

Effect of pruning on CBB infestation dynamics

The results of our study showed that, for rates equivalent to ours, CBB infestation dynamics are independent of the number of available berries, since the increase in berry production associated with pruning did not lead to an increase in the number of infested berries. This was reflected in a change in infestation rates that was significantly different for the pruned and unpruned treatments (Fig. 7). The dispersion model defined by Román-Ruiz et al. (2018) clearly explains that independence, which nonetheless seemed to lessen by the end of the second year. In fact, in an open environment such as a coffee plantation, CBB dispersion can sometimes exceed the limits of the coffee tree and focus on the most productive plants. This hypothesis might explain how the level of infestation progressed in the pruned plots after a period of relative stability. A longer study would make it possible to fine-tune these observations and define pruning rhythms with a view to curbing infestations over the long term.

Conclusion

The results of this experiment showed that pruning coffee trees, especially Arabica Var. Sigara Utang, did not play a significant role in CBB infestations, which were evenly distributed between the pruned and unpruned trees, but it did contribute to a notable increase in berry production. The fact that the production level was maintained just after pruning, and then increased right from the second year, offers at least four advantages: little or no expense for pruning, except for the workforce, which can be provided by the producers themselves, no loss of income in the first year, higher income from increasing berry sales in the second year, and encouragement to control CBB more effectively to reduce damage. In terms of a CBB control strategy, pruning can make a valuable contribution when implementing sanitation harvesting, in the aim of significantly reducing infested residual berry numbers. It facilitates their collection both on the ground and on the branches. Pruning also facilitates harvesting practices and provides better coverage for *B. bassiana* applications.

Once the pruning principle is accepted, it should be tested in blocks or complete plots where all coffee trees are pruned in the same way. It will also be necessary to become familiar with the pruning method, including topping, pruning of plagiotropic side shoots and orthotropic stems, and probably refine it over time.

If producers in the Toba region wish to prioritize "production" over "CBB control", and maintain stable production levels during the pruning year, they will choose this system. Simulations using a plant structural function model should help to optimize the pruning strategy. Thus, the combination of pruning, sanitation harvesting and other control elements should help to maintain a low and acceptable level of infestation in the field."

If their priority is CBB control, the producers will choose other methods of pruning, already used in other regions where the climate is similar, and where coffee cultivation is subject to strong pressure from CBB. In this case, control methods will become more drastic. For example, the stump pruning blocks tested and recommended in Hawaii (Aristizábal *et al.*, 2017; Kawabata et al., 2017) show a significant reduction in CBB populations compared to the results obtained with traditional methods, but stump pruning by blocks also leads to a lack of production for a year, which is an economic limit. However, when pruning is applied to only 20-30% of the coffee area, economic losses are reduced, especially if the other coffee trees are young, productive and healthy. In Colombia, five-year renovation by "zoca" or cutting-back is a method frequently used. It completely eliminates CBB populations, but involves a lack of production on 20% of the renovated coffee plantation for a period of two years (Bustillo Pardey, 2002, 2006).

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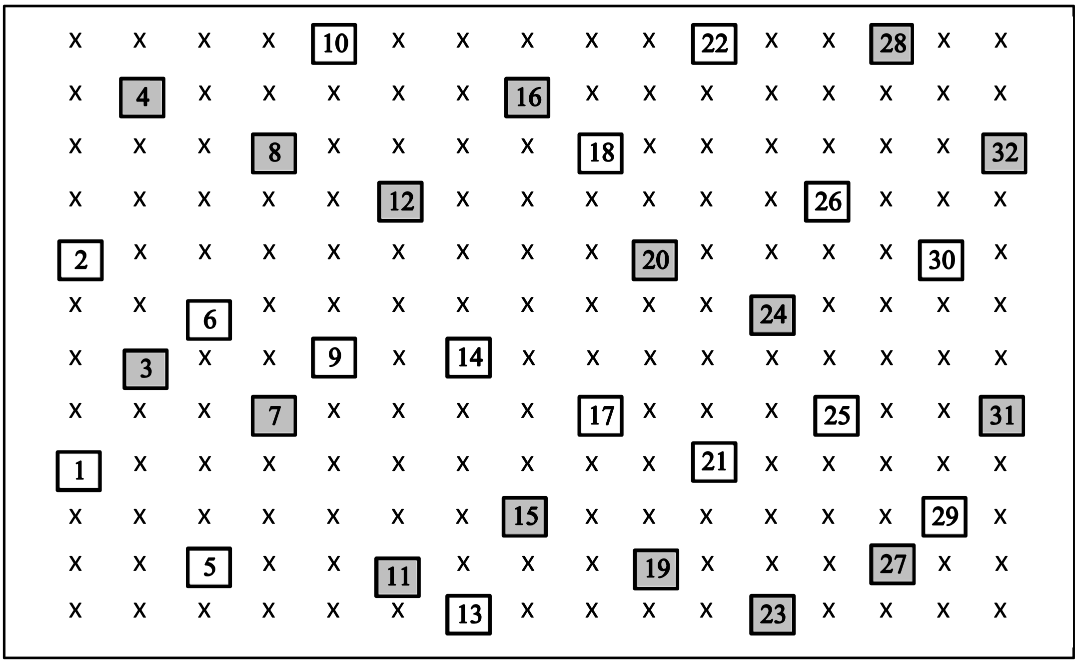

☐ Unpruned coffee trees randomly selected in rows: row 2 (trees 1 and 2), row 6 (trees 5 and 6), row 10 (trees 9 and 10), row 14 (trees 13 and 14), row 18 (trees 17 and 18), row 22 (trees 21 and 22), row 26 (trees 25 and 26), row 30 (trees 29 and 30).

■ Pruned coffee trees randomly selected in rows: row 4 (trees 3 and 4), row 8 (trees 7 and 8), row 12 (trees 11 and 12), row 16 (trees 15 and 16), row 20 (trees 19 and 20), row 24 (trees 23 and 24), row 28 (trees 27 and 28), row 32 (trees 31 and 32).

x Not-selected unpruned coffee trees.

Figure 1: Design showing the arrangement of selected pruned and unpruned coffee trees per plot

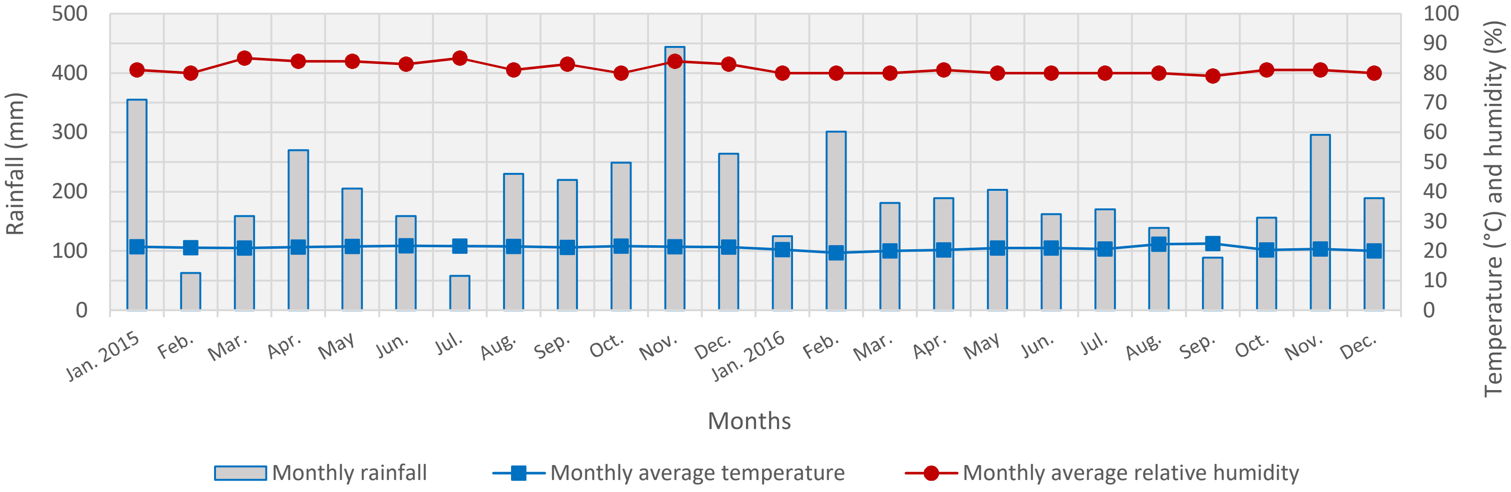

Figure 2: Climate characteristics of the Toba region from 2015 to 2016

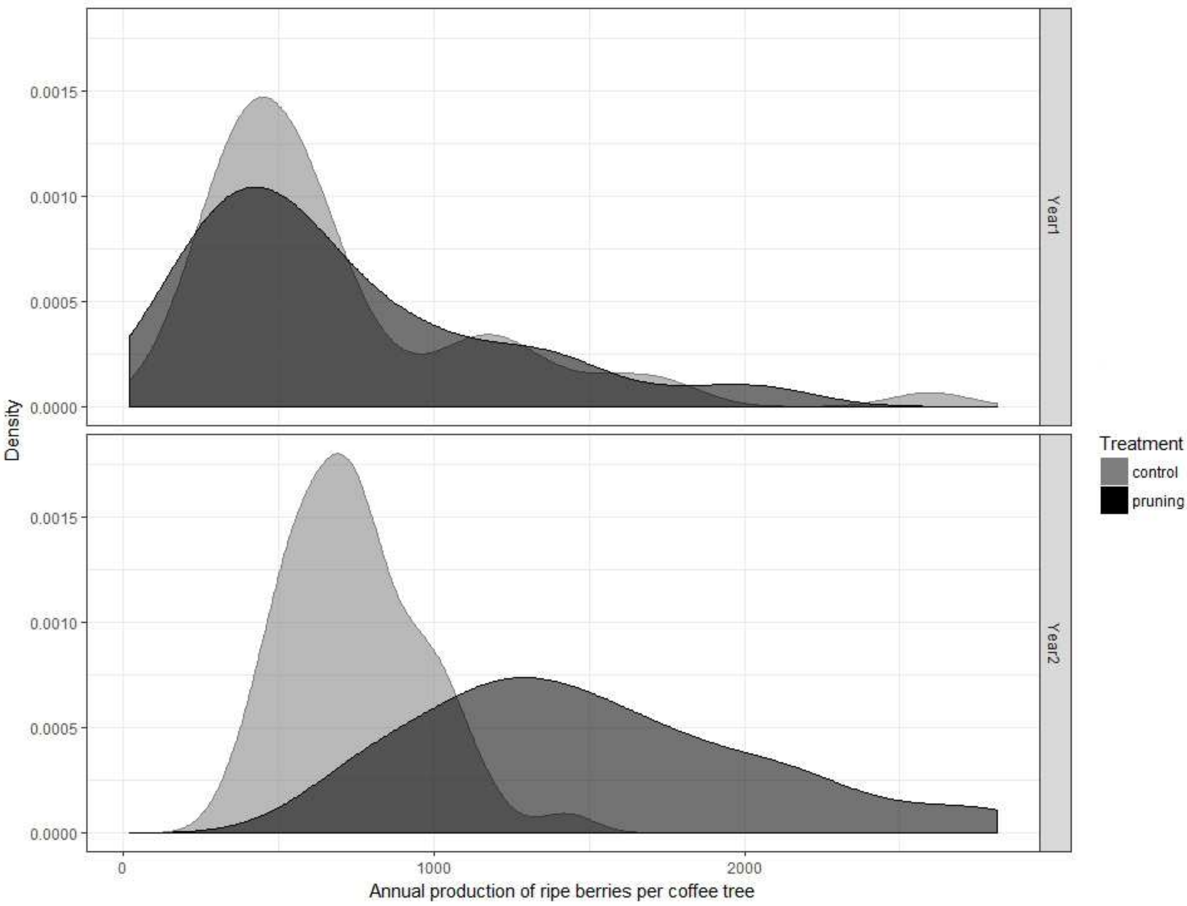

Figure 3: Density plot of annual ripe berry production per coffee tree depending on the year and treatment (control or pruning).

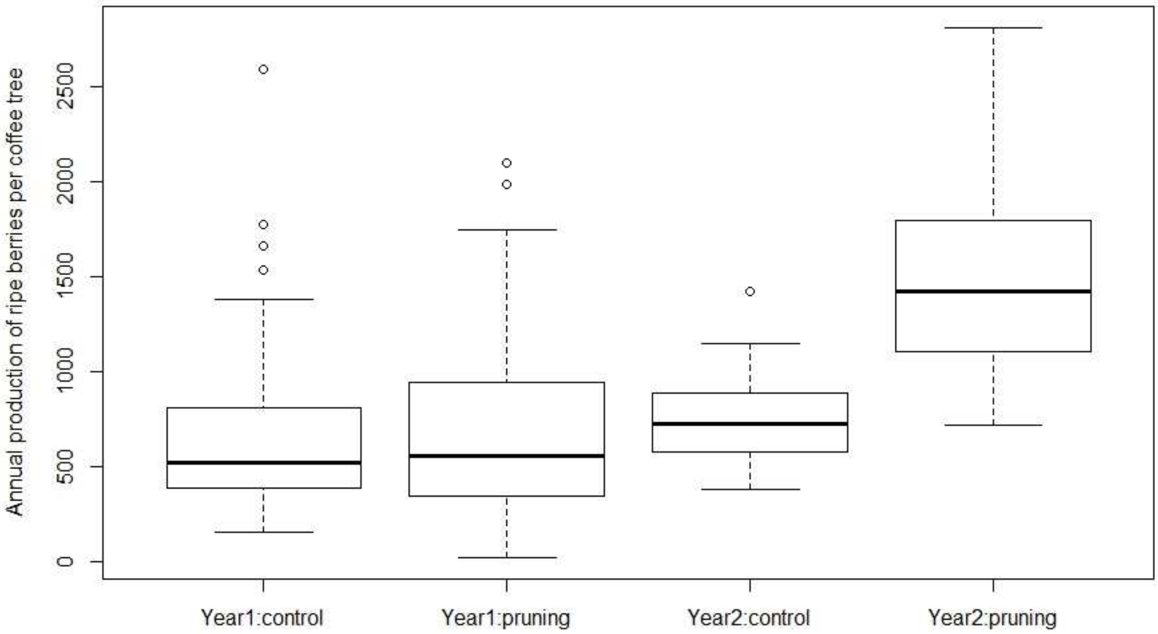

Figure 4: Boxplot of the annual production of ripe berries per coffee tree depending on the year and treatment (control or pruning).

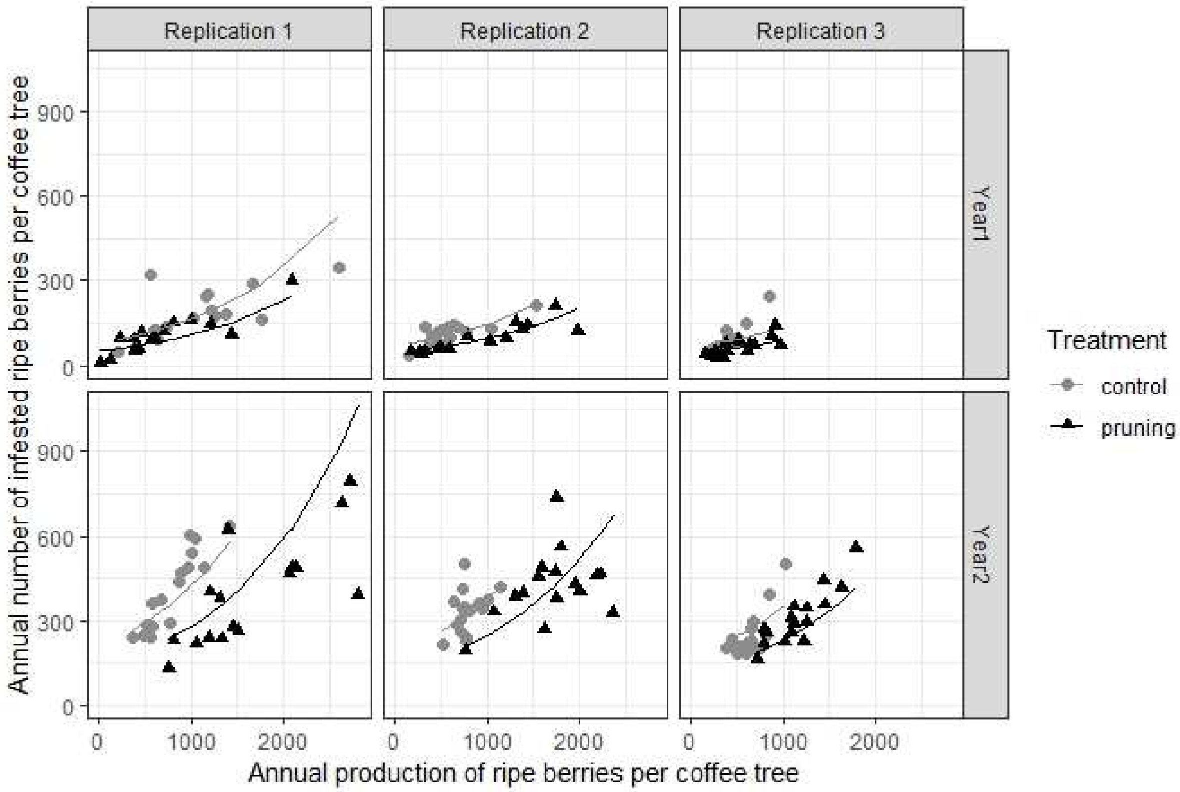

Figure 5: Relationship between the annual number of infested ripe berries per coffee tree and the annual production of ripe berries per tree per replication and year. Dots and triangles stand for measured values, the lines stand for fitted values using a simplified negative binomial generalized linear model (Model 3).

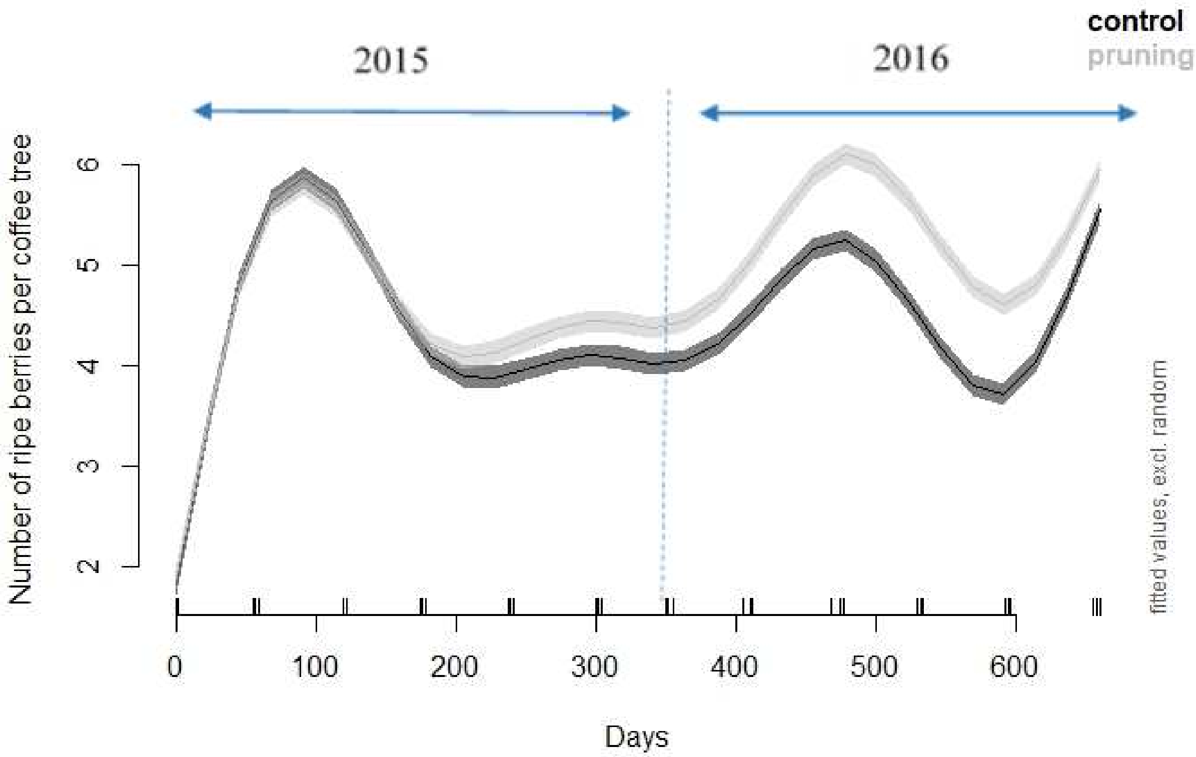

Figure 6: Smooth curves for the number of ripe berries per coffee tree and per treatment according to time, based on predictions from the generalized additive model with mixed effects (GAMM, Model 4)

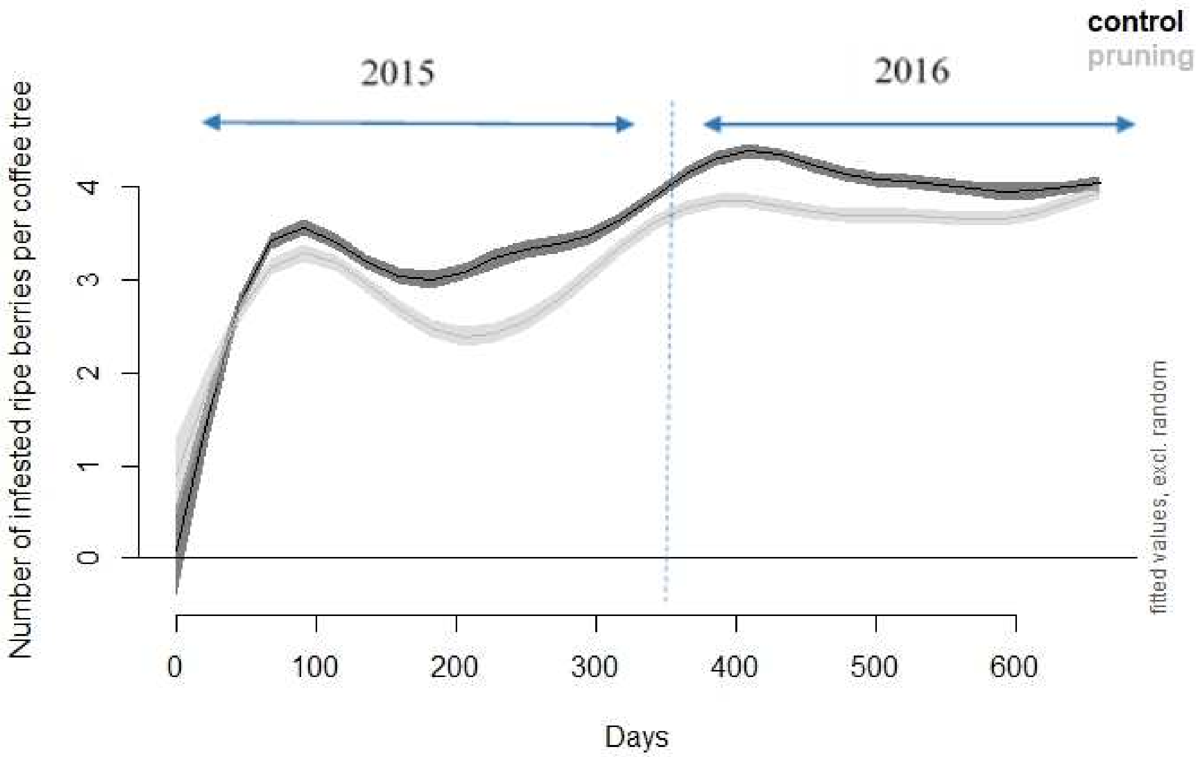

Figure 7: Smooth curve for the number of infested ripe berries with CBB per coffee tree and per treatment according to time based on predictions from the generalized additive model with mixed effects (GAMM, Model 5)

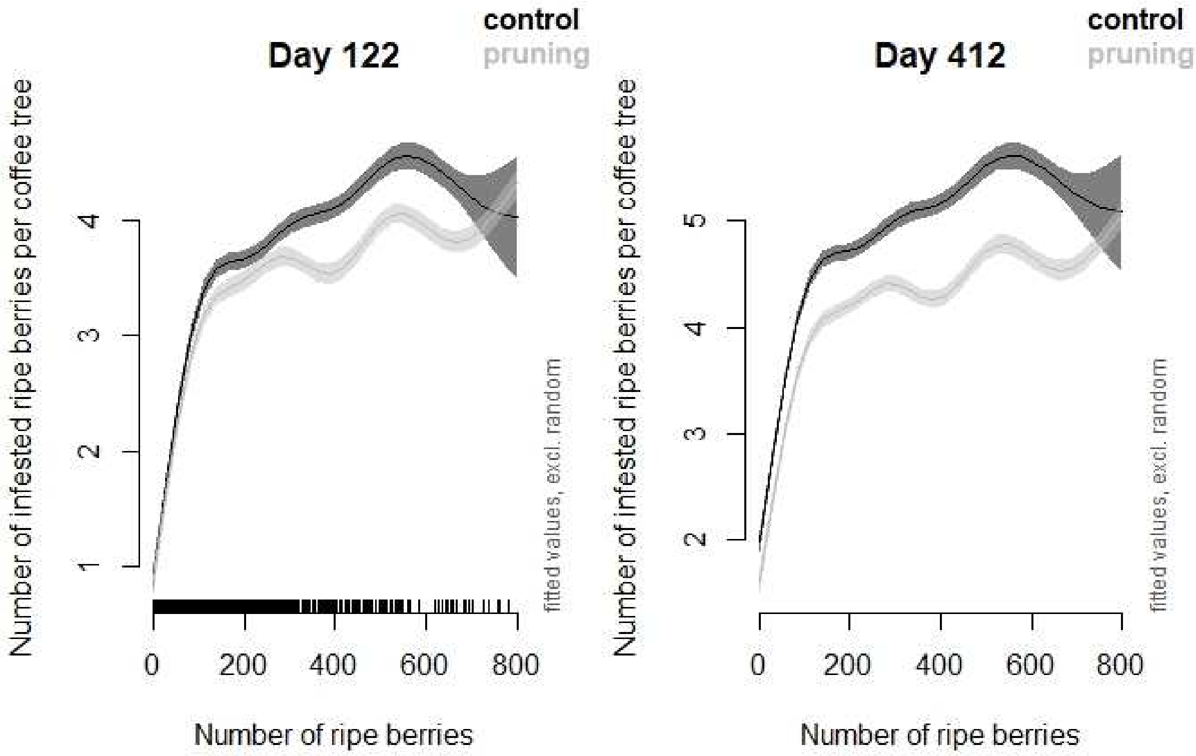

Figure 8: Smooth curves for the number of infested ripe berries with CBB per coffee tree and per treatment for 2 days (122 and 412) depending on production based on predictions from the generalized additive model with mixed effects (GAMM, Model 5)

Date	Pruning operations
September 2014	Basic-shaped pruning (Topping only)
September 2014	Pruning of plagiotropic side shoots (Removing unproductive branches)
December 2014	Pruning of plagiotropic side shoots (Removing the last unproductive branches)
April 2015 August 2015 April 2016 August 2016	Pruning of orthotropic stems (suckering)

Table 1: Details of the pruning operations carried out in coffee trees

Model	Predicted variable	Terms	Degree of freedom	Deviance	Residual deviance	Pr(>Chi)
Model 1	Number of ripe berries	Year/Treatment	3	98	232	<0.0001 *
		Replication	2	32	200	<0.0001 *
Model 2	Number of infested ripe berries	Year/Treatment	3	376	243	<0.0001 *
		Replication	2	43	200	<0.0001 *
Model 3	Number of infested ripe berries	Ripe	1	476	730	<0.0001 *
		Year	1	435	265	<0.0001 *
		Treatment	1	84	211	<0.0001 *
		Replication	2	11	200	0.004 *

* Significant (P<0.05)

Table 2: Term significance in the negative binomial GLM of annual production per coffee tree

Model	Predicted variable	Contrast	Estimate	Standard error	Pr(>|z|)
Model 1	Number of ripe berries	Year1:control - Year1: pruning	-0.03	0.1	0.98
		Year1:control - Year2: control	-0.12	0.1	0.61
		Year1:control - Year2: pruning	-0.81	0.1	<0.0001 *
		Year1: pruning - Year2: control	-0.09	0.1	0.82
		Year1: pruning - Year2: pruning	-0.78	0.1	<0.0001 *
		Year2:control - Year2: pruning	-0.69	0.1	<0.0001 *
Model 2	Number of infested ripe berries	Year1:control - Year1: pruning	0.37	0.09	<0.0001 *
		Year1:control - Year2: control	-0.96	0.09	<0.0001 *
		Year1:control - Year2: pruning	-1.11	0.09	<0.0001 *
		Year1: pruning - Year2: control	-1.33	0.09	<0.0001 *
		Year1: pruning - Year2: pruning	-1.48	0.09	<0.0001 *
		Year2: control - Year2: pruning	-0.15	0.09	0.31
Model 3	Number of infested ripe berries	Year1 - Year2	-0.94	0.05	<0.0001 *
		Control - pruning	0.41	0.05	<0.0001 *

* Significant (P<0.05)

Table 3: Post hoc tests after negative binomial generalized linear models of annual production per coffee tree for the year, treatment and production (ripe) variables only.

Parametric coefficients	Estimate	Std. Error	z value	Pr(>|z|)
Intercept	4.37	0. 055	79	<0.0001 *
Pruning	0.39	0.078	5	<0.0001 *
Approximate significance of smooth terms	**Estimated degrees of freedom (edf)**	**Ref.df**	**Chi.sq**	**p-value**
s(time)	7	7	39941	<0.0001 *
s(time):pruning	5	5	5506	<0.0001 *
s(coffee tree)	94	94	26544	<0.0001 *

* Significant (P<0.05)

Table 4: Summary results of the generalized additive model with mixed effects (GAMM, Model 4) for the number of ripe berries per coffee tree

Parametric coefficients	**Estimate**	**Std. Error**	**z value**	**Pr(>|z|)**
Intercept	2.85	0. 039	74	<0.0001 *
Pruning	-0.25	0.053	-5	<0.0001 *
Approximate significance of smooth terms	**Estimated degrees of freedom (edf)**	**Ref.df**	**Chi.sq**	**p-value**
s(time)	9	9	5112	<0.0001 *
s(time):pruning	9	9	142	<0.0001 *
s(production)	9	9	3255	<0.0001 *
s(production):pruning	8	8	234	<0.0001 *
s(coffee tree)	89	94	2051	<0.0001 *

* Significant (P<0.05)

Table 5: Summary results of the generalized additive model with mixed effects (GAMM, Model 5) for the number of infested ripe berries per coffee tree