EFFECT OF RAINFALL AND TECHNIFICATION ON ARABICA COFFEE PRODUCTIVITY IN MINAS GERAIS

Flávio Vanoni de Carvalho Júnior
Federal University of Lavras, Agricultural Engineering Department, Campus, ZIP Code 37.200-900, Lavras, MG, Brazil

Marcelo de Carvalho Alves
Federal University of Lavras, Agricultural Engineering Department, Campus, ZIP Code 37.200-900, Lavras, MG, Brazil

Luiz Gonsaga de Carvalho
Federal University of Lavras, Agricultural Engineering Department, Campus, ZIP Code 37.200-900, Lavras, MG, Brazil

Abstract: Arabica coffee is the main agricultural product of the state of Minas Gerais and its production has great social and economic importance in the state. Several factors affect coffee productivity, such as climate, fertilization, soil, cultivars, management, disease incidence, and the presence of irrigation. More than 80% of the coffee crops in the state are rainfed, and are dependent on rainfall. The availability of water, especially during flowering and grain filling, is of great importance for productivity and the consequent economic return of the activities. Thus, the objective of this study was to evaluate the effect of rainfall from September to January on Arabica productivity in coffee-growing municipalities in Minas Gerais based on monthly accumulations limited to 210 mm. Municipal agricultural production data from IBGE from 2012 to 2019 for processed Arabica coffee and monthly rainfall data with 2.5 minutes spatial resolution, made available by WorldClim for the period 2010-2018, were used for this purpose. The ratio of productivity per accumulated rainfall was calculated for the coffee municipalities to determine the level of municipal technification and to filter out discrepant data. The municipalities were divided into technification groups and linear regression curves were determined for each group. For low and medium tech municipalities, a high correlation was obtained between rainfall from September to January, with monthly accumulations limited to 210 mm, and Arabica coffee productivity. In high tech municipalities, there was no significant correlation due to the presence of irrigation. The equations obtained showed the potential to estimate the effect of rainfall during the analyzed period on the productivity of municipalities in all regions of Minas Gerais and even productivity estimates based only on monthly rainfall.

Keywords: Precipitation, WorldClim, Arabica coffee, Geocomputation.

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INTRODUCTION

Arabica coffee (*Coffea arabica* L.) accounts for about 60-70% of world production, producing beverages with appreciated flavors (CARVALHO, A. C. et al., 2017). Brazil, the world's largest producer and exporter (CALDARELLI; GILIO; ZILBERMAN, 2018; VOLSI et al., n.d.), showed a planted area of approximately 1.76 million hectares in 2016, equivalent to 80% of the national coffee park, while the remaining 20% was of the Robusta species (*Coffea canephora* L.). In the same year, the state of Minas Gerais accounted for 67% of Arabica coffee plantations in the country (CONAB, 2016). About 70% of the coffee sold worldwide is Arabica, with superior quality, sweet flavor, and higher prices (SOUZA et al., 2004; LEROY et al., 2006; ILLY; VIANI, 1996; ROMANI et al., 2012). Thus, coffee farming, as the main agricultural activity, has great importance in the economic and social scenario of Minas Gerais (VILELA; PENEDO, 2021).

Several factors affect the productivity of coffee trees, such as weather conditions, management, soil characteristics, cultivars, disease incidence, irrigation, and planting system (VOLTOLINI, 2019; BONOMO, 1999; PETEK; SERA; FONSECA, 2009; SILVA; MELO, et al., 2004; KITTICHOTSATSAWAT; TIPPAYAWONG;

TIPPAYAWONG, 2022). Among the climatic factors, water deficit and heat stress are the main limiting factors of productivity (DAMATTA; RAMALHO, 2006; CHEMURA et al., 2021). The rainfall volume requirement depends on several factors such as soil retention conditions, atmospheric moisture, cloud cover and cultivation practices (DAMATTA; RONCHI, et al., 2007). For rainfed coffee, the annual rainfall considered appropriate is around 1200 to 1800mm (ALÈGRE, 1959; THOMAZIELLO et al., 2000).

The coffee plant is known for presenting alternations in productivity, with a year of higher production followed by lower productivity in the following year. The phenomenon is called coffee biennial effect (BEAUMONT, 1939; TOSELLO; ARRUDA, 1962; SAKIYAMA et al., 2015) and occurs due to the physiology of the plant in which the reproductive and vegetative phases occur simultaneously, requiring a balance in the division of photosynthates. As a consequence, in the year of high production, there is a reduction in vegetative growth, decreasing the production of the following year (GATHAARA, 1996; BARROS, 2018). For tropical conditions in Brazil, (CAMARGO; CAMARGO, 2001) defined six phenological phases of Arabica coffee, the first two being vegetative, occurring from September to March and April to August. From the third phase on, the reproductive stage begins with flowering and fruit expansion occurring from September to December. The fourth phase occurs from January to March with the granulation of the fruits. In the fifth and sixth phase occurs the maturation of the fruits and subsequent senescence and death of the non-primary reproductive branches from July to August.

The water requirement is variable according to the phenological phase (BONOMO, 1999). Water deficiency affects mainly the reproductive phase, where there is a high water demand (PETEK; SERA; FONSECA, 2009; CARVALHO, I. R. et al., 2013). Between June and September, harvest and resting phase, the water requirement is small (MATIELLO, 1991). Tosello and Arruda (1962) obtained a satisfactory correlation between rainfall and productivity in coffee growing municipalities in the state of São Paulo in specific months of the year through linear regression. Several agrometeorological models have been studied to estimate coffee yields, including (CAMARGO; PEDRO JUNIOR, et al., 1984; PICINI et al., 1999; CAMARGO; SANTOS, et al., 2003), the last one being based on penalties for water and thermal factors in the phenological phases of the coffee tree using decadal climatological data. According to Santos and Camargo (2006), the highest penalty considered for the water deficit factor is the period from October to January.

The coffee farming in Minas Gerais is marked by the presence of producing regions with distinct characteristics. While the southwestern region of the state uses conventional production, coffee production in the cerrado of Minas Gerais uses modern fertilization and mechanization technologies, in addition to greater presence of irrigation, contributing to higher productivity (ORTEGA; JESUS, 2011; FERNANDES et al., 2012; PEREIRA et al., 2010; EMATER, 2018). The heterogeneity of several factors impacting productivity makes it necessary to divide the producing municipalities into distinct groups for a more appropriate analysis.

With the new future scenarios of climate change, it becomes essential to evaluate the importance of rainfall regime for coffee productivity in Minas Gerais. The objective was to analyze the effect of rainfall during the third phenological phase and the beginning of the fourth phase, specifically from September to January, on Arabica coffee productivity in different municipalities located in all regions of the state of Minas Gerais based on high spatial resolution monthly rainfall data using geocomputation and statistical techniques.

MATERIAL AND METHODS

Characterization of the study area

The state of Minas Gerais occupies an area of 586 513.993 km^2 in the southeastern region of Brazil, being the fourth most extensive in the country and the second most populous with an estimate for 2021 of 21.41 million inhabitants (IBGE, 2021a). In Figure 1 the location and territorial extent of the state is

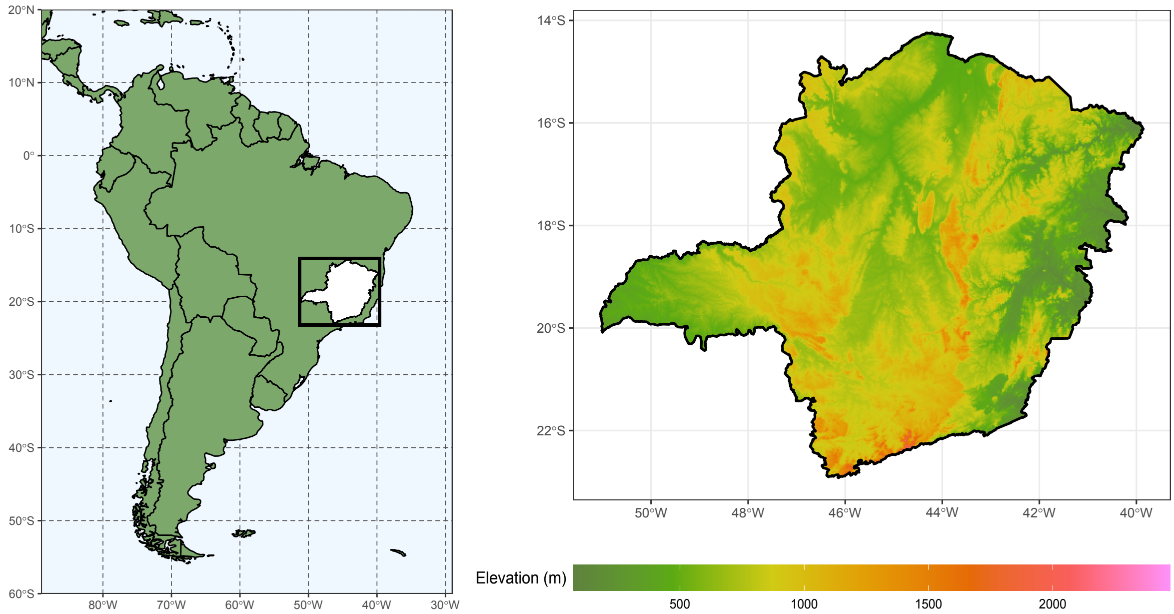

Figure 1: Location of the state of Minas Gerais with elevation map.

observed with the definition of polygon feature with boundaries of the region obtained from the product "gadm36_BRA_1" using the ggplot2 package (WICKHAM et al., 2021) of R. The elevation map of the region was prepared from the Shuttle Radar Topography Mission (SRTM) digital elevation model obtained from the getData function in the R raster package (HIJMANS et al., 2020).

The territory presents considerable climatic complexity with the relief acting with great relevance in the formation of microclimates (ÁVILA et al., 2014) and great variety of environments, such as the biomes of Atlantic Forest, Cerrado and Caatinga (DRUMMOND, 2005). According to Sá Júnior et al. (2012) the state presents the large tropical rainy (A), dry (B) and warm temperate (C) climate groups by Köppen classification, with the Aw, Cwa and Cwb classes occupying 99.89% of its territory. Considering the whole state, the months from October to March are the rainiest, while July is the driest (SILVA; REBOITA, 2013).

Municipal productivity

Based on the municipal agricultural production data (IBGE, 2021a) for the period 2012-2019, the biennial averages of harvested area (ha) and produced quantity (ton) of processed Arabica coffee beans in the periods 2012-2013, 2014-2015, 2016-2017, 2018-2019 were calculated for the Arabica coffee producing municipalities in the state. Scatter plot, linear regression of the data, and mean productivity resulting from the fit were obtained. For the mean municipal productivity, summary statistics (Min.,1st Qu., Median, 3rd Qu., Max., Mean, Boxplot) were determined for the producing municipalities and choropleth maps in the analyzed periods using the sf package of R (PEBESMA, 2018).

Monthly rainfall distribution

Downscaled monthly rainfall data (2010-2018) from the CRU-TS-4.03 database (HARRIS et al., 2014) and made available by WorldClim (FICK; HIJMANS, 2017) at 2.5 minutes spatial resolution were used. Visual representation of monthly precipitation was obtained from a single legend for the biennial means for the periods 2011-2012, 2013-2014 and 2015-2016 with use of the stars (PEBESMA, 2022) package of R.

The period of interest adopted as most significant for coffee productivity was the period comprising the months of September through January. Using the product "Malha municipal 2021" (IBGE, 2021b) and the precipitation data (FICK; HIJMANS, 2017), the average precipitation within each municipality was extracted using the raster package (HIJMANS et al., 2020) of R.

In order to estimate the portion of rainfall that generates direct runoff, the SCS (1972) method was used. The runoff curve number (CN) is a parameter that depends on the characteristics of the soil and its cover, as well as the previous moisture condition. There is a great lack of studies involving the determination of curve number (CN) in Brazilian regions. Thus, we adopted CN values based on tables presented by Tucci (2001). The maximum potential detention (S) can be obtained from the CN according to equation 1.

The runoff coefficient (C) refers to the portion of rainfall that generates runoff and is obtained by the ratio between the effective accumulated rainfall (R_e) and the accumulated precipitation (P). Equation 2 allows estimating the value of Re. The value adopted by CN depends on the previous soil humidity conditions. In case of wet soil, with rainfall in the last five days, the CN_{III} is used. For dry conditions, CNI is used. The CN value for normal conditions that appears in the tables refers to CN_{II}. The value of CNIII can be obtained as a function of the CN value according to equation 3.

$$S = \frac{25400}{CN} - 254 \tag{1}$$

$$R_e = \frac{(P - 0.2S)^2}{(P - 0.2S) + S} \tag{2}$$

$$CN_{III} = \frac{CN_{II}}{0.4036 + 0.0059CN_{II}} \tag{3}$$

The mean value of daily precipitation in January, the rainiest month in the state (SILVA; REBOITA, 2013), was estimated by obtaining data from conventional climatological stations of INMET (National Institute of Meteorology) located in the main coffee growing areas and selected according to data availability, for the period 2000-2020 (Table 1). A mean value of 13.3 mm per rainy day was obtained at the analyzed stations. Thus, a mean accumulated rainfall of 13.3 mm (P) was considered for the calculation of the runoff coefficient (C). The curve number (CN) adopted for coffee areas was 87, considering clay soil, predominant in the state. Due to the high number of rainy days, the previous wet situation (CN_{III}) was considered and the average runoff coefficient for coffee regions was calculated as follows (Table 2). Based on a study by Lemos Filho et al. (2010), the mean monthly reference evapotranspiration (ET0) for the September-January period in the state is approximately 120 mm. In coffee areas the value becomes 138 mm when a crop coefficient of 1.15 is adopted. When employing a runoff coefficient of 0.34 for coffee areas, it is estimated that on average 66% of precipitation is intercepted and the rest generates direct surface runoff. Thus, it was considered that monthly accumulations above 210 mm have a limited effect, since they tend to become surplus to the plant.

The biennial means of rainfall from September to January were calculated for the periods 2011-2012, 2013-2014, and 2015-2016, with each month's rainfall being limited to 210 mm in summation.

$$P_{2011} = P_{\text{sep}} + P_{\text{oct}} + P_{\text{nov}} + P_{\text{dec}} + P_{\text{jan}} \tag{4}$$

where, P2011 is the total precipitation considered for the period of interest (September-January) in 2011 (mm); Psep, the total precipitation for the month of September 2011 (mm) or 210 mm if Psep > 210 mm; and, Pjan, the total precipitation for the month of January 2012 (mm) or 210 mm if Pjan > 210 mm.

$$P_{2011-2012} = \frac{P_{2011} + P_{2012}}{2} \tag{5}$$

where, P2011-2012 is the biennial mean of precipitation of interest considered for the period 2011-2012 (mm).

Based on the biennial means obtained, the visual representation of rainfall for the periods 2011-2012, 2013-2014, 2015-2016 within each municipality was obtained.

Relationship between productivity and precipitation (technification)

Due to the existence of factors other than rainfall that affect productivity, such as

Table 1: January climatological means for the period 2000-2020.

Station	Rainy days	Total precipitation (mm)	Mean compensated temperature (°C)
São Lourenço	19	294	22.1
Lavras	19	286	22.9
Poços de Caldas	20	293	21.2
Caparaó	15	222	22.5
Caratinga	15	189	24.1
Araxá	20	280	22.6
Itamarandiba	15	158	22.4
Unaí	17	195	25.8
Mean	**18**	**240**	**23.0**

Table 2: Runoff coefficient using the SCS method.

CN	CN_{III}	P(mm)	S(mm)	R_e(mm)	C
87	94.9	13.3	13.6	4.6	0.34

management, fertilization, water retention characteristics in the soil, among others, it was proposed to determine the relationship between municipal productivity and the mean rainfall of interest, in order to classify the municipalities based on their technification. More technified coffee regions present higher productivity with less rainfall, while less technified plantations present productivity below the expected potential for favorable rainfall conditions.

For each Arabica coffee producing municipality in the state, the relationship of the biennial mean productivity (years n and (n+1)) and the biennial mean rainfall (years n and (n-1)) occurring within the municipality between September and January was obtained for the periods 2012-2013, 2014-2015, 2016-2017.

$$T_{2012-2013} = \frac{Pd_{2012-2013}}{P_{2011-2012}} \quad (6)$$

where, T2012-2013 is the municipality's technification for the 2012-2013 biennium ($kg\ ha^{-1}\ mm^{-1}$); Pd2012-2013, the mean productivity of the municipality in the 2012-2013 biennium ($kg\ ha^{-1}$); P2011-2012, the biennial mean precipitation of interest considered for the 2011-2012 period (mm).

The population standard deviation of the technifications of the 2012-2013, 2014-2015 and 2016-2017 periods for each municipality and summary statistics (Min.,1st Qu., Median, 3rd Qu., Max., Mean, Boxplot) were calculated for the three biennia, in addition to the means of the municipal technifications for the same periods. Based on the technification means, the municipalities were divided into 4 groups. Only precipitation and productivity were considered to determine municipal technification.

$$\sigma_{\text{mun}} = \sqrt{\sum_{i=1}^{3} \frac{(Ti - \overline{T})^2}{3}} \quad (7)$$

where, σ_{mun} is the standard deviation of the 2012-2013, 2014-2015, 2016-2017 biennial municipality technifications ($kg\ ha^{-1}\ mm^{-1}$); Ti, the biennial municipality technification ($kg\ ha^{-1}\ mm^{-1}$); $\overline{T}$, the mean municipality technification relative to the three biennia analyzed ($kg\ ha^{-1}\ mm^{-1}$).

Regression analysis for groups of municipalities

Coffee crops that adopt adequate irrigation management, in general, present higher yields than rainfed coffee. Besides irrigation, farms can change their level of technification over the years, adopting practices that increase productivity, affecting the results of the analysis.

In order to mitigate the effects of irrigated crops and temporal changes in the level of technification of municipalities in the results, we used a filtering process with the given criteria:

- Municipalities that presented harvested area of less than 200 hectares were removed from the analysis due to the low representativeness of the data and lower reliability of the data; - Municipalities that presented a standard deviation of their technification higher than 0.2 $kg\ ha^{-1}\ mm^{-1}$ were also removed from the analysis for indicating high variation in the technification level of the properties.

After the preliminary filtering process, the remaining municipalities were grouped into 4 distinct technification groups (Table 3) in order to evaluate the relationship between rainfall under the stipulated conditions and productivity, for each group of municipalities. Mapping of the groups of municipalities was performed with the R package tmap (TENNEKES, 2018).

Table 3: Distinct technification groups of municipalities.

Group	Technification range $\overline{T}(kg\ ha^{-1}\ mm^{-1})$
1	110-180
2	180-200
3	200-250
4	250-690

Scatter plots of productivity as a function of the accumulated rainfall of the months of interest were obtained according to the criteria established for each group of municipalities. The data for the biennial averages of rainfall for the periods 2011-2012, 2013-2014, and 2015-2016 were adopted. For productivity, the biennial means of the periods 2012-2013, 2014-2015, 2016-2017 were adopted. Linear regression curves were fitted for the 4 groups of municipalities analyzed and the correlation analyzed through coefficient of determination (R^2) and mean squared deviation.

RESULTS AND DISCUSSION

Municipal productivity

The scatter plot obtained of production as a function of area (Figure 2) showed little disparity of the data. The linear regression fit showed a high R^2 coefficient value, indicating strong correlation between production and harvested area.

Coffee municipalities in the state, in general showed a decrease in biennial productivity from 2012-2013 to 2014-2015, but there was a significant increase in productivity in the 2016-2017 and 2018-2019 biennia (Figure 3). The fact was also observed in the results of the productivity means for the biennia (Table 4).

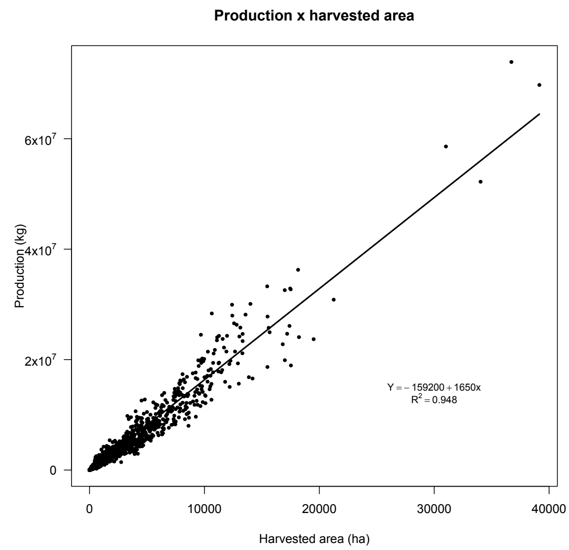

Figure 2: Production estimation based on coffee harvested area (2012-2019).

The boxplot obtained (Figure 4), indicated greater disparity of municipal biennial productions in the 2012-2013 and 2016-2017 biennia, while the 2014-2015 biennium showed the least disparity, which may be associated with rainfall distribution, aiding in the investigation of possible influence on the resulting productivities.

According to Table 4, there was an increase in the minimum municipal productivity values ($kg\ ha^{-1}$) over the biennia. The maximum productivity values, on the other hand, presented alternation.

Table 4: Summary statistics for biennial productivity.

Statistics	2012 -2013	2014 -2015	2016 -2017	2018 -2019
Min.	80	300	333	399
1st Qu.	912	980	1092	1167
Median	1200	1165	1443	1503
Mean	1310	1247	1476	1500
3rd Qu.	1536	1412	1754	1741
Max.	4500	3667	4000	3750
NAś	278	342	347	358

The high value of R^2 (0.948) obtained by the linear fit and the high correlation between planted area and production indicates a typical productivity range in the state. Based on

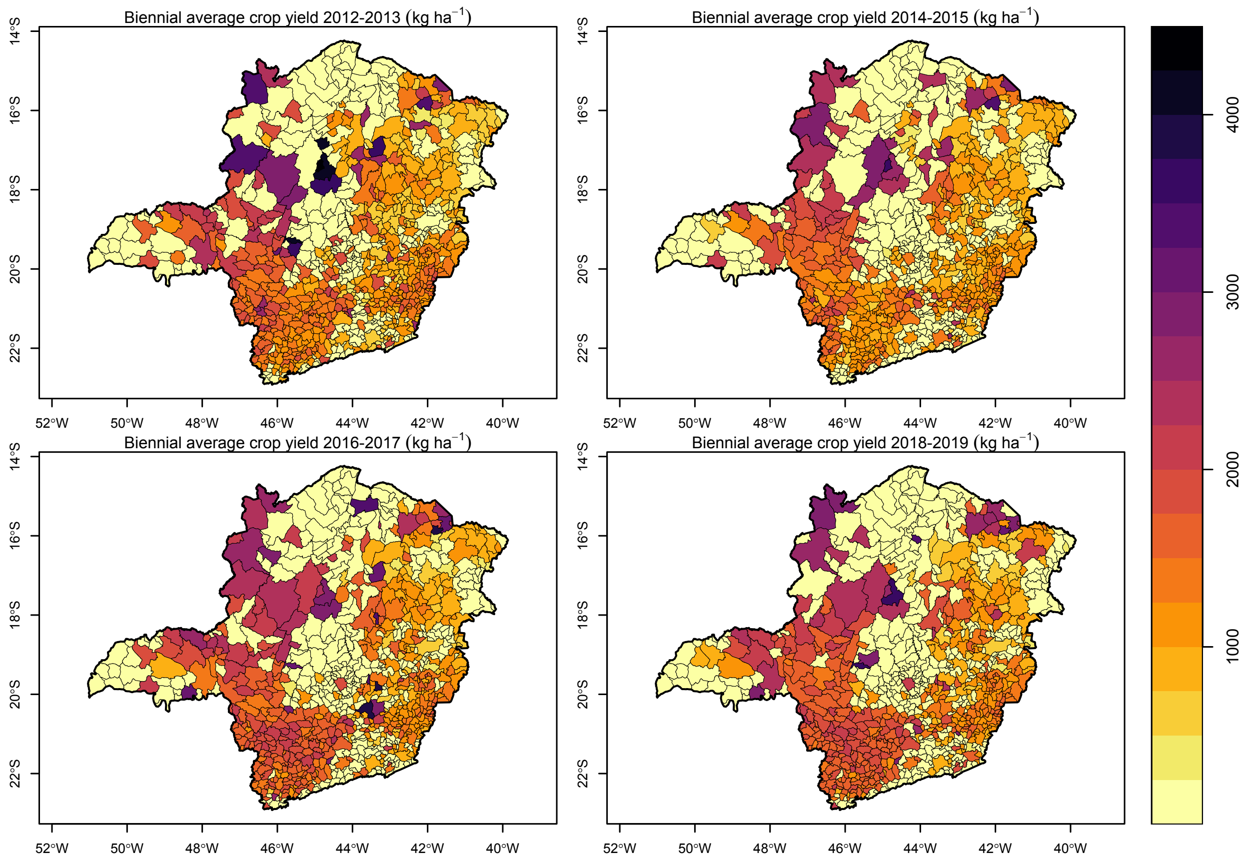

Figure 3: Biennial mean productivity per municipality.

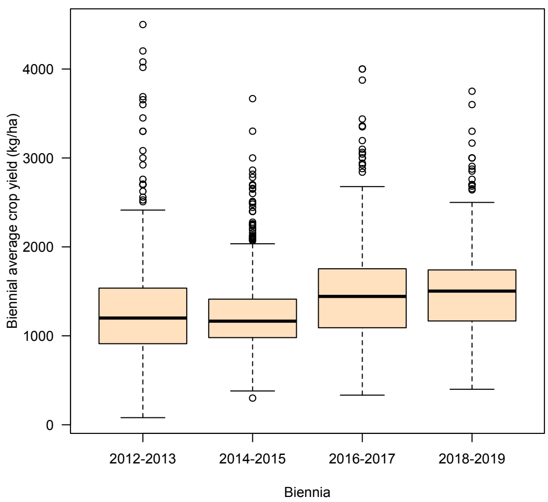

Figure 4: Boxplot for biennial productivity means.

the linear regression equation obtained, the productivity of the fit was 1650 $kg\ ha^{-1}$ or 27.5 bags (60 kg) per hectare of processed coffee in the 2012-2019 period. According to surveys made available in the CONAB crop bulletins , coffee productivity in the state of Minas Gerais ranged from 22.76 to 30.44 bags per hectare between 2013 and 2016. The presence of a typical productivity can be attributed to the search of producers for certain values considered acceptable productivity. Irrigated coffee farming, present in approximately 12% of the coffee growing area of Minas Gerais (FRANCO JUNIOR; GUIMARÃES; CARVALHO, 2019) was not able to make much impact on the production per area ratio when considering the entire state, evidencing the predominance of rainfed coffee farming in production.

Distribution of monthly rainfall

Figures 5, 6, 7 represent the biennial means of monthly precipitation in the state. It was possible to identify in the three biennia the end of the dry period in August, with the rains returning from September onwards, initiating the rainy period. It is also noted that although the start of the rains generally occurs from September on, in some regions the start occurs later, causing the flowering of coffee to occur at different times in different regions of the state.

The biennial mean of accumulations for the September-January period, with monthly

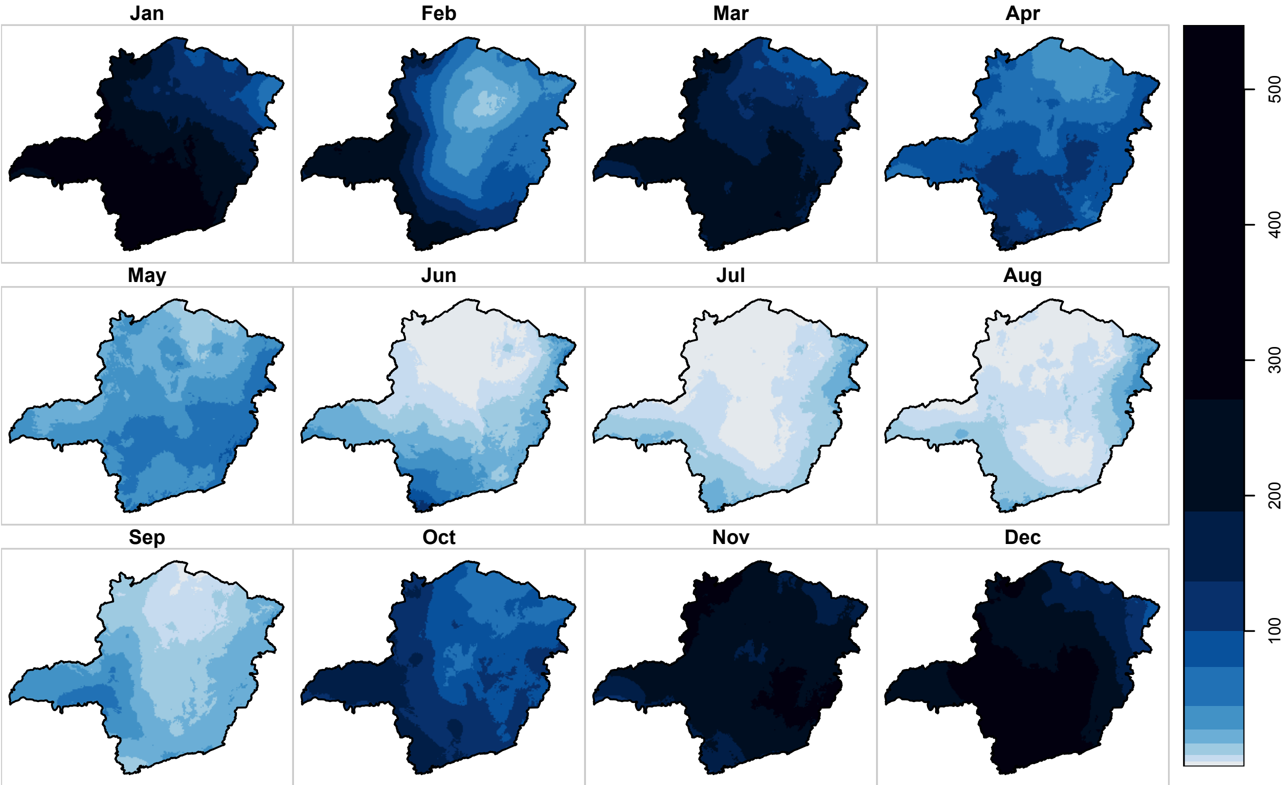

Figure 5: Biennial mean monthly rainfall for the period 2011-2012 (mm).

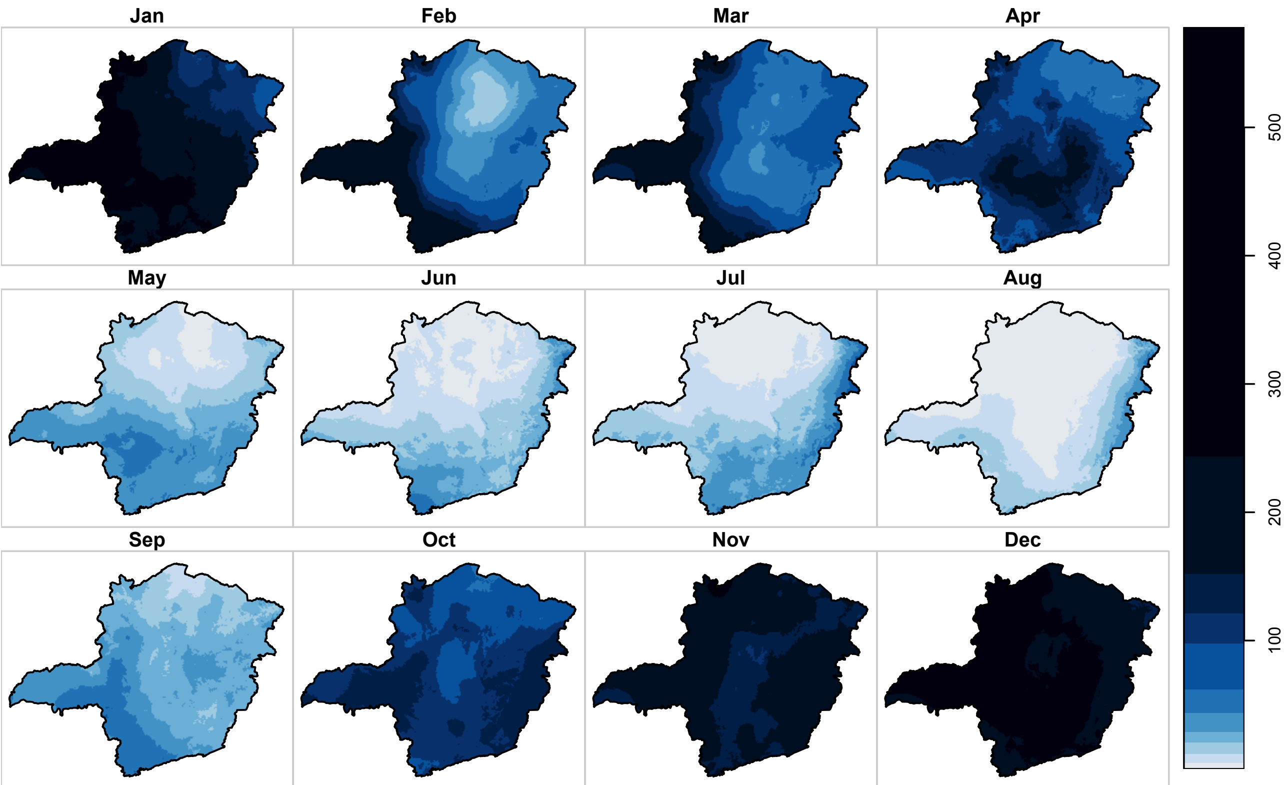

Figure 6: Biennial mean monthly rainfall for the period 2013-2014 (mm).

values limited to 210 mm for the state's municipalities was obtained in the biennia 2011-2012, 2013-2014, and 2015-2016. For the situation analyzed, greater irregularity was identified in the 2015-2016 biennium, especially in the northern region of the state,

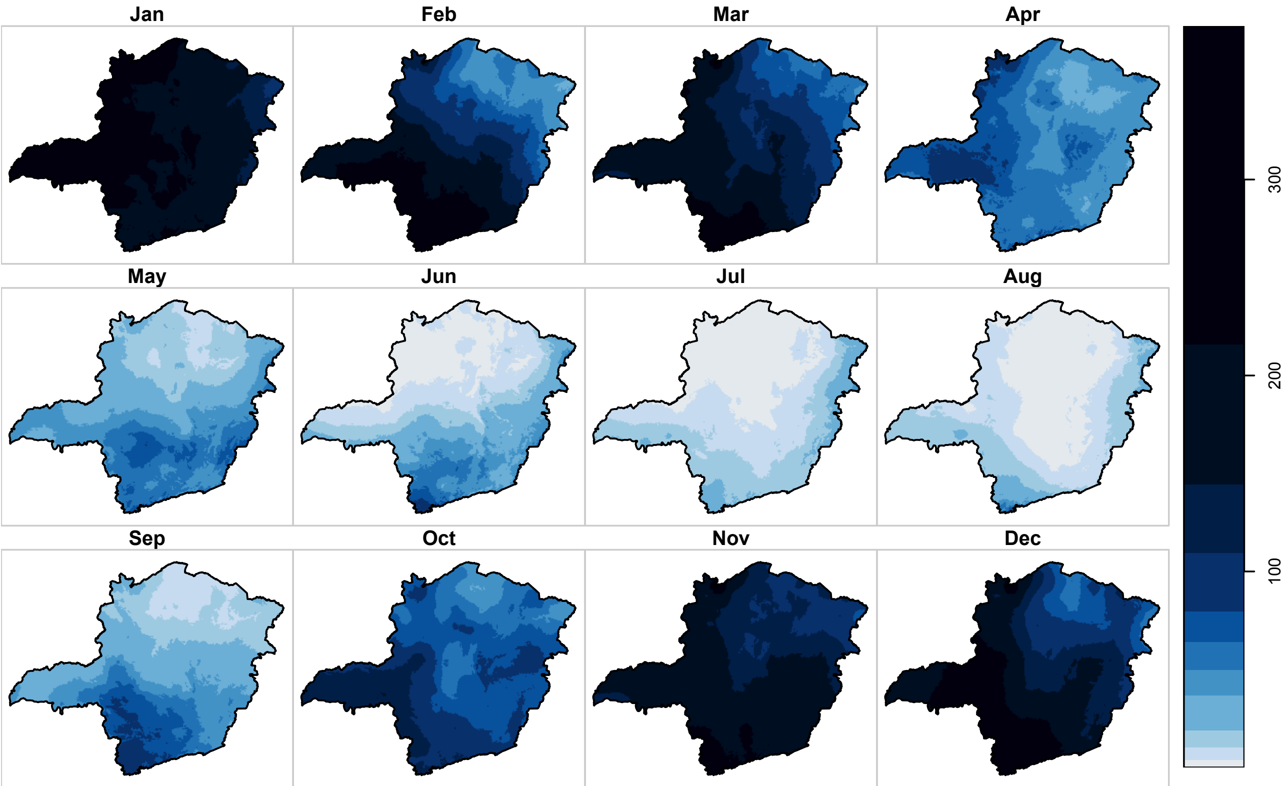

Figure 7: Biennial mean monthly rainfall for the period 2015-2016 (mm).

while in the southern region, there were lower values of accumulations in the 2013-2014 biennium. When analyzing the entire state, the boxplot evidences the greatest uniformity in the 2011-2012 biennium followed by a drop in the mean and an increase in the discrepancy of the values obtained (Figure 8).

Rainfall distribution during the phenological phases of Arabica coffee affects crop production (TOSELLO; ARRUDA, 1962; CAMARGO; CAMARGO, 2001; FAVARIN et al., 2002; CARVALHO, I. R. et al., 2013). Water stress affects mainly the reproductive phase of the crop, where maximum flowering and maturation occurs, presenting a high water demand (CARVALHO, I. R. et al., 2013), which justifies the good correlation found for rainfall from September to January. In all biennials analyzed it was noted that the beginning of the rains after the dry period occurs generally in September. The first rains are important for the beginning of the reproductive phase of the coffee plant. It is known that the availability of water caused by the beginning of the rains is the main inducer of flowering (CAMARGO; CAMARGO, 2001), making the month of September an important starting point in the analysis that was the objective of this work. According to the scheme proposed by Camargo and Camargo (2001), the chumbinho phase and fruit expansion occurs until December, making water availability important in this period. From January starts the granation of the fruits, in which the fruit is transformed into grain and occurs until March. Considering a CAD of 100 mm for the coffee tree, a value that is frequently used in the literature (MEIRELES, 2009) and an maximum average daily ETc of 5 mm in summer for coffee zones in the state, the reserves would be able to sustain 20 days without rain. The month of February showed zones with low accumulations in the 2011-2012, 2013-2014 biennia, indicating the occurrence of veranicos. In the state of Minas Gerais, as well as throughout the intertropical zone, there is the occurrence of interruption of rainfall during the rainy season, a phenomenon called veranicos (MINUZZI et al., 2005). Heavy droughts in the month of February can affect the ripening of the fruit, causing fruit hatching (CAMARGO; CAMARGO, 2001). Monthly accumulations below 100 mm have the potential to cause water deficit. Several areas of the state

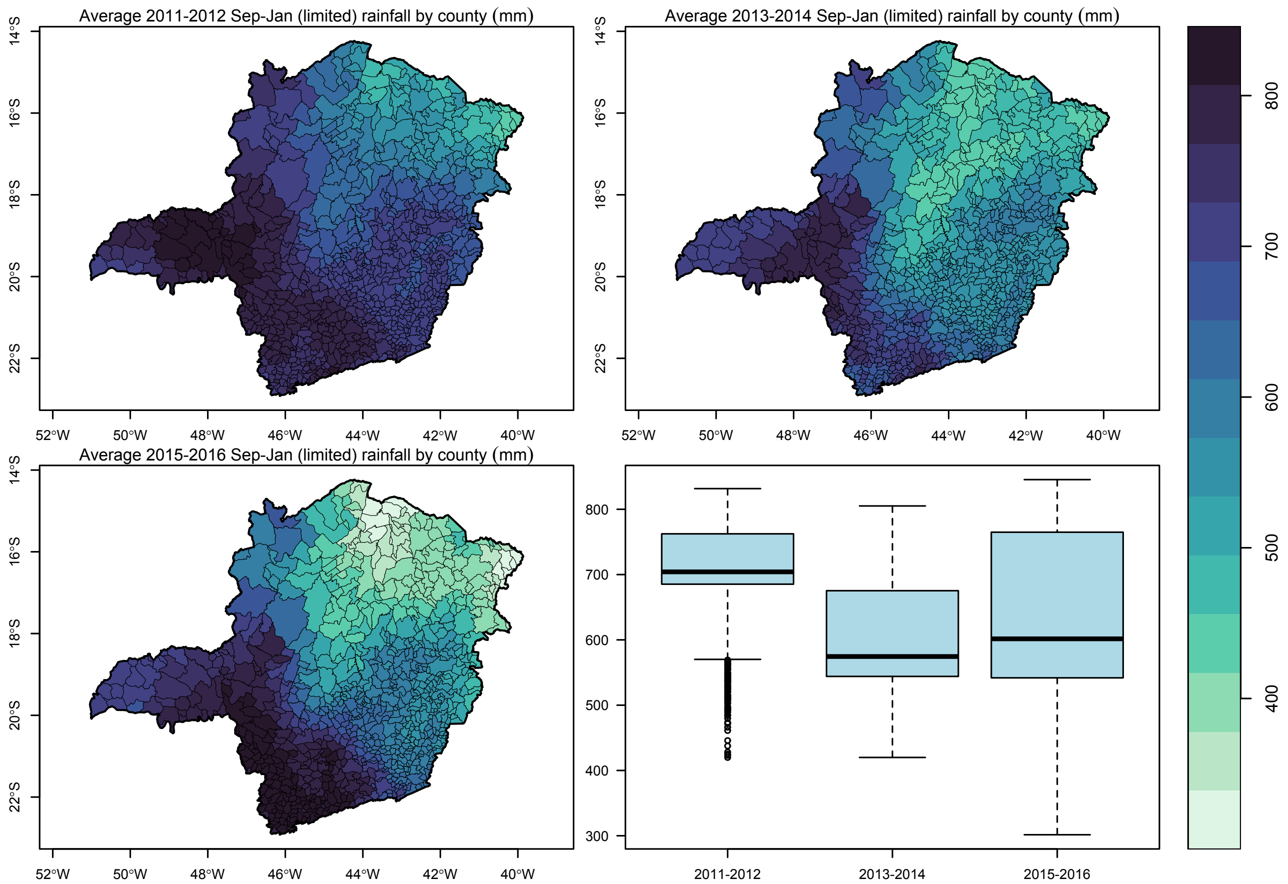

Figure 8: Limited precipitation and boxplot for the analyzed periods (mm).

showed accumulations below 100 mm in the month of February, especially in the central and northern portions in the 2011-2012 and 2013-2014 biennia. Due to the greater development of the root system of coffee trees, veranicos have less potential impact when compared to annual crops although the effect can be felt in cerrado conditions due to soils with low water retention capacity (BONOMO, 1999; LOPES, 1984). Coffee production in the south/southeast of the state and Triangulo Mineiro/Alto Paranaíba regions, which concentrate approximately 65% of production (IBGE, 2018) were not considerably affected by the February veranicos. The results for limited precipitation in the biennia analyzed showed agreement with the information contained in the CONAB coffee harvest bulletins. According to bulletins, in the production cycle started in 2012, the rainfall regime was very supportive. The year 2013 presented favorable water conditions from September to December and the presence of drought in January 2014. From then on, there was irregularity and water scarcity during the year with the occurrence of veranico in January 2015. For the next production cycle there was restriction in practically the entire area of the state in October 2015 and in November in the regions of Zona da Mata, Rio Doce, Central, Norte, Jequitinhonha and Mucuri. From the year of 2016 there were restrictions from September to January in the state. The conditions obtained with the applied methodology, represented in Figure 8, demonstrate in a similar way to that reported in CONAB bulletins, in which conditions were less favorable from the 2013-2014 biennium onwards and a greater discrepancy in the biennium 2015-2016, with the Norte, Jequitinhonha and Mucuri regions being the most affected.

Municipal technification

Higher mean biennial technifications were observed in the northern portion of the state with the presence of high productivity and lower rainfall. The standard deviation of biennial technifications showed scattered changes in the productivity to rainfall ratio in the state, but it was possible to identify a concentration in the central and northeastern portions of the state of higher standard deviation of technifications and absence of large variations in the southern region (Figure 9).

The results obtained from summary statistics (Table 5) showed progressive increases in the biennial means and maximum technification values ($kg\ ha^{-1}\ mm^{-1}$).

Coffee farming in the Minas Gerais cerrado (northwestern portion of the state) was implemented with several technological innovations, having municipalities with high productivity and presence of irrigated coffee growing (ORTEGA; JESUS, 2011; BONOMO, 1999) that enables production in areas of volume or unfavorable rainfall regime, concentrating about 84% of the irrigated coffee park in the state (FRANCO JUNIOR; GUIMARÃES; CARVALHO, 2019; EMATER, 2018). As the cerrado region of Minas Gerais, in general, has an irregular and unfavorable rainfall regime, coffee growers have a greater tendency to adopt irrigation (RONCHI et al., 2015). Similarly, the northern region of the state has also been gaining prominence with its entrepreneurial coffee farming, made possible through modern technologies (MATIELLO; FERNANDES; FERNANDES, 2013). This makes the municipalities in these regions tend to present higher technification values. Coffee municipalities in the south and east of Minas Gerais presented similar technification. The presence of irrigation in southern and eastern Minas is not very expressive in comparison to the cerrado (EMATER, 2018). In general, coffee farming in the south of the state has a large presence of small properties (BROGGIO; DROULERS; GRANDJEAN, 1999) and rugged terrain (VILAS BOAS, 2020), which makes mechanization difficult.

Given the homogeneity of productivity in the state, there are indications that municipalities that have good amounts of rainfall and consequent potential for higher yields, do not take advantage of this potential. Generally, municipalities with adequate rainfall for high productivity do not invest in the technification of farming in order to mitigate the other limiting factors. While municipalities with little rainfall adopt more technification, fertilization, management, etc., which ends up compensating the productivity. Another factor to be considered is the development of coffee diseases, influenced by climatic variables such as humidity and leaf wetness (AGRIOS, 2005; JONES, 1986). Rust *Hemileia vastatrix* Berk. et Br. is the main disease that attacks coffee trees, with the potential to cause losses in production. Its incidence is influenced by biological and meteorological factors, such as air temperature and rainfall distribution and intensity (AKUTSU, 1981). Thus, precipitation is fundamental for the dissemination of pathogens (CAMPBELL; MADDEN, 1990) and consequent interference in productivity, especially in the more humid areas of the state.

The standard deviation of the technifications indicate how much the technification of the municipality has changed over the biennia. In general, technifications tend to increase over time. The high standard deviation observed in municipalities in the north of Minas Gerais suggests the recent advance of high-tech coffee growing in this region. In the Cerrado, despite high technology, the standard deviation was not high, indicating some stagnation in technological advance compared to the north in the analyzed period.

Regression analysis for municipal groups

After classification, we obtained 46 municipalities for group 1, 42 municipalities for group 2, 42 municipalities for group 3, and 14 municipalities for group 4, totaling 144 municipalities in the spatial analysis and 3 biennia in the temporal analysis, resulting in 432 observations. The location of the municipalities and their respective groups are represented in Figure 10.

The linear regression analysis for the four groups of municipalities, considering the biennial productivity means as a function of the biennial precipitation means for the September-January period with monthly values limited to 210 mm are shown in Table 6. The linear model was significant at 1% (***)

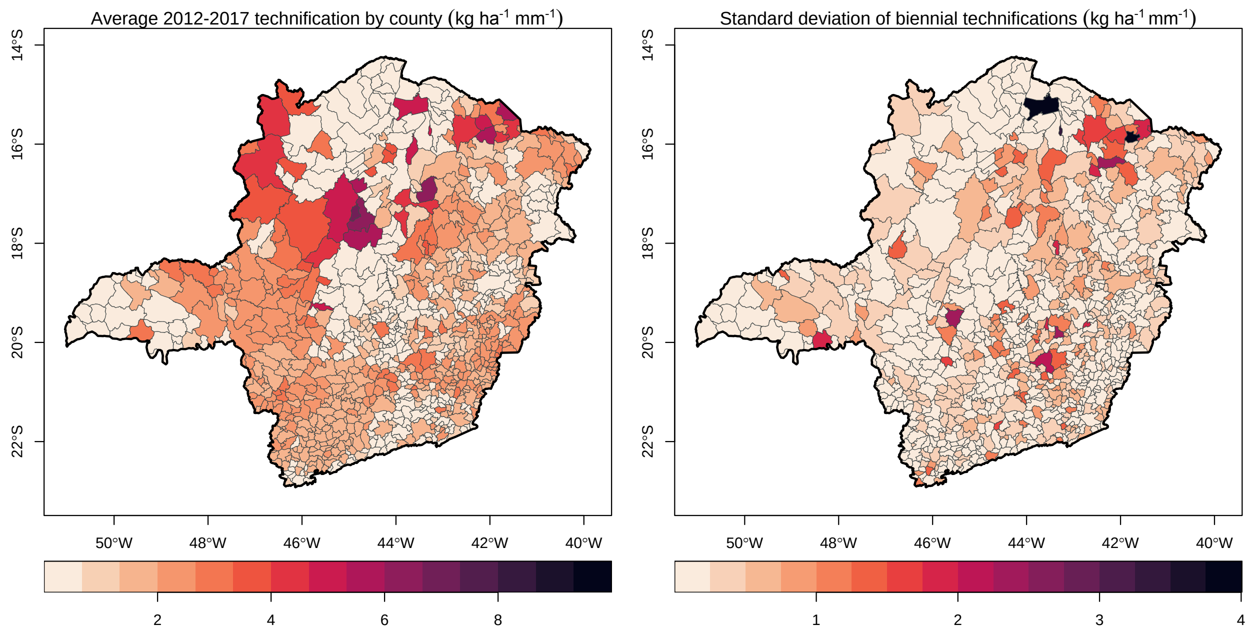

Figure 9: Mean municipal technification and standard deviation of the biennial technifications.

Table 5: Summary statistics for biennial technifications ($kg\ ha^{-1}\ mm^{-1}$).

Statistics	2012 – 2013	2014 – 2015	2016 – 2017	Mean	Standard Deviation
Min.	0.1622	0.6247	0.5973	0.1352	0.01271
1st Qu.	1.3845	1.5907	1.8187	1.3503	0.16477
Median	1.7312	1.9225	2.1013	1.8166	0.28911
Mean	1.8691	2.0865	2.3552	1.8360	0.44464
3rd Qu.	2.1576	2.2944	2.5286	2.2064	0.56104
Max.	7.1636	7.9417	9.9323	6.8419	4.00641
NA's	271	336	344	242	242

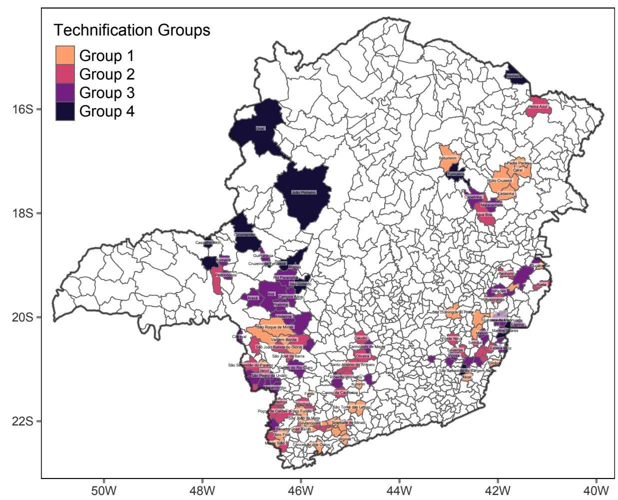

Figure 10: Technification groups.

probability by Student's t test in groups 1, 2 and 3, indicating a strong correlation. For group 4, there was no significant difference.

According to Table 7, group 2 showed the highest level of correlation with a high coefficient value R^2 (0.808) and lowest value of standard deviation of the residual (RSE = 91.5 $kg\ ha^{-1}$). Groups 1 and 2 showed good correlation, with similar values of R^2 and residual standard deviation. Group 4 showed insignificant correlation by Fisher-Snedecor's F-test and almost zero R^2 coefficient value. In Figure 11 the scatter plots and the respective linear regression fits for the groups of municipalities were obtained. It was observed in the scatter plot of group 4 the presence of observations following a linear trend line, but points of very high productivity and low precipitation affected the analysis. The probable reasons will be discussed below. From group 1 to group 3, a progressive increase in the angular coefficients of the lines was obtained. In group 1 there was an increase of 1.75 $kg\ ha^{-1}$ of productivity for each mm of precipitation, while in group 3, the increase was 1.93 $kg\ ha^{-1}$.

Group 2 showed higher correlation of productivity as a function of rainfall mainly

Table 6: Regression analysis for the four groups of municipalities.

Group	Coefficient	Estimated	Standard Error	t-value	Pr(> |t|)
1	β_0	-76.3945	69.8413	-1.094	0.276
1	β_1	1.7500	0.0987	17.731	0.000***
2	β_0	55.4122	56.7921	0.976	0.331
2	β_1	1.8249	0.0799	22.845	0.000***
3	β_0	203.8188	84.1148	2.423	0.017*
3	β_1	1.9305	0.1188	16.249	0.000***
4	β_0	1440.4377	447.3915	3.220	0.002**
4	β_1	0.8802	0.6672	1.319	0.194

[1]Significance level: *** (0.001%), ** (0.01%), * (0.05%).

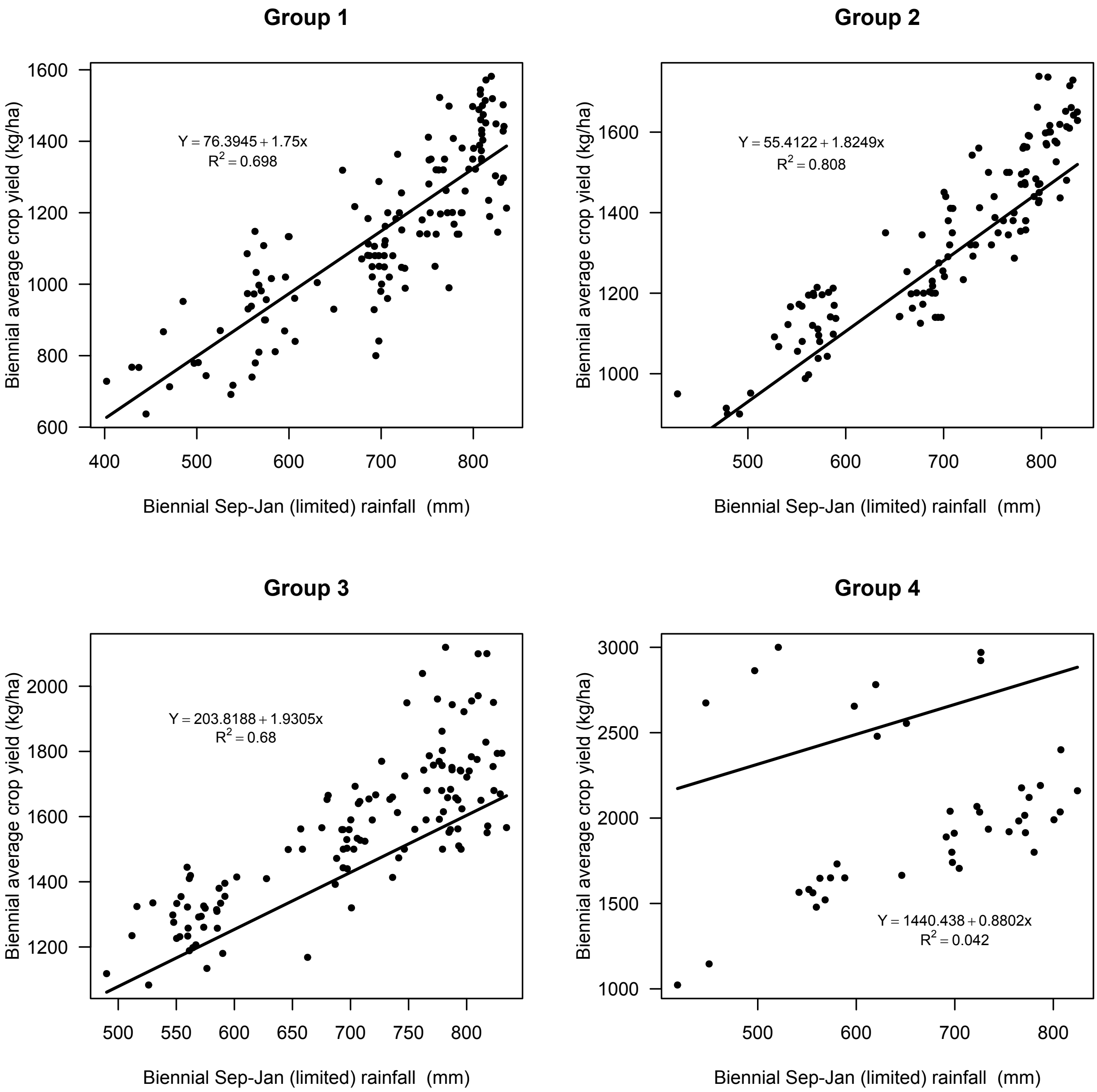

Figure 11: Regression curves for groups of municipalities.

due to the lower technification range adopted for this group (Table 3). The technification range adopted for group 2 (180-200 $kg\ ha^{-1}\ mm^{-1}$) covers the general average of technification in the state (Table 5), which causes a larger amount of municipalities to be close to these

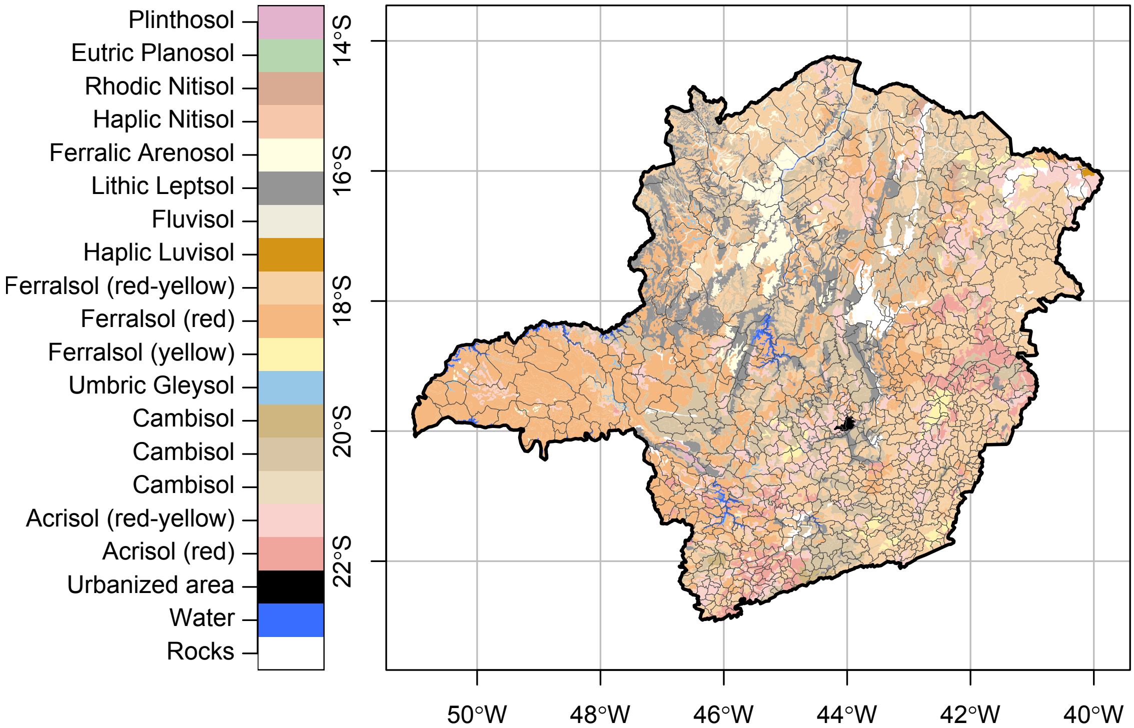

Figure 12: Map of soils of the state of Minas Gerais.

Table 7: Regression uncertainty analysis.

Group	RSE ($kg\ ha^{-1}$)	R^2	F	p-value
1	126.1	0.698	314.4	0.000***
2	91.5	0.808	521.9	0.000***
3	130.0	0.680	264.0	0.000***
4	474.3	0.042	1.7	0.195

[2]Significance level: *** (0.001%), ** (0.01%), * (0.05%).

values. For the other groups, larger ranges were necessary in order to cover a satisfactory amount of municipalities, which reduces the correlation. In relation to group 4, the range adopted was much larger, covering municipalities of high technification with a greater presence of irrigated agriculture. It was possible to observe in group 4 the presence of productivities still dependent on rainfall and totally independent observations with high productivity and low rainfall. These last points refer to municipalities with a high percentage of participation of irrigation in their coffee park, so that the rainfall regime does not significantly affect their productivity.

Among the groups that presented significant correlation, group 1 was of the highest technification range and presented the second best correlation. The results are justifiable because group 1 accounts for the municipalities with lower technification, which naturally tend to be more dependent on rainfall. Group 3, despite the lower technification range adopted, presented a lower correction in relation to group 1. The result was expected due to the greater presence of irrigation in these municipalities in relation to group 1. It is important to emphasize that the maximum effect of irrigation depends on adequate project and management (CONCEIÇÃO et al., 2019), which does not always occur in the properties.

When analyzing the angular coefficients of the significant correlation groups, the results showed that the productivity obtained for each mm of precipitation increases as the technification of the groups increases. This is due to the fact that more technified properties have fewer limiting factors, being able to produce more with less rain and consequently the increase in their productivity is more intense as the accumulations become more favorable.

One of the factors capable of influencing the relationship between productivity and precipitation is the soil in the regions. Latosols are the most common in the state (AMARAL et al., 2004) and have great depths, reasonable storage capacity, but in most cases are dystrophic and have low cation exchange capacity (CEC) (RESENDE et al., 2014). In general, the presence of latosols occurs on higher ground surfaces (plateaus) (RESENDE et al., 2014) where mechanization is generally more feasible and the air temperature is milder, favoring coffee productivity. Based on the soil data of Minas Gerais (FEAM, 2010) (Figure 12), we notice a greater number of municipalities in groups 2 and 3 in areas of latosols, which contributes to greater technification and higher productivity response. When analyzing group 1, its municipalities showed a higher incidence of less developed soils, such as litholic neosols, cambisols and argissolos. As the water storage capacity in less developed soils is reduced, besides the fact that their occurrence is associated with more rugged relief and consequent increase in direct surface runoff, there is a tendency that the effect of rainfall generates lower productivity due to the lower use of water. This fact was observed in group 1, which presented the lowest yield response per mm of rainfall (1.75 $kg\ ha^{-1}$).

CONCLUSIONS

The distribution of rainfall and productivity in the municipalities of Minas Gerais state can be identified, as well as the typical productivity between 2012 and 2019.

The relationship of productivity by precipitation enabled classifying the municipalities into technification groups and identifying their performances in generating productivity according to the volume of precipitated water.

A high correlation was identified between the accumulated September to January monthly values limited to 210 mm and Arabica coffee productivity for 130 municipalities in all regions of Minas Gerais. The used method also allowed the identification of irrigating municipalities, in which there is no significant effect of rainfall on their productivity.

The equations obtained allow estimating the resulting effect of rainfall from January to September on productivity in different environments in a simple and easily applicable way, based only on monthly rainfall data. It is possible to determine, based on productivity and precipitation, the technification value of a coffee-growing location and classify it into one of four groups. This way, the producer will be able to have an estimated quantification of how favorable the rainfall regime was and the impacts on his future production.

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