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ECOSYSTEMS

Exposure To Climate Risk: A Case Study For Coffee Farming In The Region Of Alta Mogiana, São Paulo

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Abstract: Studies around the world show an increase in global average temperatures, with a consequent increase in extreme events and changes in the distribution of precipitation, causing a decrease in agricultural production and changes in planting areas. This study analyzed the exposure to climate risk that the coffee crop in the region of Alta Mogiana/SP, Brazil has been presenting in the past thirty years (1991-2021). Time series of daily data of maximum and minimum temperature and precipitation were used. By the statistical tests we observed a trend of increase in maximum temperatures daily of approximately 1.4°C and minimum daily of 0.8°C in the municipalities of the region and a trend towards a decrease in precipitation of 0.9 mm daily, indicating greater exposure of the coffee crop in the region to climate risk and increased vulnerability for the coffee producer. In view of these analyses, a literature review was carried out, suggesting agroforestry systems and mechanical irrigation as the most promising strategies to manage climate risk in coffee plantations. In addition, drought-resistant cultivars, training courses for farmers, increased rural insurance, and nutritional control of the plants can also be considered efficient options for climate exposure in coffee plantations from Alta Mogiana.

Key words: Agriculture, climate change, climate risk management, coffee tree, Mann-Kendall.

INTRODUCTION

Agriculture is the dominant form of land use globally, involving important economic, social, and cultural activities and providing a wide range of ecosystem services (Shiferaw et al. 2014). However, due to its nature, agriculture remains highly sensitive to climatic variations (Shiferaw et al. 2014) because plants require specific climatic conditions in the phenological stages of plant development, for example, flowering or ripening of fruits. Thus, one can say that “despite technological advances over the past few decades, agricultural production continues to depend on weather and climate” (Santos et al. 2018). About 80% of the variability of agricultural production relates to atmospheric conditions during its cycle, since farmers cannot control natural phenomena (Hoogenboom 2000, Assunção & Wander 2014, Heinemann et al. 2017).

In the 21st century, discussions on the relationship between climate and agriculture have gained great relevance in the context of climate and environmental change. In 2018, the Special Report of the Intergovernmental Panel on Climate Change (IPCC) warned about the impacts of global warming of 1.5°C above pre-industrial levels. These changes can cause environmental and economic damage in various sectors, compromising development and social security (IPCC 2018, 2021) and increasing the vulnerability of certain social groups. Direct impacts of climate change on agricultural activity can affect income and production, among other aspects, and cause changes in geographic distribution, with sectoral and regional repercussions in several economic sectors, thus compromising food security.

In this context, coffee is one of the most important cash crops for the economy of South American countries, with a production in 2019 reaching 32 million tons (FAO 2019). Brazil stands out as the largest producer and exporter of coffee and in 2019, the equivalent of 45 million dollars of this product was exported (FAO 2019). In the Southeast of the country, the states of Minas Gerais, Espírito Santo, and São Paulo accounted for the largest productions in the country in the 2019/2020 biennium (EMBRAPA 2020).

For Brazil, studies (Assad & Pinto 2008, Schaeffer et al. 2008, CEDEPLAR & FIOCRUZ 2008, Marengo et al. 2009) show the negative consequences of climate change, since Brazilian agribusiness has production and export volumes that contribute to the nutrition of several countries, with this sector being one of the most important for the Brazilian trade balance. In a more recent scenario, it has been observed that several natural systems are being affected by regional climate change (Resende et al. 2019). It is assumed that impact from these changes will be greater in the agricultural sector, especially in countries that have agriculture as their primary economic activity (Porfirio et al. 2018), such as Brazil (Tavares et al. 2018, Resende et al. 2019).

The Arabica coffee crop in Brazil is economically viable under specific climatic conditions, with average annual temperatures between 18°C and 23°C and ideal annual temperatures between 19°C and 21°C, average annual rainfall levels between 1.200 mm and 1.800 mm, and altitudes between 400*m* and 1.200*m* (Thomaziello et al. 2000). In addition, rainfall must also have adequate intensity/distribution to promote plant phenological development and crop management (Coffe & Climate 2015). Due to the importance of temperature for the flowering of the coffee bean, only the months of September and October were analyzed regarding the maximum temperature of the series. According to Gornall et al. (2010), extremes of temperature can be decisive in the growth of this crop, especially when they coincide with the main reproductive or vegetative phases of the coffee tree.

In the state of São Paulo, several studies show that climate change is taking place. An increase in the frequency of hotter days (Dufek & Ambrizzi 2008) and a greater number of days with heavy rains (Marengo & Camargo 2009) are some of the examples of changes in weather patterns already identified in the state.

The Alta Mogiana region, located in the West of São Paulo state, has the largest volume of coffee exports (CCCMG 2017). Studies carried out for Franca and Mococa, municipalities that make up the Mogiana Average, showed evidence of change in the rainfall regime, which started to arrive in late October, when the expected month is September (Torres et al. 2020). These changes, therefore, can jointly affect the amount of water available in the soil (Martins et al. 2019), the patterns of evapotranspiration and water balance (Assad et al. 2004, Tanasijevic et al. 2014, Martins et al. 2018). All these changes will harm the sustainability of agricultural systems, as well as the areas suited to crops (Assad et al. 2004, Santos et al. 2017). For coffee,Rodrigues & dos Reis (2014) point out that climate is considered the main influencing factor in the productive performance of the plant and, thus, in the formation of production costs.

It is estimated that more than 80% of coffee-producing farms in the country are family establishments with low adaptive capacity to adverse climatic events, making national coffee production more vulnerable to the effects of climate change, since Brazilian family agriculture accounts for about 37% of that production (Tavares et al. 2018). Coffee growing is an activity that highly depends on climatic conditions and is therefore vulnerable to the effects of climate change. For this reason, studies that seek to discuss ways to increase the adaptive capacity and resilience of agricultural systems are extremely important. When deepening works on the relationship between climate change and society in coffee production, as is the case of this study, one must consider concepts such as vulnerability, sensitivity, adaptive capacity, and exposure, so as to contribute to climate risk management.

Thus, vulnerability can be understood as the propensity of a given population/locality to be affected by climate change due to three fundamental elements: sensitivity, adaptive capacity and exposure (IPCC 2007). Sensitivity refers to how a system can be affected, adversely or not, while adaptive capacity is related to the ability to reduce or prevent damage from the exploitation of beneficial opportunities existing in systems (Obermaier & Rosa 2013). Exposure concerns the presence of people, systems, and their relationships, which can be adversely affected by climate change (IPCC 2007, Obermaier & Rosa 2013).

Due to the complexity surrounding these concepts, indicators and indexes have been widely used in view of their ability to systematize the collection of information and facilitate the visualization of complex phenomena (Quintão et al. 2017, Menezes et al. 2018). Nevertheless, for the construction of these indicators, one must understand the different factors associated with vulnerability, sensitivity, adaptive capacity, and exposure of the studied locations. Authors have been dedicating themselves to understanding how the combination of biophysical, social, geographic, and economic factors may contribute to shaping the risks and susceptibility of populations to climate change. Therefore, there is a set of possible approaches (social, risk-hazard, social ecological) (Adger 2006, Füssel 2007, Cutter & Finch 2008).

The understanding of how much a given location is susceptible to changes in climate dynamics enables the development of climate risk management strategies as an alternative for agricultural producers to adapt, including alternatives for cultivation that will allow them to maintain the quality and productivity of their crops. Thus, the study of climate variables as a means to assess climate conditions is an important tool in climate risk management (Kath et al. 2021).

Based on the assumption that climate change can cause damage to coffee production, this study aimed to analyze, by statistical tests, the exposure to climate risk to which the Alta Mogiana coffee-producing region, in São Paulo, is susceptible. It proposes, based on a literature review, alternative strategies to be adopted by farmers as a way of managing climate risk in the region.

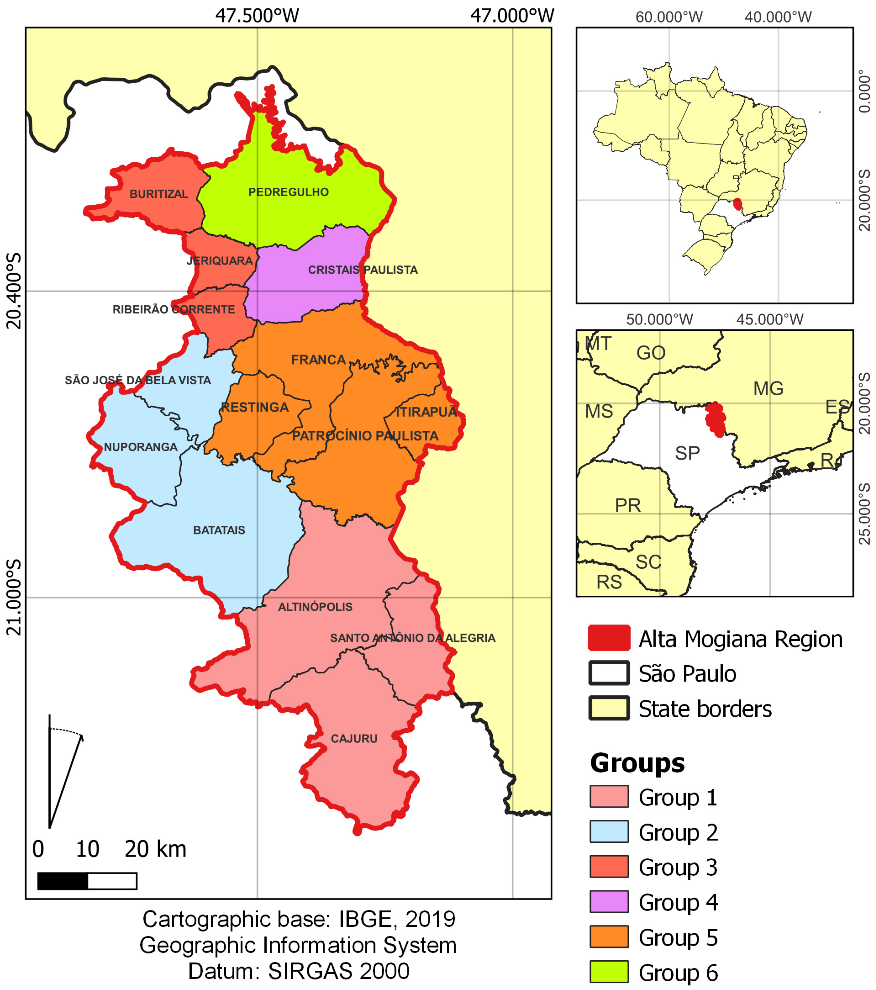
MATERIALS AND METHODS

Study area

The study region called "Alta Mogiana Paulista" is known for concentrating municipalities in the Northwest of São Paulo with altitude above 800*m*, distinguishing itself in the state of São Paulo mainly by the production of excellent quality coffee due to favorable climatic conditions for growing this bean (Faleiros et al. 2020).

The following municipalities stand out: Altinópolis, Batatais, Buritizal, Cajurú, Cristais Paulista, Franca, ltirapuã, Jeriquara, Nuporanga, Patrocínio Paulista, Pedregulho, Restinga, Ribeirão Corrente, Santo Antônio da Alegria, and São José da Bela Vista, as shown in Figure 1.

According to the Köppen climate classification, the Alta Mogiana region has a tropical alternating rainy season climate (Aw), with rainy summers and dry winters (Alvares et al. 2013). For Dubreuil et al. (2019), if one had to choose a typical "Brazilian" climate, it would probably be this one.



Cartographic base: IBGE, 2019
Geographic Information System
Datum: SIRGAS 2000

Figure 1. Location of the study area – Alta Mogiana region in the state of São Paulo – Brazil.

Meteorological data

For this study, daily meteorological data were used, provided by the NASA Power Project, available on www.power.larc.NASA.gov. This NASA project provides a set of surface meteorological and solar radiation data estimated from information and models (Sayago et al. 2020). The NASA's data are widely used in agricultural modeling to understand, for example, the development of agricultural crops (Bai et al. 2010, Van Wart et al. 2015), cultivation simulations (Ojeda et al. 2017), and modeling of planting-related diseases (Savary et al. 2012).

NASA Power data were initially produced on a global grid of ½ degree by ⅔ degree and then crosslinked via bilinear interpolation to a global grid of half degree of longitude by half degree of arc latitude (Sayago et al. 2020). It should be noted that the meteorological data provided by the NASA Power Project are freely available for download (Sparks 2018), expanding this possibility for scientific studies.

In the study area, data were obtained from 6 different grids, which were automatically generated by NASA Power, taking into account the spatial distribution of each municipality in the State of São Paulo. In this case, smallest municipalities were framed together in the same grid, while the largest occupied a single grid, totalizing 15 municipalities that make up the region delimited as Alta Mogiana Paulista.

The 15 municipalities were divided as follows: Group 1: Altinópolis, Cajuru, and Santo Antônio da Alegria; Group 2: Batatais, Nuporanga, and São José da Bela Vista; Group 3: Buritizal, Jeriquara, and Ribeirão Corrente; Group 4: Cristais Paulista; Group 5: Franca, Itirapuã, Patrocínio Paulista, and Restinga; Group 6: Pedregulho. Daily data of maximum temperature, minimum temperature, and precipitation were used, considering the period from January 1991 to January 2021, generating a historical series of 30 years, which is the recommended period for climate analysis according to the World Meteorological Organization (WMO 2019).

Statistical analyses were performed in two stages, which in the first stage daily maximum/minimum temperature and precipitation data were considered for the evaluation of the full period (1991 to 2021). In the second, daily maximum temperature data was considered in the months of September and October (for the full time series), since these months are considered decisive for the growth of the plant as they are marked by the flowering of the coffee bean. For both stages, the data were analyzed for understanding whether there are positive or negative trends that could affect coffee trees. Statistical tests were executed taking into account the climatic and environmental conditions recommended for the proper development of the coffee tree.

Validation of the meteorological data

The data from the NASA Power Project model were validated, comparing the maximum and minimum temperature, as well as precipitation, with data from Xavier et al. (2016), which also refer to a set of meteorological data in high resolution (0.25 × 0.25) grids and which are freely available. The data from Xavier et al. (2016) were considered real data because they are field observations, obtained by meteorological stations and homogenized using advanced interpolation techniques.

The statistical procedure is the most important tool to investigate the quality of fit and accuracy of estimated data compared to measured data (Aboelkhair et al. 2019). Thus, two statistical indexes were applied and executed between the data from NASA and from Xavier et al. (2016).

These statistical measures are Root Mean Square Error (RMSE) (1) and Mean Bias (MB) (2).

$$RMSE = \sum_{i=1}^{n} \frac{(O_i - P_i)^2}{n} \tag{1}$$

$$MB = \sum_{i=1}^{n} \frac{(P_i - O_i)}{n} \tag{2}$$

It should be noted that in the equations presented, P_i is the predicted value (NASA Power model) and O_i is the observed value (values by Xavier et al. (2016)).

RMSE represents the average standard deviation of the model's prediction compared to the observation (Kobayashi & Salam 2000, Bai et al. 2010), and it is important to highlight, in this case, that the differences between prediction and observation are squared, so that this index shows the greatest deviations between one and the other. MB has an equal dimension between predicted and observed values, and its value is interpreted as the mean deviation between the samples (Yaghoubi et al. 2020).

Many studies employ mean square error (MSE) and its rooted variant (RMSE), or mean absolute error (MAE) and its percentage variant (MAPE). Although they are useful, these rates share a common drawback: since their values can range between zero and $+\infty$, a single value of them does not give much information about the performance of the regression with respect to the distribution of the ground truth elements (Yaghoubi et al. 2020).

Statistical tests

The tests for trend analysis in monthly time series aim to build models and analyses by non-parametric tests, being widely used in meteorology to assess the periodicity of phenomena (Morettin & Toloi 2006).

According to Neves (2012), in non-parametric tests, the original values are replaced by a rank order of values to calculate their statistics and are independent of the probability distribution of the studied data. Thus, non-parametric data are recommended for detecting trends in climatological data by the original characteristic of these data, which do not have a normal frequency and present positive asymmetries (Sonali & Nagesh Kumar 2013).

The non-parametric test proposed by Mann (1945) and later adapted by Kendall (1975) verifies the value of the historical series with the other values, always following a sequential ordering process, counting the number of times the remaining terms are greater than the analyzed value.

Therefore, it is based on the rejection or acceptance of a null hypothesis (H_0), giving it the ability to deny or confirm the existence of a trend in the analyzed historical series with a certain significance level (95%).

The Mann-Kendall test, as it is known, can only be applied if the series is serially independent. Thus, the observations of the series are tested to understand whether they are independent and identically distributed, that is, the hypotheses are tested considering that: Hypothesis 0 (H_0): The observations in the series are independent and evenly distributed (there is no trend); Hypothesis 1 (H_1): The observations in the series have a trend over time (there is a trend).

The variable S of the Mann-Kendall test can be obtained by Equations (3) and (4) (Hirsch & Slack 1984):

$$S = \sum_{c=1}^{n-1} \sum_{d=c+1}^{n} sign(x_d - x_c) \tag{3}$$

Considering that:

$$sign(x_d - x_c) = \begin{cases} +1, & x_d > x_c \\ 0, & x_d = x_c \\ -1, & x_d < x_c \end{cases} \tag{4}$$

Where x_c, x_d represent the data points at position c and d, respectively, and n is the size of the data series. The significance level, Z, can be calculated by Equation (5):

$$Z = \begin{cases} S - \frac{1}{\sqrt{Var(S)}}, & S > 0 \\ 0, & S < 0 \\ \frac{(S+1)}{\sqrt{Var(S)}}, & S = 0 \end{cases} \tag{5}$$

In this case, t_c accumulates for t and c denotes the iteration times. In this study, the confidence level was set at 95%.

The Mann-Kendall test is widely used to detect significant trends in meteorological data series, since this test compares the relative importance of sample data, which gives it the advantage of not requiring normalized distribution. Another advantage is its low sensitivity to abrupt interruptions in series (Tabari et al. 2011). If there is a trend observed by the Mann-Kendall test, the Pettitt (1979) test (1979) is applied to characterize abrupt changes in a time series, without restrictions on the probability distribution (Zhang & Lu 2009). The statistical method is calculated by Equation (6):

$$U_{t,r} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sign(x_i - x_j), \quad 1 \leq t < T \tag{6}$$

In this sense, x_i and x_j are data points in the time series of T. $U_{t,T}$, in turn, represents the statistical variable. Thus, the possible abrupt change point K_t can be calculated by Equation (7):

$$K_t = max|U_{t,T}| \tag{7}$$

Meanwhile, the corresponding significance probability p associated with K_t is defined by Equation (8):

$$p = 2\exp\left(\frac{-6K_t^2}{T^3 + T^2}\right) \tag{8}$$

Literature review

To analyze alternative strategies published in the literature that could be adopted by farmers as a means of climate risk management in the region, a literature review. In this sense, the following keywords was used: “Climate Risk Management Coffee”, “Adaptation and Mitigation Coffee” and “Climate Change Coffee” in the Scopus and SciELO databases, where articles published in national and international journals from 2011 to 2021 were selected, totalizing 13 studies in 13 different journals. The studies report research experiences that have shown success in climate change mitigation and adaptation for coffee producing areas. From this research, a summary table was created with the main studies and their respective intervention proposals.

RESULTS AND DISCUSSION

Validation of meteorological data

The results of the RMSE and MB indexes, presented in Figures 2, 3 and 4, showed that the NASA Power model was able to represent the maximum and minimum temperature, as well as the precipitation of the study area.

The RMSE values for maximum temperature were, on average, 2.125°C (Figure 2a), with the highest value recorded at 2.448°C (group 1) and the lowest at 1.738°C (group 5). The MB values for maximum temperature were, on average, 0.840°C (Figure 2b), lower than those observed in the model by Xavier et al. (2016). The highest recorded value was 0.994°C (group 3) and the lowest was —1.224°C (group 1).

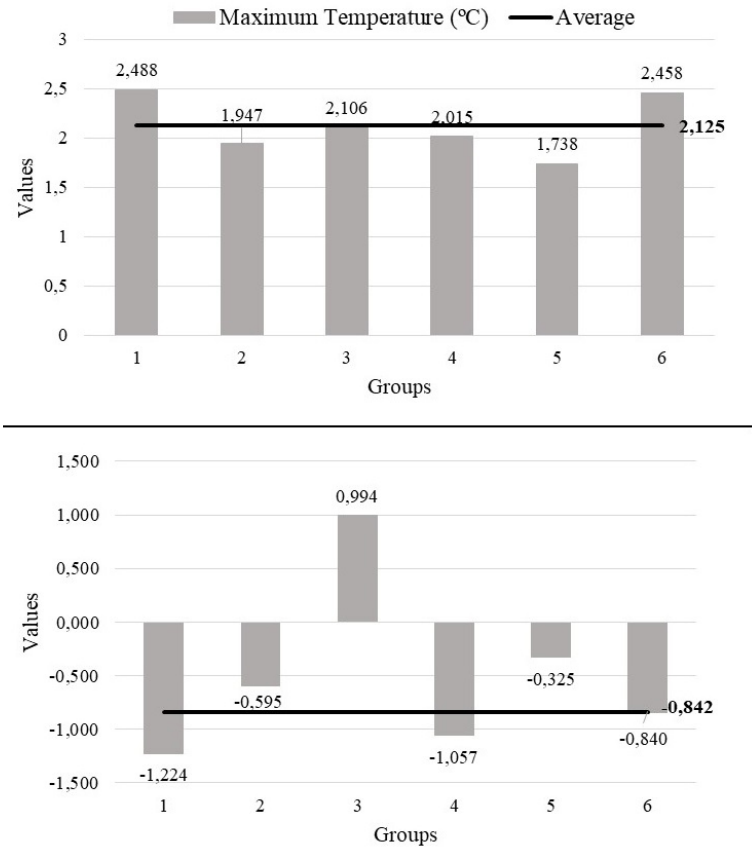


Figure 2. **RMSE (a) and MB (b) values for the study area - maximum temperature (°C).**

For minimum temperature, the average RMSE was 1.396°C(Figure 3a), with the highest value recorded at 1.532°C(group 2) and the lowest at 1.242°C(group 3). In turn, MB presented a value of 0.183°C(Figure 3b), higher than the data from Xavier et al. (2016), on average. The highest recorded value was 0.808°C(group 6) and the lowest was —1.118°C(group 4).

For precipitation, RMSE presented average values of 7.714 mm (Figure 4a), with the highest value at 13.487 mm (group 6) and the lowest at 4.888 mm (group 4). MB had an average value of -0.129 mm (Figure 4b); the highest value was 2.210 mm (group 6) and the lowest was -2.826 mm (group 5).

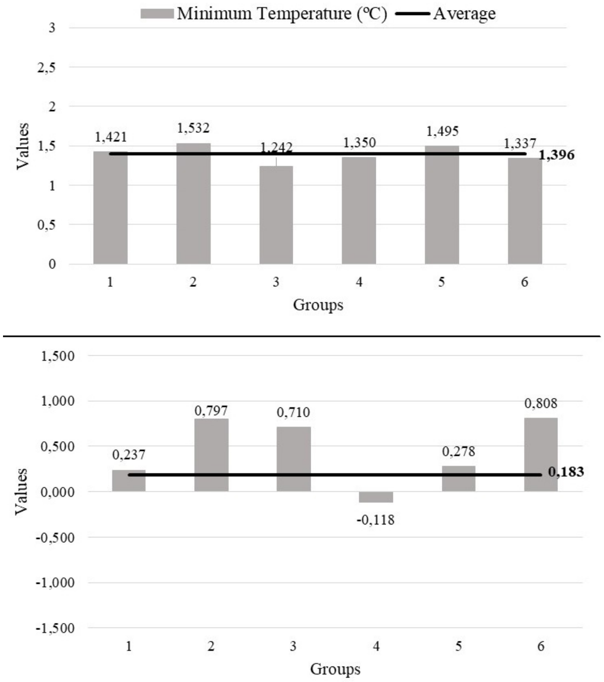


Figure 3. RMSE (a) and MB (b) values for the study area - minimum temperature (°C).

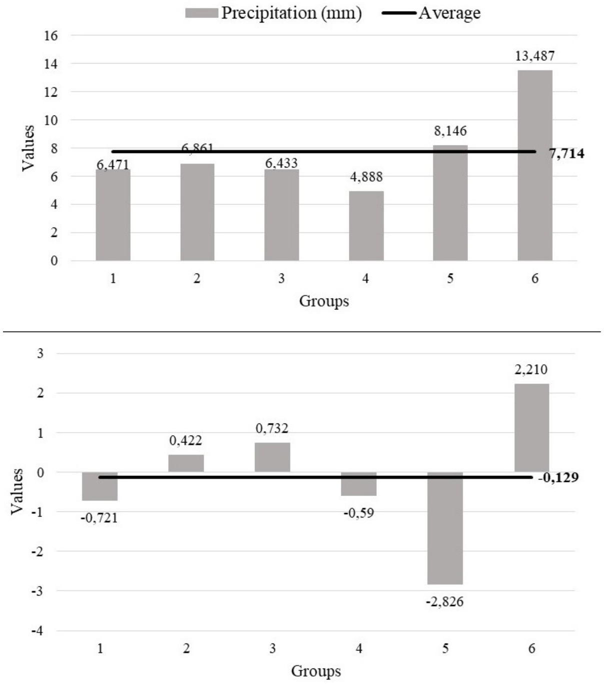


Figure 4. RMSE (a) and MB (b) values for the study area - precipitation (mm).

Despite the variability found between the predicted and observed values, the model was able to reproduce the average behavior of the variables under analysis, as well as their seasonality, indicating the possibility of using data from the NASA Power model for climate studies in this area.

In this sense, it is understood that the model reproduced seasonality satisfactorily, as the values of the analyzed parameters, mainly maximum and minimum temperature, were close to the observed values, showing that in the period of 30 years, the model was able to highlight the different temperatures at different times of the year.

Statistical tests

Table I presents the results from the Mann-Kendall test and Pettitt test regarding the maximum temperature historical series, and Table II shows the results from the minimum temperature historical series. Table III refers to the statistical analysis of precipitation data. All analyzed data had a p-value of < 0.0001, and Sen's slope of 95% indicating high data reliability, including the analysis of trends for the months of coffee flowering presented in Figure 5.

The results of the Mann-Kendall test for daily maximum temperature data in the study area pointed to an increasing trend throughout the analyzed time series (Rejects H_0). For the 6 groups studied, there was, according to the Pettitt test, a break in the data series with an abrupt increase in maximum temperatures in 2012 for the municipality of Pedregulho and in 2013 for the other municipalities that make up the region of study. The average temperatures before and after the series break year can also be seen in Table I. The average temperatures for the municipalities in groups 2, 3 and 4 showed an increase of 1.2 °C from 2012 (group 4) and 2013 (groups 2 and 3), representing an increase of more than 1.0 °C in 23 years of analysis for groups 2 and 3 and 22 years for group 4. In turn, the municipalities of groups 1 and 4 showed an increase in average daily temperature of 1.3 °C for the same period of years.

It is possible to highlight again the municipality of Pedregulho as the one that presented, within the study area, the greatest difference in daily average temperature after the break year (about 1.4 °C). However, it should be noted that Pedregulho is located in group 6, the same one that presented the greatest difference between the data from Xavier et al. (2016) and from NASA. Thus, there are uncertainties regarding the magnitude of this result, although the p-value of < 0.0001 and Sen's slope of 95% are significant values.

Table I. **Mann-Kendall test and Pettitt test values for maximum temperature.**

Municipalities	Group	Kendall's Tau	Interpretation	Temperature before the break year (°C)	Break year	Temperature after the break year (°C)
Altinópolis, Cajuru, and Santo Antônio da Alegria	1	0.111	Rejects H0 (there is a positive trend)	27.7	2013	29.0
Batatais, Nuporanga, and São José da Bela Vista	2	0.100	Rejects H0 (there is a positive trend)	28.5	2013	29.7
Buritizal, Jeriquara, and Ribeirão Corrente	3	0.107	Rejects H0 (there is a positive trend)	28.1	2013	29.3
Cristais Paulista	4	0.111	Rejects H0 (there is a positive trend)	26.9	2012	28.1
Franca, Itirapuã, Patrocínio Paulista, and Restinga	5	0.109	Rejects H0 (there is a positive trend)	27.4	2013	28.7
Pedregulho	6	0.106	Rejects H0 (there is a positive trend)	24.8	2012	26.2

According to the Mann-Kendall test, the minimum temperature series of Alta Mogiana (Table II) also showed an increasing trend. Based on the Pettitt test, a break in the data series, with an increase in minimum temperatures as of 2012 was observed in all municipalities in the region. Unlike the results found in Table I for maximum temperatures before and after the break year, minimum temperatures before the break year (2012) did not present differences greater than 1.0 °C daily compared to temperatures after the break year. The greatest differences were recorded in groups 3 and 5 (0.8 °C daily average), which correspond to the municipalities of Buritizal, Jeriquara, Ribeirão

Corrente, Franca, Itirapuã, Patrocínio Paulista, and Restinga. Groups 1, 2 and 4 showed an increase of 0.7 °C in 22 years while group 6 showed the smallest increase (0.6 °C) within the same period.

Table II. **Mann-Kendall test and Pettitt test values for minimum temperature.**

Municipalities	Group	Kendall's Tau	Interpretation	Temperature before the break year (°C)	Break year	Temperature after the break year (°C)
Altinópolis, Cajuru, and Santo Antônio da Alegria	1	0.061	Rejects H0 (there is a positive trend)	16.3	2012	17.0
Batatais, Nuporanga, and São José da Bela Vista	2	0.061	Rejects H0 (there is a positive trend)	17.2	2012	17.9
Buritizal, Jeriquara, and Ribeirão Corrente	3	0.062	Rejects H0 (there is a positive trend)	17.2	2012	18.0
Cristais Paulista	4	0.062	Rejects H0 (there is a positive trend)	16.3	2012	17.0
Franca, Itirapuã, Patrocínio Paulista, and Restinga	5	0.063	Rejects H0 (there is a positive trend)	16.5	2012	17.3
Pedregulho	6	0.039	Rejects H0 (there is a positive trend)	14.1	2012	14.7

Unlike the maximum/minimum temperature variables analyzed, the Mann-Kendall test for the precipitation series (Table III) presented a negative trend, thus indicating a decrease in daily rainfall in this study area. The Pettitt test showed a break in the data series with a decrease in rainfall in 2004 for group 6, in 2005 for group 1, and in 2007 for the other groups. The greatest difference in rainfall for the data before and after the break year was observed in the municipalities from group 2 (Batatais, Nuporanga, and São José da Bela Vista), where a daily average difference of 0.9 mm was observed. The other municipalities showed differences of 0.8 mm, which represents a difference higher than 0.5 mm of daily precipitation in 17 years of analysis for groups 3, 4 and 5.

From Tables I, II, and III, it is important to emphasize Kendall's Tau, which assumed values between −1 and +1, with a positive correlation indicating that the classifications of both variables increase together (for maximum and minimum temperature). It is observed also that exist a negative correlation observed in the precipitation series indicating that as the classification of one variable increases, the other decreases (Karmeshu 2012). The tests carried out, therefore, suggest that in the past 30 years there has been an increase in daily average minimum and maximum temperatures in the Alta Mogiana region, as well as a drop in daily average rainfall in the region.

Table III. Mann-Kendall test and Pettitt test values for precipitation.

Municipalities	Group	Kendall's Tau	Interpretation	Precipitation before the break year (mm)	Break year	Precipitation after the break year (mm)
Altinópolis, Cajuru, and Santo Antônio da Alegria	1	−0.048	Rejects H0 (there is a negative trend)	4.1	2005	3.3
Batatais, Nuporanga, and São José da Bela Vista	2	−0.043	Rejects H0 (there is a negative trend)	4.2	2007	3.3
Buritizal, Jeriquara, and Ribeirão Corrente	3	−0.045	Rejects H0 (there is a negative trend)	4.3	2007	3.5
Cristais Paulista	4	−0.058	Rejects H0 (there is a negative trend)	4.3	2007	3.5
Franca, Itirapuã, Patrocínio Paulista, and Restinga	5	−0.053	Rejects H0 (there is a negative trend)	4.2	2007	3.4
Pedregulho	6	−0.080	Rejects H0 (there is a negative trend)	4.4	2004	3.6

Analysis of trends for coffee flowering months

Figure 5 presents the results of the analyses carried out for maximum temperatures of coffee flowering months. All the municipalities presented a positive trend (Rejects H_0). Analyzing only the maximum temperatures in the months of September and October in Alta Mogiana, an even more significant increase trend was noticed compared to the total set of maximum temperature data presented in Table I. The Pettitt test indicated a break in the temperature series, with an increase as of 2011 for group 6 and from 2013 for the other groups. Temperatures before and after the break year for group 6 showed a difference of 2.4 °C, the highest compared to the other groups. The other groups showed an increase of 1.9 °C (groups 1, 2 and 5), 2.0 °C (group 4), and 2.1 °C (group 3), representing an average increase of 1.9 in 23 years for flowering months.

It should be noted in this case that the analysis of flowering months suggests that Pedregulho is the most sensitive area to drought and has been more exposed to climate variability since 2011, prior to the period described in Table I, which dated 2012 as the series break year. According to Jaramillo et al. (2011), increase in temperature can cause changes in the location of coffee plantations, as well as an increase in pests of this plant in several areas worldwide, such as Hypothenemus Hampei, better known as "Coffee Drill." For Alfonsi et al. (2019) these changes also lead to an increase in typical coffee diseases, such as rust.

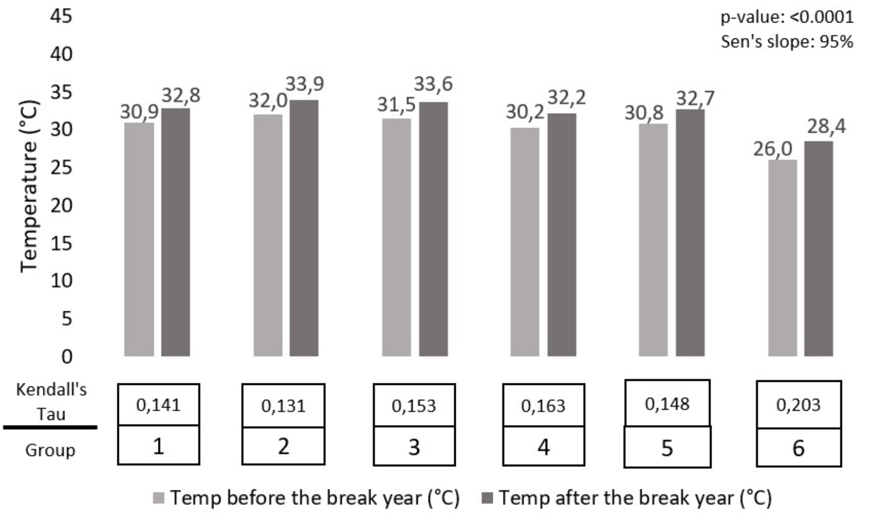


Figure 5. **Mann-Kendall test and Pettitt test values for maximum temperature (months of September and October).**

The Alta Mogiana region still has great economic viability for coffee production (Goes & Chinelato 2018), but its profitability may be harmed by changes in weather patterns observed in the tables presented. For Petek et al. (2009), the combination of temperature and precipitation affects the determination of suitable areas for cultivation. On the one hand, water stress reduces the plant's thermal need, and, on the other hand, excess water requires an increase in temperature to complete the phenological stages, which are decisive for the productivity of the coffee tree (Petek et al. 2009).

A fundamental condition is the dry period of about three months for the induction of the floral bud of coffee plants, which cannot be long, followed by a period of rain to start anthesis, which cannot be long either so as not to affect the fruiting stage. In addition, is necessary mild temperatures, since high temperatures cause physiological changes such as flower absorption (Coffe & Climate 2015). However, the increased drought period observed for the Alta Mogiana region is a harmful factor to Arabica coffee plants, because with a longer dry season period there is damage to the phenological phases of flower bud induction and of the floral bud (Matiello et al. 2010), impairing the final quality of the product.

These observations reinforce the fact that the Arabica coffee crop needs specific and adequate climatic conditions for its development. In a situation of reduced water availability, the coffee plant presents symptoms of leaf wilt, leaf fall, senescence of branches, induced deficiency of nutrients, and root death (Assad et al. 2000). In some regions, it may be necessary to use irrigation (Mesquita et al. 2016). The water deficit condition accelerates the maturation of Arabica coffee fruits, which impairs the development of the different physiological stages of seed formation and later their germination capacity (Petek et al. 2009).

Due to climate change, coffee crop are more susceptible to phenological damage, which will consequently affect farmers. Lower productivity combined with a drop in product quality places them in an economically vulnerable situation. Thus, techniques aimed at managing climate risk are necessary as a means to mitigate financial losses and reduce the vulnerability of Alta Mogiana coffee producers.

Climate risk management for the Alta Mogiana region

In the case of coffee growing, climate risk management can be done at all stages of production, from the selection of beans for planting to post-harvest procedures. For this study, climate risk management can be understood as activities, initiatives, and proposals that contribute to the adaptation of coffee plantations to changes in the region's climate dynamics (Coffe & Climate 2015).

First of all, the use of cultivars that are more resistant to drought events is one of the solutions with the greatest potential for adapting coffee production to climate change (Tavares et al. 2018). In addition, cultivars that are more resistant to pests and diseases will be necessary, since the increase in temperature and the decrease in the amount of precipitation also contribute to the increase in pests and diseases inherent to the coffee tree. Tavares et al. (2018) point out that the interactive or complementary use of agricultural practices with the use of cultivars that are more tolerant to heat and drought can contribute to climate adaptation and, thus, to the sustainability of coffee growing even in areas where there will be climate restrictions in the future.

Another way to increase farmers' resilience is by providing them more information about climate change and ways in which they can adapt (Coffe & Climate 2015). Improving access to early warning systems, such as local climate maps and expert committees, adopting of adaptation as part of the local development strategy, strength farmers' organizations to facilitate and improve access to climate information and other support services (training, investment credit, agricultural insurance, etc.), are ways to prepare producers for future adverse scenarios (Coffe & Climate 2015). One of the examples of strategies for managing climate risk to coffee can be found in Southeastern Minas Gerais, where measures have been adopted focusing on production diversification, off-farm income diversification, increased access to irrigation, and expanded climate-related agricultural insurance (Koh et al. 2020).

The offer of courses to expand climate education for farmers also has positive results. In Australia, for example, the offer of courses related to climate and agriculture showed results such as increased knowledge of farmers regarding meteorological monitoring and climatic effects on production, and greater awareness of future problems related to climate change (George et al. 2009).

Nevertheless, studies carried out in different locations in Brazil (Hernandes et al. 2004, Gonçalves et al. 2021) and in countries such as Mexico (Lin 2006), Nicaragua (López-Sampson et al. 2020), and Colombia (De Leijster et al. 2021) point to the feasibility of using trees intercropped with coffee plantations as an option to reduce climate impacts on the coffee tree. With adequate shading intensity, intercropping can produce larger fruits and increase the productive capacity of coffee trees (Hernandes et al. 2004). Cultivation intercropped with tree crops can increase the amount of phytomass on the soil surface, offering protection against the impact of raindrops and avoiding sudden variations in humidity and temperature, in addition to being directly linked to the development of microbial communities, which are capable of indicating the level of soil degradation (Alvarenga & Martins 2004). In other words, as pointed out by De Leijster et al. (2021), the afforestation of coffee plantations can offer a wide range of long-term ecosystem services. In this context, we can mention an increase in insects such as bees, responsible for crop pollination (Souza & Halak 2012) and a high potential for carbon sequestration, as pointed out by Gonçalves et al. (2021). Thus, for the Alta Mogiana region, agroforestry systems have a great potential to contribute to climate risk management by providing, among other benefits, thermal protection. Since the statistical tests pointed to a trend of temperature increase over the past 30 years in the region, this is of great importance.

In addition to these initiatives, other proposals have been studied as an option for managing climate risk in coffee farming, significantly contributing to expanding the mitigation and adaptation possibilities that farmers will have to adopt in the near future. The wide range of possibilities for managing climate risk is also needed due to the considerable variety of geographical conditions of crops around the world (Pinheiro et al. 2021). Table IV compiles some of the most promising initiatives for adaptation to climate change tested in different coffee producing areas in Brazil and worldwide.

Table IV. Scientific articles showing proposals for climate risk management for coffee growing.

Authors and year	Country where the study was carried out	Main topic addressed	Main conclusions
Hernandes et al. 2004	Brazil	Analysis of solar radiation indices in an agroforestry system	Agroforestry systems can provide thermal comfort to coffee plantations, in addition to increasing production and fruit size.
Sasaki et al. 2013	Brazil	Efficiency of electrostatic spraying on coffee plantations.	Savings in the use of agrochemicals by electrostatic spraying (37% efficiency) can provide a financial margin for investing in climate risk management initiatives.
Gonçalves et al. 2021	Brazil	Carbon sequestration in agroforestry systems	Agroforestry systems have a high potential for carbon sequestration, also contributing to climate change mitigation.
Lopes et al. 2021	Brazil	Smart irrigation	Feasibility of the project on Smart Irrigation of coffee plantations using smartphones for monitoring, contributing to water control in the plantation.
Tavares et al. 2018	Brazil	Consequences of climate change for coffee growing in Brazil	Use of heat and drought-resistant cultivars combined with innovative agricultural practices can minimize the impacts of climate change.
De Leijster et al. 2021	Colombia	Ecosystem services	Agroforestry systems are great enablers of long-term ecosystem services, contributing to environmental preservation.
Koh et al. 2020	Brazil	Climate risk for coffee production in Brazil	Diversification of production/income of the property and expansion of rural climate insurance, protecting the coffee producer from extreme weather events.
Ramírez-Builes & Küsters 2021	Colombia	Plant nutritional control	Nutrition with calcium and potassium showed an increase in plant nutrition. The plant presented greater resilience to biotic (pests) and abiotic (environment/climate) factors.
Tran et al. 2021	Vietnam	Efficiency of irrigation systems	Irrigation systems are more efficient when accompanied by public policies for rural credit and labor qualification. The technique is promising for locations with changes in the standard precipitation distribution.
Varona & Zayas 2016	Cuba	Analysis of the best cost-benefit in coffee irrigation	Irrigation of 52% of the area every 5 days presented the best cost-benefit. The efficient use of water contributes to lower production costs, making room for investments in climate risk management initiatives.
López-Sampson et al. 2020	Nicaragua	Effects of shading on coffee plantation	Agroforestry systems have shown significant benefits to coffee plantations, such as protection from high temperatures that can be a consequence of heat waves.
George et al. 2009	Australia	Results of applying a course focused on climate education for farmers.	The application of courses aimed at climate education for farmers increases their understanding of the subject.
Lin 2006	Mexico	Analysis of indicators of agroforestry systems against climatic events	Agroforestry systems have great potential to reduce the impacts of extreme temperatures on coffee plantations.

The initiatives presented in Table IV have great potential for success in the Alta Mogiana region. The increase in temperatures and the drop in rainfall observed in statistical tests will require farmers to employ new techniques and technologies for coffee crops. Thus, the use of technology, such as irrigation, will be essential to meet the water needs of crops. For Lopes et al. (2021), irrigation in crops can be done in a practical way, with the sole use of a smartphone. In the research, smart irrigation, which aims to supply the plant's water needs at the right time with the correct amount of water, showed savings in water use and greater water control by producers for their plantations, using a smartphone app (Lopes et al. 2021). According to Varona & Zayas (2016), correct irrigation of the coffee plantation at the correct period can lead to a decrease in production costs, as it contributes to the physiological need of the plant at that time. This opens up a financial margin for coffee farmers to invest in new techniques and technologies aimed at managing climate risk. In addition, water control in the plantation is essential for the Alta Mogiana region due to the reduction in rainfall observed in statistical tests, as it avoids wasting water.

However, according to Tran et al. (2021), the expansion of irrigation in a given region must be accompanied by public policies for rural credit, in addition to professional qualification programs, for a better use of the technique. The need to qualify farmers is supported by Sasaki et al. (2013) in the use of electrostatic sprayers, which also requires skilled labor. Such sprayers presented savings in the use of agrochemicals in the plantation, contributing to lessening environmental damage (Sasaki et al. 2013) and, consequently, to mitigating climate change.

Another promising alternative that can be integrated into coffee crops is nutritional control of the plant. For Ramírez-Builes & Küsters (2021), nutrition with calcium and potassium showed a nutritive increase in the plant, causing it to develop greater resistance to biotic factors (such as pests and diseases) and abiotic factors (such as changes in precipitation and temperature) present in the environment. However, it is pointed out that, like smart irrigation and electrostatic spraying, plant nutrition also requires skilled workforce.

CONCLUSION

To analyze the exposure of coffee trees to climate risk in the Alta Mogiana region, one of the most important coffee-producing regions in Brazil, climate trend tests were carried out, which, in general, suggest an increase in maximum and minimum temperatures and a decrease in precipitation during the period 1991-2021. It is possible to say that changes in temperature and precipitation patterns have been occurring in the region within the past 30 years.

Statistical tests showed a trend of increase in daily maximum temperatures in the region, with the highest increase (1.4° C) in the municipality of Pedregulho. The range of maximum temperature increase was 1.2° C to 1.4° C. Daily minimum temperatures also showed an increase, with the municipalities of Buritizal, Jeriquara, Ribeirão Corrente, Franca, Itirapuã, Patrocínio Paulista, and Restinga presenting the highest increase (0.8° C) in the region. The range of minimum temperature increase was 0.6° C to 0.8° C. For the rainfall statistical tests, the highest difference was observed in the municipalities of Batatais, Nuporanga, and São José da Bela Vista, where a daily average difference of 0.9 mm was observed. The other municipalities showed differences of 0.8 mm. These values suggest that the annual rainfall deficit ranges between 292 and 328 mm / rain per year. The maximum temperatures of coffee flowering months also presented an increasing trend, the highest increase (2.4° C) being in the municipality of Pedregulho. This may affect the flowering of the coffee trees and, thus, the quantity and quality of the fruits.

Thus, one can conclude that there is greater exposure of coffee crops to climate risk in the region, corroborating the IPCC reports on climate change already underway on the planet and its potential impacts on agricultural production. Thus, measures must be taken to mitigate losses in production related to the quantity of bags produced and the quality of the fruits.

Thus, from the literature review, it was possible to conclude that despite the greater exposure of coffee cultivation to climate change in Alta Mogiana, possible solutions can be adopted as climate risk management strategies. The literature review pointed to agroforestry systems and the use of irrigation in crops as the most prominent initiatives. Agroforestry systems contribute to the thermal protection of the plant against rising temperatures, in addition to providing ecosystem services such as pollination and environmental preservation, helping mitigate climate change. Crop irrigation was a promising solution for places where changes in the pattern of precipitation distribution have been observed, as inferred from the statistical tests for the Alta Mogiana region. However, other initiatives, such as research on cultivars that are more resistant to drought, pests, and diseases; training courses for farmers; increased credit and rural insurance; and electrostatic spraying and nutritional control of the plant have shown great potential for mitigating climate change.

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