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Coffee crops adaptation to climate change in agroforestry systems with rubber trees in southern Brazil

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ABSTRACT: Adaptation to climate change is a strategy for crops to cope with the scenario of rising temperatures worldwide. In the case of *Coffea arabica* L., the use of agroforestry systems (AFS) with woody species is a promising practice to reduce excessive heat during the day. This study aimed to 1) evaluate air temperature changes that occur in an AFS of coffee and double alleys of rubber trees (*Hevea brasiliensis* Müell. Arg.) and 2) carry out an analysis of future warming scenarios by comparing the cultivation of Arabic coffee in full sun and in an AFS of double alleys of rubber trees. The microclimatic variables were measured between two rows of coffee trees at 1.0 m of height from June 2016 to June 2018. The results indicate that the AFS with double alleys of rubber trees spaced 16 m apart had an average temperature reduction from 1.4 to 2.5 °C from 10h00 to 16h00. The study also simulated temperature increases of 1.7, 2.6, 3.1, and 4.8 °C from 2018 to 2099, according to scenarios predicted by the Intergovernmental Panel on Climate Change (IPCC), and the impact in coffee production in Paraná State, Brazil. Using the climatic generator PGECLIMA_R, simulations suggest a progressive reduction of traditional areas suitable for open-grown coffee in the state. Production conditions can be maintained through the AFS, since the systems attenuate mean temperatures by 1-2 °C. We conclude that the AFS of coffee and rubber trees contribute to coffee crop adaptations to a future warmer environment.
Keywords: Microclimate, shading, temperature, global warming, zoning

Introduction

Global climate change is a reality with significant impacts on agricultural areas worldwide (IPCC, 2014). The Paris Climate Agreement recommended a series of measures to keep global warming below 2 °C and suggested various efforts, including mitigation and adaptation strategies to limit the global temperature increase to 1.5 °C by the end of the 21st century (United Nations, 2015; Dimitrov, 2016). Agriculture plays a vital role in greenhouse gas (GHG) emissions and thus more sustainable production systems can contribute to reductions of GHG emissions as well as to crop adaptations to a future warmer environment (IPCC, 2019). Adaptation measures should focus on ensuring crop productivity, given the difficulties in reducing GHG emissions and the impacts already underway. Implementing of adaptive measures to cope with global warming and ensure agricultural yield by 2050 could avoid emissions of about 15 GT CO2e (Gourdji et al., 2013). However, the difficulty to adopt adaptation measures lies in the scarcity of empirical studies to demonstrate the efficiency of sustainable practices (Panda, 2018).

According to scenarios presented by IPCC (2014), global temperature is expected to increase between 1.7 and 4.8 °C until the end of the century. Coffee will be one of the most affected species by global warming, mainly *Coffea arabica* L., which is very sensitive to high temperatures. Temperatures above 30 °C are associated to depressed growth, leaf yellowing, tumors at the stem base, and they may cause flower abortion when associated to water stress for prolonged periods (DaMatta, 2004; DaMatta and Ramalho, 2006). In addition, high temperatures during the reproductive period accelerate fruit development, intensifying the demand for nutrients, increasing water stress, and depleting the quality of coffee beans and the coffee drink (DaMatta, 2004). In a future warmer environment, studies have pointed to profound changes in the geographic distribution of cultivated areas (Bunn et al., 2015; Ovalle-Rivera, 2015).

The agroforestry systems (AFS) are recommended as an alternative to increase crop sustainability, add income to producers, and increase the stock of sequestered carbon (Zaro et al., 2020). In addition, the AFS may contribute to a reduction of temperatures during the warmest periods of the year (Gomes et al., 2020). Rubber trees (*Hevea brasiliensis* Müell. Arg.) can generate additional income to producers while showing little competition with coffee trees in the upper soil layers, due to their characteristics of adaptation, rusticity, upright crown, and deep root system (Zaro et al., 2020; Nunes et al., 2021).

Our work analyzes microclimate changes in an AFS consisting of coffee and rubber trees in a traditional cultivation region of southern Brazil. We further explore the zoning of open-grown and AFS-grown coffee in the same region considering future warming scenarios foreseen by the IPCC. The results can drive future policymaking and encourage the adoption of new cultivation practices to maintain the productive potential and quality of coffee in traditional planting regions.

Material and Methods

Microclimate analysis

The study was carried out in a 16-year-old AFS of coffee and rubber trees in Londrina, Paraná State (Brazil) (23°23′ S, 50°11′ W, altitude 610 m). The climate is a typical Cfa, described as a humid subtropical climate with hot summers, according to the Köppen classification (Alvares et al., 2013). According to historical records from a weather station next to the site, the mean annual temperature is 21.1 °C, the mean of the hottest month is 23.9 °C (Jan) and the mean of the coldest month is 16.9 °C (July). The mean annual precipitation is 1,641 mm, with Dec, Jan, and Feb as the rainiest months, and June, July, and Aug as the driest months. The soil at the site is classified as Typic Rhodic Haplustox, according to USDA soil taxonomy and Rhodic Ferralsol according to the FAO classification.

The coffee cultivar used was IAPAR 59. Coffee seedlings were planted spaced 2.5 m between rows by 0.8 m in the rows, with one plant per hole in Feb 2000, composing a population of 4,500 plants ha^{-1}. Perpendicular to the coffee tree rows, double alleys of rubber trees clone PB 235 were planted at every 16 m spaced 4.0 m between alleys by 2.5 m in May of 1999, resulting in 500 plants ha^{-1}. A plot of open-grown coffee was simultaneously implanted in a contiguous area for comparison. The experiment comprised a randomized complete block design with two treatments and four replications. During the study period, coffee trees showed around 1.5 to 2.0 m and rubber trees 18 to 20 m in height. The rubber trees had partial leaf fall of 30 to 50 % during autumn and winter, depending on water deficit and temperature of each year evaluated. Figure 1 illustrates the experimental site and shows the rubber tree alleys (A) and a weather station installed between the coffee rows (B). Three automatic meteorological stations continuously measured air temperature. The first station was installed between the double alleys of rubber trees to measure the temperature at the AFS. The second was installed under the canopy of two rubber trees inside the double alley to measure the temperature in the shaded area. The third was installed in a contiguous open-grown area. The measurements in open-grown and under the double alleys served as a reference to verify the changes in the AFS, recommended for crops. Air temperature was measured at the height of 1.0 m, with copper-constantan thermocouple sensors.

The data was collected from June 2016 to June 2018. Day temperatures were considered from 10h00 to 16h00 and night temperatures from 22h00 to 6h00. Readings were taken every 10 s and averages were calculated every 15 min. Data was stored in a datalogger, transferred to spreadsheets for further

Figure 1 – (A) Double alleys of rubber trees intercropped with coffee trees. (B) Automatic weather station installed at the mean distance between the double alleys spaced 16 m apart. Source: the authors (2018).

analysis and then compiled and processed to obtain the average temperature in 24 h, 10h00 to 16h00 and 22h00 to 6h00. Temperatures were grouped by seasons and comparisons were made between open-grown, the AFS, and under the double alleys of rubber trees. Data was then submitted to an exploratory analysis using box plots, obtaining quartiles 25 %, 50 % (median), 75 %, lower limit (10 %), and upper limit (90 %). The temperature differences measured at the stations under the double alleys of rubber trees and spaced 16 m apart were then analyzed for each year season by comparing each temperature with means from the open-grown, using the t test paired with a significance level of 5 %.

Changes in climate risk zoning

In order to conduct an agroclimatic risk zoning for arabica coffee, we based our analysis on projections of temperature increases due to global warming of 1.7, 2.6, 3.1, and 4.8 °C until the end of the 21st century, as predicted by the IPCC (2014). Data was obtained from 35 automatic meteorological stations, with an observation period from 2000 to 2017 (Figure 2). Disturbances in the data series were carried out with the PGECLIMA_R climate scenario generator (Virgens Filho et al., 2013), a tool that has already been used in several studies to simulate changes in climate data series. The program adjusts the data series considering climatic variabilities caused by large-scale phenomena, such as the El Niño Southern Oscillation, and then projects the daily values until the end of the 21st century based on the temperature increases specified by the user.

The impact studies were based on the current zoning of climatic risk of coffee cultivation in Paraná (Caramori et al., 2001), which is used to guide coffee planting in the state. Since the focus of our study is on the warming effect due to climate change, the critical annual average temperature was used as a parameter to define the areas not recommended for cultivation.

The zoning for the current climate was classified according to three classes of aptitude (Caramori et al., 2001): (i) Apt, for areas with average temperature between 19 and 23 °C; (ii) Marginal, for areas with average temperature between 23 and 24 °C; and (iii) Inapt, for areas with average temperature above 24 °C.

Considering that heating stress to coffee trees happens during the day, the average of daily temperatures from 10h00 to 16h00 is more representative than the 24 h average. A regression was undertaken between the values of temperature averages in 24 h and the daily temperatures from 10h00 to 16h00, using hourly data from 2000 to 2017 from the stations of Londrina (23°22′ S, 51°10′ W, altitude 585 m), Apucarana (23°30′ S, 51°32′ W, altitude 746 m), Maringá (23°25′ S, 51°56′ W, altitude 556 m), Paranavaí (23°05′ S, 52°26′ W, altitude 480 m) and Umuarana (23°44′ S, 53°17′ W, altitude 480 m) (Figure 2).

Based on the temperatures of each weather station, multiple linear regression equations were generated between the average temperature from 10h00 to 16h00 corrected for 24 h with altitude, latitude, and longitude thus obtaining estimation equations of the type: y = a + x.lat + y .long + z.alt. The digital model of the Shuttle Radar Topography Mission (SRTM) terrain with a resolution of 90 m over Paraná State was transferred to

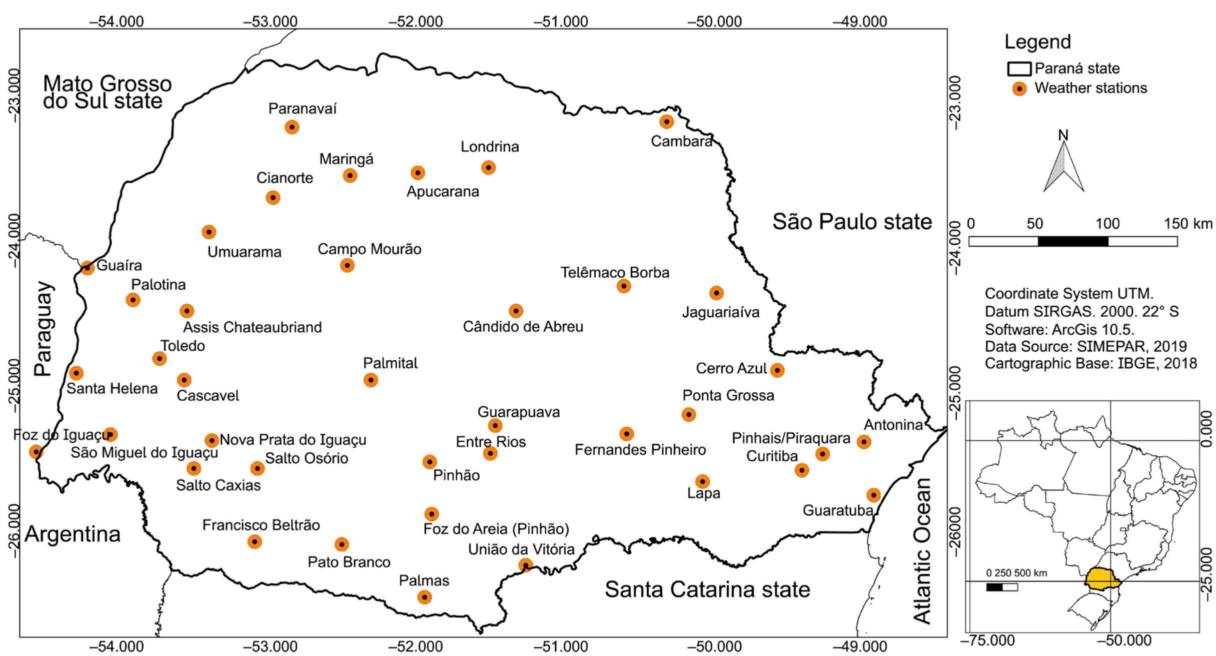

Figure 2 – Network of automatic weather stations from Meteorological System of Paraná State (SIMEPAR) in Paraná State, Brazil. Source: the authors (2019).

the ArcGis Geographic Information System version 10.2 and the estimation equations were solved for each pixel, generating the adjusted maps of temperature.

Next, the areas apt and inapt for cultivation in the different climatic scenarios were established, assigning to each pixel the value 1 for apt mean temperature lower than or equal to 24 °C, and 2 for inapt mean temperature higher than 24 °C . The final map of the agroclimatic risk zoning of coffee for each scenario estimates the representative areas apt and inapt for cultivation. Based on the average values attenuated with the AFS with rubber trees, the temperature values of each of the four simulated scenarios were reduced, generating zoning maps for coffee in the AFS with rubber trees for the periods 2018–2058 and 2059–2099.

Results and Discussion

Microclimate analysis

The exploratory analyses of air temperature differences using boxplots for the four seasons of the year are shown in Figures 3A, 3B, and 3C. The analyses consider values for daytime from 10h00 to 16h00, night time from 22h00 to 6h00, and for the average of 24 h. Comparisons were made in pairs of each of the two rubber tree environments related to open-grown. Boxplots show the median for each pair, quartiles 25 % and 75 %, minimum and maximum. Results show that the two environments containing rubber trees caused differences in temperatures throughout the year.

Observations during the day (10h00 to 16h00) show higher temperatures in open-grown, resulting in positive differences. The median values show air temperature differences from 1.0 °C to 2.0 °C for the double alleys of rubber trees spaced 16 m apart (AFS), and differences of up to 4 °C under the double alleys of rubber trees. On the other hand, the AFS remain warmer during the night due to the partial interception of heat emission by the surface, resulting in minor positive or negative differences. Thus, when the average temperature of 24 h is considered, the values are attenuated by the nocturnal condition, resulting in smaller differences between open-grown and the AFS. The historical data series usually considers the average temperature of day and night periods. In scenarios of climate change, the high temperatures that occur during the day may become restrictive.

Table 1 shows the comparison of the average air temperatures at 1.0 m above the ground during different seasons. The tests are paired through the t test, comparing the measurements under the double alleys (shade), or between double alleys spaced 16 m apart (AFS) with the open-grown cultivation. In most comparisons, both environments with rubber trees presented lower values during the summer in relation

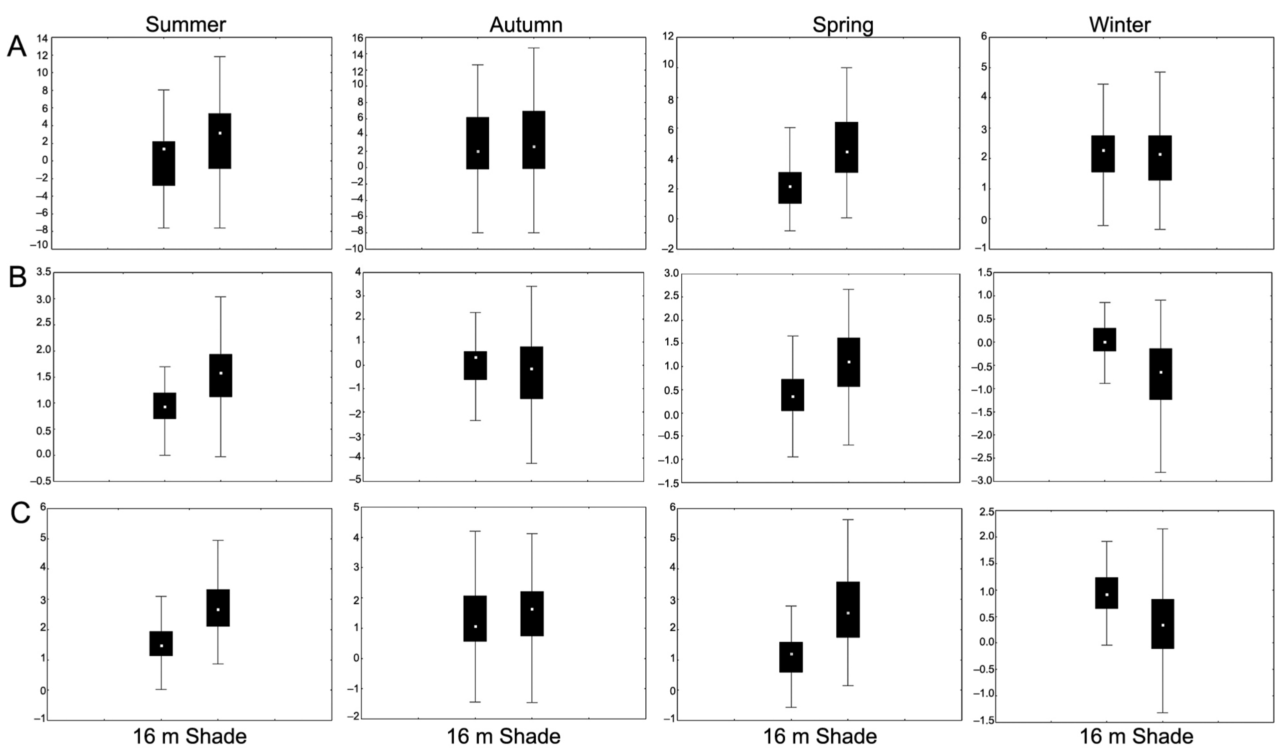

Figure 3 – Boxplot graphs of the average temperature differences between the open-grown compared to the agroforestry systems (AFS) of rubber trees in double alleys spaced 16 m (16 m) and under two alleys of rubber trees (shade), 1.0 m of height, from 10h00 to 16h00 (A), 22h00 to 6h00 (B), and 24 h (C). June 2016 to June 2018. Londrina, Paraná State, Brazil.

to the cultivation in the open-grown system in most comparisons. During autumn, winter, and spring, temperature increases within the environments with rubber trees were observed only during the day. Results from the winter season revealed temperature differences during the night period, while no differences were registered through autumn in the same period, possibly because shaded coffee trees have a higher fraction of the heat radiated intercepted. Morais et al. (2006) studied microclimate characterization in coffee trees shaded with pigeon pea (*Cajanus cajan*) and found that air temperatures were between 1 and 4 °C higher under the shade of pigeon pea at night when compared to coffee plants exposed to open sky.

The average temperature differences varied between 1.4 and 2.5 °C throughout the year, with more significant differences observed during summer and spring. Studies on the AFS with green dwarf coconut (*Cocos nucifera* L.), banana (*Musa* L.), and macadamia (*Macadamia* F.Muell) under varying shading conditions report a reduction in maximum daytime temperatures from 3 to 5 °C due to the interception of incident solar radiation (Pezzopane et al., 2007; Pezzopane et al., 2011). The changing intensity in the microclimate depends on the species and planting density. Several studies have shown that dense shading reduces coffee productivity and is economically unviable (Araújo et al., 2016; Morais et al., 2006). Shading with a maximum interception from 25 to 40 % of the solar irradiance is adequate to ensure coffee crop productivity (Baggio et al., 1997; Caramori et al., 1996; Zaro et al., 2020).

Table 1 – Average air temperature (°C) from 10h00 to 16h00 (day), 22h00 to 6h00 (night) and daily average (24 h) at 1.0 m of height in the seasons. Coffee trees in open-grown (1), midpoint between two double alleys spaced 16 m apart (2) and under the double alleys of rubber trees (3).

Seasons	Day	Night	24 h
Summer			
1	26.03	23.28	25.05
2	23.74*	22.78*	23.25*
3	21.88*	21.97*	21.63*
Autumn			
1	25.85	19.45	21.78
2	23.06*	19.30	20.88*
3	20.72*	19.81	20.13*
Winter			
1	18.84	15.10	16.62
2	16.26*	15.10	15.64*
3	16.44*	15.85*	16.07*
Spring			
1	23.88	20.40	21.80
2	21.69*	19.88*	20.68*
3	19.12*	19.07*	18.99*
Difference 1–2	2.5	0.3	1.2
Difference 1–3	4.1	0.4	2.1

*p-value ≤ 0.05.

Considering the commitments of the IPCC member countries signed in the Paris Agreement to keep the warming levels below 2 °C until the end of this century, the AFS of coffee with rubber trees can contribute to the adaptation of coffee crops to warmer environments.

Relationship between average daily temperature and average temperature from 10h00 to 16h00

There is a linear relationship between the two variables, expressed by the equation $T_{24} = 0.8627 + 6.2457\, T_{10-4}$, with R^2 of 0.5809, where: T_{24} = mean 24 h air temperature and T_{10-4} = mean air temperature from 10h00 to 16h00. The F test showed regression significance at the 1 % level. The slope of the line was also significant at the 1 % level according to the t test. Thus, it is possible to relate the average daily temperatures to the average temperatures from 10h00 to 16h00, when global warming may bring greater damage to coffee crops. As the average air temperature of 24 °C was considered a tolerable upper limit for *C. arabica*, there was a correspondence of this temperature with 27 °C from 10h00 to 16h00. Therefore, the upper limit of 27 °C was used in the simulated data series from 10h00 to 16h00 to identify the cutoff point in each of the four scenarios.

PGECLIMA_R simulations

Historical meteorological databases were organized and simulations were performed with the PGECLIMA_R generator. Figure 4 shows the disturbing data series for the municipalities of Londrina and Paranavaí for the warming scenarios of 1.7, 2.6, 3.1, and 4.8 °C. The critical limit of 27 °C was reached in different periods according to the warming scenario, a temperature of 4.8 °C is exceeded in 2060, 3.1 °C in 2075, 2.6 °C in 2090, and the critical temperature of 1.7 °C is not exceeded until the end of this century.

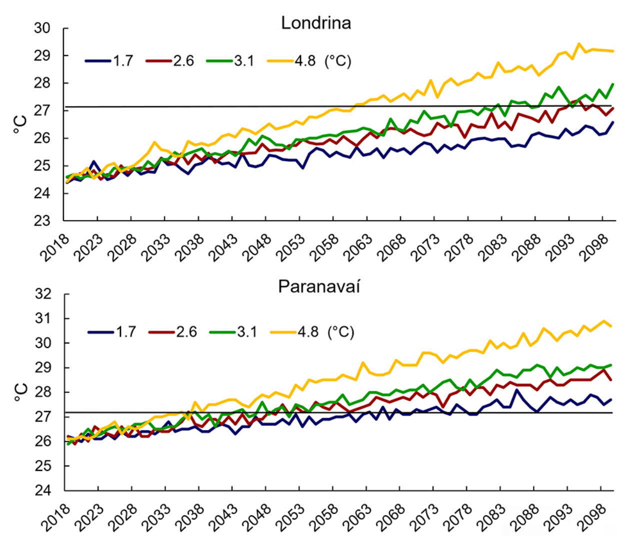

Figure 4 – Disturbed data series for Londrina and Paranavaí for the warming scenarios of 1.7, 2.6, 3.1, and 4.8 °C.

Paranavaí is located in a region with higher temperatures than the Londrina region. Scenarios for the region are even more critical, suggesting that coffee cultivation may become unviable earlier. An increase of 4.8 °C exceeds the critical limit in 2030, 3.1 °C in 2040, 2.6 °C in 2050, and 1.7 °C in 2065. During the subsequent decades, the cultivation of arabica open-grown coffee may also become unviable in warmer regions, such as the valleys of Paraná and Paranapanema rivers and the northwest of the state, if the warming trend remains.

The climatic risk zoning of arabica coffee in Paraná State was carried out by Caramori et al. (2001) (Figure 5). The average annual temperature of 24 °C was used as a criterion for the cutoff point in the warmest areas in the northern region of the state. As this value has not yet been reached, this region currently has no restrictions in practice. However, according to several studies reported by IPCC (2014), temperatures have been increasing rapidly and warming is inevitable. Nevertheless, the intensity of this warming can change, depending on current and future actions to reduce emissions and sequester atmospheric CO_2.

The warming scenarios of 1.7, 2.6, 3.1 and 4.8 °C suggest a progression of the inapt area from the Paraná River valley (border with Mato Grosso do Sul State – Brazil – and Paraguay) from 2018 to 2058 (Figure 6), evolving to the Paranapanema River valley (northern border with São Paulo State – Brazil) and the northwestern region of the state. For the period 2059 to 2099 (Figure 7), the situation becomes critical, revealing

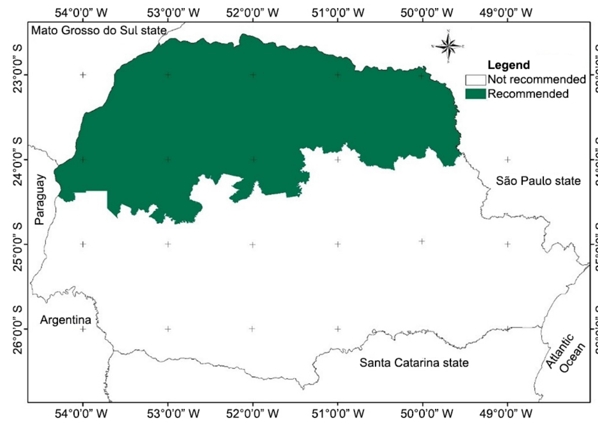

Figure 5 – Current agricultural zoning of arabica coffee for Paraná State, Brazil. Source: Caramori et al. (2001).

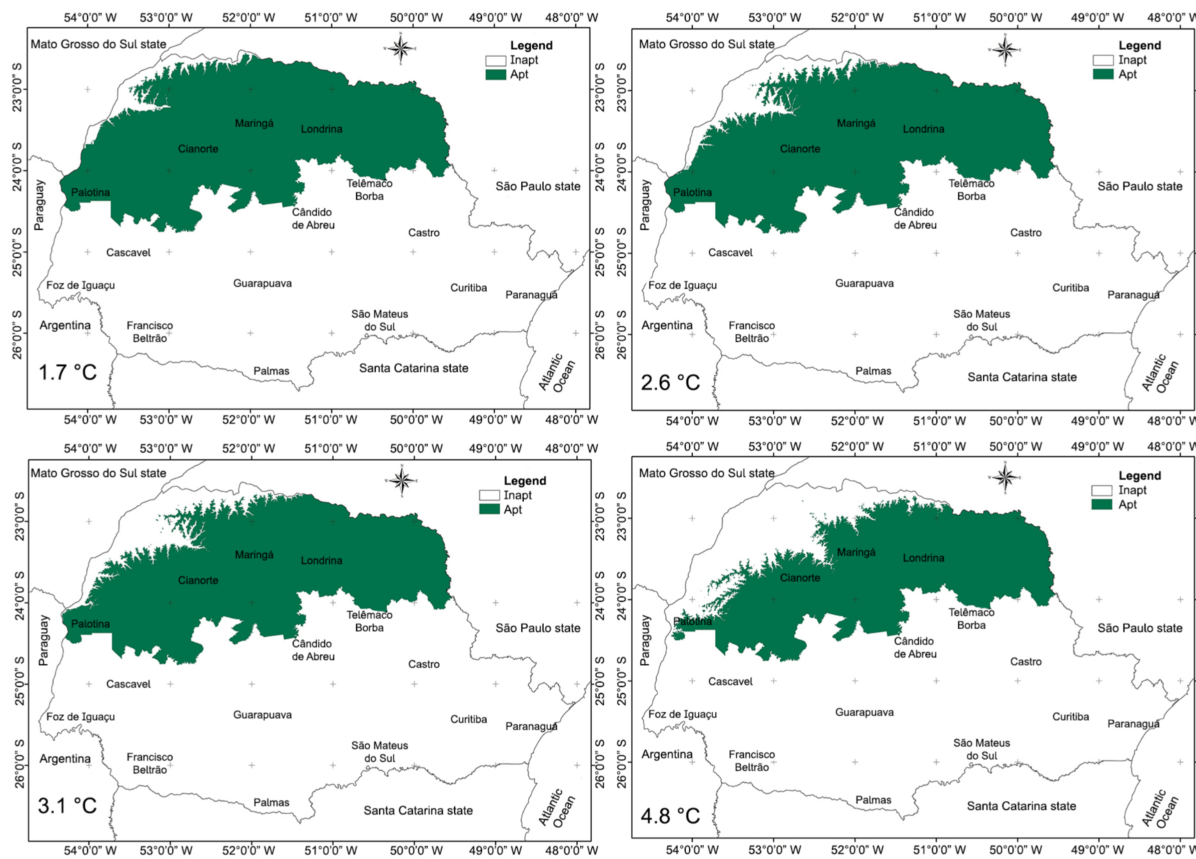

Figure 6 – Impact of the four climate change scenarios on the zoning of open-grown coffee in Paraná State, Brazil, for the period 2018–2058. Source: the authors.

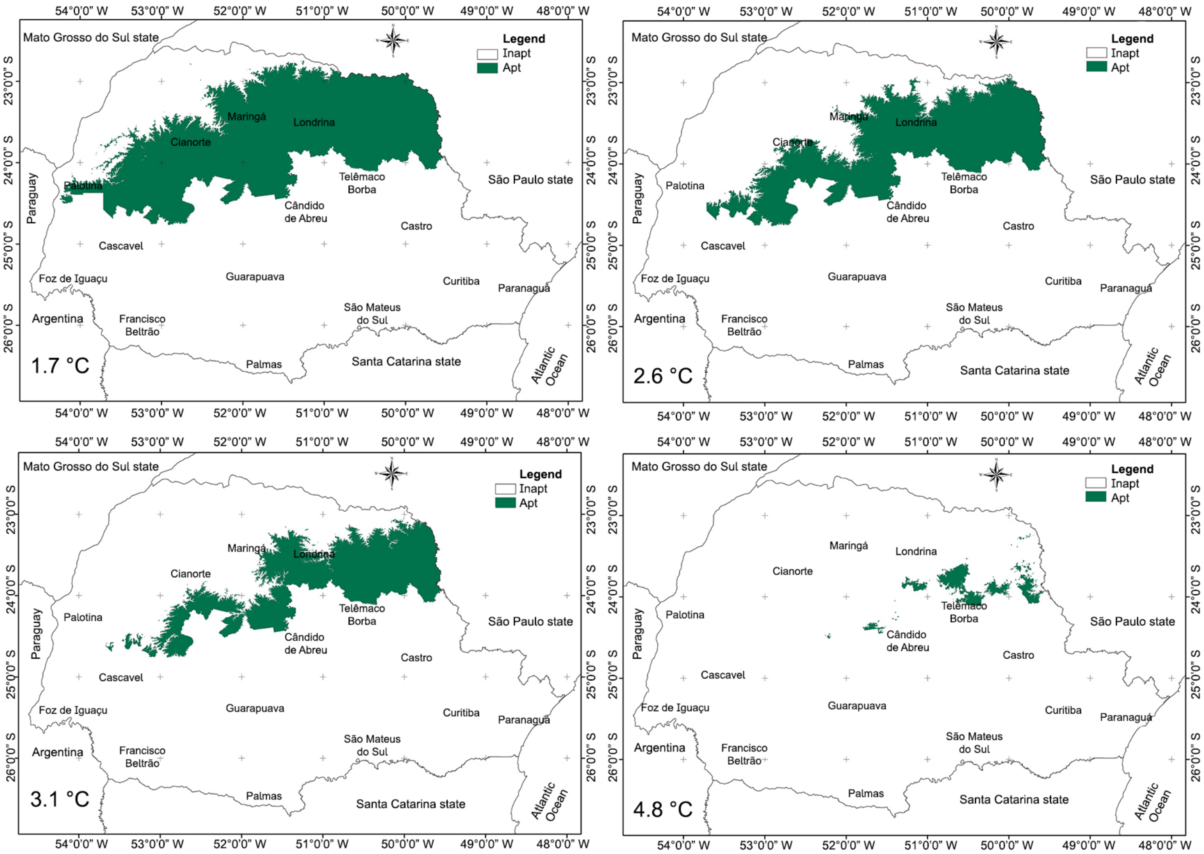

Figure 7 – Impact of the four climate change scenarios on the zoning of open-grown coffee in Paraná State, Brazil, for the period 2059–2099. Source: the authors.

that the northwestern region is no longer viable for coffee cultivation if warming levels reach 1.7 °C. Cultivation areas will progressively reduce until cultivation becomes unviable throughout the entire Paraná State in the case of an increase of 4.8 °C, except for small fragments at higher altitudes in the Northeast of the state.

Impact simulations of climatic scenarios for coffee in an agroforestry system with rubber trees

Two scenarios were generated based on the microclimate analysis of this study for the periods from 2018 to 2058 and 2059 to 2099, considering a temperature attenuation of 1 °C and 2 °C due to the presence of rubber trees (Figures 8 and 9). Sections collored in green represent areas that will remain apt for arabica coffee cultivation without AFS. Sections in blue represent area gains with temperature attenuation of 1 °C and yellow sections represent area gains with an attenuation of 2 °C.

Scenarios from 2018 to 2058 (Figure 8) indicate that a reduction from 1 °C to 2 °C allows for coffee cropping in areas previously considered inapt by the projected warming scenarios. However, the use of the AFS may favor the continuity of coffee planting in regions from the Paraná River valley, Paranapanema River valley, and the northwestern region of the state. From 2059 to 2099 (Figure 9), the northwestern region (altitudes 300 to 500 m) will become unviable above 1.7 °C and the remaining apt areas will progressevely become inapt, as the warming levels increase up to 4.8 °C. The AFS with a reduction of 1 °C and up to 2 °C will allow coffee production in the entire region presently recommended up to the 2.6 °C scenario. From the 3.1 °C projection, there is a reduction in the area in the Paraná River region, making it inapt if the warming is confirmed. In the projection of 4.8 °C, the entire northwestern region becomes inapt and cultivation with the AFS is only recommended with a reduction of 1 and 2 °C in the rest of the state. Figures 10 and 11 show the remaining percentage of the area suitable for arabica coffee cultivation, considering that the AFS can attenuate 1 °C or 2 °C under the four possible warming scenarios according to IPCC (2014).

Some authors suggest that global warming will allow the migration of coffee production towards southern areas of Brazil due to the possible decrease of frosts and rising temperatures in colder areas currently unsuitable for coffee cultivation (Zullo et al., 2011). Nevertheless, there are no guarantees that this will happen since these regions do not have a tradition in coffee cultivation and extreme events, such as frosts and excessive rainfall during the crop cycle, may persist and undermine coffee

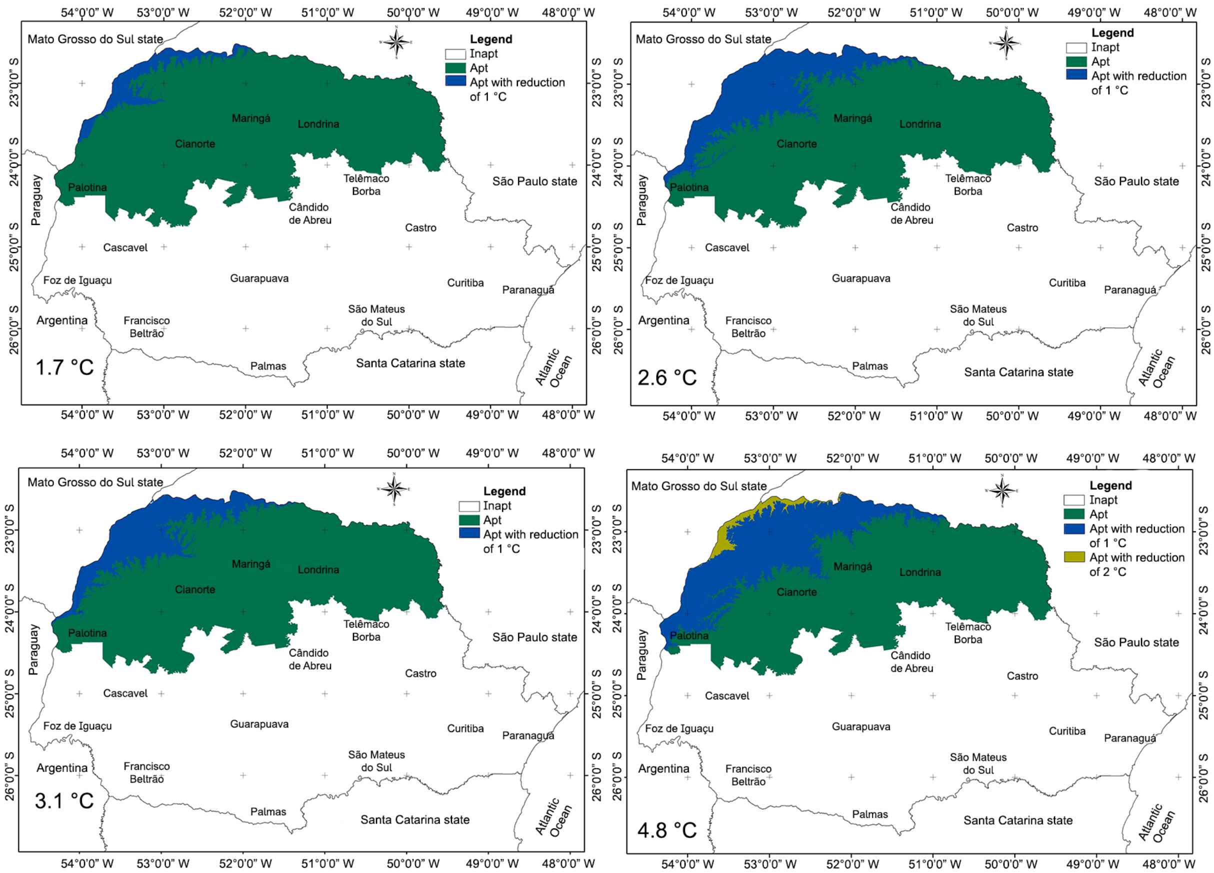

Figure 8 – Zoning of arabica coffee with agroforestry systems (AFS) with attenuation of 1 °C and 2 °C in the warming scenarios of 1.7, 2.6, 3.1, and 4.8 °C in Paraná State, Brazil, for the period 2018–2058. White – inapt; green – apt; blue – apt with attenuation of 1 °C; yellow – apt with attenuation of 2 °C. Source: the authors.

cultivation in these regions. Our study analyzed only the impacts on the traditional coffee sites in Paraná State and our simulation does not take into account the possibility of genetic breeding for heat tolerance in *C. arabica*.

There is great resistance to adopting the AFS in extensive coffee crops that use mechanization and external inputs to achieve maximum productivity. Therefore, empirical studies are needed to evaluate combinations of the AFSs in different environments and socio-economical conditions to identify benefits and enable the use of adequate technological options.

Conclusions

The agroforestry system of coffee with double alleys of rubber trees spaced 16 m apart can reduce high daytime temperatures. This represents an important approach to cope with the warming scenarios predicted by the IPCC until the end of the 21st century. The system has the potential to reduce the negative impacts regionally of possible global warming on coffee production in southern Brazil thus contributing to adaptations of coffee crops to warmer environments in the coming decades.

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Authors' Contributions

Conceptualization: Zaro, G.C.; Caramori, P.H.; Wrege, M.S.; Morais, H. **Data acquisition**: Morais, H.; Yada Junior, G.M. **Data analysis**: Wrege, M.S.; Caldana, N.F.S.; Caramori, P.H.; Virgens Filho, J.S. **Design of methodology**: Zaro, G.C.; Caramori, P.H.; Wrege, M.S.; Caldana, N.F.S. **Software development**: Virgens Filho, J.S. **Writing and editing**: Zaro, G.C.; Caramori, P.H.; Caldana, N.F.S.; Caramori, D.C.

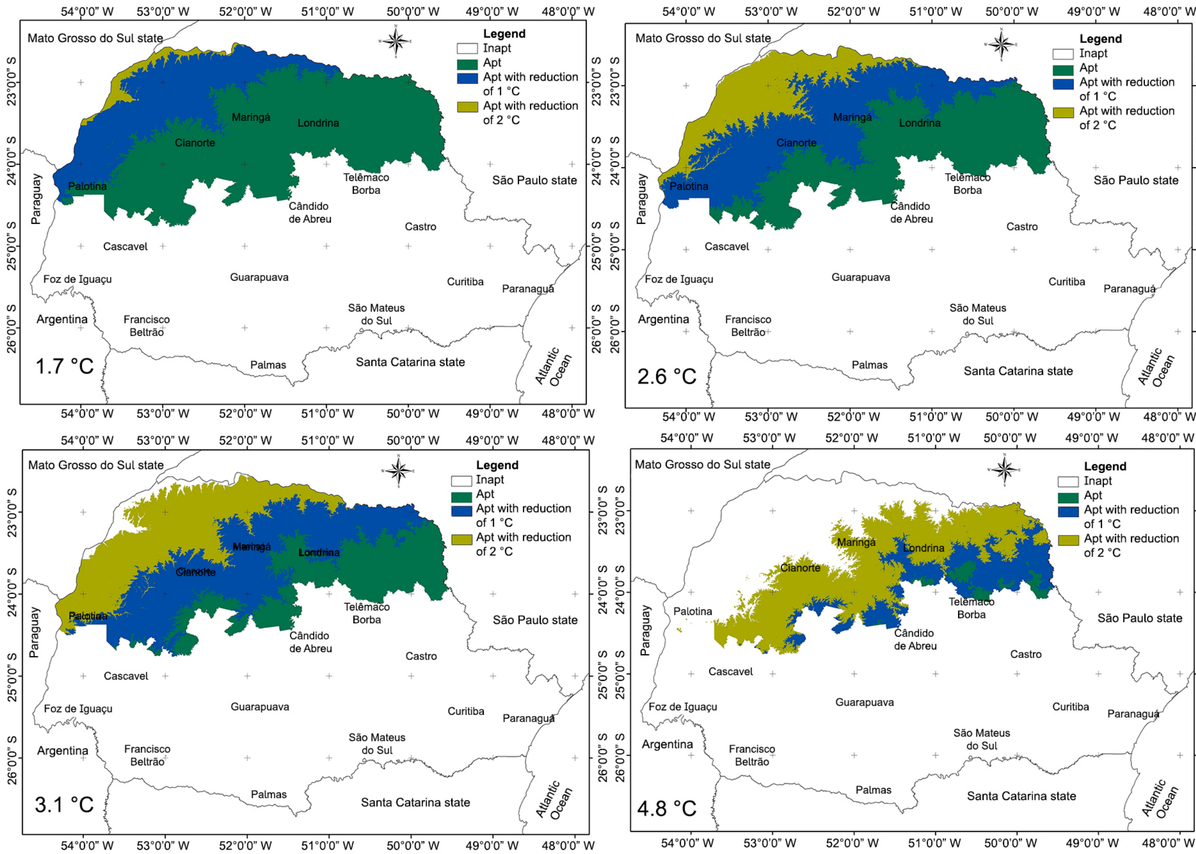

Figure 9 – Zoning of arabica coffee with agroforestry systems (AFS) with a reduction of 1 °C and 2 °C in the warming scenarios of 1.7, 2.6, 3.1, and 4.8 °C in Paraná State, Brazil, for the period 2059–2099. White – inapt; green – apt; blue – apt with reduction of 1 °C; yellow – apt with reduction of 2 °C. Source: the authors.

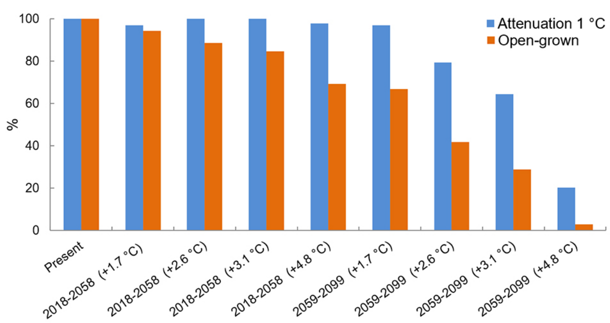

Figure 10 – Percentage of the area that remains in open-grown cultivation and in agroforestry system (AFS) with an attenuation of 1 °C, considering the warming scenarios of 1.7 °C, 2.6 °C, 3.1 °C, and 4.8 °C in the periods of 2018–2058 and 2059–2099.

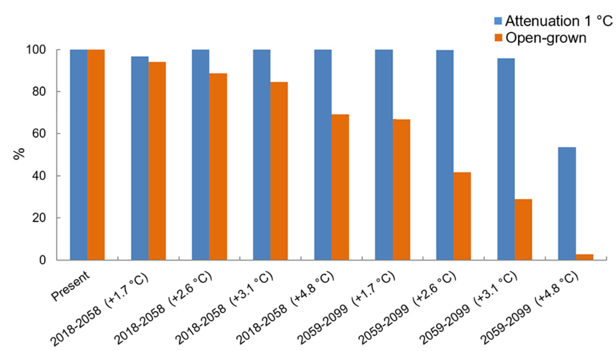

Figure 11 – Percentage of the area that remains in open-grown cultivation and in agroforestry system (AFS) with attenuation of 2 °C, considering the warming scenarios of 1.7 °C, 2.6 °C, 3.1 °C, and 4.8 °C in the periods of 2018–2058 and 2059–2099.

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