Impact of climate on grain filling, flowering, and productivity of arabica coffee

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Abstract

The yield of Arabica coffee is greatly affected by climatic factors, particularly temperature. This study investigated the impact of climate variability on Arabica coffee cultivars across four phenological stages in the Agrotechnological District (DAT) region of Caconde, São Paulo. Pearson correlation analyses and the Mann-Kendall trend test were employed in this assessment. The results indicate that the grain-filling period is the most sensitive to rising temperatures, which directly influences yield. Furthermore, climate trends show a steady warming during the flowering stage, making it especially vulnerable. These findings highlight the importance of implementing adaptive management strategies in response to climate change.

Keywords: Agricultural productivity; Climate variability; Phenological phases.

1. Introduction

Coffee cultivation is a strategic sector of Brazilian agriculture and plays a crucial role in the country's economy. However, its productivity is significantly affected by a range of complex factors, with climate being the most critical and unpredictable element. Variations in temperature, humidity, and precipitation have direct impacts on all

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phenological stages of the coffee plant, from flowering to grain maturation (Dias et al., 2024).

In this context, utilizing meteorological data in conjunction with phenological information is essential for effective agricultural planning. High temperatures, in particular, can hinder flower set, reduce photosynthesis, and accelerate the plant's growth cycle, resulting in adverse effects on yield. It is vital to understand how different cultivars respond to these climatic variations, especially during the most sensitive stages, in order to implement adaptive management practices.

Thus, this study aimed to evaluate the impacts of climate variability, with a focus on temperature, on the productivity of Arabica coffee. It involved analyzing cultivar responses across various phenological stages and identifying the periods most vulnerable to climate change within the study region.

2. Methods

The study was conducted at the Boa Vista da Fumaça farm, situated in the DAT region of Caconde, São Paulo, characterized by a Cwa climate according to the Köppen classification. Productivity data were collected over a span of 14 years (2011-2024) from three Arabica coffee cultivars (Mundo Novo 376/4, Catuaí IAC 144, and Bourbon Vermelho) across 26 plots. Yield was measured per plant to minimize the impact of gaps within the plots.

Climatic variables, including precipitation, temperature, humidity, wind, and atmospheric pressure, were obtained from an INMET weather station, covering the period from 2007 to 2024. Thermal time (Tse) was calculated following the methodology of Pezzopane et al. (2008), using a base temperature of 12 °C.

Phenological phases were defined based on the criteria established by Camargo and Camargo (2001), dividing the coffee life cycle into two years: vegetative (bud formation and maturation) and reproductive (flowering and grain filling). The correlation between yield and climatic variables was analyzed using Pearson's correlation coefficient, with statistical significance ($p < 0.05$) assessed via the t-test. Climatic trends were evaluated using the Mann-Kendall test, which identifies monotonic patterns of increase or decrease in time series data, and were further supported by Kendall's τ coefficient to indicate the strength of these trends.

3. Results and Discussion

Climate is the most impactful and least controllable factor affecting coffee productivity, with temperature being the most critical element. Temperature negatively influences the development of both fruits and branches across all phenological stages. Pearson correlation analyses (Figure 1) revealed significant relationships between productivity and climatic variables such as maximum temperature (Tx), average temperature (Ta), and relative humidity (RUa, RUm), with temperature having the most detrimental effect during the second phenological year, corresponding to the reproductive phase. Excessive rainfall was found to adversely affect bud formation, likely due to nutrient limitations and a higher incidence of diseases (Monteiro, 2009; Dias et al., 2024). Conversely, relative humidity showed positive correlations with yield and was associated with reductions in Tx.

Among the phenological stages (Figure 2), grain filling was identified as the most sensitive to rising temperatures, as evidenced by negative correlations with maximum temperature (Tx) and thermal time. Flowering and fruit development were also impacted by lower minimum temperatures (Tm), which are typical during the transition from winter to spring. Excess rainfall during this period may trigger premature flowering and compromise the quality of the reproductive process (Zacharias et al., 2008; Roman et al., 2024). Climatic variables that positively correlate with yield tend to be antagonistic to thermal increases, suggesting that strategies aimed at mitigating heat stress could enhance coffee productivity.

Temperature variations during critical stages of Arabica coffee development, particularly during grain filling and fruit development, significantly impact yield. These phases have high water demand and are more susceptible to thermal stress, as rising temperatures intensify evapotranspiration and increase dependence on soil water availability (Thornthwaite, 1948; Humphries et al., 2024). This effect also influences the development of foliar buds, as it coincides with grain filling, explaining the negative correlations with thermal variables during this period (Camargo; Camargo, 2001).

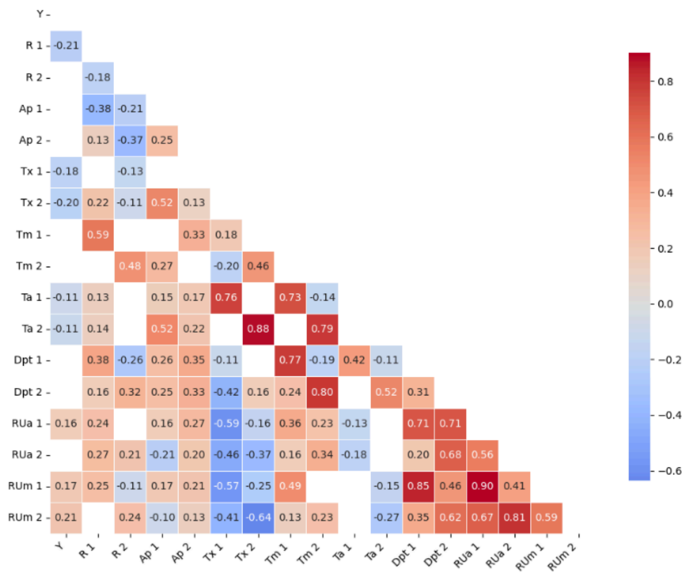

Figure 1. Pearson correlation matrix showing significant values ($p < 0.05$) between coffee yield (Y) and climatic factors: Precipitation (R), atmospheric pressure (Ap), maximum temperature (Tx), minimum temperature (Tm), average temperature (Ta), dew point temperature (Dpt), average relative humidity (RUa), and minimum relative humidity (RUm) in the first (1) and second (2) phenological year.

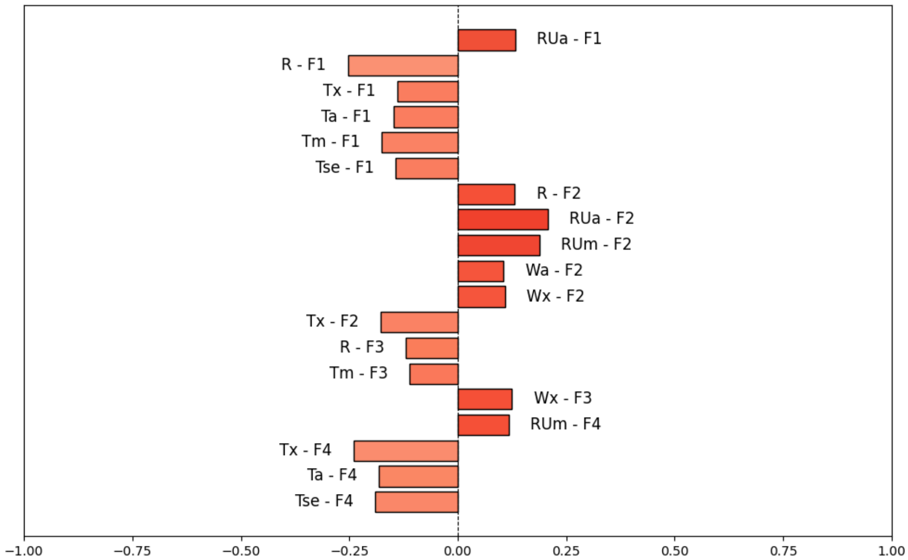

Figure 2. Significant correlations ($p < 0.05$) between coffee yield and climatic variables: Precipitation (R), maximum temperature (Tx), minimum temperature (Tm), average temperature (Ta), average relative humidity (RUa), minimum relative humidity (RUm), average wind speed (Wa), maximum wind speed (Wx), and thermal sum (Ste) during the phases of vegetative growth and bud formation (F1), floral bud induction and maturation (F2), flowering and fruit expansion (F3), and fruit filling (F4).

The results of the Mann-Kendall test indicated significant upward trends in temperature (Tx and Ta) throughout the time series, particularly during the months of March, April, July, August, September, and October (Figure 3). September recorded the highest trend values (τ = 0.55 for Tx and 0.48 for Ta), coinciding with the onset of spring and the flowering period of coffee plants, which is recognized as highly sensitive to climate change (Camargo; Camargo, 2001). Furthermore, warming trends in autumn and winter may adversely affect the maturation of buds.

Figure 3. Monthly trends of climatic variables over a 16-year period, based on the Mann-Kendall test. Colors indicate: green (significant decreasing trend), blue (significant increasing trend), and gray (non-significant trend). The numbers from 1 to 12 represent the months from January to December. Z refers to the test statistic, and τ (Tau) indicates the strength of the temporal trend.

Variables such as minimum relative humidity (RUm), average relative humidity (RUa), dew point temperature (Dpt), and wind speeds (Wx and Wa) exhibited downward trends, particularly in December, a critical period characterized by intense cell division during fruit expansion. While the increase in temperature was not significant across all these months, its negative correlation with these variables indicates potential combined adverse effects. Consequently, climate trends suggest a heightened risk of thermal stress during the flowering and fruit expansion stages, which could have detrimental implications for yield.

4. Conclusion

Climatic variations, especially rising temperatures, have a significant impact on coffee productivity. The grain filling stage was identified as the most affected, while flowering emerged as the stage most vulnerable to future climate change. These findings offer a foundation for developing management strategies aimed at mitigating adverse effects during the critical phases of the phenological cycle. By focusing on these key stages, producers can better adapt to changing climatic conditions and enhance overall coffee yield.

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