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Irrigation demand for fruit trees under a climate change scenario using artificial intelligence[1]

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ABSTRACT

Fruit growing, especially in family farming, has a significant income potential in small areas, but climate change is a major challenge. This study aimed to quantify the irrigation requirements for citrus, papaya, mango and passion fruit, in the Vão do Paranã region, Goiás state, Brazil. The climate data encompassed the observed periods from 1961 to 2020 and future scenarios from 2021 to 2100. The irrigation demand was obtained from the daily water balance, while the reference evapotranspiration (ETo) was estimated using the Penman-Monteith method and then compared with an artificial intelligence tool. The future scenarios indicated a higher increase for air temperature and a lower increase for rainfall. The ETo levels raised from 1,528 mm year^{-1}, in 1991-2020, to 1,614-1,656 mm year^{-1}, in 2021-2050. The artificial intelligence performance was limited in the ETo estimation, with a mean absolute error of 0.71 mm day^{-1} and an "r" value of 0.59, when considering the air temperature as the input variable. For the 2021-2050 period, when compared with 1991-2020, there was an increase in irrigation demand, in which, under the extreme scenario, the citrus demand reached 690 mm year^{-1} (+11 %); papaya (+10 %) and passion fruit (+5 %) surpassed 800 mm year^{-1}; and mango reached 491 mm year^{-1} (+14 %). An increase in demand for irrigation was observed, with management alternatives in association with strategies for maximum cultivation area based on water supply being recommended.

KEYWORDS: Climate resilience, water demand, machine learning, future climate scenarios.

RESUMO

Demanda de irrigação para frutíferas sob cenário de mudanças climáticas utilizando-se inteligência artificial

A fruticultura, especialmente na agricultura familiar, possui grande potencial de renda em pequenas áreas, mas as mudanças climáticas são um grande desafio. Objetivou-se quantificar a demanda de irrigação para citros, mamão, manga e maracujá, na região do Vão do Paranã, Goiás. Os dados climáticos compreenderam os períodos observados de 1961 a 2020 e cenários futuros de 2021 a 2100. A demanda por irrigação foi obtida com base no balanço hídrico diário, enquanto a evapotranspiração de referência (ETo) foi estimada pelo método de Penman-Monteith e então comparada com uma ferramenta de inteligência artificial. Os cenários futuros indicaram aumento da temperatura do ar, em maior intensidade, e de chuvas, em menor intensidade. A ETo passou de 1.528 mm ano^{-1}, em 1991-2020, para 1.614-1.656 mm ano^{-1}, em 2021-2050. O desempenho da inteligência artificial na estimativa da ETo foi limitado, com erro médio absoluto de 0,71 mm dia^{-1} e r de 0,59, quando considerada a temperatura do ar como dado de entrada. Para o período de 2021-2050, em relação a 1991-2020, houve aumento na demanda por irrigação, em que, no cenário extremo, os citros atingiram 690 mm ano^{-1} (+11 %); mamão (+10 %) e maracujá (+5 %) ultrapassaram 800 mm ano^{-1}; e a manga chegou a 491 mm ano^{-1} (+14 %). Observou-se aumento na demanda por irrigação, sendo recomendadas alternativas de manejo associadas a estratégias de área máxima de cultivo com base na oferta de água.

PALAVRAS-CHAVE: Resiliência climática, demanda hídrica, aprendizado de máquina, cenários climáticos futuros.

INTRODUCTION

Fruit cultivation has emerged as a valuable alternative to commodity production, being particularly beneficial for small-scale family farmers with limited land resources, as is the case of the Vão do Paranã region, Goiás state, Brazil (Brasil 2019, Codevasf 2021).

This region was included in the fruit route by the National Integration Routes project (Brasil

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2018), as a strategy for regional development and productive inclusion. The fruit route comprises three hubs, with the Vão do Paranã region being included in the third one (northeast region), focusing on mango, passion fruit, papaya and lemon, while the first included banana, pineapple and watermelon in the São Patrício Valley, and the second orange, tangerine and jabuticaba in the Goiânia metropolitan region (Brasil 2018). Additionally, the Vão do Paranã region is the poorest one in the Goiás state, with socioeconomic indicators well below the state average (human development index < 0.713) (IBGE 2023).

In fruit production, the implementation of irrigation practices significantly enhances yield and facilitates cultivation in regions prone to water deficits (Silveira et al. 2020). Water scarcity is a notable risk to production in this area (Teixeira et al. 2008). Consequently, there is demand for supplemental water in the region, particularly from May to September, what improves yield and fruit quality (Conesa et al. 2021).

Fruit cultivation has a perennial cycle, and it is crucial to account for future climate forecasts, given that these crops remain in the field for several years after planting (Fischer et al. 2016). The Intergovernmental Panel on Climate Change has indicated that human activities, particularly greenhouse gas emissions, have raised the global surface temperature by 1.1 ºC, when comparing 1850-1900 to 2011-2020 (IPCC 2023). Linked to this, the Goal 13, out of 17 Sustainable Development Goals proposed by the United Nations, aims at taking urgent action to combat climate change and its impacts, integrating climate change measures into national policies, strategies and planning (Target 13.2), and improving education and institutional capacity for climate change mitigation and adaptation (Target 13.3) (United Nations 2023).

The Goal 6 aims at ensuring the availability and also the sustainable management of water and sanitation for all, with the Target 6.4 focusing on increasing the water-use efficiency across all sectors and the essential planning of water demand and supply within the region (United Nations 2023). Fruit production can be an alternative to address the Goal 2, aimed at ending hunger, achieving food security and improving nutrition in association with a sustainable agriculture capable of adapting to climate change (Target 2.4) (United Nations 2023).

The increase in water-use efficiency is dependent on adequate water management based on the crop water demand, which can be measured using weight lysimeters (Antunes Junior et al. 2021, Silva et al. 2021) or by measuring the soil-water balance (Dingre & Gorantiwar 2020, Pereira et al. 2020). Furthermore, the crop water demand can be estimated using reference evapotranspiration (ETo) multiplied by the crop coefficient (kc) (Allen et al. 1998), what can be a source of uncertainty owing to crop responses to the environment (Marin et al. 2016). The ETo can be estimated using the standard Penman-Monteith method, adapted by Allen et al. (1998), or by using alternative methods with fewer climate variables (Pilau et al. 2012). In this context, artificial intelligence and machine learning algorithms have been tested for various applications, including ETo estimation, in conjunction with traditional methodologies for estimating crop water demand. These algorithms have been applied in various regions worldwide, including by Torres et al. (2011), who demonstrated an application in Utah, USA; Patil & Deka (2016), who showed results in the arid regions of India; and Ferreira et al. (2019), in Brazil.

Thus, fruit production has a great potential; however, water supply is currently an important factor that tends to worsen in the future, owing to climate change. Based on that, this study aimed to evaluate future climate conditions until 2100, in relation to 1961-2020; test artificial intelligence to estimate reference evapotranspiration (ETo) based on climate variables; and quantify the irrigation demand during historical (1961-2020) and future (2021-2100) periods for citrus, passion fruit, mango and papaya crops.

MATERIAL AND METHODS

The region of study was Vão do Paranã, Goiás state, Brazil (Figure 1), characterized by an Aw-type climate, a tropical climate with dry winter, following the Köppen classification (Alvares et al. 2013). The current daily climate data were obtained for the period from Jan. 01, 1961, to Dec. 31, 2020, from the gridded data of Xavier et al. (2022). The data included maximum, mean and minimum air temperature (ºC), solar radiation (MJ m^{-2} day^{-1}), rainfall (mm day^{-1}), relative humidity (%) and 2-m wind speed (m s^{-1}). Future climate scenarios were obtained from 15 combinations of models and climate scenarios from the Coupled Model Intercomparison

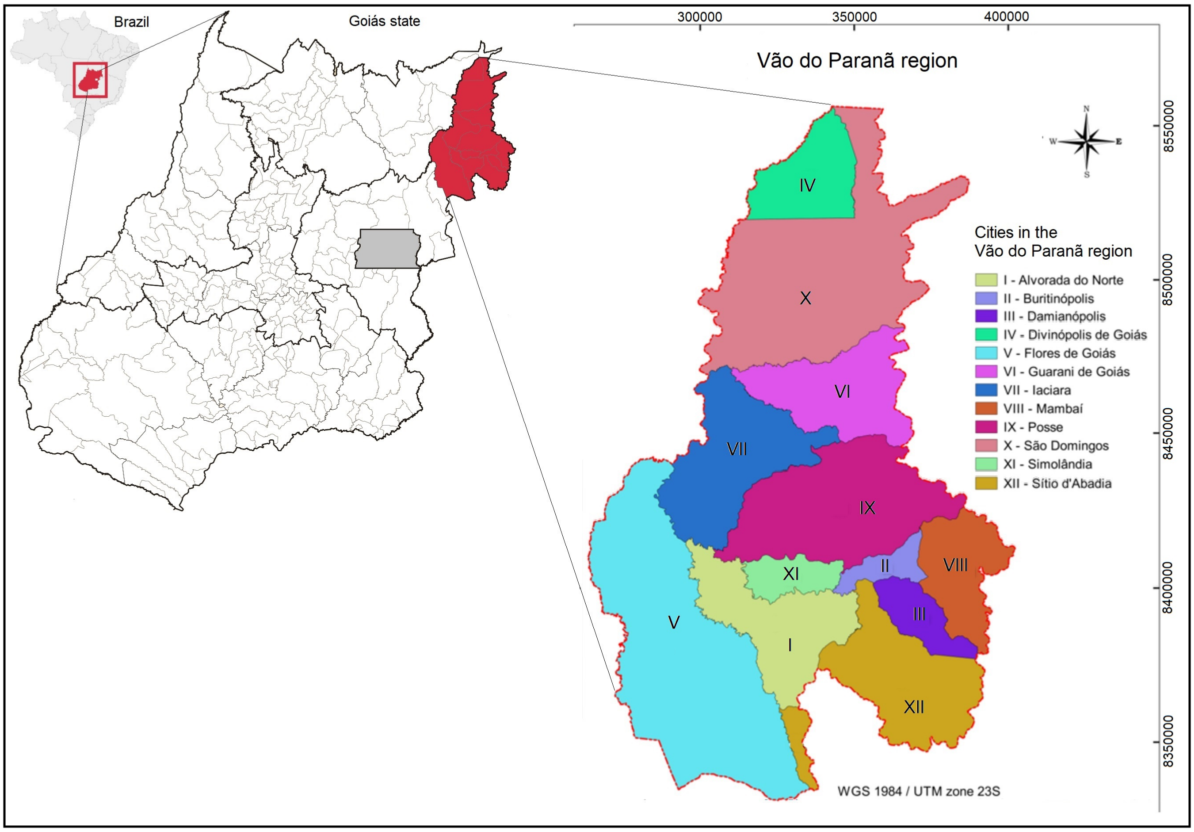

Figure 1. Location of the Vão do Paranã region and its cities in the Goiás state, and the state location in Brazil.

Project Phase 6 (CMIP6). The models included GFDL-ESM4, IPSL-CMGA-IR, MPI-ESM1-2hr, MRI-ESM2-0 and UKESM1-OLL, which represented the variations among the tested models (Papalexiou et al. 2020). Additionally, three future climate scenarios were included from 2021 to 2100, the Shared Socioeconomic Pathways (SSP) SSP1-26, SSP3-70 and SSP5-85, representing scenarios of low, high and very high greenhouse gas emissions, respectively.

In the SSP1-26 scenario, the global development system is sustainable and green, focusing on quality of life rather than economic growth, with a reduction in income inequality and a focus on minimizing energy use (IPCC 2023), which limits the global air temperature increase to 2 ºC by 2100. In the SSP3-70 scenario, conflicts between nations place global emission reduction goals in the background, reducing investments in education and technology. This scenario results in 7.0 W m^{-2} of additional energy retention by 2100 (IPCC 2023). The SSP5-85 scenario was developed based on fossil fuels and integration of global markets, leading to technological development and innovation. This scenario results in 8.5 W m^{-2} of additional energy retention by 2100, which is the most extreme scenario (IPCC 2023).

The reference evapotranspiration (ETo) was calculated based on the current climate data and future scenarios. For standard conditions, the ETo was estimated using the Penman-Monteith method (Allen et al. 1998), referred to as FAO-56, as described by Pereira et al. (2002). The ETo results obtained using the Penman-Monteith method for current climate conditions (1961-2020) were used to train and validate the artificial intelligence (AI) algorithm for a simplified estimation of the ETo. The training process of the AI algorithm was based on linear regression, in order to minimize the sum of the squares of the residuals (or errors) between the actual observed values and the values predicted by the model. The model had input data conditions considering all the climate variables from Xavier et al. (2022); only maximum, mean and minimum air temperatures; and only mean air temperature.

The irrigation demand for each crop was obtained from the balance of readily available soil water. In the first step, the crop evapotranspiration (ETc) was obtained based on the ETo multiplied by the crop coefficient (Kc). Papaya and citrus cultivation had constant Kc values throughout the year, with respective values of 0.87 (Posse et al. 2008) and 0.80 (Volpe et al. 2009). However, for mango and passion fruit, the values were applied based on the crop phenological stages throughout the year (Table 1).

The total available soil water capacity between the field capacity and permanent wilting point was 1.15 mm cm^{-1} (Paixão et al. 2021), obtained considering the average of the region. This value was converted for each crop based on the maximum root system depth: 200 cm for mango (Teixeira et al. 2008), 100 cm for citrus (Santos et al. 2005), 75 cm for papaya (Coelho et al. 2005) and 40 cm for passion fruit (Sousa et al. 2002). The total available soil water capacity values for each crop were 230, 115, 86 and 46 mm, respectively. The maximum fraction of readily available water was considered as 50 % of the total available soil water capacity for each crop (Doorenbos & Kassan 1994), representing the amount of water that the plant can use without experiencing water deficit conditions.

The irrigation demand was quantified by calculating the water inputs and outputs in the soil to obtain the readily available water. The inputs were rainfall and irrigation and the outputs were ETc and excess water. The total annual irrigation was obtained from the accumulated daily values across the crop's annual production cycle. The irrigation demand (I) was obtained based on readily available water, according to the following equations (Pereira et al. 2002): $RAW_i = RAW_{i-1} + (P_i + I_{i-1} - ETc_i)$, but if $RAW_i > RAW_m$, then $RAW_i = RAW_m$; $I_i = 15$ mm day^{-1}; if $RAW_i < ETc_1$, then $I_i = 0$ mm day^{-1}, where RAW is the readily available water in mm, P is rainfall in mm day^{-1}, I is irrigation in mm day^{-1}, ETc is the maximum crop evapotranspiration in mm day^{-1}, i represents the simulation day and m the maximum readily available water value for each crop.

The maximum, mean and minimum air temperatures, rainfall, ETo and irrigation demand were analyzed over different periods and scenarios (current and future) through linear regression using the ExpDes package in R (Ferreira et al. 2021). The T-LSD test was used to compare the absolute data distribution for 1961-1990, 1991-2020 and 2021-2050, using the package ExpDes in R (Ferreira et al. 2021). The ETo from the AI algorithm was analyzed based on the mean error, mean absolute error, D-Wilmott index, root mean square error, correlation coefficient (r), correlation graphs and linear equations.

RESULTS AND DISCUSSION

The maximum (Figure 2A), mean (Figure 2C) and minimum (Figure 2E) air temperatures increased from 1961 to 2020. The trend was statistically significant for both periods for minimum and mean values from 1961 to 1990 and also from 1991 to 2020. The trends were, respectively, 0.0374 and 0.0217 ºC year^{-1} for mean air temperature and 0.0739 and 0.0209 ºC year^{-1}, respectively, for minimum air temperature. The maximum air temperature showed a significant trend only from 1991 to 2020, with an increase rate of 0.022 ºC year^{-1} (Figure 2A).

A higher increase in the minimum than in the maximum air temperature was reported in other studies. In a longer time-series data, from 1901 to 2020, in Alberta, Canada, Mapfumo et al. (2023) observed that the minimum air temperature increased at a rate of 0.05 ºC year^{-1} against 0.03 ºC year^{-1} for

Table 1. Month, development phase and crop coefficient (Kc) used in the irrigation management for mango and passion fruit.

Month	Phase[1]	Kc[2]	Month	Phase[3]	Kc[3]
Mango			Passion fruit		
Jan.	Vegetative growth	0.80	Jan.	Fruit post-ripening	1.05
Feb.	Stem maturation	0.80	Feb.	Fruit post-ripening	0.85
Mar.	Flower induction	0.80	Mar.	Fruit post-ripening	0.65
Apr.	Flowering/fruit growth	0.80	Apr.	Stem growth	0.50
May-July	Fruit growth	0.80	May	Vegetative growth	0.50
Aug.	Harvest	0.65	June	Vegetative growth	0.60
Sep.-Oct.	Dormancy	0.45	July	Vegetative growth	0.70
Nov.	Vegetative growth	0.65	Aug.-Sep.	Flowering and frutification	0.85
Dec.	Vegetative growth	0.80	Oct.-Dec.	Fruit maturation	1.05

Sources: [1] Teixeira et al. (2008); [2] Embrapa (2015); [3] Silva et al. (2006). September for mango and May for passion fruit represent the start of a new yearly cycle.

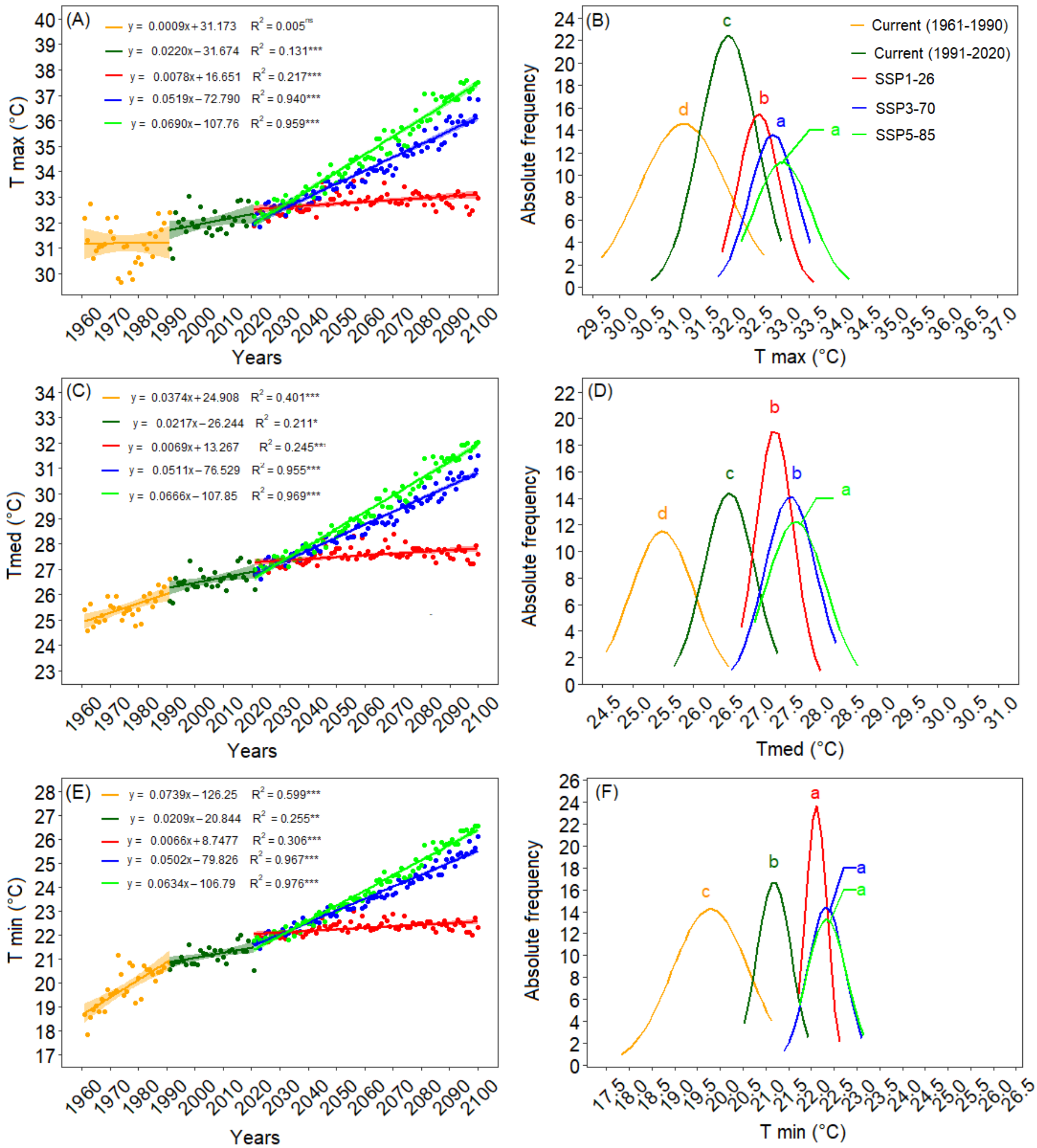

Figure 2. Linear regression (A, C and E) and absolute frequency (B, D and F) for maximum (Tmax, A and B), mean (Tmed, C and D) and minimum (Tmin, E and F) air temperature. ns, *, ** and ***: linear regression not significant, and significant at 5, 1 and < 1 %, respectively. Distribution followed by the same letter does not differ by the T-LSD test at 5 % of significance for the period between 2021 and 2050.

maximum air temperature. A higher concentration of greenhouse gases increases the retention of longwave radiation (Philipona et al. 2004), preventing the Earth from losing heat during the night and consequently increasing the minimum air temperature.

The SSP1-26 future scenario showed a lower rate of increase in regard to air temperature, with a rate below 0.0078 ºC year^{-1} (Figures 2A, 2C and 2E). However, the scenarios SSP3-70 and SSP5-85 had a temperature rate ranging from 0.0502 ºC year^{-1} in minimum air temperature for SSP3-70 (Figure 2E) and 0.0690 ºC year^{-1} in maximum air temperature for SSP5-85 (Figure 2A). In these scenarios, the mean air temperature can increase 1.5 and 2.0 ºC, respectively, for SSP3-70 and SSP5-85, from 2021 to 2050 (Figure 2C), owing to doubled gas emissions until 2100 for SSP3-70 and 2050 for SSP5-85 (IPCC 2023), increasing the impact on agricultural production. Dias et al. (2024) verified that Arabica coffee accounts for 85 % of the current production area classified as moderate to very high risk for the SSP3-70 and SPP5-85 scenarios in Brazil.

The absolute frequency showed statistical difference between 1961-1990 and 1991-2020, in regard to the air temperature (Figures 2B, 2D and 2F). These current periods were statistically different from the future scenarios for 2021-2050. The SSP1-26 and SSP3-70 future scenarios had similar maximum air temperatures, but both differed from SSP5-85 (Figure 2B). SSP1-26 differed from SSP3-70 and SSP5-85, in terms of mean air temperature (Figure 2D), whereas the three future scenarios had similar absolute frequency distributions for minimum air temperature (Figure 2F).

The current periods of 1961-1990 and 1991-2020 did not show a significant trend for rainfall, probably due to the huge variability; however, there was a trend for a reduction of 3.1 mm year^{-1} in 1991-2020 (Figure 3A), similarly to the value of 3.7 mm year^{-1} observed by Casaroli et al. (2018) in Goiânia, Goiás state, from 1979 to 2015. Ortega et al. (2021) tested climate models from CMPI6 over South America, where the models were able to reproduce rainfall over the Cerrado (Brazilian Savannah) biome, showing consistent trends across the models to reduce the rainfall amount.

The SSP3-70 scenario was the only one with a significant trend, with an increasing rainfall of 1.3596 mm year^{-1} (Figure 3A). The 2021-2050 future scenario had a rainfall distribution similar to the

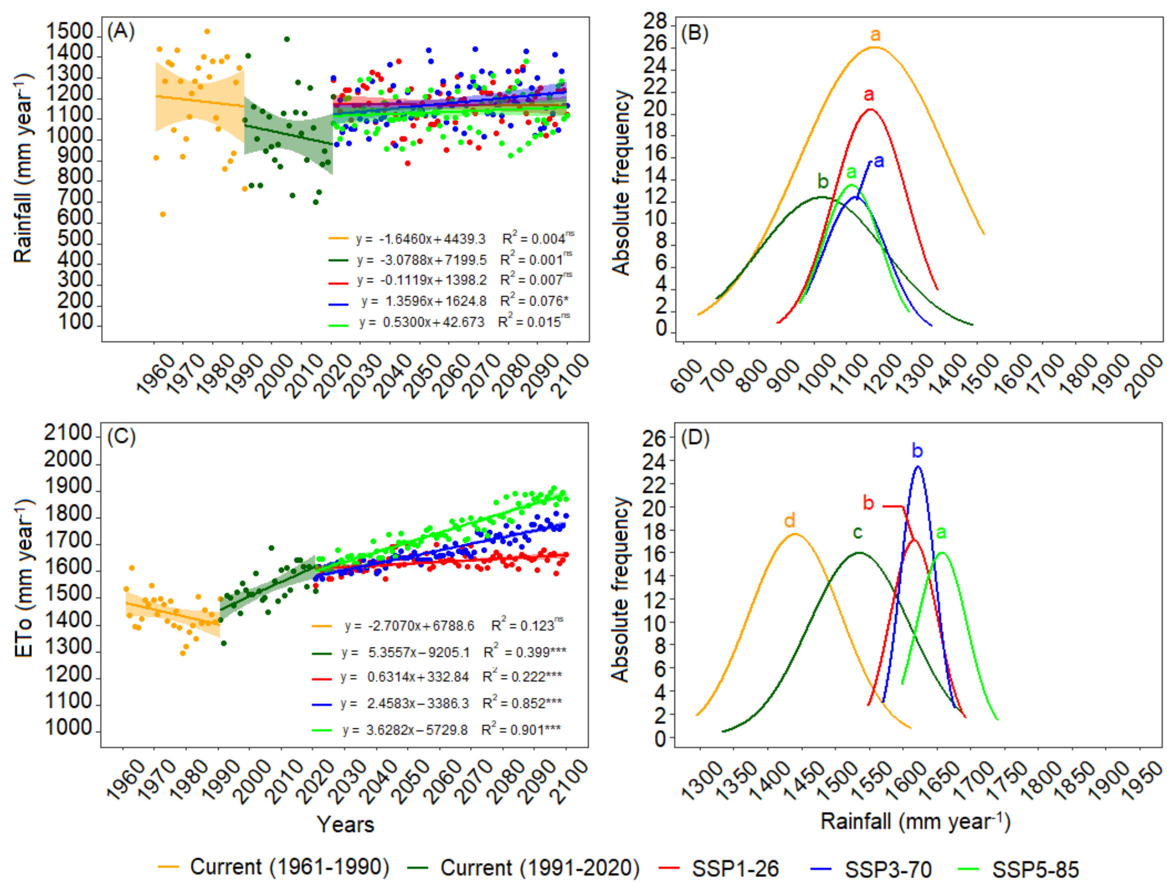

Figure 3. Linear regression (A and C) and absolute frequency (B and D) for rainfall (A and B) and reference evapotranspiration (ETo, C and D). ns, *, ** and ***: linear regression not significant, and significant at 5, 1 and < 1 %, respectively. Distribution followed by the same letter does not differ by the T-LSD test at 5 % of significance for the period between 2021 and 2050.

current conditions from 1961 to 1990. The 1990-2020 period differed from the other scenarios, with a mean of approximately 1,000 mm year^{-1}. Owing to climate change, Batista et al. (2023) observed a reduction that reached -50 % of rainfall during the wetter period from 2011 to 2020 due to deforestation.

The ETo did not show a significant trend from 1961 to 1990, even with an increase in air temperature (Figure 3C), indicating that the air temperature increase was not sufficient to significantly increase the ETo due to interaction with other climate elements (Valle Júnior et al. 2020). This could be associated with a reduction in solar radiation around 1980, when the minimum value of the current data series was 16.37 MJ m^{-2} day^{-1} against 18.53 MJ m^{-2} day^{-1} for the mean value between 1961 and 2020. The ETo trend showed a significant increase after 1991, at a rate of 5.36 mm year^{-1}. The future scenarios had increases of 0.63, 2.46 and 3.63 mm year^{-1}, respectively for SSP1-26, SSP3-70 and SSP5-85, from 2021 to 2100 (Figure 3C). The absolute frequency was different between the current periods (1961-1990 and 1991-2020), which differed from the future scenarios (2021-2050) (Figure 3D). SPP1-26 and SPP3-70 had similar absolute frequencies, but both differed from SPP5-85 (Figure 3D).

The AI method showed a satisfactory performance when using all climate data as input, with a linear coefficient of 0.97 between AI and the standard Penman-Monteith method and a bias of 0.15 mm day^{-1} (Figure 4A). However, when considering only air temperature (Figures 4B and 4C), a variable that is easily observed in the field by small farmers to simplify the estimation of ETo, a decrease in the performance of the statistical indices was observed. Based on these results, it was noted that simplification based solely on air temperature did not ensure accuracy in estimating ETo. In this study, a linear regression based on AI was tested, and further studies could focus on different AI methods (Torres et al. 2011, Makwana et al. 2023). Thus, the irrigation demand considers only the classical Penman-Monteith method for the ETo.

The irrigation demand showed a non-significant trend from 1961 to 1990 for any crop (Figures 5A, 5C, 5E and 5G), differing from that in 1991-2020 and the future scenarios between 2021 and 2050 (Figures 5B, 5D, 5F and 5H). The mean irrigation demands were 510, 630, 360 and 675 mm year^{-1}, respectively for citrus, papaya, mango and passion fruit, from 1961 to 1990 (Figures 5B, 5D, 5F and 5H). The increase ranged from 17 to 21 %, when compared to 1961-1990 and 1991-2020. The difference in irrigation demand for the two current periods is associated with the increase in ETo (Figure 3C) due to the climate changes already observed in the past, which, at a global level, increased the air temperature to 0.5 ºC until 1990, and above 1.5 ºC until 2020 (IPCC 2023).

In the future scenarios, SSP1-26 had a similar demand from 2020 to 2050 than for 1991-2020 (Figures 5B, 5D, 5F and 5H). However, SSP3-70 and SSP5-85 had a rate of increase ranging, respectively, from 1.61 (mango) to 2.34 mm year^{-1} (passion fruit), and from 2.55 (mango) to 3.73 mm year^{-1} (passion

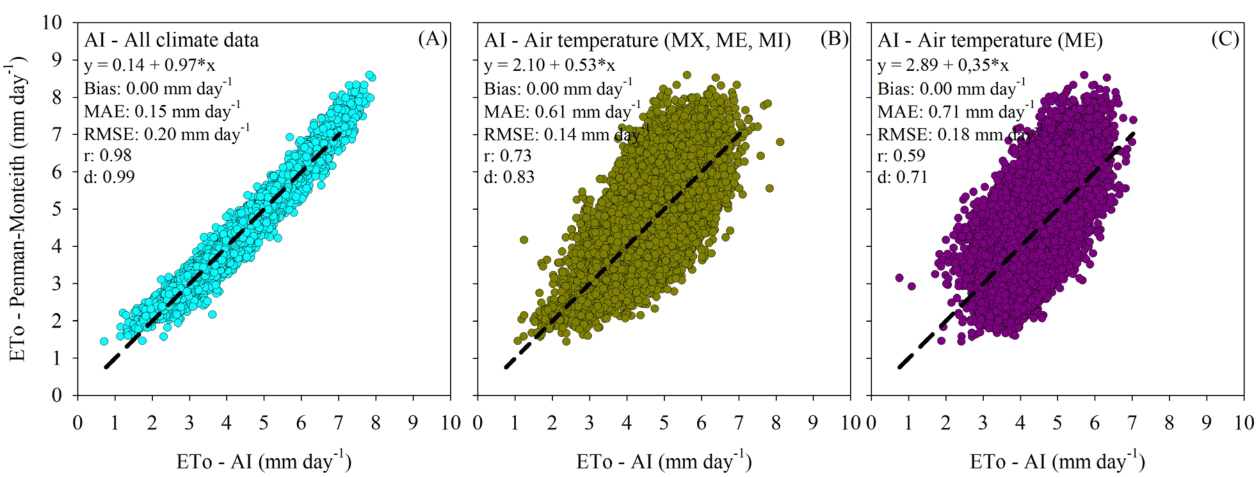

Figure 4. Reference evapotranspiration correlation between the Penman-Monteith method and artificial intelligence (AI) using all climate data (A), maximum (MX), mean (ME) and minimum (MI) air temperature (B), and using only mean air temperature (C). MAE: mean absolute error; RMSE: root mean square error.

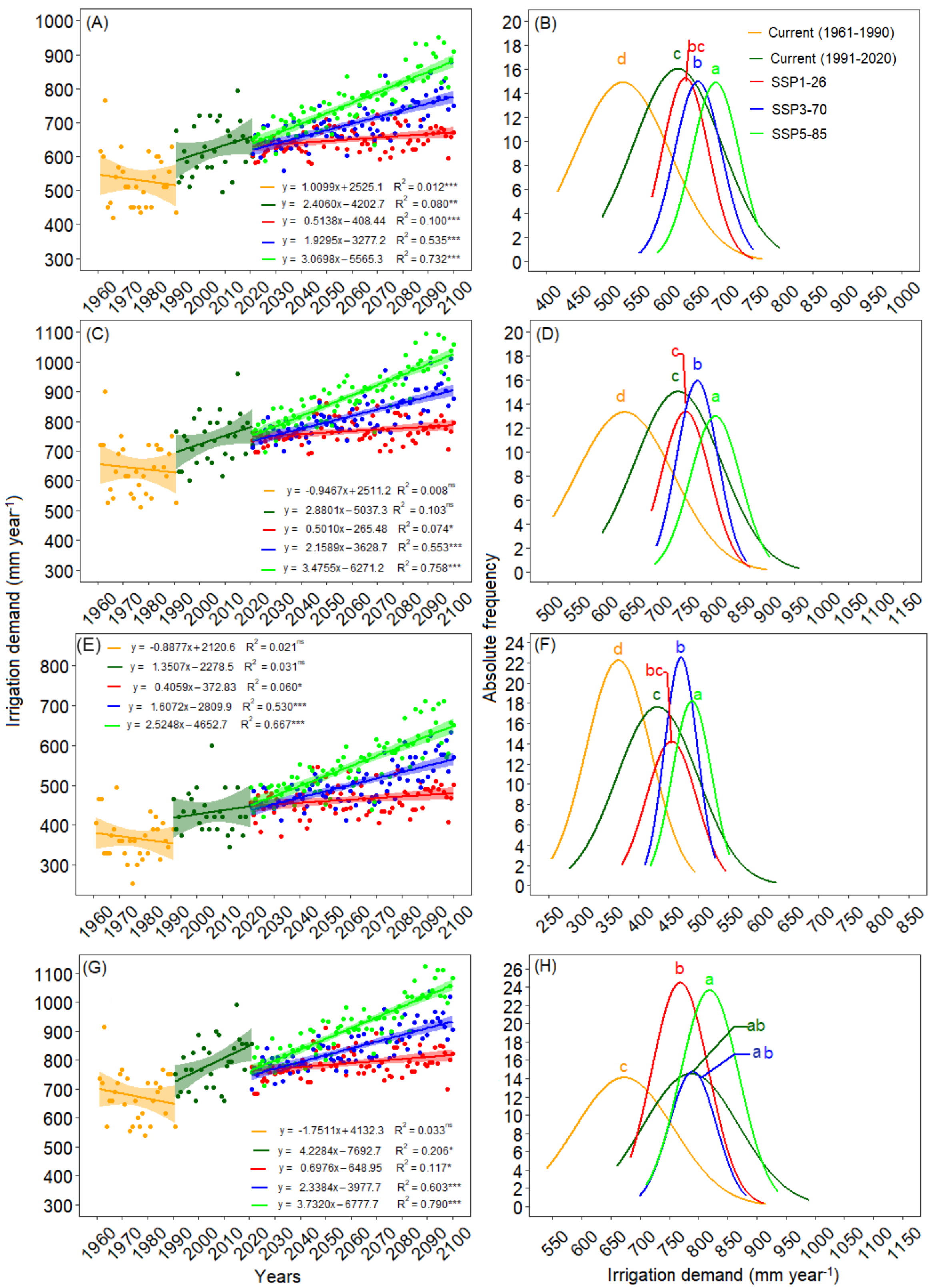

Figure 5. Linear regression (A, C, E and F) and absolute frequency (B, D, F and H) for citrus (A and B), papaya (C and D), mango (E and F) and passion fruit (G and H). ns, *, ** and ***: linear regression not significant and significant at 5, 1 and < 1 %, respectively. Distribution followed by the same letter does not differ by the T-LSD test at 5 % of significance for the period between 2021 and 2050.

fruit) (Figures 5E and 5G). SSP5-85 differed from the other periods and the scenarios for most crops, leading to mean irrigation demands of 685, 801, 495 and 826 mm year^{-1} between 2021 and 2050, respectively for citrus, papaya, mango and passion fruit. SSP5-85 led to an additional irrigation demand of 5-18 % between 2021 and 2050, when compared to 1991-2020. These results are in line with Lima & Minuzzi (2019), who observed an increase in irrigation demand from 5.5 to 11.4 % for 2016-2035 and between 13.0 and 26.1 % for 2046-2065, at the RCP 8.5, for orange, in Rio de Janeiro.

The irrigation demand followed the differences in climatic conditions, keeping constant parameters across crops. Thus, there was an uncertainty that needed to be highlighted in this study, related to Kc, crop phenology and readily available water. Kc responds to environmental conditions, as verified by Marin et al. (2016), who observed that the ETc did not respond linearly to the ETo increase, but showed a limitation of ETc at higher ETo levels. A similar process can occur for readily available water, which is affected by daily ETc, to define the fraction of total available soil water capacity in a crop (Wilson et al. 2020). These factors will affect the irrigation demand in the future owing to higher air temperatures and ETo. Temperature can also change the crop phenology and crop development stages (Pertille et al. 2022), affecting periods throughout the year with higher or lower irrigation demands.

Based on the results of the present study, public policies should consider the climate change over the next decades by providing support through subsidized credit, technical assistance for planning irrigation systems and management, and improved collaboration with public universities, in order to provide short- to medium-term courses for both young and adult people, and encouraging the formation of cooperatives among producers as a promising avenue for success among fruit farmers and small producers in the area. This may provide fruit farming in the region with a great potential to improve socioeconomic indicators and the quality of life for small-scale family farmers.

CONCLUSIONS

1. The air temperature showed a consistent increase between 1961 and 2020, with predicted stabilization under the SSP1-26 climate scenario. However, the extreme scenarios (SSP3-70 and SSP5-85) showed intense warming in this region;
2. Artificial intelligence (AI) showed an unsatisfactory performance in estimating the reference evapotranspiration when using a simplified climate dataset based only on air temperature, requiring further testing with different AI methods. However, the performance was better when the same climate dataset was used than when applying the Penman-Monteith method;
3. The irrigation demand has increased due to climate change, especially in high-emission scenarios. This requires further strategies to improve the water-use efficiency at the crop and system levels in the region.

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