Research Article

Climate drivers affecting upland rice yield in the central region of Brazil[1]

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ABSTRACT

The upland rice production is primarily concentrated in a vast area of central Brazil. Given the region's environmental variability, the performance of rice cultivars can differ significantly. This study aimed to identify the key climate factors influencing the upland rice yield in the central region of Brazil, encompassing four states: Goiás, Mato Grosso, Tocantins and Rondônia. A dataset comprising 177 trials involving commonly cultivated and well-adapted upland rice varieties, derived from the Embrapa's rice breeding dataset, was analyzed. These trials were conducted in randomized blocks, with three replications, from 1996 to 2018. The generalized additive model approach was employed to adjust the non-linear relationships between environmental factors and grain yield, revealing four climatic variables: maximum air temperature throughout the growth cycle, minimum air temperature at panicle initiation, degree-days from emergence to panicle initiation and degree-days throughout the growth cycle. An increase in the maximum air temperature and degree-days throughout the growth cycle tend to decrease rice yield, while an increase in the minimum air temperature at the panicle initiation and degree-days from emergence to panicle initiation tend to increase it.

KEYWORDS: *Oryza sativa* L., generalized additive model, enviromics prediction.

RESUMO

Fatores climáticos que afetam a produtividade do arroz de terras altas na região central do Brasil

A produção de arroz de terras altas está concentrada em uma vasta área do Brasil central. Devido à variabilidade ambiental na região, o desempenho das cultivares varia substancialmente. Objetivou-se determinar as principais variáveis climáticas que afetam a produtividade do arroz de terras altas na região central do Brasil, considerando-se quatro estados: Goiás, Mato Grosso, Tocantins e Rondônia. Utilizou-se um conjunto de dados composto por 177 ensaios, com variedades adaptadas e comumente cultivadas de arroz de terras altas, derivadas do conjunto de dados de melhoramento de arroz da Embrapa. Os ensaios foram conduzidos em blocos casualizados, com três repetições, de 1996 a 2018. A abordagem do modelo aditivo generalizado foi utilizada para ajustar as relações não lineares entre fatores ambientais e produtividade de grãos, tendo sido discriminadas quatro variáveis climáticas: temperatura máxima do ar durante todo o ciclo, temperatura mínima do ar na iniciação da panícula, graus-dia da emergência à iniciação da panícula e graus-dia durante todo o ciclo. O aumento da temperatura máxima do ar e dos graus-dia durante todo o ciclo tende a reduzir a produtividade do arroz, e o aumento da temperatura mínima do ar na iniciação da panícula e dos graus-dia da emergência à iniciação da panícula tende a aumentá-la.

PALAVRAS-CHAVE: *Oryza sativa* L., modelo aditivo generalizado, previsão ambiental.

INTRODUCTION

Upland rice cultivation in Brazil primarily occurs at latitudes lower than 20º South, concentrated in the central region, particularly in four key states: Mato Grosso, Rondônia, Tocantins and Goiás (Heinemann et al. 2021). This central area stands as the primary upland rice growing region in the country and the largest rainfed rice cultivation area in Latin America.

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The importance of upland rice cultivation cannot be overstated, as it plays a critical role in ensuring food security for a substantial portion of both farming and non-farming populations (Heinemann et al. 2019). However, over the past two decades, the upland rice cropped area has shrunk by 70 %, primarily due to elevated levels of agro-climatic risk (Heinemann et al. 2019).

Recent data from the Intergovernmental Panel on Climate Change estimates that, by the end of this century, the global average temperature will increase by approximately 3.2 ºC, leading to a rise in the frequency of extreme meteorological events like droughts and floodings (IPCC 2022). Of particular concern is thermal stress during the initial stages of panicle initiation, which increases spikelet sterility and disrupts floral organ development, ultimately reducing rice yield (Sánchez et al. 2014, Wang et al. 2019). These climate changes could have significant repercussions on rice production and pose a substantial threat to food security. Moreover, climate change is anticipated to decrease yield by 200-600 kg ha^{-1} (up to 20 %) and disrupt yield stability across the entire upland rice-growing region (Ramirez-Villegas et al. 2018).

Upland rice presents a viable option for increasing the overall national rice production, given the growing population, increasing food demand, and a generally lower environmental footprint (West et al. 2014). While closing yield gaps and improving stress tolerance through crop breeding can enhance yield (Heinemann et al. 2015), expanding the upland rice cultivation area by integrating it into existing crop rotation systems (e.g., soybean-maize, cotton-maize) offers another avenue for boosting the total upland rice production (Heinemann et al. 2017).

As aforementioned, the upland rice production is concentrated in the expansive central region of Brazil. However, due to environmental variability, cultivar performance exhibits a significant variation across this region. Thus, achieving maximum genetic gains in this production area requires a more comprehensive environmental characterization to provide insights that can inform breeding strategies aimed at developing adapted yield germplasm for this specific region. To address this need, the concept of "enviromics prediction" is introduced, which involves the use of statistical models to relate comprehensive environmental data and phenotypic data (grain yield) for research and analytical purposes.

In this sense, this study aimed to identify the primary climate drivers influencing upland rice yield in the central region of Brazil.

MATERIAL AND METHODS

The study encompasses a diverse range of edaphoclimatic conditions across four Brazilian states: Goiás, Mato Grosso, Tocantins and Rondônia, situated between the latitudes 7 and 20 ºS and longitudes 65 and 45 ºW. In 2022, this region contributed to 13 % of the Brazil's total rice production (IBGE 2022).

The climate in the area is tropical, characterized by distinct wet and dry seasons, classified under the Köppen classification as Aw, with average annual rainfall of 1,000-1,500 mm (monomodal summer rains) and altitudes ranging from 85 to 1,190 m (Alvares et al. 2013).

This study used an extensive dataset of accumulated upland rice yields derived from multiple trials involving commonly grown and well-adapted rice varieties sourced from the Embrapa's rice breeding dataset (Breseghello et al. 2021). Each field trial, following the Embrapa's nationwide rice breeding program standards, consists of the top 20 performing genotypes from the current elite germplasm, and was conducted in randomized blocks, with three replications, being selected 177 trials conducted between 1996 and 2018. The geographic distribution of these field trials is illustrated in Figure 1.

To facilitate a comprehensive assessment of weather variables in relation to upland rice yields across the four states, the genotype yields were averaged by trial. Figure 2 displays the coefficients of variation for trials across the states, with most of them being below 30 %, affirming the representativeness of the multi-environment trial average values used in the analysis.

A script developed in the R software (R Core Team 2023) was employed to integrate agronomic variables from breeding programs with daily climate data which were collected from the nearest weather station (Brasil 2023) in the trial municipality. In cases where no weather station was available, daily climate data from the Nasa Power (Sparks 2018) was used, following the approach outlined by Heinemann et al. (2022).

After aligning the trials with climate data, environmental covariates were selected, as summarized

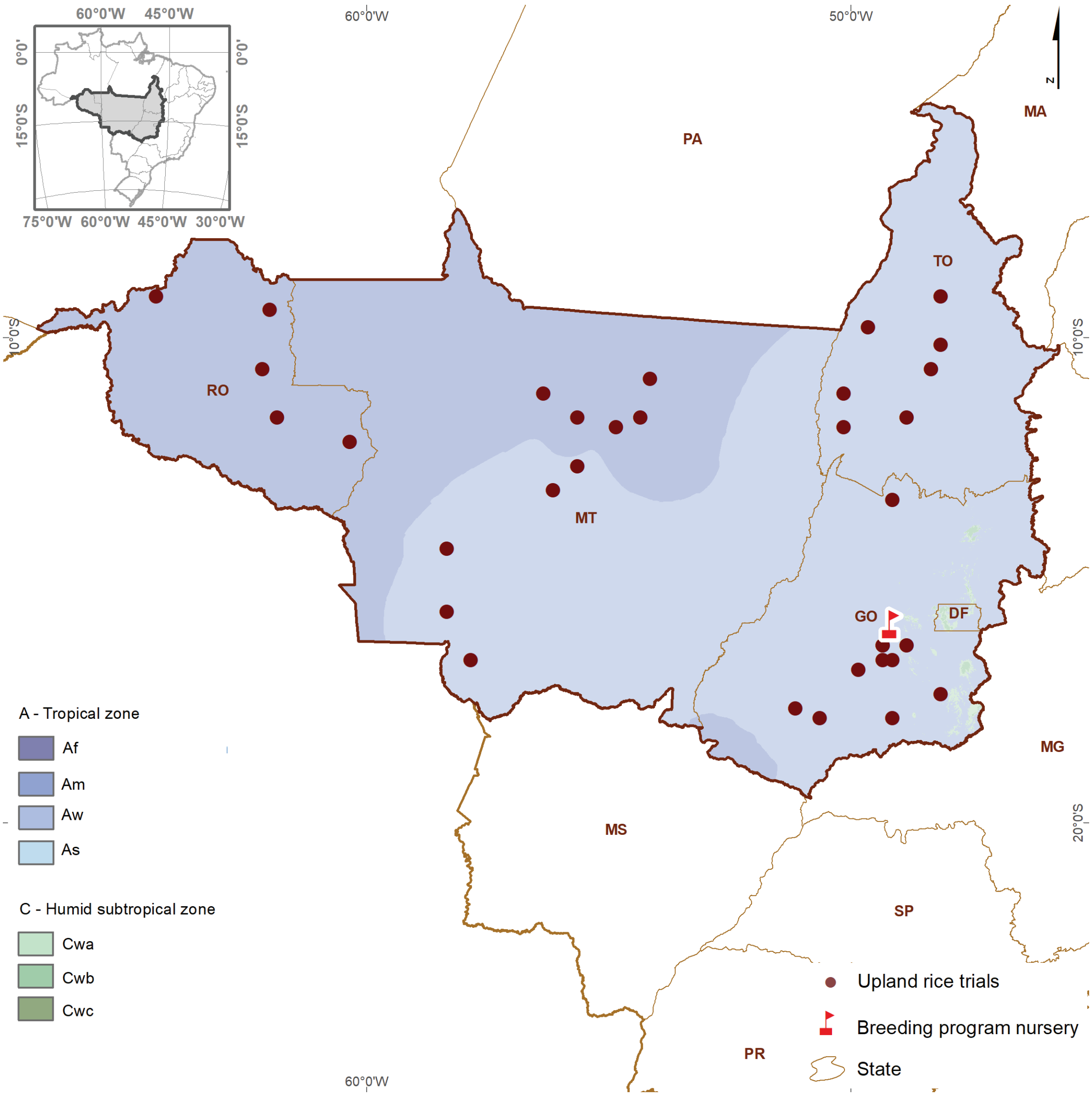

Figure 1. Geographic distribution of the upland rice field trials used in the study region and their Köppen's climate classification for the states of Goiás (GO), Mato Grosso (MT), Rondônia (RO) and Tocantins (TO). Af: tropical climate without dry season; Am: tropical monsoon climate; Aw: tropical climate with dry winter; As: tropical climate with dry summer; Cwa: oceanic climate without dry season, with hot summer; Cwb: oceanic climate without dry season, with temperate summer; Cwc: oceanic climate without dry season, with short and cool summer.

in Table 1, which effectively captured temporal variations across the crop life cycle. Development stages were calculated at the field trial level using mean values of flowering day and physiological maturation observed in each trial. For the reproductive stage, panicle initiation (corresponding to stage R0) was assumed to begin at 25 days before the flowering day, as panicle initiation is not directly observed in field trials. The calculation of effective daily heat units (degree-days) considered the daily mean temperature and three cardinal temperatures: base (8 ºC), optimum (30 ºC) and maximum (42 ºC) thresholds, following the equation described by Heinemann et al. (2017). This approach allowed to screen environmental covariates for their impact on upland rice grain yield in the Brazilian central region.

Using the environmental covariates presented in Table 1, a generalized additive model (GAM) was applied and tested, with the mean upland rice grain yield for each trial as the dependent variable. This approach aimed to assess the sensitivity and predictive capabilities of the GAM models when

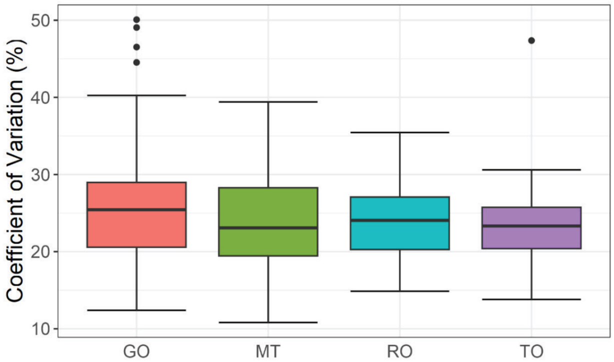

Figure 2. Coefficient of variation for all trials used in this study across the states of Goiás (GO), Mato Grosso (MT), Rondônia (RO) and Tocantins (TO).

resizing the original dataset, thus increasing the confidence in identifying grain yield's climate factors across the four states. The hypothesis was that environmental covariates with stronger explanatory power would compose the best GAM model for each state, unveiling potential climate drivers influencing the upland rice adaptation.

Hastie & Tibshirani (1986) proposed the GAM model as an alternative to generalized linear models (GLM). The GAM model enables the enhancement of non-parametric functions as potential predictors. In general, the linear predictor of the GAM model is represented as it follows: $g(\mu_i) = A_i\beta + f_1(X_{i1}) + \cdots + f_J(X_{iJ}) + f_k(X_{ik_1}, X_{ik_2}) + \cdots + fk(X_{iK_1}, X_{iK_2})$, with $i = 1, ..., n$, wherein: g is a specified link function; $g(\mu_i) = g[E(Y_i)]$, with mean $E(Y_i) = \mu_i$ and Y_i representing the dependent variable; A_i is the matrix row of the model's parametric components; β is the corresponding parameter vector; $f_j(.)$, j = 1, 2, ..., J, denotes smooth functions (non-parametric or semi-parametric functions) of the variable vector considered, X_J (e.g., Wood 2017); and k = k + 1, k + 2, ..., K, is a factor smooth interaction between two considered variables, X_{k_1}, X_{k_2}.

The estimation process employed by GAM is analogous to that of GLM, specifically using the Fisher's scoring. The key distinction lies in the fact that the linear predictor in GAM incorporates smooth functions, denoted as f_j of at least some, if not all, covariates. This incorporation allows for the modeling of non-linear relationships between covariates and the target variable Y. Hastie & Tibshirani (1990) outlined various approaches for smoothing functions, including moving means and cubic smoothing splines. Consequently, GAM becomes the preferred choice over GLM when there is evidence of an unknown deterministic pattern in the data.

For the GAM parametrization, significance was attributed to environmental covariates with a p-value lower than 5 % ($p \leq 0.05$). The environmental covariates variables falling within the 5-10 % p-value range were excluded based on their predictive impact. Subsequently, a cross-validation algorithm was applied to determine the most robust model based on the observed data. The predicted mean square error served as the criterion for model selection, ultimately identifying the model with the smallest mean square error through cross-validation executions.

Following the GAM selection via cross-validation, the grain yield was predicted for each environmental covariate considering the GAM adjusted with all available data. These predictions were carried out based on the median values of numerical covariates within the GAM. The yield was evaluated across multiple scenarios, using mean performance, to determine optimal values for certain climatic variables in the study region.

RESULTS AND DISCUSSION

Figure 3 displays the observed yield variations for upland rice trials in the states of Goiás (GO), Mato Grosso (MT), Rondônia (RO) and Tocantins (TO). Notably, there was no significant difference in grain yield among these states, although Goiás boasted the highest median grain yield, followed by Rondônia, Mato Grosso and Tocantins. The substantial dispersion of grain yield (Figure 3A) stems from climatic variations between years (Figure 3B) within these states. Specifically, Goiás experienced the highest solar radiation and the lowest temperatures (both maximum and minimum), rainfall, degree-days and humidity.

Figure 4 presents the Spearman correlation matrix between yield and environmental covariables. Although these covariables exhibit signs of monotonic correlation, this did not interfere with the adjustment of the GAM model.

The results from the GAM model (Table 2) identified four key climatic drivers: maximum air temperature throughout the entire cycle, minimum air temperature at panicle initiation, degree-days from seed emergence to panicle initiation, and degree-days

Table 1. Acronyms for the environmental covariates applied in the study.

Factor	Acronym	Computed environmental covariable	Unit	Period
Air Temperature	Tmax_Max	Maximum daily maximum temperature	ºC	Whole crop cycle
	Tmax_Min	Minimum daily maximum temperature	ºC	Whole crop cycle
	Tmax_Mean	Mean maximum temperature	ºC	Whole crop cycle
	Tmax_PI	Daily maximum temperature	ºC	Panicle initiation (PI)
	Tmax_FLO	Daily maximum temperature	ºC	Flowering (FLO)
	Tmax_V	Daily maximum temperature	ºC	Vegetative (V)
	Tmax_ACC_V	Cumulative daily maximum temperature	ºC	Vegetative (V)
	Tmax_R	Daily maximum temperature	ºC	Reproductive (R)
	Tmax_ACC_R	Cumulative daily maximum temperature	ºC	Reproductive (R)
	Tmax_FG	Daily maximum temperature	ºC	Grain filling (GF)
	Tmax_ACC_FG	Cumulative daily maximum temperature	ºC	Grain filling (GF)
	Tmin_Max	Maximum minimum temperature	ºC	Whole crop cycle
	Tmin_Min	Minimum daily minimum temperature	ºC	Whole crop cycle
	Tmin_Mean	Mean daily minimum temperature	ºC	Whole crop cycle
	Tmin_PI	Daily minimum temperature	ºC	Panicle initiation (PI)
	Tmin_FLO	Daily minimum temperature	ºC	Flowering time (FLO)
	Tmin_V	Daily minimum temperature	ºC	Vegetative (V)
	Tmin_ACC_V	Daily minimum temperature	ºC	Vegetative (V)
	Tmin_R	Daily minimum temperature	ºC	Reproductive (R)
	Tmin_ACC_R	Cumulative minimum temperature	ºC	Reproductive (R)
	Tmin_FG	Daily minimum temperature	ºC	Grain filling (GF)
Solar Radiation	Radiation_ACC_V	Daily accumulated solar radiation	MJ m^{-2}	Vegetative (V)
	Radiation_ACC_R		MJ m^{-2}	Reproductive (R)
	Radiation_ACC_FG		MJ m^{-2}	Grain filling (GF)
	Radiation_ACC		MJ m^{-2}	Whole crop cycle
Humidity	Hum_Mean	Average daily humidity	%	Whole crop cycle
	Hum_FLO		%	Flowering time (FLO)
	Hum_V		%	Vegetative (V)
	Hum_R		%	Reproductive (R)
	Hum_FG		%	Grain filling (GF)
Rainfall	Prec_ACC_V	Daily accumulated rainfall	mm	Vegetative (V)
	Prec_ACC_R		mm	Reproductive (R)
	Prec_ACC_FG		mm	Grain filling (GF)
	Prec_ACC		mm	Whole crop cycle
Degree-days	Degree_days_PI	Growing degree-days	ºC d	Emergence to panicle initiation (PI)
	Degree_days_FLO		ºC d	PI to flowering time (FLO)
	Degree_days_FM		ºC d	FLO to physiological maturation (PM)
	Degree_days_Cycle		ºC d	Emergence to PM

Table 2. Results from the generalized additive model (GAM).

Parametric coefficient				
Factor	Standard deviation	Error	t-value	Pr(> |t|)
Intercept	2.267	0.5215	4.347	2.7e-05
Tmin_PI**	0.033	0.0114	2.892	0.0044
Degree_days_PI	0.001	0.0003	3.565	0.0005
Approximate significance of smooth terms				
	Edf*	Ref.df[&]	F	p-value
s(Tmax_Max)	2.405	3.102	3.462	0.0175
s(Degree_days_Cycle)	2.464	3.130	5.679	0.0009

* Edf: effective degrees of freedom; [&] Ref.df: estimated residual degrees of freedom; ** PI: panicle initiation.

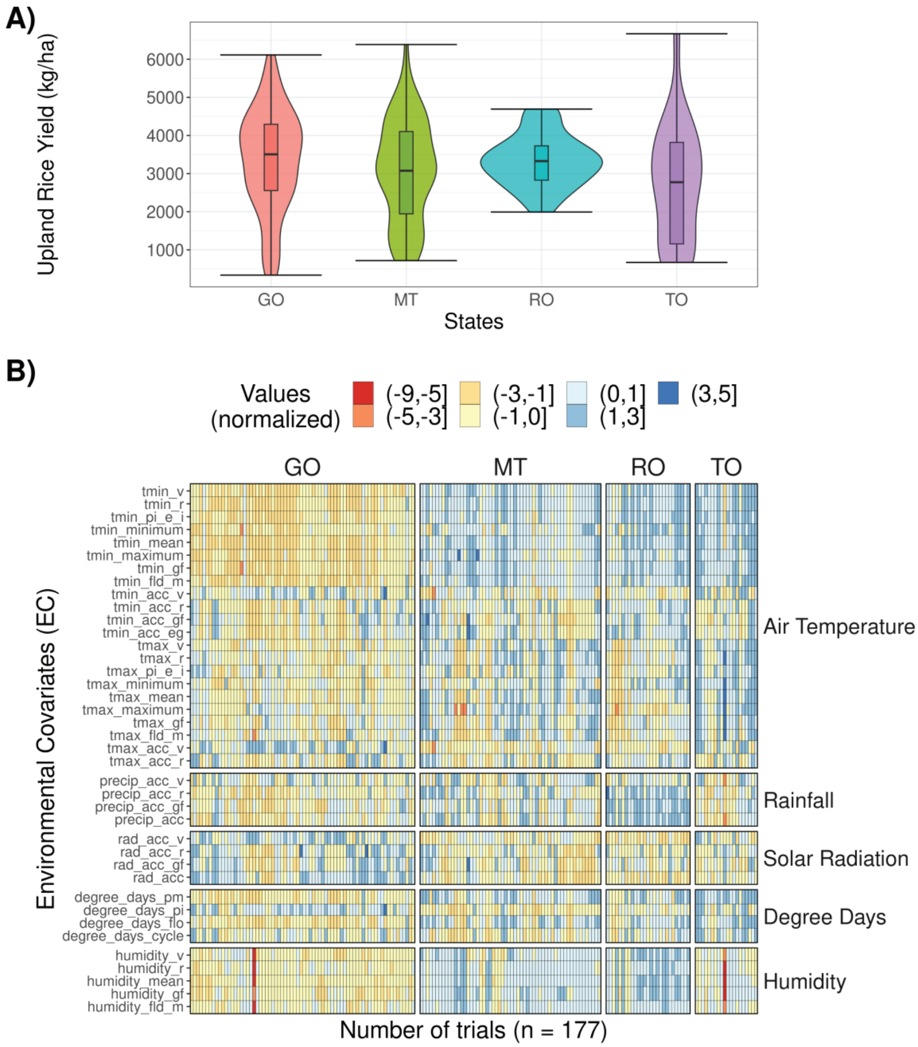

Figure 3. Characterization of yield variations in upland rice trials for each state (A), namely, Goiás (GO), Mato Grosso (MT), Rondônia (RO) and Tocantins (TO), and comprehensive macro-environmental characterization of the four states (B). It displays a panel of the main climatic covariates standardized as Z-scores across each of the 177 field trials.

during the whole cycle. Increases in maximum air temperature and degree-days throughout the whole cycle tend to reduce rice yield (Figures 5A and 5D). Conversely, increases in the minimum air temperature at panicle initiation and degree-days from seed emergence to panicle initiation tend to enhance rice yield (Figures 5B and 5C).

Studies have focused on understanding crop yield through the analysis of environmental variables in recent years. For instance, Heinemann et al. (2022) assessed the impact of climatic factors on common bean yield in various production environments in Brazil using GAM, revealing temperature variables as crucial factors, particularly during the reproductive phase. Porker et al. (2020) explored the influence of temperature and photoperiod on barley phenology, identifying critical development periods with pronounced effects. Similarly, Romay et al. (2010) found that temperature-related covariates play a significant role in corn yield.

Temperature holds a paramount position among climatic elements influencing rice crop growth, development and yield. While optimal temperatures may vary throughout the crop cycle according to the phenological phase, it is generally accepted that values near 28 ºC are ideal for the entire cycle. Temperatures below 13.5 ºC and above 35 ºC are considered critical. High maximum temperatures can lead to spikelet sterility, particularly when exceeding 35 ºC (Sánchez et al. 2014).

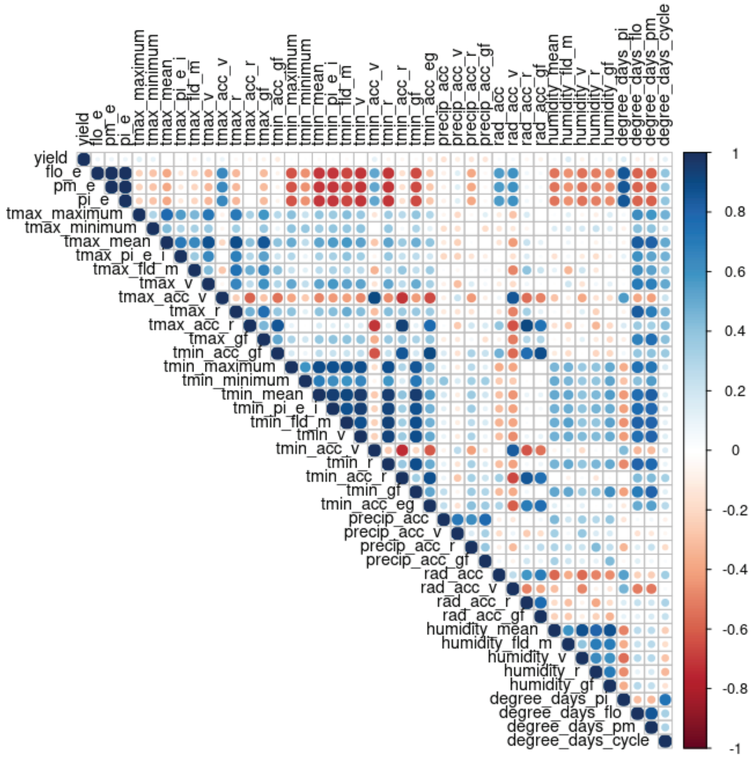

Figure 4. Spearman correlation matrix between upland rice yields and the environmental covariables described in Table 1.

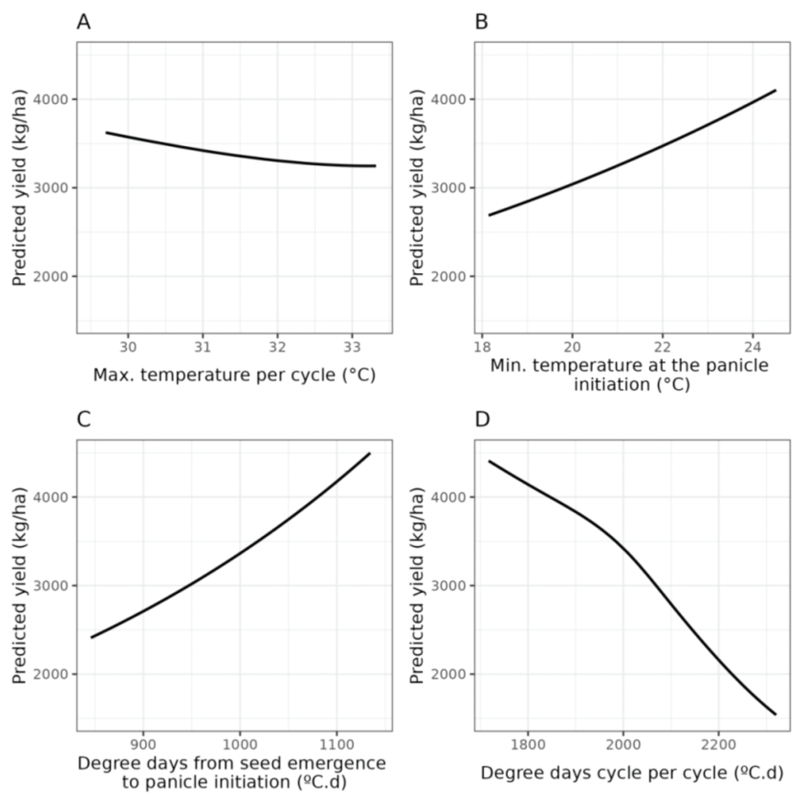

Figure 5. Predicted yields for upland rice fields in the study region (Goiás, Mato Grosso, Rondônia and Tocantins) as a function of the variation in the main climatic drivers: A) maximum temperature (ºC) per cycle; B) minimum temperature (ºC) at panicle initiation; C) degree-days (ºC d) from seed emergence to panicle initiation; D) degree-days (ºC d) per cycle.

Rice exhibits a high sensitivity to temperature in the period just before anthesis, significantly affecting yields. Both low and high temperatures at panicle initiation can increase spikelet sterility, resulting in reduced yields (Sánchez et al. 2014). Sterility is typically associated with poor anther dehiscence, spikelet malformation, low pollen viability and reduced germination of pollen grains on stigmata, leading to ineffective fertilization (Prasad et al. 2006). During the panicle initiation stage, high temperatures exacerbate spikelet degeneration and disrupt floral organ development (Wang et al. 2019). Similarly, temperatures below 16 ºC at panicle initiation induce spikelet sterility, primarily due to reduced pollen germination rather than the number of spikelets reaching anthesis (Zeng et al. 2017). For this stage, an optimal temperature of approximately 27 ºC is recommended (Prasad et al. 2006).

Thermal sum, often represented as degree-days, reflects the energy availability within the environment. It represents the daily accumulation of temperatures that fall between the minimum and maximum requirements for the rice plant. An increase in minimum temperature from seed emergence to panicle initiation leads to higher average temperatures and, consequently, an increased thermal sum during this stage, contributing to a greater grain yield. However, an increase in maximum air temperature can cause thermal stress when exceeding the optimal value of 28 ºC, potentially reducing photosynthetic rates and increasing respiratory rates (Monteith 1981). Consequently, higher maximum temperatures may lead to decreased grain yield. Furthermore, an increase in degree-days per cycle can render upland rice more susceptible to both biotic and abiotic stress factors. While longer crop cycles may accumulate more biomass and photoassimilates for grain development, extended field exposure makes them vulnerable to biotic and abiotic stressors, such as drought, extreme temperatures and pests (Alvar-Beltrán et al. 2022, Silva Júnior et al. 2023).

CONCLUSIONS

1. The generalized additive model identified four key climatic factors influencing rice yield: maximum air temperature throughout the entire cycle, minimum air temperature at panicle initiation, degree-days from seed emergence to panicle initiation and degree-days during the entire cycle;
2. Increased maximum air temperature and degree-days throughout the entire cycle tend to have a negative impact on upland rice yield, while higher minimum air temperature at panicle initiation and more degree-days from seed emergence to panicle initiation tend to positively affect yield;
3. Upland rice yield does not exhibit a significant variation among the analyzed Brazilian states (Goiás, Mato Grosso, Rondônia and Tocantins);
4. The significant dispersion in upland rice yield within these states can be attributed to climatic variations across different years.

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