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FUTURE CLIMATE RISKS TO COTTON PRODUCTION IN BRAZIL: EVIDENCE FROM EC-EARTH3 PROJECTIONS AND FROM THE SENSITIVITY OF GENETIC PARAMETERS

RISCOS CLIMÁTICOS FUTUROS À PRODUÇÃO DE ALGODÃO NO BRASIL: EVIDÊNCIAS DE PROJEÇÕES EC-EARTH3 E DA SENSIBILIDADE DE PARÂMETROS GENÉTICOS

RIESGOS CLIMÁTICOS FUTUROS PARA LA PRODUCCIÓN DE ALGODÓN EN BRASIL: EVIDENCIA DE PROYECCIONES EC-EARTH3 Y DE LA SENSIBILIDAD DE PARÁMETROS GENÉTICOS

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ABSTRACT

This study used the DSSAT/CROPGRO-Cotton model and climate projections from EC-Earth3 (SSP2-4.5 and SSP5-8.5 scenarios) up to 2059 to assess the response of cotton yield components to climate change and the sensitivity of the crop genetic parameters in three municipalities representative of Brazilian producing regions: Sapezal (MT), Coromandel (MG) and Luiz Eduardo Magalhães (BA). In order to isolate the climate effect, soil, cultivar and management were kept constant across municipalities; simulations were run under rainfed conditions and without nitrogen limitation. Projections indicate progressive warming and increased interannual variability of maximum temperature and rainfall under SSP5-8.5, with median maximum temperatures approaching 40 °C in Luiz Eduardo Magalhães (BA). The yield response was regionally heterogeneous: Coromandel (MG) showed an increase in productivity up to the 2050s under SSP5-8.5, whereas Luiz Eduardo Magalhães (BA) exhibited a decline after the initial decade and Sapezal (MT) remained relatively stable. The Morris sensitivity analysis identified the maximum leaf photosynthesis rate (LFMAX) as the dominant parameter for total above-ground biomass (CWAD). For lint yield (LIWAM), threshing percentage (THRSH) became the main limiting factor, indicating that the bottleneck under future stress lies in reproductive allocation rather than in maximum carbon assimilation. The duration of the seed-filling phase to physiological maturity (SD-PM) showed increased sensitivity in Coromandel, associated with heat-induced cycle shortening. The σ/μ* ratio revealed a predominantly linear behaviour for LFMAX and THRSH and a non-linear or interaction-dominated response for SFDUR and PODUR. The results, which are comparative

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in nature across scenarios, support breeding strategies focused on THRSH and on reproductive thermal tolerance for the resilience of Brazilian cotton production.

Keywords: Cotton. DSSAT/CROPGRO. Morris Method. Sensitivity Analysis. CMIP6. Climate Change.

RESUMO
Este estudo utilizou o modelo DSSAT/CROPGRO-Cotton e projeções climáticas do EC-Earth3 (cenários SSP2-4.5 e SSP5-8.5) até 2059 para avaliar a resposta dos componentes de rendimento do algodão às mudanças climáticas e a sensibilidade dos parâmetros genéticos da cultura em três municípios representativos das regiões produtoras brasileiras: Sapezal (MT), Coromandel (MG) e Luiz Eduardo Magalhães (BA). Para isolar o efeito do clima, solo, cultivar e manejo foram mantidos constantes entre municípios; as simulações foram executadas sob condições de sequeiro e sem limitação de nitrogênio. As projeções indicam aquecimento progressivo e aumento da variabilidade interanual da temperatura máxima e precipitação sob SSP5-8.5, com temperaturas máximas medianas aproximando-se de 40 °C em Luiz Eduardo Magalhães (BA). A resposta de rendimento foi regionalmente heterogênea: Coromandel (MG) apresentou aumento de produtividade até os anos 2050 sob SSP5-8.5, enquanto Luiz Eduardo Magalhães (BA) exibiu declínio após a década inicial e Sapezal (MT) permaneceu relativamente estável. A análise de sensibilidade de Morris identificou a taxa máxima de fotossíntese foliar (LFMAX) como o parâmetro dominante para a biomassa total acima do solo (CWAD). Para rendimento de fibra (LIWAM), a porcentagem de debulhação (THRSH) tornou-se o principal fator limitante, indicando que o gargalo sob estresse futuro está na alocação reprodutiva e não na assimilação máxima de carbono. A duração da fase de enchimento de sementes até a maturidade fisiológica (SD-PM) mostrou sensibilidade aumentada em Coromandel, associada ao encurtamento do ciclo induzido pelo calor. A razão σ/μ* revelou comportamento predominantemente linear para LFMAX e THRSH e resposta não-linear ou dominada por interações para SFDUR e PODUR. Os resultados, comparativos por natureza entre cenários, apoiam estratégias de melhoramento focadas em THRSH e tolerância térmica reprodutiva para a resiliência da produção de algodão brasileiro.

Palavras-chave: Algodão. DSSAT/CROPGRO. Método de Morris. Análise de Sensibilidade. CMIP6. Mudança Climática.

RESUMEN
Este estudio utilizó el modelo DSSAT/CROPGRO-Cotton y proyecciones climáticas de EC-Earth3 (escenarios SSP2-4.5 y SSP5-8.5) hasta 2059 para evaluar la respuesta de los componentes de rendimiento del algodón al cambio climático y la sensibilidad de los parámetros genéticos del cultivo en tres municipios representativos de las regiones productoras de Brasil: Sapezal (MT), Coromandel (MG) y Luiz Eduardo Magalhães (BA). Para aislar el efecto del clima, el suelo, la cultivar y el manejo se mantuvieron constantes entre municipios; las simulaciones se ejecutaron bajo condiciones de secano y sin limitación de nitrógeno. Las proyecciones indican un calentamiento progresivo y un aumento de la variabilidad interanual de la temperatura máxima y la precipitación bajo SSP5-8.5, con temperaturas máximas medianas aproximándose a los 40 °C en Luiz Eduardo Magalhães (BA). La respuesta de rendimiento fue regionalmente heterogénea: Coromandel (MG) mostró un aumento de productividad hasta los años 2050 bajo SSP5-8.5, mientras que Luiz Eduardo Magalhães (BA) exhibió un declive después de la década inicial y Sapezal (MT) se mantuvo relativamente estable. El análisis de sensibilidad de Morris identificó la tasa máxima de fotosíntesis foliar (LFMAX) como el parámetro dominante para la biomasa total sobre el suelo

(CWAD). Para el rendimiento de fibra (LIWAM), el porcentaje de desgranación (THRSH) se convirtió en el principal factor limitante, indicando que el cuello de botella bajo estrés futuro está en la asignación reproductiva y no en la asimilación máxima de carbono. La duración de la fase de llenado de semillas hasta la madurez fisiológica (SD-PM) mostró sensibilidad aumentada en Coromandel, asociada al acortamiento del ciclo inducido por el calor. La relación σ/μ* reveló un comportamiento predominantemente lineal para LFMAX y THRSH y una respuesta no lineal o dominada por interacciones para SFDUR y PODUR. Los resultados, comparativos por naturaleza entre escenarios, apoyan estrategias de mejoramiento enfocadas en THRSH y tolerancia térmica reproductiva para la resiliencia de la producción de algodón brasileño.

Palabras clave: Algodón. DSSAT/CROPGRO. Método de Morris. Análisis de Sensibilidad. CMIP6. Cambio Climático.

1 INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is one of the most relevant natural fibres for Brazilian and global agribusiness, supplying textile, food and input industrial chains and reinforcing Brazil's position as a leading exporter (Klein & Luna, 2023). Although the most recent surveys of the Brazilian National Supply Company show a growing national output in the 2024/25 season, of about 4.0 million tonnes of cotton lint, this expansion trajectory takes place in a context of increasing climatic instability (CONAB, 2025).

Over the last decades, production has strongly migrated to the Central-West and Northeast regions, with key states such as Mato Grosso, Bahia and Minas Gerais taking a leading role in national cotton production (Raphael *et al.*, 2019). It should be noted that, among these states, Minas Gerais displays a substantially smaller cropped area and output, constituting a specific production niche. In parallel, the global climate change context, characterised by rising mean temperatures, changes in rainfall patterns and greater interannual variability, has increased uncertainty regarding the yield stability of cotton (Jans *et al.*, 2021). Agroclimatic zoning studies in Brazil indicate that areas currently favourable may show reduced production suitability under warming and rainfall-change scenarios (Assad *et al.*, 2013). Recent work reinforces this trend by estimating future production suitability under different climate trajectories projected by CMIP6 (Lorençone *et al.*, 2025).

Given this edaphoclimatic heterogeneity, understanding not only the future risks to yield but also how the physiological and genetic components of cotton respond to these scenarios becomes essential. Mechanistic models such as DSSAT/CROPGRO-Cotton allow the crop behaviour to be evaluated under different combinations of climate, soil and management, incorporating genetic parameters that represent photosynthetic efficiency, phenological duration, biomass partitioning and stress tolerance. The sensitivity of these parameters indicates how much each genetic component influences yield and is recognised as a central step to identify points of physiological vulnerability, guide breeding programmes and improve crop adaptation (Paleari *et al.*, 2021; Colombi *et al.*, 2024).

In this context, projecting future scenarios for the yield response of cotton in the main producing regions of Brazil over the next three decades becomes relevant. Anticipating climate variables such as temperature, rainfall, radiation and the frequency of extreme events allows not only potential yield changes to be estimated, but also regional vulnerabilities to be identified, management improvements to be guided, public policies to be supported and more resilient agricultural systems to be fostered (dos Santos *et al.*, 2020).

Therefore, this study aims to assess the sensitivity of genetic parameters and the response of cotton (*Gossypium hirsutum* L.) yield components to the climate changes projected for Mato Grosso, Minas Gerais and Bahia, under the SSP2-4.5 and SSP5-8.5 scenarios up to 2059, keeping soil conditions, cultivar and management constant so as to isolate the climate signal. We tested the hypothesis that, under progressive warming, the relative importance of parameters linked to reproductive allocation and cycle duration (THRSH and SD-PM) increases relative to that of the maximum assimilation parameter (LFMAX), especially for lint yield. The aim is thus to provide support for breeding oriented towards the resilience of Brazilian cotton production.

2 MATERIAL AND METHODS

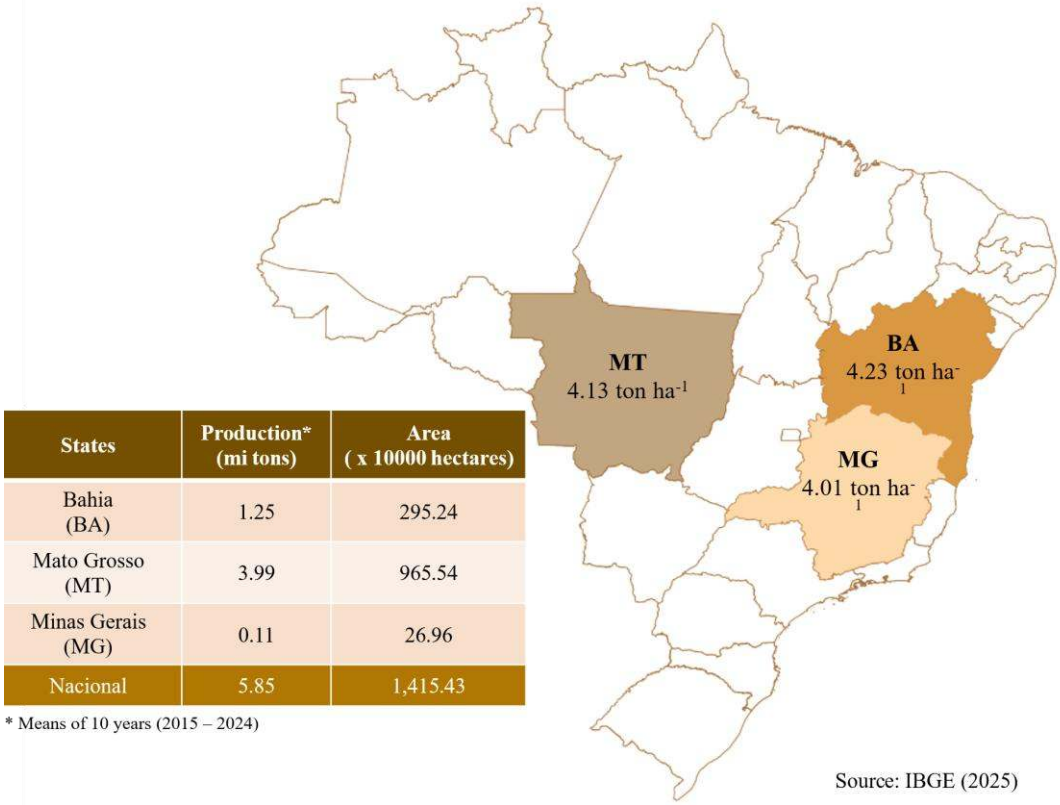
2.1 CLIMATE MODEL

The climate projections used in this study were obtained from the EC-Earth3 model, part of CMIP6, which is widely employed in future projection studies because it adequately represents temperature and rainfall patterns in different regions of the world (Wyser *et al.*, 2020; Döscher *et al.*, 2022). The model was used to generate the future climate series for the SSP2-4.5 and SSP5-8.5 scenarios, in which SSP2-4.5 represents an intermediate trajectory, with moderate economic and population growth and some emission mitigation effort, and SSP5-8.5 describes a high-emission future, marked by strong dependence on fossil fuels and low adoption of environmental policies (Tebaldi *et al.*, 2021).

Projections were carried out for the states of Mato Grosso, Bahia and Minas Gerais, which show economic relevance and edaphoclimatic variability representative of national cotton production (IBGE, 2025; Figure 1), providing the atmospheric conditions required for the simulations and for the sensitivity analysis of the genetic parameters under the projected climate. For both scenarios, daily climate series were extracted for the period 2030–2059, organised into three decadal windows (2030–2039, 2040–2049 and 2050–2059), following guidelines recommended for agronomic studies addressing gradual changes in future climate (Zabel *et al.*, 2021; Pereira *et al.*, 2024).

Figure 1

Overview of cotton production and yield in selected regions (mean data for 2015–2024)



States	Production* (mi tons)	Area (x 10000 hectares)
Bahia (BA)	1.25	295.24
Mato Grosso (MT)	3.99	965.54
Minas Gerais (MG)	0.11	26.96
Nacional	5.85	1,415.43

* Means of 10 years (2015 – 2024)

Source: IBGE (2025).

2.2 DECISION SUPPORT SYSTEM FOR AGROTECHNOLOGY TRANSFER (DSSAT)

The climate data generated by the EC-Earth3 model were converted to the weather file format (.WTH) required by DSSAT v4.8, as described by Hoogenboom *et al.* (2019). The input variables considered were the daily series of solar radiation, maximum and minimum temperature, rainfall, dew point temperature, wind speed, mean daily relative humidity and atmospheric CO_2 concentration. The EC-Earth3 series were used without bias correction, an option supported by the relative nature of the inferences of this study — comparisons among scenarios, decades and municipalities under the same climate model, and ranking of parameter sensitivity — in which systematic model errors tend to partially cancel out (see the Limitations section).

For each combination of municipality, scenario and projected period, an experiment file (.COX) was created, as presented in Table 1, covering the decadal windows 2030–2039, 2040–2049 and 2050–2059.

Table 1

Distribution of experiment files (.COX) by municipality, climate scenario and simulated period

Cenário SSP2-4.5	
Experimento	**Descrição**
COMG2501.COX	COTTON | COROMANDEL - MG | SSP245 | 30-39
COMG2502.COX	COTTON | COROMANDEL - MG | SSP245 | 40-49
COMG2503.COX	COTTON | COROMANDEL - MG | SSP245 | 50-59
LUBA2501.COX	COTTON | LUIZ EDUARDO MAGALHAES – BA | SSP245 | 30-39
LUBA2502.COX	COTTON | LUIZ EDUARDO MAGALHAES – BA | SSP245 | 40-49
LUBA2503.COX	COTTON | LUIZ EDUARDO MAGALHAES – BA | SSP245 | 50-59
SAMT2501.COX	COTTON | SAPEZAL- MT | SSP245 | 30-39
SAMT2502.COX	COTTON | SAPEZAL- MT | SSP245 | 40-49
SAMT2503.COX	COTTON | SAPEZAL- MT | SSP245 | 50-59
Cenário SSP5-8.5	
Experimento	**Descrição**
COMG2601.COX	COTTON | COROMANDEL - MG | SSP585 | 30-39
COMG2602.COX	COTTON | COROMANDEL - MG | SSP585 | 40-49
COMG2603.COX	COTTON | COROMANDEL - MG | SSP585 | 50-59
LUBA2601.COX	COTTON | LUIZ EDUARDO MAGALHAES – BA | SSP585 | 30-39
LUBA2602.COX	COTTON | LUIZ EDUARDO MAGALHAES – BA | SSP585 | 40-49
LUBA2603.COX	COTTON | LUIZ EDUARDO MAGALHAES – BA | SSP585 | 50-59
SAMT2601.COX	COTTON | SAPEZAL- MT | SSP585 | 30-39
SAMT2602.COX	COTTON | SAPEZAL- MT | SSP585 | 40-49
SAMT2603.COX	COTTON | SAPEZAL- MT | SSP585 | 50-59

Source: Prepared by the authors.

Growth and yield simulations were performed with the CROPGRO model, which represents the physiological and biophysical processes related to phenology, vegetative growth, assimilate partitioning and responses to abiotic stresses, including temperature and water availability (Boote *et al.*, 1998; Thorp *et al.*, 2014).

2.3 SOIL, CULTIVAR AND MANAGEMENT

Simulations were parameterised with the soil profile LE00850001, corresponding to a Nitosol (Typic Eutrudox; “Terra Roxa Estruturada”), of clayey texture (62–65% clay), 150 cm depth, albedo of 0.14 and plant-available water capacity of approximately 107 mm in the profile. The same soil profile, cultivar and management were adopted for the three municipalities, with the deliberate purpose of isolating the effect of the climate projections on yield and on the sensitivity of the genetic parameters, keeping soil and management conditions constant (see Limitations).

The cultivar DP 555 BG/RR (CROPGRO-Cotton genotype code CO0006) was used; its genetic and ecophysiological coefficients, widely used in DSSAT applications under tropical conditions (Kumar *et al.*, 2017; Thorp *et al.*, 2014), provided the basis for the reference values in Table 3. Sowing was fixed on Julian day 319 (mid-November), with a population of 14 plants m^{-2}, row spacing of 0.70 m and sowing depth of 5 cm. Simulations were run under rainfed conditions, with the soil water balance activated and the profile initialised at field capacity at the beginning of each growing season. Nitrogen dynamics were not simulated (non-N-limited production), so as to isolate the response to climate and to the genetic parameters, and the atmospheric CO_2 concentration was read dynamically from the climate series of each scenario and decade. Each municipality × scenario × decade combination corresponded to a continuous 10-year simulation.

2.4 MORRIS SENSITIVITY ANALYSIS (PEST++)

The sensitivity analysis of the model parameters was carried out using the Morris method (Morris, 1991), implemented in the PEST++ framework (pestpp-sen), which allows direct integration with DSSAT and automates the iterative execution of simulations with systematic parameter perturbations (Welter *et al.*, 2015). The Morris method was selected for its computational efficiency and its ability to simultaneously identify the most influential parameters and possible non-linear or interactive effects, features that are essential in mechanistic models applied to agriculture (Confalonieri *et al.*, 2010; Paleari *et al.*, 2021; Colombi *et al.*, 2024).

For each parameter, variation ranges were defined based on the agronomic literature and on known ecophysiological limits for cotton (Table 3). The parameter space was discretised into p levels, and the magnitude of the perturbations followed the increment recommended for the method, $\Delta = p / [2(p - 1)]$, according to Campolongo *et al.* (2007).

Simulations adopted the one-at-a-time (OAT) scheme, in which only one parameter is perturbed at a time, with r = 30 trajectories over 5 genetic parameters, for each of the 18 municipality × scenario × decade combinations. The main settings of the method are presented in Table 2, and the parameter variation ranges in Table 3.

Elementary effects were summarised into the metrics μ* (mean of the absolute values of the elementary effects) and σ (standard deviation of the elementary effects). The μ* metric was adopted as the primary sensitivity measure, since it represents the mean magnitude of the influence of each parameter without sign cancellation, whereas σ was used as a complementary diagnostic of non-linearity and of interaction among parameters (Campolongo *et al.*, 2007; Morris, 1991). For the comparative visualisation of the sensitivity pattern within each run, μ* values were normalised by min-max scaling, column by column, using exclusively the data of the respective municipality × scenario × decade combination; no cross-run normalisation was performed. Thus, the normalised values presented in Figures 4 to 6 express the relative importance of the parameters within each panel and are not directly comparable in magnitude across panels. The absolute magnitude and the degree of non-linearity, in aggregate form, are presented in Table 5.

Table 2

Settings of the Morris method used in PEST++

Argument	Description	Value
++gsa_morris_r()	Sample size: number of trajectories (sequences of m model runs; each trajectory computes one elementary effect per parameter)	30
++gsa_morris_p()	Number of levels used to divide the [0,1] interval of each transformed parameter (number of subintervals = p − 1)	4
++gsa_morris_delta()	Step of the Morris method. By default, p / [2 × (p − 1)]; must be a multiple of 1 / [2 × (p − 1)]	0,667

Source: Prepared by the authors.

Table 3

Variation ranges of the genetic parameters used in the sensitivity analysis

Parameter*	Reference		
	Base	Minimum	Maximum
SD-PM	36,00	24,00	56,00

LFMAX	1,200	1,000	1,350
SFDUR	36,00	24,00	42,00
PODUR	12,00	5,000	17,00
THRSH	76,00	60,00	80,00

Source: Prepared by the authors.

SD-PM: time between the beginning of seed filling (R5) and physiological maturity (R7); LFMAX: maximum leaf photosynthesis rate at 30 °C, 350 ppm CO_2 and high light; SFDUR: seed-filling duration per fruit cohort under standard conditions; PODUR: time for the cultivar to reach its final fruit load under optimal conditions; THRSH: threshing percentage — maximum seed/(seed + shell) ratio at maturity. Ranges were defined based on ecophysiological limits reported in the literature [insert parameter-specific reference where available].

2.5 DATA ANALYSIS AND PROCESSING

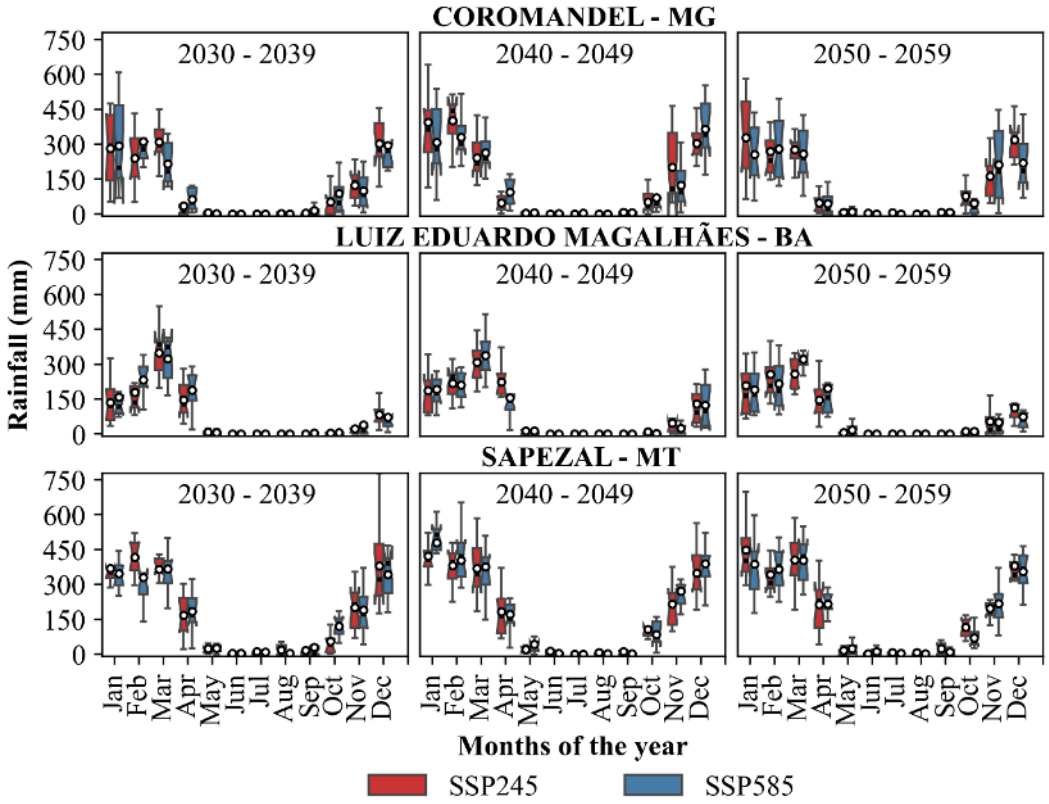
After running the simulations, the elementary effects generated by PEST++ were processed in Python, with routines based on the Pandas, NumPy and SciPy packages for data handling and statistical analysis, and Matplotlib/Seaborn for graphical visualisation. The final organisation of the results, including the comparison among municipalities, scenarios and time windows, was carried out in combination with structured spreadsheets, following practices adopted in sensitivity studies of crop models (Rathnappriya *et al.*, 2022; Casallanovo *et al.*, 2023). This integrated set of procedures made it possible to identify the parameters contributing most to the variability of projected yield, providing support for model calibration, for the interpretation of climate impacts and for cotton breeding strategies.

3 RESULTS AND DISCUSSION

The rainfall projections for the three municipalities (Figure 2) indicate a well-established seasonal pattern, with a rainy period concentrated between November and April and a severe dry season from May to October. Sapezal (MT) shows the highest median rainfall volumes, with peaks above 300 mm projected for the summer months in the subsequent decades. Although median rainfall values are similar between the SSP2-4.5 and SSP5-8.5 scenarios across decades, the more pessimistic scenario (SSP5-8.5) frequently projects greater interannual variability (as seen in the amplitude of the boxplots) during the peak rainfall months, mainly in Coromandel (MG).

Figure 2

Monthly rainfall projections from the EC-Earth3 model, for the SSP2-4.5 and SSP5-8.5 scenarios, in three Brazilian municipalities



Boxes represent the interquartile range and the median; whiskers represent interannual dispersion (n = 10 years per decadal window).
Source: Prepared by the authors.

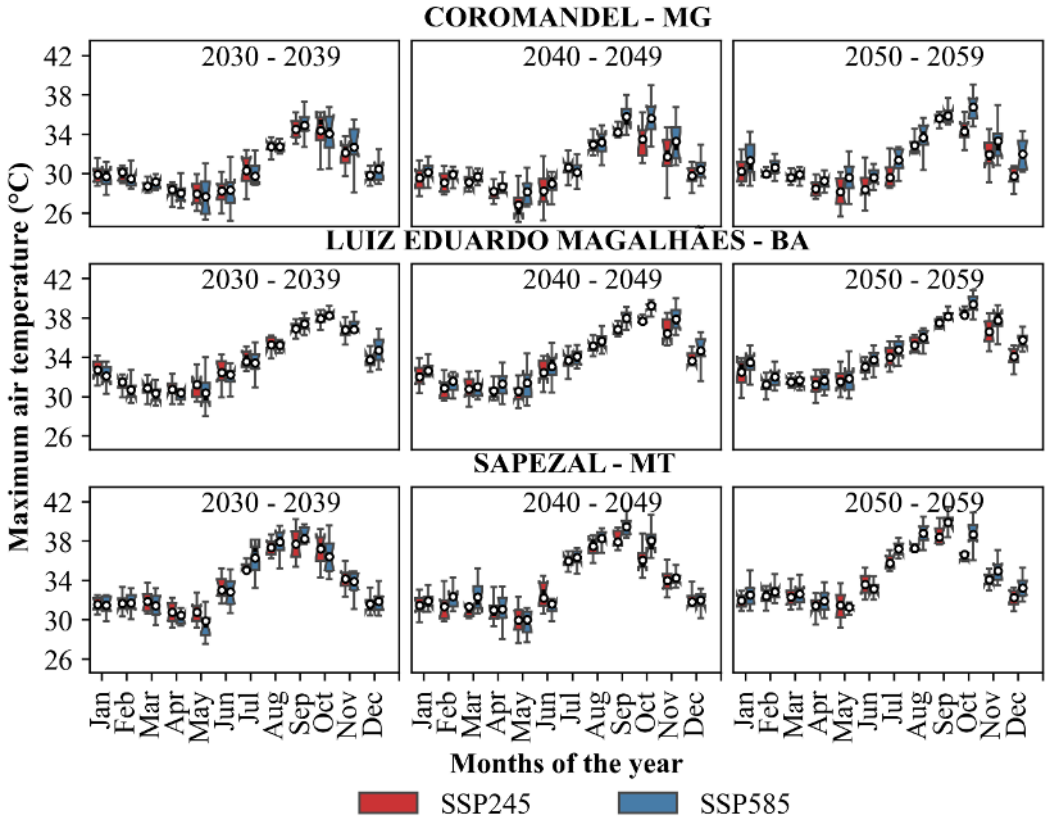
The increase in dispersion indicates greater interannual rainfall variability; characterising extreme events as such would require specific indices (e.g. the R95p percentile or the number of days above thresholds), which were not evaluated in this study. Even so, this pattern is consistent with Commar *et al.* (2024), who highlight the urgency of agricultural planning actions in view of future trends of the rainy season in Mato Grosso.

Maximum air temperature (Tmax) in the three locations shows a well-defined seasonal pattern, with peaks in the transition and dry-season months (August to October) and a trend of progressive warming over the decades, with the highest median values projected for 2050–2059 (Figure 3). The SSP5-8.5 scenario intensifies this warming, with Tmax medians consistently higher than those of SSP2-4.5 during the seasonal peak. Medians in these critical months approach or exceed 38 °C in the three areas by 2059, reaching a critical level

in Luiz Eduardo Magalhães (BA), where the median value under SSP5-8.5 approaches 40 °C in October.

Figure 3

Projections of maximum air temperature (°C) from the EC-Earth3 model, for the SSP2-4.5 and SSP5-8.5 scenarios, in three Brazilian municipalities



Source: Prepared by the authors.

The analysis of interannual dispersion indicates that Tmax variability increases in the hottest and driest months (June to October). This increase in temperature uncertainty under the high-emission scenario suggests a higher probability of extreme heat events, raising the risk of thermal stress in agricultural systems and requiring management adaptations (Abbass *et al.*, 2022; Lesk *et al.*, 2022; dos Santos Dias *et al.*, 2025).

The 77 ppm difference in CO_2 concentration between scenarios in the 2050s (Table 4) is consistent with the greater radiative forcing of SSP5-8.5, associated with the more pronounced warming of maximum temperature projected for certain locations under this scenario.

Table 4

Annual mean and standard deviation (±) of the projections of atmospheric CO_2 concentration (ppm) for the two climate scenarios

Projections	Scenario	
	SSP245	SSP585
2030 - 2039	458,1 ±8,99	472,25 ±13,79
2040 - 2049	489,54 ±9,09	526,98 ±17,89
2050 - 2059	520,69 ±8,76	597,26 ±22,86

Source: Prepared by the authors.

Projections confirm that the SSP5-8.5 scenario shows continuous and accelerated growth in mean CO_2 concentration, with an increase of approximately 26% between the first and the last projected decade (2030–2059) and a mean concentration about 14.7% higher than that of SSP2-4.5 in the final decade. The interannual standard deviation under SSP5-8.5 increased by about 66% in internal magnitude; specifically for 2050–2059, it was approximately 161% higher than that recorded under SSP2-4.5. This increase in CO_2 variability suggests greater instability in the atmospheric thermal energy balance, which, together with the associated uncertainty, imposes a more significant adaptive risk on agricultural systems (Nunes, 2023; Wu *et al.*, 2025).

In view of the projected climatic instability and extreme heat, with a risk of shortening of the vegetative cycle, it becomes essential to identify the parameters that most critically control final crop production, in order to guide adaptation strategies. In this context, the Morris sensitivity analysis identifies the parameters that most drive production variability under future scenarios (Paleari *et al.*, 2021; Colombi *et al.*, 2024).

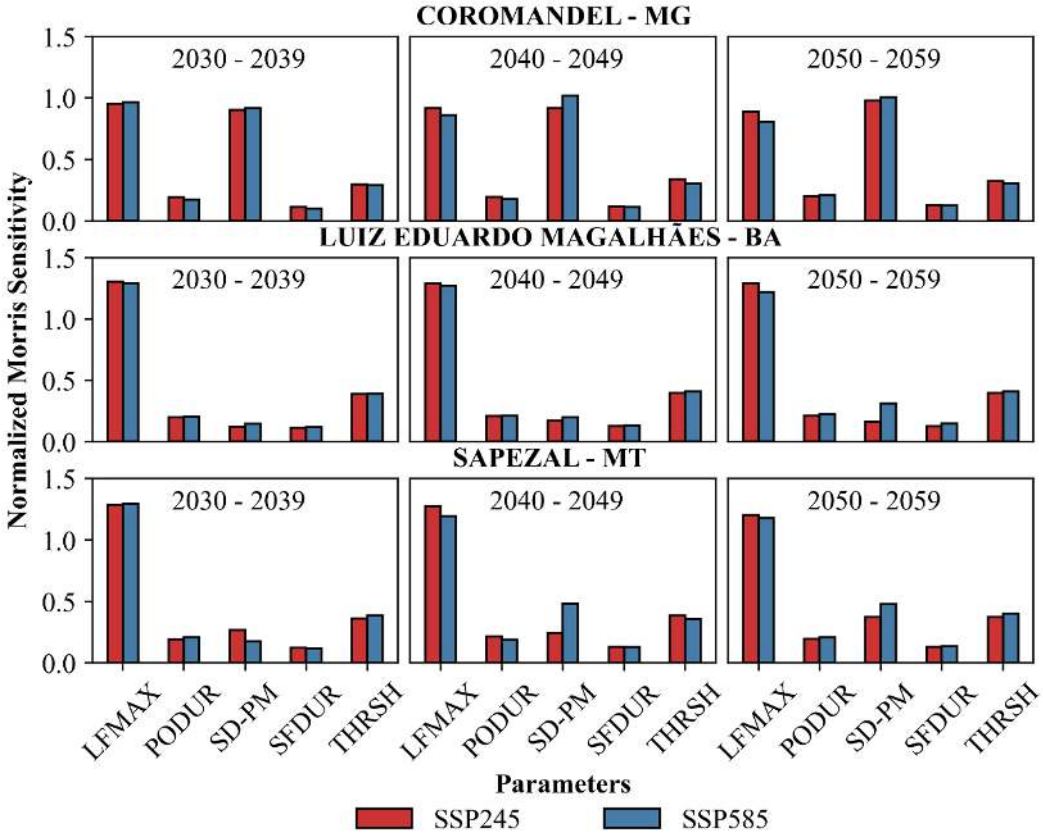
The maximum leaf photosynthesis rate (LFMAX) proved to be the dominant factor, consistently recording the highest normalised sensitivity indices (close to 1.0) under all conditions evaluated for total above-ground biomass (CWAD) (Figure 4). This result highlights the importance of canopy architecture and radiation interception for biomass accumulation, regardless of the emission scenario (SSP2-4.5 or SSP5-8.5).

Next in importance are threshing percentage (THRSH), with moderate influence in all regions, and the time between the beginning of seed filling (R5) and physiological maturity (R7) (SD-PM), whose sensitivity is variable. In Coromandel (MG), the sensitivity of SD-PM increases in the 2040s and 2050s (approaching 1.0), indicating that the duration of this

reproductive phase will become a controlling factor almost as important as LFMAX in that region. The parameters PODUR and SFDUR showed the lowest influence, with residual sensitivity in all scenarios. The predominance of LFMAX suggests that breeding strategies focused on optimising leaf area index and light-use efficiency are promising for the stability of biomass production under climate change.

Figure 4

Normalised sensitivity (min-max per run) of CROPGRO model parameters to total above-ground biomass (CWAD), as a function of municipalities, scenarios and climate projections



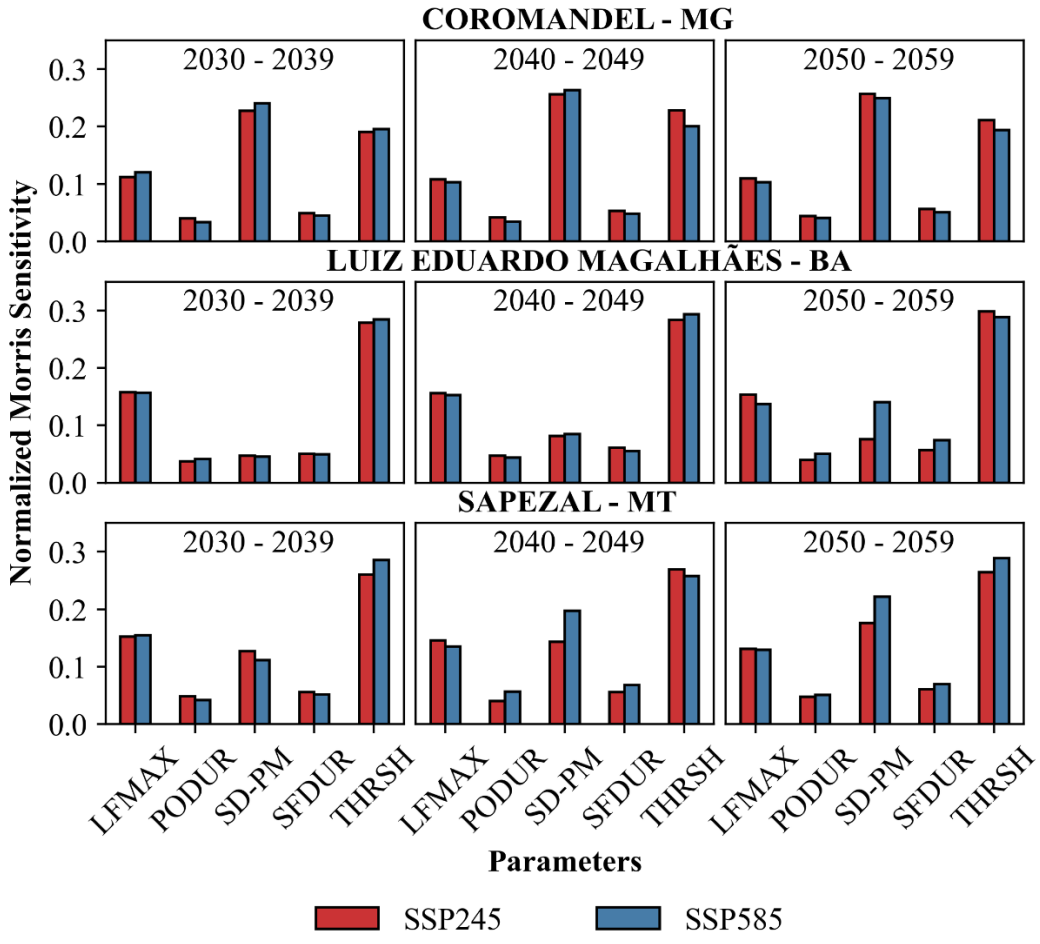
Values express relative importance within each panel and are not comparable in magnitude across panels (see Table 5).
Source: Prepared by the authors.

The increase in SD-PM sensitivity in Coromandel (MG) is a direct consequence of the warming projected under SSP5-8.5, since high temperatures shorten the cycle of several crops, impairing final biomass accumulation (Lesk *et al.*, 2022; dos Santos Dias *et al.*, 2025). The low residual influence of the early phenological parameters (PODUR and SFDUR) reiterates that the most strategic adaptive focus for biomass production should lie in thermal tolerance during filling and in the continuous improvement of LFMAX.

The sensitivity of the parameters to lint yield at maturity (LIWAM) diverges from that observed for CWAD, revealing that the most influential parameter is THRSH (Figure 5). The sensitivity indices of THRSH remain consistently high across all regions and decades, followed by SD-PM and LFMAX. The SD-PM parameter gains substantial importance in Coromandel (MG), becoming, in that region, the most influential factor for LIWAM.

Figure 5

Normalised sensitivity (min-max per run) of CROPGRO model parameters to lint yield at maturity (LIWAM), as a function of municipalities, scenarios and climate projections



Source: Prepared by the authors.

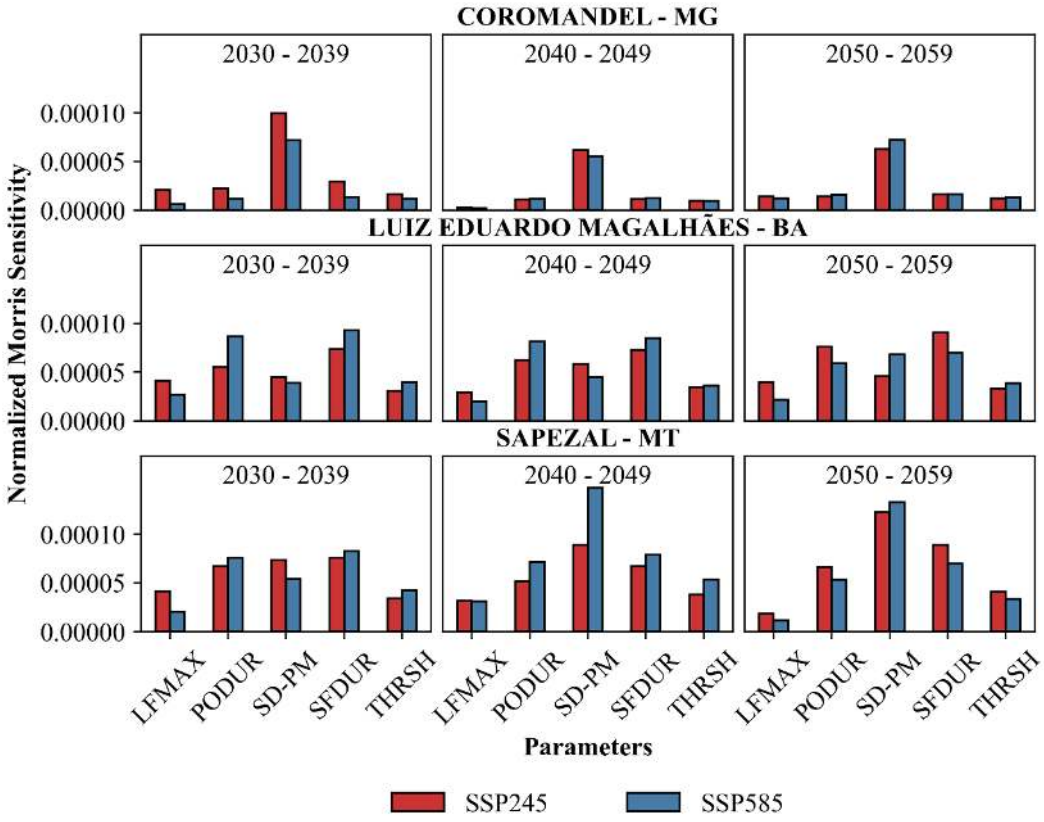
The sensitivity of LIWAM to both THRSH and SD-PM tends to be higher under SSP5-8.5, particularly in the 2040s and 2050s in Luiz Eduardo Magalhães (BA) and Sapezal (MT). This pattern suggests that, under a more adverse future climate, threshing percentage and the duration of the reproductive phase become the main limiting factors of lint yield. Thus, for the economic yield of the crop, the main bottleneck does not lie in maximum carbon

assimilation (LFMAX), but in threshing percentage (THRSH) — which defines the maximum seed fraction within the fruit, given by seed/(seed + shell) at maturity — and in the duration of the filling phase to maturity (SD-PM).

SD-PM and SFDUR were the parameters that showed the highest and most consistent sensitivity for lint percentage in cotton seed (LINTP) across all regions and projections (Figure 6).

Figure 6

Normalised sensitivity (min-max per run) of CROPGRO model parameters to lint percentage in cotton seed (LINTP), as a function of municipalities, scenarios and climate projections



Source: Prepared by the authors.

The analysis of the σ/μ* ratio (Table 5) complements the sensitivity ranking by characterising the nature of the response of each parameter. Considering the mean of the 18 runs, the sensitivity order (μ*) was LFMAX > THRSH > SD-PM > SFDUR > PODUR. LFMAX and THRSH, besides concentrating the greatest sensitivity magnitude, showed a low σ/μ* ratio (0.10 and 0.25, respectively), indicating a predominantly linear and additive effect. In

contrast, SFDUR and PODUR, despite their lower absolute magnitude, exhibited a high σ/μ* ratio (0.69 and 0.53), suggesting a non-linear response or one dominated by interactions among parameters. SD-PM occupied an intermediate position on both axes (σ/μ* = 0.33). This pattern was consistent across the 18 runs, with LFMAX and THRSH leading the μ* ranking in all combinations of municipality, scenario and decade.

Table 5

Morris sensitivity metrics (μ and σ) by genetic parameter, aggregated as the mean of the 18 runs (municipality × scenario × decade)*

Parameter	Mean μ*	Mean σ	σ/μ*
LFMAX	7,728.6	747.3	0.10
THRSH	3,928.5	969.5	0.25
SD-PM	1,723.2	568.2	0.33
SFDUR	602.6	415.2	0.69
PODUR	375.2	200.5	0.53

The μ* and σ values correspond to the mean of the 18 runs, aggregating the output variables, and serve as a relative ranking of magnitude. The dimensionless σ/μ* ratio indicates the degree of non-linearity and of interaction among parameters.
Source: Prepared by the authors.

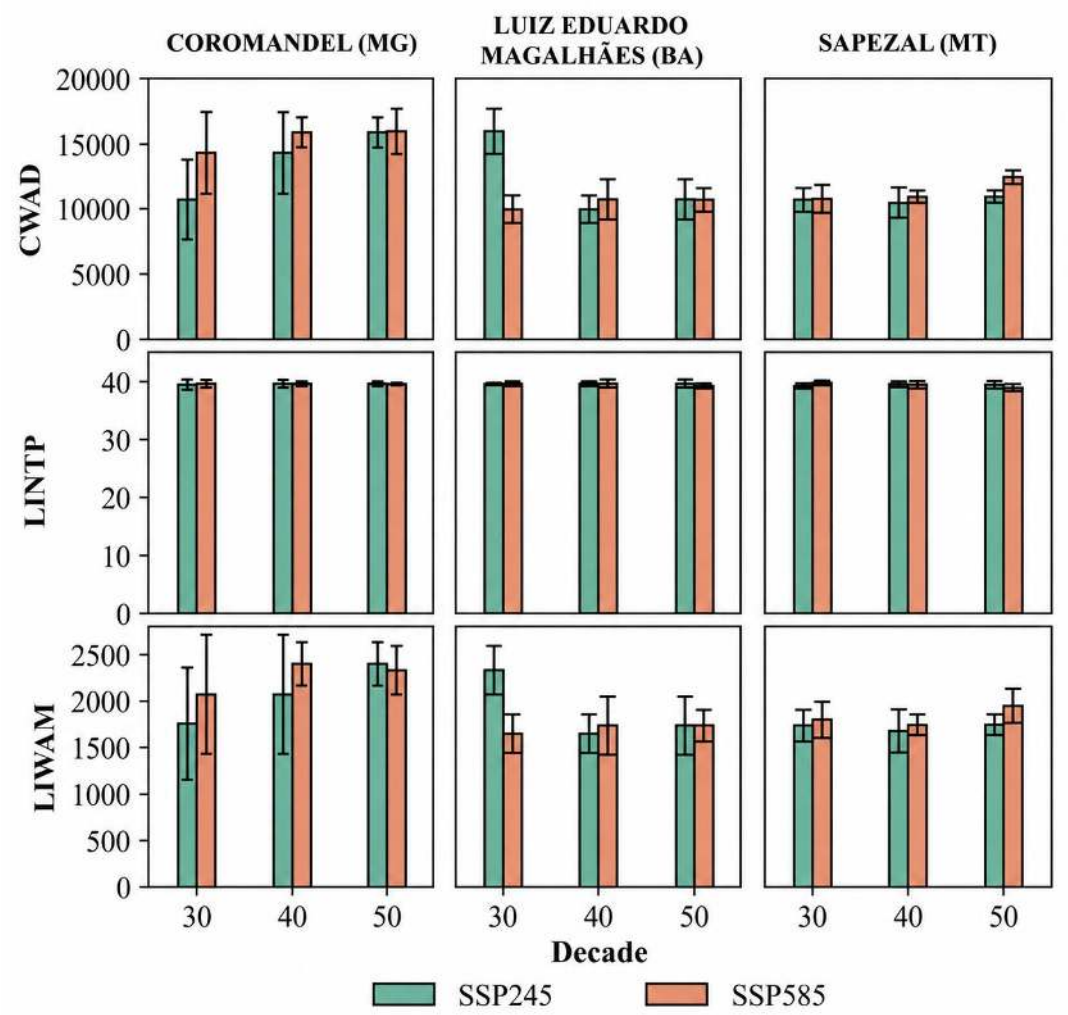
The μ* and σ values correspond to the mean of the 18 runs, aggregating the output variables, and serve as a relative ranking of magnitude. The dimensionless σ/μ* ratio indicates the degree of non-linearity and of interaction among parameters.

The yield variables CWAD and LIWAM show correlated patterns and greater variability (Figure 7). In Coromandel (MG), an increase in productivity over time is observed: both variables reach peaks in the 2050s, with the SSP5-8.5 scenario projecting higher means of CWAD (about 15,900 kg ha^{-1}) and LIWAM (about 2,400 kg ha^{-1}), with peaks of 17,780 kg ha^{-1} and 2,740 kg ha^{-1}, respectively. This behaviour suggests a favourable yield response to warming in this region, possibly associated with the CO_2 fertilisation effect overriding thermal stress — a hypothesis that requires specific investigation.

In contrast, Luiz Eduardo Magalhães (BA) exhibits a yield decline after the initial decade (2030s). CWAD, which starts high under SSP2-4.5 (16,000 kg ha^{-1}) in the 2030s, stabilises at around 10,000 to 11,000 kg ha^{-1} in the following decades, a reduction reflected in LIWAM, which stabilises at approximately 1,700 kg ha^{-1}. In Sapezal (MT), the yield variables are the most stable among the three regions, remaining at around 10,000–12,000 kg ha^{-1} for CWAD and 1,700–1,900 kg ha^{-1} for LIWAM, with little variation across scenarios and decades.

Figure 7

Cotton yield variables in different municipalities, climate scenarios and future projections, simulated by the CROPGRO/DSSAT model



CWAD – total above-ground biomass (tops weight), kg ha^{-1}; LINTP – lint percentage in seed, %; LIWAM – lint yield at maturity, kg ha^{-1}.
Source: Prepared by the authors.

In contrast to the yield variables, LINTP remains stable in all simulations, close to 40%. This suggests that the impact of the projected climate changes tends to manifest predominantly in quantity (seed and lint yield) rather than in relative fibre quality. These results indicate that the future physiological limits of the crop will be associated more with the maintenance of reproductive allocation and with phenological resilience than with maximum carbon assimilation capacity.

4 LIMITATIONS

This study adopted methodological assumptions intended to isolate the climate signal, which must be taken into account when interpreting the results. Soil, cultivar and management were kept constant across municipalities; therefore, the observed regional differences arise exclusively from the climate projections, and not from soil × climate interactions or from local varietal adaptation. The soil profile used, of high water-holding capacity, differs from the Oxisols prevailing in the producing regions of the Cerrado, and simulations were run under rainfed conditions, without nitrogen limitation and with initialisation at field capacity; consequently, the simulated yields are potential and comparative in nature, and do not constitute estimates of absolute regional productivity.

The genetic coefficients correspond to a cultivar that was not locally recalibrated, which affects absolute values more than the sensitivity ranking, the latter being recognisably more robust to calibration uncertainties. The EC-Earth3 series were used without bias correction, an option supported by the relative nature of the inferences — comparisons among scenarios, decades and municipalities under the same climate model — in which systematic errors tend to partially cancel out; even so, this choice reinforces the potential nature of the absolute values. Finally, the absence of a historical reference period limits the quantification of changes relative to the current climate, and the inclusion of a baseline and of bias correction is recommended in future studies for the estimation of absolute yields.

5 CONCLUSION

The set of simulations based on EC-Earth3 projections shows that the climate response of Brazilian cotton production, under controlled soil and management conditions, is markedly regional, with potential gains in Coromandel (MG), relative stability in Sapezal (MT) and thermal vulnerability in Luiz Eduardo Magalhães (BA).

The sensitivity analysis revealed that, while total above-ground biomass (CWAD) remains controlled by the maximum photosynthesis rate (LFMAX), lint yield (LIWAM) is determined mainly by threshing percentage (THRSH) and by the duration of the filling phase to maturity (SD-PM), especially under extreme heat. The σ/μ^* ratio indicated that LFMAX and THRSH act in a predominantly linear manner, whereas the parameters of lower magnitude (SFDUR and PODUR) exhibit more non-linear or interaction-dominated behaviour.

Thus, the adaptation of future cotton production requires breeding strategies aimed at reproductive thermal resilience and at the maintenance of photoassimilate allocation. It

should be stressed that the sensitivity ranking is robust, whereas absolute yield values should be interpreted as potential and comparative across scenarios.

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