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Abstract

Mato Grosso (MT) state, the agricultural giant of Brazil, owes its success to the long rainy season that has allowed for the extensive adoption of double cropping, elevating the region to one of the world's leading grain producers. However, recent studies warn of the adverse impacts of deforestation and climate variability, which are causing a decrease in rainfall and a delay in the rainy season onset. These changes pose significant threats to both ecosystems and intensive agriculture. To assess these threats, we compared past and present rainfall and rainy season duration in MT and conducted robust climate projections using climate simulations forced by realistic deforestation scenarios. Our analysis of observed rainfall data from the past four decades and Community Earth System Model simulations affirmed a worrying trend of decreasing rainfall volumes, delayed rainy season onset, and shorter rainy season length. Climate projections indicate that this pattern will intensify, with onsets expected in late October and rainy season durations shorter than 200 d by mid-century. These findings underscore the potential impact on MT's double-cropping system, a cornerstone of the region's agricultural success, and emphasize the urgent need for sustainable large-scale agricultural practices and strategic interventions by regional decision-makers to mitigate agricultural losses and ecosystem degradation.

1. Introduction

Mato Grosso (MT) is a state in Brazil that has undergone significant growth in recent decades. In 1980, the state's population was 1.1 million, and by 2000, it had doubled to 2.1 million. As of 2022, the population has further increased to 3.6 million. Agriculture in MT has also experienced rapid growth, especially in the production of soy and maize. In 1980, the total production of these crops was only 260 000 tons, while in 2023, it reached 90 million tons over 12 million ha.

Most of the maize production increase relates to its adoption as a second crop, given that regions with longer rainy seasons, like MT, can support a double-cropping system as an intensification method (Arvor *et al* 2014, Abrahão and Costa 2018).

MT has been under a double-cropping system for the last three decades, especially using soy-maize and soy-cotton combinations, with the second crop becoming as economically important as the first (Abrahão and Costa 2018, Brumatti *et al* 2020). Currently, about 70% (8.5 Mha) (Zhang *et al* 2021a) of cropland area in MT is cultivated with two crops per year, significantly increasing the state's grain production (Hampf *et al* 2020).

Although agriculture is well established in the state, it is heavily influenced by climate variability, since most double-cropping areas are rainfed (Brumatti *et al* 2020, Hampf *et al* 2020). A reduced rainy season might pose a severe challenge for farmers. Deforestation in concert with climate variability is delaying the rainy season onset, lengthening the dry season over the different parts of the state, and thereby impacting agribusiness and natural ecosystems within the biomes (Araujo and Casta 2018, Leite-Filho *et al* 2019, Marengo *et al* 2021a, Hofmann *et al* 2023). The enhanced dry period has harmed rainfed agriculture, where soybean and maize experienced yield losses of 26 and 892 kg ha^{-1} per season, respectively (Rattis *et al* 2021). This elevates concern for the feasibility of double cropping in light of reduced rainy season duration over MT in the future (Cohn *et al* 2016, Costa *et al* 2019).

Reduced rainfall, delayed onset of the rainy season, and lengthening of the dry season have been attributed to both large-scale (warming of the oceans) and local-scale (deforestation) factors and their interactions (Costa *et al* 2019, Smith *et al* 2023, Commar *et al* 2023a). Modeling studies have effectively represented the link between hydroclimate and deforestation. These studies reveal that deforestation disrupts the energy balance, evapotranspiration, and surface roughness, leading to feedback mechanisms with a drier atmosphere and shifting the circulation, reducing the rainfall, and delaying the rainy season onset (Fu *et al* 2013, Khanna *et al* 2017, Staal *et al* 2020, Commar *et al* 2023a).

Nevertheless, recent research highlighted a compelling association between declining Amazon rainfall and the intensification of the Hadley and Walker cells (Arias *et al* 2015, Fu 2015, Espinoza *et al* 2019). The strengthening of the Hadley cell reduces precipitation through increased subsidence, influenced by elevated sea surface temperatures in the Pacific and Atlantic, alongside a decline in deep convective circulation (Fu 2015, Espinoza *et al* 2021, Bochow and Boers 2023). Additionally, the Walker circulation, particularly during the warm phase of El Niño-Southern Oscillation, exacerbates this effect by inducing subsidence over the continent, leading to severe droughts and delayed rainy seasons (Cai *et al* 2020, Leite-Filho *et al* 2020).

This interaction between Amazon climatic dynamics and the Hadley and Walker circulations reflects the interconnected nature of these atmospheric phenomena. These interactions profoundly influence the region's hydroclimatic patterns, particularly in response to anthropogenic changes (Ruiz-Vásquez *et al* 2020, Sierra *et al* 2022).

The expansion of agricultural areas has been characterized as a no-win situation for agribusiness. The conversion of natural vegetation to agriculture is usually associated with a delay in the rainy season onset (Leite-Filho *et al* 2021). Adding climate change scenarios to this equation intensifies the consequences, resulting in an even later onset and a shorter rainy season (Pires *et al* 2016, Costa *et al* 2019, Commar *et al* 2023a). These extensive effects could cause economic losses of millions and heavy ecosystemic damage (Strand *et al* 2018, Brumatti *et al* 2020, Leite-Filho *et al* 2021). The potential losses should arouse the concern of regional leaders. Even changing sowing dates and adopting shorter-cycle cultivars might decrease gross revenues when deforestation and climate change are considered (Brumatti *et al* 2020, Carauta *et al* 2021).

Although the correlation between the rainy season onset and duration to climate change and deforestation is recognized, a thorough assessment focused on agricultural and ecosystem impact is still overlooked. Therefore, this study aims to comprehensively evaluate changes and trends in MT state's rainfall and rainy season onset and duration. Using coupled climate models forced by realistic deforestation scenarios, we also seek to provide a robust climate projection for MT. Having such foresight will allow decision-makers to prepare effectively, mitigating agricultural losses and averting ecosystem degradation.

2. Methods

2.1. Study area

MT, situated in Central-West Brazil within the southern legal Amazon, encompasses three distinct biomes: the Amazon in the northwest, the Pantanal in the southwest, and the Cerrado across the remainder of the state. Primarily an agricultural region (figure 1(a)), MT predominantly cultivates crops such as soybeans, maize, and cotton (Arvor *et al* 2014, Abrahão and Costa 2018, Zhang *et al* 2021b).

The agricultural expansion in the region prompted the development of significant agricultural hubs such as Sorriso and Primavera do Leste (figures 1(a) and (b)). This expansion of crops across the state contrasts with the presence of vast conservation units and indigenous lands, which predominantly maintain their native vegetation (figure 1).

2.2. Study period and data

We used daily precipitation from two databases, extending from 1981 to 2020, to diagnose past and current behavior of rainfall and rainy seasons for MT: (i) the first is Brazilian daily weather gridded data with a spatial resolution of 0.1° × 0.1° (∼11 km) for the whole of Brazil; this dataset is derived from the spatialization of observational data from 11 473 rain gauges and 1252 meteorological stations distributed across the country (Xavier *et al* 2022) and is from now on referred to simply as 'Xavier.' (ii) The second, the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset, with a spatial resolution of 0.05° × 0.05° (∼5 km), combines satellite and rain gauge data; CHIRPS is widely used in Brazil (Funk *et al* 2015). We divided these datasets into two periods, representing past and more recent decades, 1981–2000 (P1) and 2001–2020 (P2).

We used the Community Earth System Model version 1.0.6 (CESM) (Hurrell *et al* 2013) to produce the future projection. CESM is a fully coupled model, combining atmospheric, surface, ocean, river,

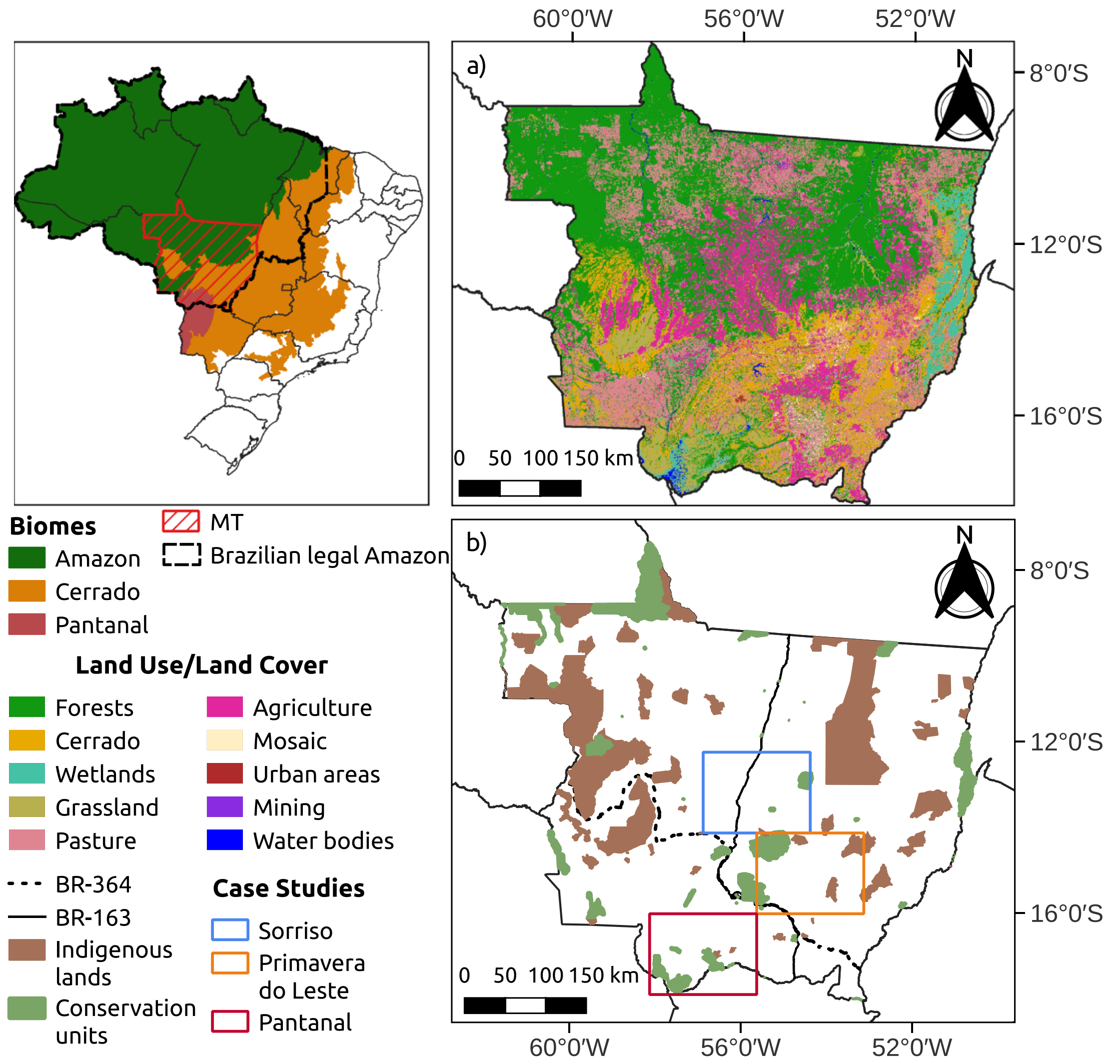

Figure 1. Study area showing (a) land use and land cover for Mato Grosso in 2020 and (b) locations of indigenous lands, conservation units, and case study regions. Main roads are also shown.

and cryosphere models, producing adequate simulations of earth system interactions (Hurrell *et al* 2013, De Hertog *et al* 2023). We reproduced the original RCP2.6 and RCP8.5 CMIP5 simulations coupled with all the components cited above, excluding the land use/land cover inside Brazil, where the RCP land model was replaced by environmental governance (EG) scenarios derived from recent Brazilian environmental policy, land use, and cover.

The EG scenarios represent strong EG (SEG) and weak EG (WEG). The weak scenario mirrors historical trends pre-2005, characterized by policies supporting agriculture with limited sustainability, thereby increasing deforestation in the Amazon and Cerrado regions. The strong scenario considers a shift towards sustainability with robust governmental support and preservationist practices. (Rochedo *et al* 2018).

With this setup, we conducted four initializations for each scenario, with initial historical conditions from four ensemble members of the historical experiment from the original CESM, thus replicating the original initial conditions in the RCP scenarios. Here, we used precipitation data with a spatial resolution of 0.9° × 1.25° (∼100 km) from the historical CESM simulations ranging from 1990 to 2000 and a projection for the four combined scenarios—RCP2.6-WEG, RCP2.6-SEG, RCP8.5-WEG, and RCP8.5-SEG—from 2020 to 2050. For more comprehensive insights into the CESM simulations, readers are referred to (Commar *et al* 2023a).

2.3. Rainy season onset and duration

We employed a modified anomalous accumulation (AA) method to define the onset and duration of the rainy season (Arvor *et al* 2014). This method establishes a relationship between daily rainfall (R_n) and a reference value (R_{ref}) (equation (1)) and has proven effective in studies across agricultural regions in Brazil, utilizing both observed and modeled data (Abrahão and Costa 2018, Commar et al 2023a, 2023b).

In our investigation, we initiated accumulation on 1 July, aligning with the midpoint of the dry season in MT. The onset of the rainy season coincides with the day of minimum AA, while its demise corresponds to the day of maximum AA. Consequently, the duration of the rainy season spans the interval between these dates (Arvor *et al* 2014),

$$\mathrm{AA}_t = \sum_n^t R_n - R_{\mathrm{ref}} \tag{1}$$

where AA_t = anomalous accumulation at day t; R_n = daily rainfall (mm d^{-1}) on day n; and R_{ref} = reference value. We used a reference value of 2.5 mm d^{-1}, which is the precipitation requirement for soybean seedlings (Abrahão and Costa 2018).

3. Results

3.1. Rainy season changes and trends

Rainfall exhibited heterogeneous patterns over time. During period P1, higher precipitation levels were observed in southern MT, contrasting with period P2, where a considerable decrease occurred, with the rainfall decreasing across the state (figures 2(a), (b) and S1(a), (b)). Significant reductions were observed in the Pantanal region, with anomalies exceeding 150 mm and prominent decreasing trends (figures 2(c), (d) and S1(c), (d)). Similarly, Primavera do Leste experienced substantial decreases in rainfall, accompanied by significant downward trends (figures 2(c), (d) and S1(c), (d)). By contrast, the patterns observed for rainy season onset and length were more homogeneous. Across most of the state, a trend toward later onset and shorter duration of the rainy season was noticeable (figures 2(e)–(l) and S1(e)–(l)). Excluding northwestern MT, the trend of the later onset and shorter rainy season is apparent, and most of the eastern and southern regions exhibited significant changes in P2 (figures 2(g), (h), (k) and (l)).

Sorriso, Primavera do Leste, and Pantanal showed at least five days of delay in onset and a rainy season shorter by ten days (figures 2(g) and (k)). Furthermore, trends in rainy season delay and reduction over these regions were significant (figures 2(h), (l) and S1(h), (l)), suggesting a drier P2.

The Sorriso and Primavera do Leste regions showed a decreasing rainy season duration trend, accentuating the concern regarding intensive agriculture, the main economic activity in these regions. This same trend in the Pantanal region may influence local biodiversity. Thus, these regions highlight potential economic and ecosystem impacts of a reduced rainy season.

Moreover, the historical analyses reveal reductions in precipitation (figures 2(c) and (d)), delayed onset (figures 2(g) and (h)) and reduced length of the rainy season (figures 2(k) and (l)) in the Primavera do Leste region, coinciding with areas dominated by agriculture (figure 1(a)).

3.2. Climate projections

The cumulative distribution function (CDF) of the rainy season onset shows the likelihood of the rainy season onset occurring before a given day of the year (figure 3). The CDF of the onset dates for both observed and CESM data ranging between 15 August and 15 November, for the period 1990–2000 is shown in figures 3(a)–(c).

To evaluate the model's skill in defining rainy season onset probabilities, we computed the mean errors in the onset within probability intervals of 10% (figure 3(d)). Primavera do Leste is the region with the least accurate model representation, which is particularly evident for earlier onsets (cumulative probability <50%), with errors in the range of 20 d (figure 3(d)). Conversely, Sorriso and the Pantanal exhibit anomalies below 10 d for the cumulative probability of onset >30% (figure 3(d)). Furthermore, the model demonstrates a skillful representation of rainy season onset across all three regions, notably capturing late onsets better than early ones.

Figure 4 summarizes the three regions' observed and simulated CDFs for the rainy season onset. Consistent with the anomalies and trends observed in rainy season onset (figures 2(g) and (h)), P2 (2001–2020) shows later onset dates than P1 (1980–2000) for all probability levels across all three regions (figures 4(a)–(c)). Analysis of observed data indicates a decrease in the probability of early-onset dates (before 30 Sep) in Sorriso (figure 4(a)) and in the Pantanal (figure 4(c)) and, in particular, a remarkable reduction in Primavera do Leste (figure 4(b)). This analysis of past and present underscores a reduction of early-onset years between P1 and P2, with an increased frequency of late-onset years.

The CESM cumulative distribution indicates that future decades will likely experience later rainy season onsets compared to P2, suggesting a delay in the onset dates at all probability levels for Sorriso and Primavera do Leste (figures 4(a) and (b)). As time progresses, projected onsets tend to occur later, with even later onsets projected for the 2041–2050 period. The impact of these shifts is notably pronounced in Sorriso and Primavera do Leste, with their onset distributions shifting by up to 15 d when compared to observed data, and 10 compared to historical simulations (figures 4(a) and (b)). Although the Pantanal region exhibits later onset dates in the observations than the projections (figure 4(c)), early-onset dates still lag those observed in P1.

We define an early rainy season onset as occurring on or before September 30. A rainy season starting on or before this date typically indicates a larger rainy period and the potential for successful double cropping in MT. However, with onsets occurring after

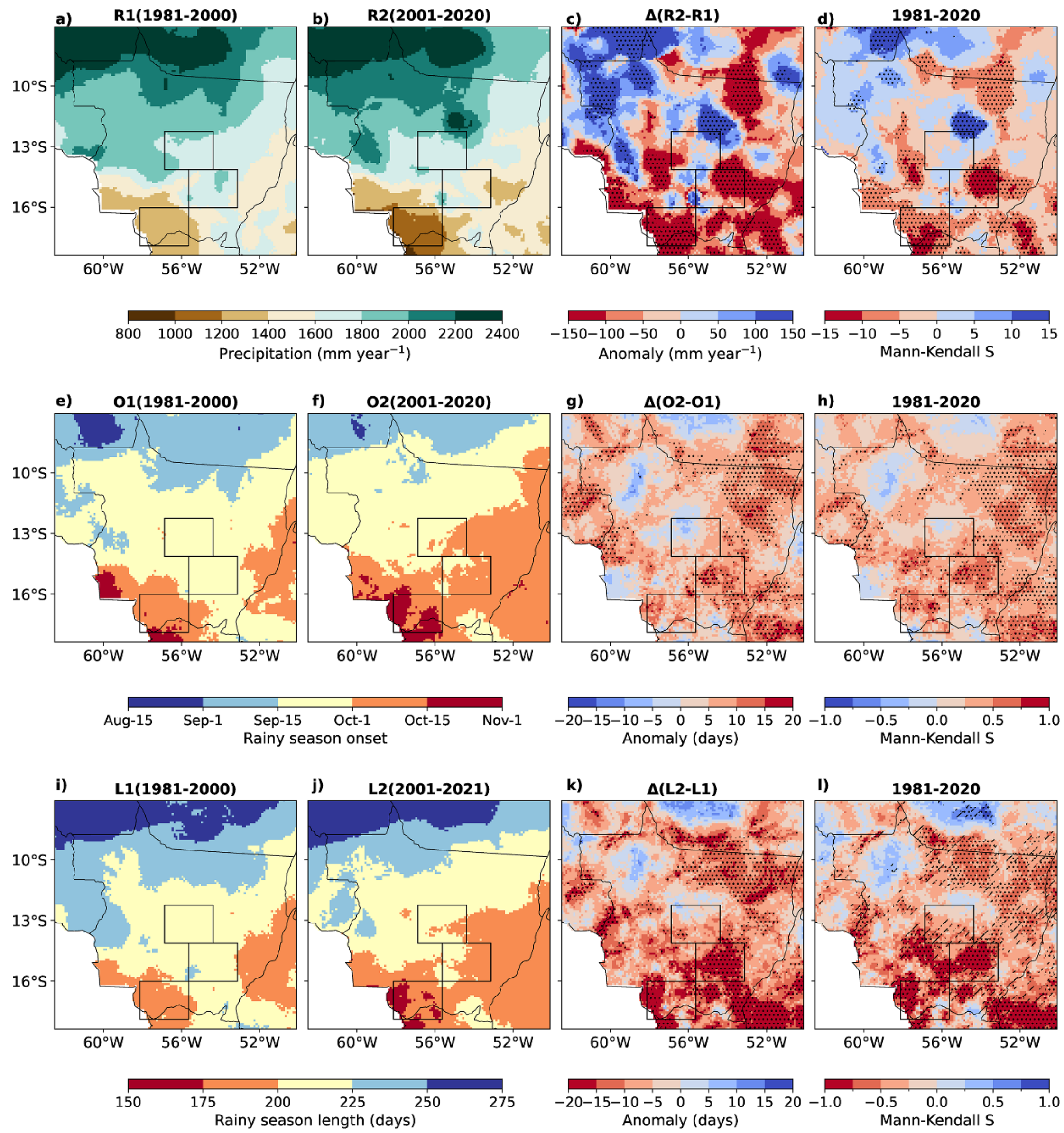

Figure 2. Changes in rainfall patterns and rainy season over four decades using Xavier data, with comparative analysis and significance testing. Maps represent mean rainfall (R), rainy seasons onsets (O), and length (L) for two periods, R1, O1 and L1 (a), (e), (i) and R2, O2 and L2 (b), (f), (j), shown alongside the differences between P1 and P2 (c), (g), (k), and the Mann–Kendall S statistic for the entire period (d), (h), (l). Dotted areas denote significant differences at $\alpha = 0.05$ via Student's t-test (c), (g), (k) or the Mann–Kendall test (d), (h), (l). Oblique diagonal lines indicate significance at $\alpha = 0.10$ according to the Mann–Kendall test (d), (h), (l). The black rectangles represent the three case studies—Sorriso, Primavera do Leste, and Pantanal—as defined in figure 1.

1 October, the likelihood of failure for double cropping increases, resulting in lower yields for the second crop. Onsets after 1 November prompt farmers to refrain from planting a second crop due to climate risks associated with later sowing dates.

The probabilities of projected rainy season onset dates exhibit a distinct gradient across MT, with early onsets concentrated in the northwestern region (figures 5(a), (e) and (i)). A northwest–southeast gradient of onset dates is apparent (figures 5(b)–(d)). In the northwest part of the state, over the decades the probability of early onset decreases from 60%–80% in the 2000s to 40%–60% in the 2040s (figures 5(a), (e), and (i)). Onsets between 1 and 15 October show an increasing probability in the northwest and southwest regions. A similar trend is observed in the eastern part of the state for later October dates.

Notably, Sorriso and Primavera do Leste demonstrate an increase in the probability of onset occurring between 16 and 31 October, rising from 20%–40% in 2021–2030 to a 40%–60% chance by mid-century (figures 5(g) and (k)). Concurrently, the likelihood of an early onset decreases to 20% for these regions (figures 5(e) and (i)). There is a noticeable shift in the probability distribution across these date thresholds as the decades progress, with the probability of an

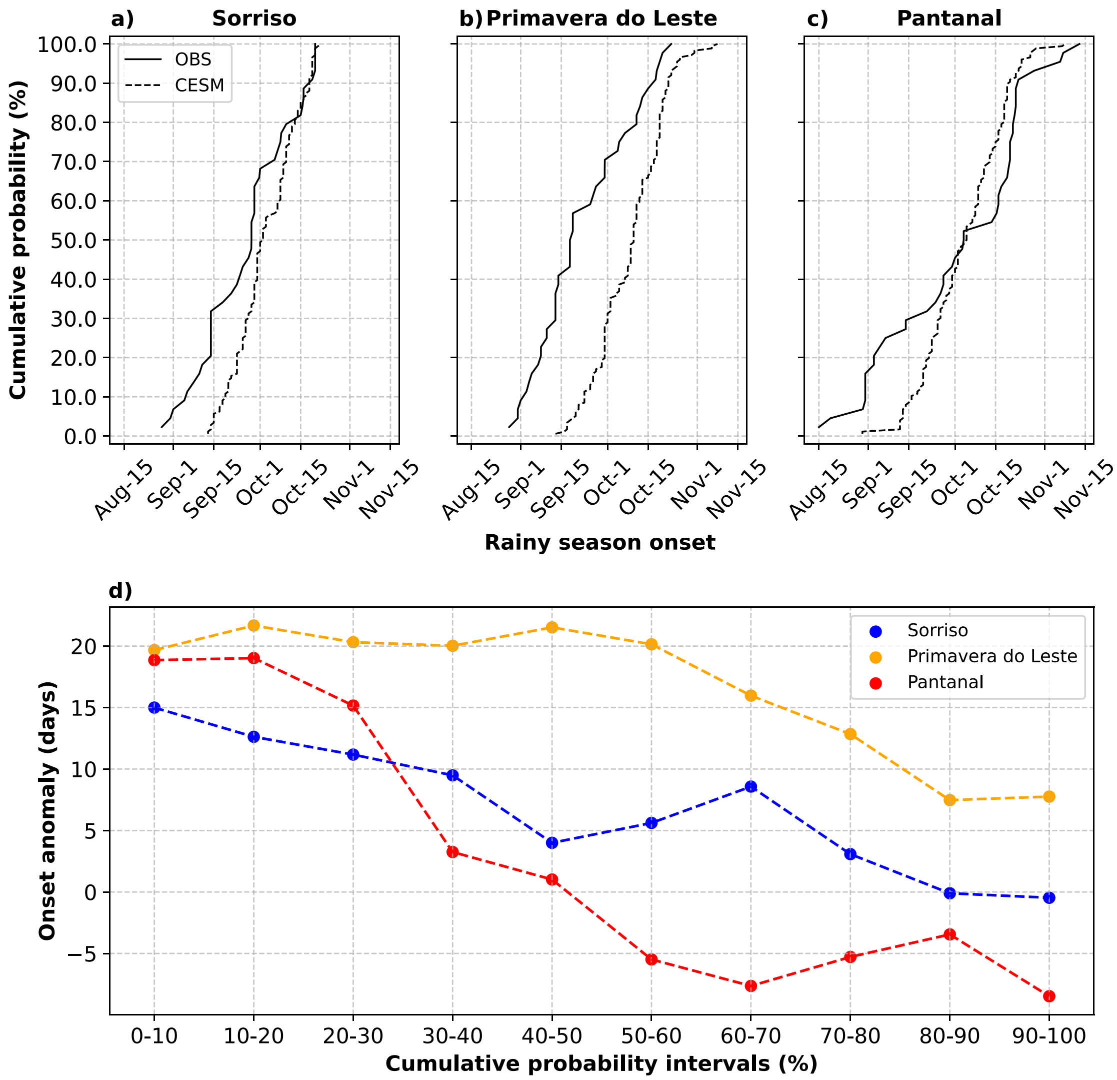

Figure 3. Cumulative probability of rainy season onset for the Xavier observed data (OBS) and CESM historical simulations from 1990 to 2000 for each case study region: (a) Sorriso, (b) Primavera do Leste, and (c) Pantanal. (d) Illustrates the difference in the cumulative probability of rainy season onset between CESM simulations and observed data, calculated at various probability intervals. Positive values indicate that the simulated rainy season happens with later onset than was observed, while negative values indicate earlier onset. The error varies between +20 and −10 d.

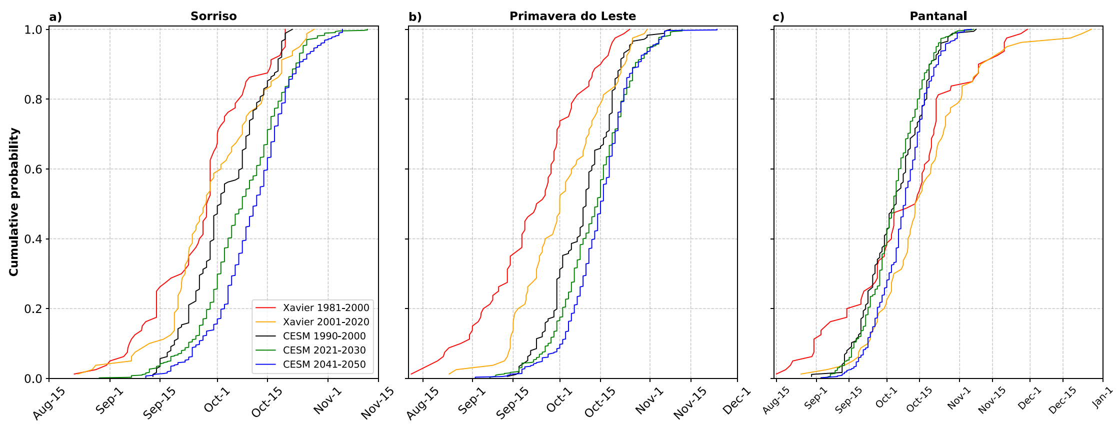

Figure 4. Cumulative probability of rainy season onset. Comparison between Xavier for periods P1 (1981–2000) and P2 (2001–2020) and climate simulations (CESM) for the historical period (1990–2000), and future decades across each case study (a)–(c).

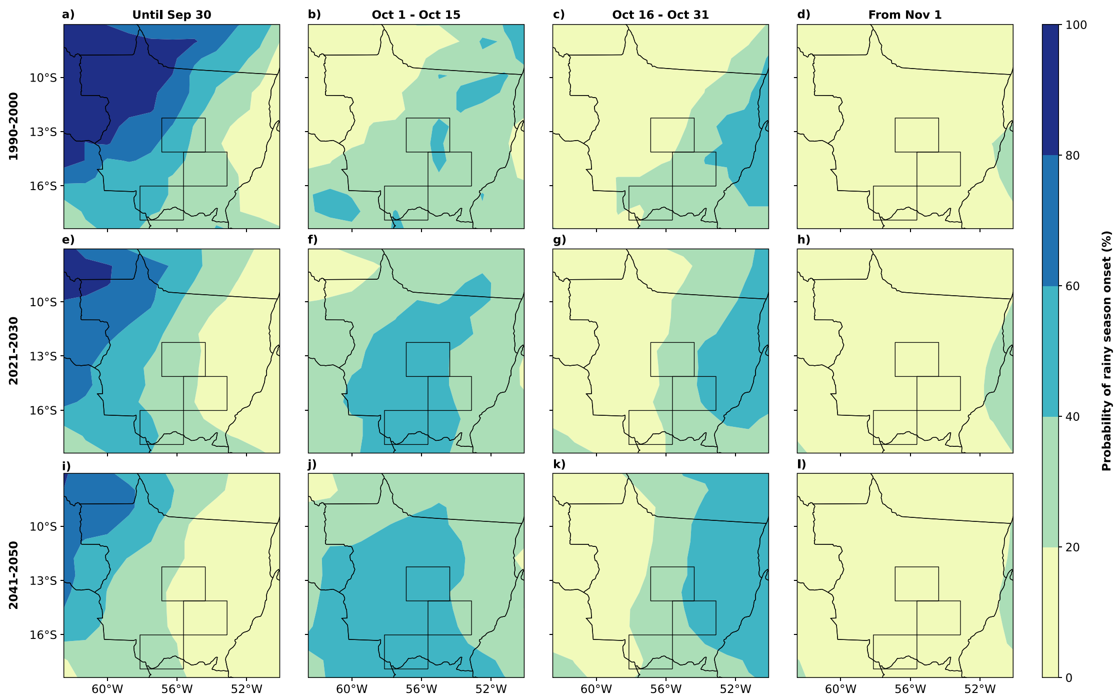

Figure 5. Probability of rainy season onset occurrence within specific time ranges. Each column represents the probability of onset for certain dates: on or before 30 Sep (a), (e), (i), 1 October–15 October (b), (f), (j), 16 October–31 October (c), (g), (k), and on or after 1 Nov (d), (h), (l). The rows represent three different decades: 1990–2000 (a)–(d), 2021–2030 (e)–(h), and 2041–2050 (i)–(l). The black rectangles indicate the three case study regions—Sorriso, Primavera do Leste, and Pantanal—as defined in figure 1.

early onset shifting from September to early and later October dates, indicating a progressive delay for the climate change and deforestation projection scenarios. This same shift in onset dates can be noticed in the Pantanal region, with most of the region maintaining a high probability of onset in early October.

Complementary to our analysis of onset thresholds, we defined intervals for the rainy season length. Rainy seasons lasting more than 220 d indicate a prolonged rainy period that leads to successful double cropping. As the rainy season shortens towards 180 d, the probability of failure for double cropping increases, leading to an increased possibility of low yields for the second crop. If the rainy season lasts less than 180 d, sowing a second crop becomes unfeasible for farmers.

Probabilities for rainy season length show a similar gradient to that of onset, with longer rainy seasons concentrated in the northwestern region (figures 6(d), (h) and (l)). Over the decades, the probability of extensive rainy seasons decreases, while areas with durations shorter than 180 d come to cover half of MT with probabilities exceeding 30% (figures 6(e) and (i)). Lengths of 181–200 d show increasing probabilities in central MT, and by mid-century, most of the state exhibits more than a 50% chance of being in this range (figures 6(f) and (j)). Similarly to rainy season onset, there is a transition towards shorter rainy season lengths, and the probability for these shorter rainy periods increases across the state (figure 6(m)).

Additionally, Sorriso, Primavera do Leste, and Pantanal demonstrate a decrease in the probability of longer rainy season lengths, with durations of 181–200 d notably increasing from 2021–2030–2041–2050 (figures 6(n)–(p)). Concurrently, the likelihood of a rainy season shorter than 200 d for these regions surpasses 80% (figures 6(n)–(p)).

4. Discussion

4.1. Rainy season diagnosis

Previous studies investigating precipitation across areas broader than MT have consistently registered decreasing rainfall over MT. Specifically, eastern, southwestern, and southern MT have shown increased drought and diminishing rainfall trends (Araujo *et al* 2018, Hofmann *et al* 2023, Marengo *et al* 2021b), which corroborates our diagnosis (figure 2). These trends are particularly pronounced during the transition from dry to wet periods (Araujo *et al* 2018, Hofmann *et al* 2023), marked by the rainy season onset. Furthermore, the expansion of drier trends has been observed in the Cerrado and Pantanal regions of the state (Araujo *et al* 2018, Hofmann *et al* 2023). In addition to analyzing the region's rainfall, we explored trends and anomalies in rainy season onset and duration, enhancing our understanding of the changing climatic patterns in the region.

Among the possible causes of these changes are the shifts in regional atmospheric circulation induced

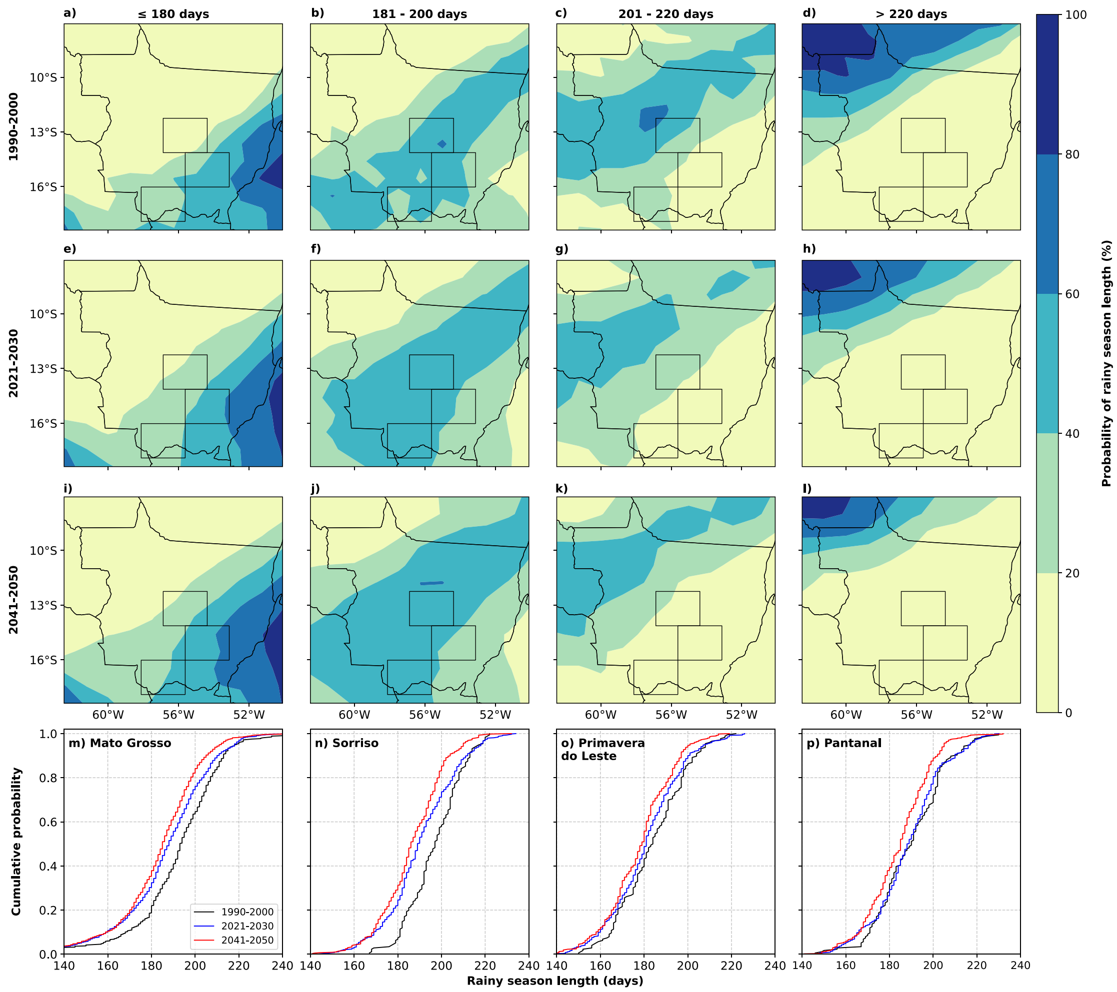

Figure 6. Probability of rainy season length occurrence within specific time ranges and cumulative probability of rainy season duration. Each column represents a specific duration in days: less than 180 (a), (e), (i), 181–220 (b), (f), (j), 201–220 (c), (g), (k), and more than 220 (d), (h), (l). The top three rows represent three different decades: 1990–2000 (a)–(d), 2021–2030 (e)–(h), and 2041–2050 (i)–(l). The black rectangles indicate the three case study regions—Sorriso, Primavera do Leste, and Pantanal—as defined in figure 1. The bottom row shows cumulative probability for the whole of Mato Grosso state (m) and each case study: Sorriso (n), Primavera do Leste (o), and Pantanal (p).

by land use and land cover within the region (Araujo *et al* 2018, Michot *et al* 2024). Extensive deforestation in tropical areas promotes a negative effect on precipitation (Smith *et al* 2023) and, for Amazon areas comprising northern MT, each 10% increment of deforestation might delay the rainy season onset by 1.7 d (Leite-Filho *et al* 2019). Also, modulations in the South Atlantic Convergence Zone characterized by increased intensity might promote a subsidence movement, affecting the rainy season and precipitation amounts (Arvor *et al* 2017, Michot *et al* 2024). We consider these sources of variation likely to be among the causes since these studies have shown similar results to ours, with a delayed onset and consequent shorter rainy season length.

With agriculture as the main economic activity in MT, the current behavior of the rainy season onset and duration, along with the observed trends, have raised concern for farmers. Similar studies have verified that a decrease of 100 mm in precipitation might reduce the possibility of double cropping by 3.6% (Rattis *et al* 2021). Similarly, delayed onset and shorter length of the rainy season severely affect or even eliminate the possibility of a second crop (Abrahão and Costa 2018, Rattis et al 2021, Leite-Filho *et al* 2024). Our analysis found rainfall anomalies surpassing 150 mm, with significant decreasing trends in onset and length, with anomalies of up to 20 d between two 20 year periods (figure 2(k)). However, trend analyses indicate a trend of up to one day reduction of rainy season duration per year, equivalent to a trend of nearly 40 d in 40 years from 1981 to 2020 (figure 2(l)). These results, together with the previous findings, are especially concerning for Sorriso and Primavera do Leste, which rely on agricultural development. Despite the potential for irrigation to mitigate yield losses, similar studies for MT have reported reductions in yields even in irrigated areas (Rattis *et al* 2021).

The economic consequences of agriculture are not the only concern for MT. In 2020, the Pantanal region experienced an unusually long and severe drought associated with a heat wave, leading to massive, widespread fires (Marengo *et al* 2021a, Libonati *et al* 2022). This reduction in rainfall and delayed rainy season onset could present challenges for the region's biodiversity and society (Mataveli *et al* 2021, Libonati *et al* 2022). Our analysis of observed trends in the Pantanal over the last four decades reveals a significant reduction in rainfall and a delayed onset of the rainy season, aligning with previous studies.

4.2. Model skill and projection configuration

As we are aiming to provide valuable information to MT decision-makers regarding sowing dates and double cropping feasibility, the distribution of rainy season onset probability was our main concern. Thus, errors of less than 10 d by the end of our probability spectrum (figure 3) emerge as a reliable representation of the onset for the regions, given the region's seasonal precipitation variability (Hofmann *et al* 2023, Michot *et al* 2024). Moreover, CESM has presented consistent rainfall volumes for dry-to-wet transition months (Commar *et al* 2023a), with comparable behavior to studies using multimodel ensembles, including underestimated rainfall in the Brazilian Amazon region (Monteverde *et al* 2022, Olmo *et al* 2022).

Concerning CESM configuration, the Community Land Model represents surface processes as having higher evapotranspiration than observed for tropical regions with C4 plants (Spracklen *et al* 2018, Boysen *et al* 2020). Since our simulations replace the natural vegetation with C4 grasses, this parameterization might impact local rainfall values. However, this setup preserved the original CMIP5 configuration.

We grouped CESM simulations into decades comprising all four scenarios (RCP2.6-WEG, RCP2.6-SEG, RCP8.5-WEG, and RCP8.5-SEG), enabling the occurrence of extreme-onset events (early and delayed) in our probability distributions. This promoted the understanding of how the extremes place in each projected decade since, for decision-makers, extreme events are the major cause of disasters in planning and yield failures.

4.3. Climate projections

Studies using models have shown a strong correlation between deforestation, precipitation, and the duration of the rainy season. These studies demonstrate that widespread deforestation can seriously disrupt the energy balance, evapotranspiration, and surface roughness, ultimately triggering feedback mechanisms that reduce rainfall and delay the onset of the rainy season by up to 40 d. (Khanna *et al* 2017, Staal *et al* 2020, Commar *et al* 2023a). This delay in rainfall increases the dry season duration in several studies using CMIP5 due to the increase in temperature, the raised concentration of greenhouse gases, the intensification of El Niño, changes in the behavior of the subtropical jet, or changes in the moisture transport (Fu *et al* 2013, Costa *et al* 2019, Brumatti *et al* 2020, Douville *et al* 2023). Likewise, our MT results show a considerable shift towards a later onset and shorter length of the rainy season in climate change scenarios.

Increased deforestation scenarios combined with climate change could lead to a US$2.8 billion gross revenue decrease by 2050, and even using more adapted cultivars aiming for mitigated impact for double cropping does not maintain healthy revenue values (Brumatti *et al* 2020). Indeed, climate change is expected to reduce second-crop productivity by 17% in 2040 (Hampf *et al* 2020). Considering the Amazon biome, which is part of the MT ecosystem, agriculture might lose US$15 billion yearly due to the advance of deforestation (Commar *et al* 2023a). Our finding that there is a higher probability of shorter rainy seasons with later onset reaffirms these disastrous scenarios from previous studies but adds graduated information about the progress of these changes decade by decade to help with developing mitigation strategies.

Deforestation scenarios analogous to ours have demonstrated a 20% loss in double-cropping yield for MT, with projections indicating that regions such as Sorriso and Primavera do Leste may face yield losses of up to 15% under similar conditions (Spera *et al* 2020). This is particularly concerning, as climate projections suggest that these regions are among the most vulnerable to potential losses in second crops (Hampf *et al* 2020, Carauta *et al* 2021). Thus, combining these effects can severely harm the double-cropping potential for those regions.

Other agricultural regions in Brazil increased their production through agricultural intensification practices, especially irrigation. However, this intensification, together with precipitation variability, has triggered regional water stress (Pousa *et al* 2019, Santos *et al* 2020, Commar *et al* 2023b). While sustainable intensification of agriculture may offer a partial solution for MT (Rattis *et al* 2021, Marin *et al* 2022), it is crucial to acknowledge and address this potential conflict.

Compared to agricultural areas, the Pantanal region faces ecological issues instead. Details about the 2020 drought (Marengo *et al* 2021a, Libonati *et al* 2022) support our observations concerning reduced rainfall (figure 2(c)) and shortened rainy seasons (figure 2(k)). This severe dryness has significant consequences for the local economy, population, and ecosystems, all of which rely on the biome (Tomas *et al* 2019, Mataveli *et al* 2021, de Moraes *et al* 2022). The 2024 widespread fire event and the potential amplification of other severe events due to the rainfall and rainy season characteristics presented here cannot be ignored. Regional policies must consider these projections to secure the welfare of Pantanal biodiversity, economy, and local population.

5. Conclusions: a call for action

The past and present diagnostic analysis and the projected analysis for future climate indicate consistent patterns. The trends towards late onset of the rainy season and reduced duration of the rainy season, trends that started in the last few decades, are expected to continue. Those who moved to MT in the late 20th century and got used to its rainy climate and long rainy season should not expect a similar climate in the first half of the 21st century. Agricultural and ecological conservation practices used before are no longer sustainable in the 21st century.

This highlights the urgent need for action to adapt to climate change. These climate projections, which are consistent with recent climate changes, represent a critical opportunity. Regional decision-makers might use these projections and develop regional adaptation strategies to make agriculture and ecosystem conservation more sustainable in future decades.

For agriculture, despite the state's historical reliance on agricultural intensification through rainfed double cropping over the past several decades, climate projections indicate that this practice is under increasingly severe climate risk, which may lead to reduced yields in the first or second crop. A possible solution lies in irrigation. Supplementary irrigation during the beginning of the first crop season and the end of the second crop season might resolve the problem without using much water. Yet, while this solution is promising, it will be a challenge. Because of MT's climate, irrigation was virtually non-existent in the state until 2000 and has been increasing since then. Still, MT had less than 200 000 ha irrigated in 2020, while the need for irrigation now amounts to ~10 Mha (Rocha Junior *et al* 2020), a 50-fold difference. This brings significant challenges in terms of energy production and distribution, and availability of credit to farmers. In addition, careful monitoring of water resources is essential to mitigate the risk of water stress and water use conflicts.

The challenges are even stronger for ecosystem conservation. Future climate projections indicate that the Pantanal is a region highly susceptible to desertification (de Moraes *et al* 2022). Desertification in this region increases the probability of fires and results in low river levels that limit the population's mobility and the transport of commodities to the Atlantic Ocean via the Paraná–Paraguay waterway (Marengo *et al* 2021a). Solutions for the Pantanal drought that preserve the functioning of this delicate ecosystem are still to be proposed.

In summary, MT faces significant challenges due to ongoing and upcoming climate change. Previous agricultural and conservation practices are no longer viable, and immediate action is needed. Specific agricultural policies that facilitate the implementation of irrigation systems without compromising water security are as urgent as specific ecosystem conservation policies that realize that the Pantanal is at imminent risk of desertification through fire.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

Conceptualization, L F S C and M H C; methodology, G M A, L F S C, and L L; software, L L and L F S C; formal analysis, L L and L F S C; resources, M H C; writing—original draft preparation, L F S C; writing—review and editing, L F S C, L M B, and M H C; visualization, L L; funding acquisition, M H C. All authors have read and agreed to the published version of the manuscript.

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