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The time since land-use transition drives changes in fire activity in the Amazon-Cerrado region

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Deforestation and climate change are expected to alter fire regimes along the Cerrado-Amazon transition, one of the world's most active agricultural frontiers. Here we tested the hypothesis that the time since land-use transition (age of frontier) and agricultural intensification also drive changes in the region's fire regimes by reducing fire probability in both drought and non-drought years. We modeled fire probability as a function of the time since land-use transitions based on MapBiomas Project datasets from 1986 to 2020. We find that, while burned area declined as pasturelands aged and croplands advanced, deforestation abruptly increased fire activity before (Amazon: 4 years; Cerrado: 3 years) and after (Amazon: 8 years; Cerrado: 7 years) land clearing for pasture, especially in the Amazon. Additionally, the combination of ignition risk, drought, and air-dryness increased the likelihood of large extents of burned areas associated with deforestation. Incorporating frontier age as a proxy for governance in fire modeling is crucial, given the ecological implications of changing fire regimes despite declining rates of fire probability. Most importantly, protecting against deforestation and preserving native vegetation are vital.

One of the world's largest agriculture frontiers has emerged in the transition zone between the Amazon and Cerrado biomes—due largely to cattle ranching expansion via the conversion of native forests and savannas. More recently, this frontier has been characterized by the intensification of pasturelands, as well as large-scale replacement of pasturelands with mechanized production of crops such as soybean, cotton, and corn[1–3]. These activities can fundamentally change the region's fire regimes[4]. Deforestation-related fires accounted for 4% of the burned area in the Cerrado and 13% in the Amazon over the past 36 years[5]. Management of low-productivity pasturelands accounted for 7% of burned area in the Cerrado and 58% in the Amazon over the same period[5]. These fires have the potential to escape into neighboring ecosystems and degrade native vegetation, especially during unusually dry and hot years[6–9]. Over time, increasing environmental governance may drive a decline in fire activity in this large agricultural frontier, especially where mechanized agriculture replaces the use of fire as a management tool[4]. An understanding of how fire activity changes with the evolution of the Amazon-Cerrado agricultural frontier is currently limited, yet these trajectories of fire usage are crucial for the development of effective conservation strategies.

The transitional region between the Amazon and Cerrado houses two distinct biomes, each characterized by unique ecological dynamics and responses to fire. In the Amazon, fire suppression in agricultural fields may lead to fewer fires escaping into standing forests and less carbon being emitted to the atmosphere[10,11]. In contrast, the Cerrado biome—a fire-adapted savanna ecosystem where fire has shaped ecosystem structure and function[12]—may experience woody encroachment and increased potential for high-intensity fires induced by fire suppression[13–16]. Although a growing body of work suggests reduced fire activity due to agriculture

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intensification[4,17,18], opposing patterns of fire response to human activities are expected in the Amazon and Cerrado[19]. Nevertheless, a comprehensive analysis of lagged fire responses to different types of land-use transitions at the interface of these biomes is currently lacking. In this study, we model fire probability as a function of time since land clearing and test how the age of the different land-use frontiers and climate drivers influence spatiotemporal patterns of burned area across the Amazon-Cerrado transition.

Despite increased crop yields and food security, the intensification of agriculture can still have unintended and long-lasting ecological consequences in the Amazon and Cerrado. Most of the landscapes experiencing widespread agriculture intensification are also highly fragmented[19–22]. Despite evidence of fire suppression with agricultural intensification, even scarce fire ignitions can ignite dried-out vegetation (fuel) and elevate burning activity. These dry fuels are increasingly common due to prolonged dry and warm periods across degraded, fragmented transition zones. Moreover, by decreasing burn rates, agricultural intensification may promote the accumulation of biomass and low-moisture fuel given the absence of frequent, low-intensity fires[13,23]. A 'zero-fire' policy has been widely recognized to have negative effects in fire-dependent systems like the Cerrado, where fuel accumulation increases the intensity of fires when they occur, particularly in conjunction with drought and heatwaves[13]. Furthermore, the absence of regular fire events and altered burn timing can change overall ecosystem functioning of the Cerrado, with potential cascading effects and further losses in biodiversity[13,24]. While fire suppression has clear positive ecological implications for wetter Amazonian forests, it is important to consider the broader ecological context of the Amazon-Cerrado transition and the factors that can negatively impact biodiversity and overall ecosystem functioning in the Cerrado.

In addition to the potentially distinct responses of Amazon and Cerrado vegetation, the transition zone between these two biomes faces additional pressures due to climate changes[25]. Although dry season fires account for a considerable proportion of the total annual burned area across this transition[26], the dry-to-wet transition seasons are becoming warmer, drier, and longer (late onset of wet season), thus elevating the risk of fire beyond the usual periods[25]. Another pressing concern is the anticipated rise in flammability of fuels near the edges of fragmented forests and savannas surrounded by agricultural areas. Increasing anthropogenic warming is predicted to amplify the potential for high-intensity fires in the Amazon-Cerrado frontier[26,27]. Most importantly, under the most severe climate projections, land-use contraction alone demonstrates limited effectiveness in reducing Amazon understory fires, suggesting that future fire risk in Amazon forests depends strongly on the interactions between land use and climate change mitigation[28].

Considering the emergence of both new and existing agricultural frontiers, as well as the uncertainty surrounding the combined effects of land use transitions and increasing climate extremes, our objective is to evaluate the complex interplay between these factors and their impact on fire dynamics. As global food demand grows, so do incentives to intensify agriculture and pressure to expand the frontier[29], impacting land-use change and fire variability. Here we investigate how specific land-cover/land-use transitions and the time since transition, together with climate drivers, have contributed to patterns of historic fire activity. Our study area includes much of the agricultural frontier between the Amazon and Cerrado (Fig. 1a). This vast savanna-forest transition zone is under strong anthropogenic pressure due to the combined effects of fragmentation, fire, and climate and weather extremes[22]. We investigated annual land use and burned areas from 1986 to 2020, based on time series data from MapBiomas 6.0[30] and MapBiomas Fire 1.0[5]. This allowed us to capture fire responses to the conversion of native vegetation (forest, savanna, and grassland) to agriculture (pasture and croplands), modeling the proportion of burned area associated with each type of transition as a function of time since land clearing ("Methods"). The time interval between land conversion and burned area provides a proxy for how the age of frontiers relates to fire activity. In addition, we explored the joint impact of land-use change and climatic drivers of fire activity: estimated vapor pressure deficit (VPD) and maximum cumulative water deficit (MCWD), two common measures of flammability and drought impact[3,26].

Results

Both Amazon and Cerrado native vegetation experienced large-scale conversion to agriculture during our study period (Fig. 1). Over the past three decades, the proportion of area converted indicates widespread replacement of forests by pasture, followed by the replacement of pastures by croplands (Fig. 1b). This historical pattern of pasture replacing natural vegetation has more recently been overtaken by the dominance of mechanized crop production, aimed at converting potentially degraded pastures and meeting the growing demand for food. Comparing the prevalence of all land-use transitions, forest replacement by pasture ranked first (37%), pasture replacement by cropland second (21%), and savanna by pasture third (20%).

These land-use transitions strongly influenced burned area probability (Fig. 1c). Of all the burned areas associated with land conversion, 76% occurred during forest conversion to either pasture (72%) or croplands (4%), followed by pasture conversion to croplands (9%). These findings highlight that, while most of the burning associated with conversions to agriculture relates to deforestation (forest conversion to pasture or croplands), pasture replacement by croplands also involves the use of fire and thus contributes to total burned area. Similar patterns emerge when analyzing each biome individually (Supplementary Figs. 1 and 2), underscoring the influence of land-use transitions on the probability of burned area across the ecotone.

Agricultural frontier age as a driver of fire probability

While burned area tended to decrease after 2004 across the study region due to decreased clearing of native vegetation (Supplementary Fig. 2c, d), we observed recent increases in fire activity in some regions resulting from the replacement of pasture by cropland (Fig. 1c, Supplementary Figs. 1 and 2). These findings highlight contrasting effects of fire suppression induced by agricultural intensification. To inspect potential opposing patterns, we analyzed fire probability associated with the time interval between different land-use transitions (Figs. 2 and 3) and the resulting burned area at the grid-cell level ("Methods"). The time since transition will be henceforth referred to as the age of the frontier, ranging from −35 years to 34 years (spanning 35 years from 1986 to 2020), where age 0 year represents the time of conversion. This approach allowed us to understand how the age of different types of conversion impacts ignition sources and, thus, how it influences fire probability.

Our results point to contrasting patterns of fire activity between forest conversion to pasture and the transitions to croplands both in terms of fire probability and duration. Fire probabilities associated with forest to pasture conversion exhibited an initial increase in burned area before land clearing, which remained elevated for several years post-transition (Fig. 2a, d). When Amazon forests were converted to pasturelands (Fig. 2a), the burned area spiked (45% fire probability) during the year of conversion and then gradually declined over time as the frontier aged (Fig. 2a). However, despite this declining trend, fire probability remained elevated for at least 8 years after deforestation (Supplementary Fig. 3a, d). Although Amazon fire probability leveled off after that, we still detected a 21% chance of these older frontiers burning (Supplementary Fig. 3a). This suggests that the complete elimination of fire from the landscape takes time in the case of Amazon forest conversion, and that fire suppression is not immediate after clearing.

In the Cerrado, the shape of the burned area response to frontier age (Fig. 2d) exhibits similarities to that of forest to pasture conversion in the Amazon (Fig. 2a), but the impact of frontier age is comparatively smaller. In addition, the Cerrado experienced lower fire probabilities during the year of conversion (Fig. 2). Similarly, the response of fire probability to the transition of forest to cropland (Fig. 3a, e) resembled patterns observed in the conversion of forest to pasture (Fig. 2a, d) in both biomes. However, the impact was comparatively weaker, and there were lower fire probabilities during the year of conversion. These findings contrast with the expectation that the transition from forest to cropland would result in more fire activity

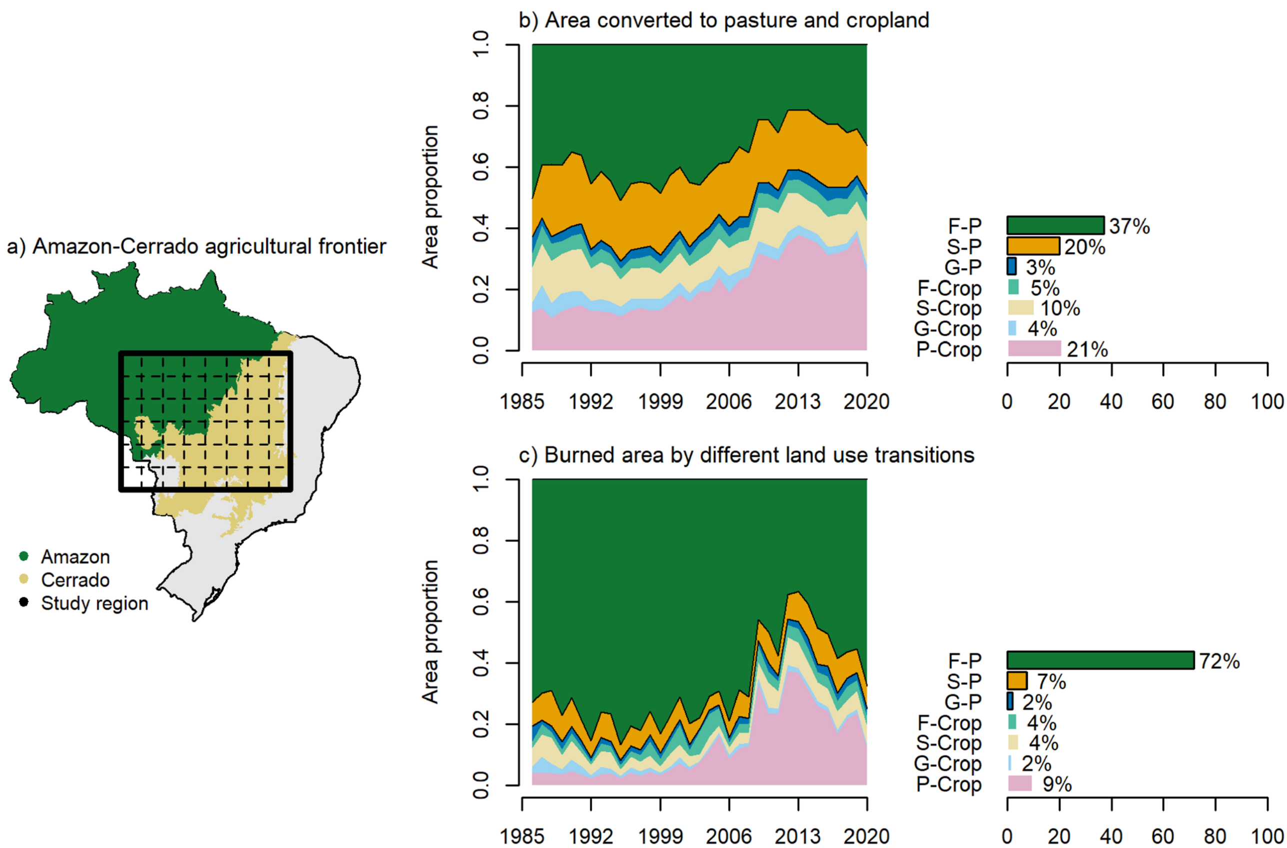

Fig. 1 | Annual land-use transitions and associated burned area. a Study region including the growing Amazon-Cerrado agricultural frontier and adjacent areas (the gray areas indicate biomes outside the Amazon and Cerrado, which were excluded from this analysis). **b** Proportional area of each land-use transition: forest to pasture (F-P, green), savanna to pasture (S-P, yellow), grassland to pasture (G-P, blue), forest to cropland (F-Crop, marine green), savanna to cropland (S-Crop, beige), grassland to cropland (G-Crop, light blue) and pasture to cropland (P-Crop, pink). Transitions to pasture (F-P, S-P, and G-P) are delineated with a black border. **c** Proportion of burned area for each land use transition. Panel (**a**) shows the 2.5-degree grid used to calculate the fraction of burned area (**c**) associated with a given land transition (**b**) at 500-m resolution based on MapBiomas Fire 1.0 and MapBiomas 6.0 data from 1986 to 2020 ("Methods").

(compared with the transition from forest to pasture) given the need to clear all woody debris for mechanized agricultural production.

Compared with transitions from forest to pasture (Fig. 2a, d), fire probabilities associated with the transition to cropland are generally lower at the year of conversion (Fig. 3), especially in the Amazon (Fig. 3a–d). Moreover, conversion to cropland resulted in earlier elimination of fire from the landscape compared with conversion of forest to pasture (Fig. 3 and Supplementary Fig. 4). In fact, in areas transitioning to cropland (including soybeans, maize, and cotton, Fig. 3), fire probabilities were already decreasing before the transition in both the Amazon (Fig. 3b, c) and Cerrado (Fig. 3e–h). With the aging effect, the decline in fire probabilities continued after the transition to cropland, reaching low values of fire activity with more recent frontiers than deforested areas for pasture. This suggests that the establishment of croplands contributes to the suppression of fire activity, leading to more rapid and sustained reductions in fire probability.

Spatiotemporal patterns of fire probability pre- and post-conversion

The aging effect among different transitions also leads to contrasting trends in fire probability between the Amazon and Cerrado biomes. Compared with the transition from forest to pasture, the spikes in fire activity associated with the conversion of savanna and grassland to pasture are relatively less pronounced and vary markedly between the two biomes (Fig. 2). The conversion of Amazonian savannas and grasslands to pasture exhibits lower fire probabilities (19% and 14%, respectively) compared to deforestation at the year of transition (age 0) (Fig. 2a–c), but there is still a notable increase in fire probability associated with that transition. This increase is preceded by a rising trend in fire probability and followed by a subsequent decline, similar to the pattern observed in forest to pasture conversions in the Cerrado and Amazon (Fig. 2a, d). In contrast, before transition (negative values of frontier age), conversion of Cerrado savannas and grasslands to pasture (Fig. 2e, f) exhibit a different trend compared to forest to pasture transitions in both biomes (Fig. 4b). In this case, declining trends in fire probability before the transition in the Cerrado contrast with the increasing trends observed in the Amazon (Figs. 3a, b and 4a, b). The negative trends and lower fire probabilities observed during the transition from Cerrado savannas and grasslands to pasture indicate greater fire suppression for pasture expansion in this region.

A clear spatial outline of the boundary between the two biomes is also observed after transitions to pasture (Fig. 4c, d), but all trends show a negative trajectory in both biomes, consistent with declining fire activity in older frontiers. The pronounced fire probability rates in the Amazon compared to the Cerrado can be attributed to higher fire probabilities at the moment of transition (Fig. 2). While forested ecosystems typically have higher biomass, the Cerrado biome consists of a mixture of savanna and grassland vegetation, which generally has lower biomass compared to dense forests. As a result, the transitions to pasture in the Cerrado may require less fire for conversion compared to the Amazon, where even though fire probability declines faster each year, it takes more time to remove fire from the landscape completely (e.g., Fig. 2a).

The spatial pattern of fire trends before and after the transition to cropland (Fig. 5) also shows predominantly negative fire rates in both biomes before and after conversion (with a few exceptions in the Amazon before transition, Figs. 5b and 3a, d). In other words, transitions to croplands exhibit less noticeable shifts in fire activity before and after the transition (i.e., more subtle changes in fire regimes) due to declining burning before

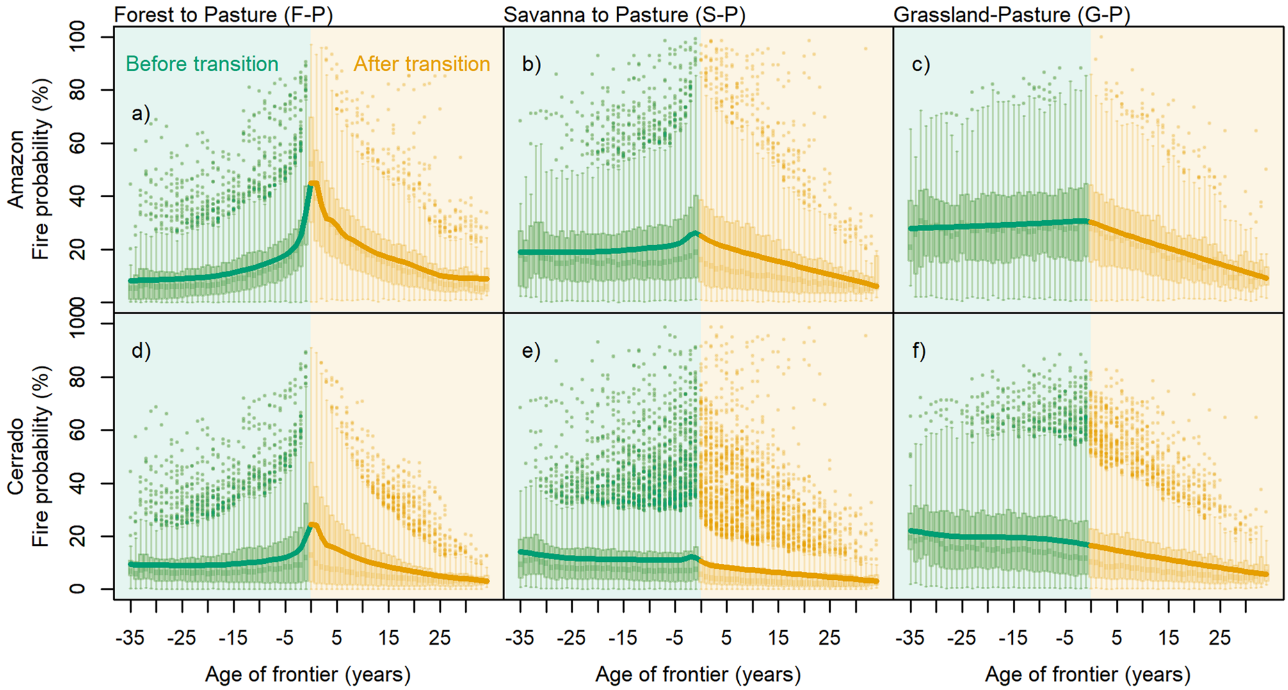

Fig. 2 | Fire response to the time since conversion to pasture (age of frontier). Fire probabilities in the Amazon (**a**–**c**) and Cerrado (**d**–**f**) associated with conversion of forest (**a**, **d**), savanna (**b**, **e**), and grassland (**c**, **f**) to pasture, shown as a function of years since the transition (from 1986–2020). The curved response line was estimated based on a Generalized Additive Model (GAM) using an adaptive Gaussian kernel smoothing method ("Methods"). At the moment of conversion (age 0), fire probabilities transition from pre-conversion (green) to post-conversion (orange) trends. Time-lagged annual fractions of burned area associated with conversion are represented using boxplots, with each point representing a 2.5-degree cell from the grid depicted in Fig. 1.

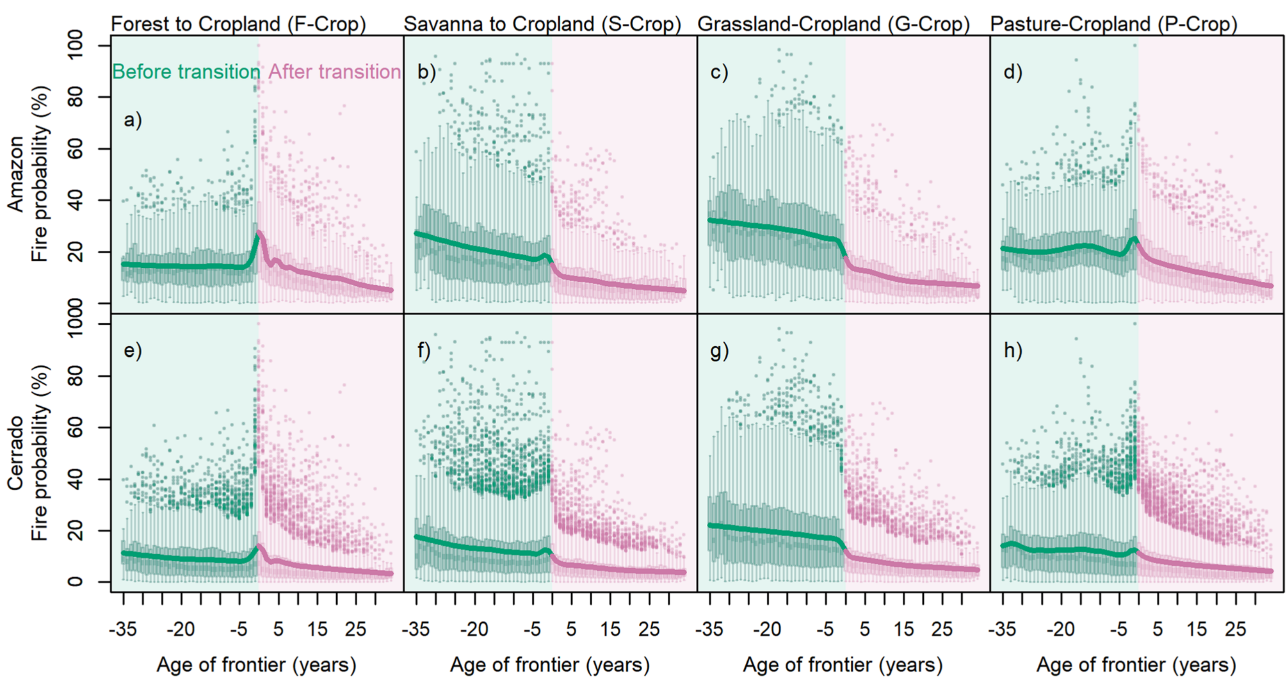

Fig. 3 | Fire response to the time since conversion to cropland (age of frontier). Fire probabilities in the Amazon (**a**–**d**) and Cerrado (**e**–**h**) associated with conversion of forest (**a**, **e**), savanna (**b**, **f**), grassland (**c**, **g**) and pasture (**d**, **h**) to cropland, shown as a function of years since the transition (from 1986–2020). The curved response line was estimated based on a Generalized Additive Model (GAM) using an adaptive Gaussian kernel smoothing method ("Methods"). At the moment of conversion (age 0), fire probabilities transition from pre-conversion (marine green) to post-conversion (pink). Time-lagged annual fractions of burned area associated with conversions are represented using boxplots, with each point representing a 2.5-degree cell from the spatial surface grid depicted in Fig. 1.

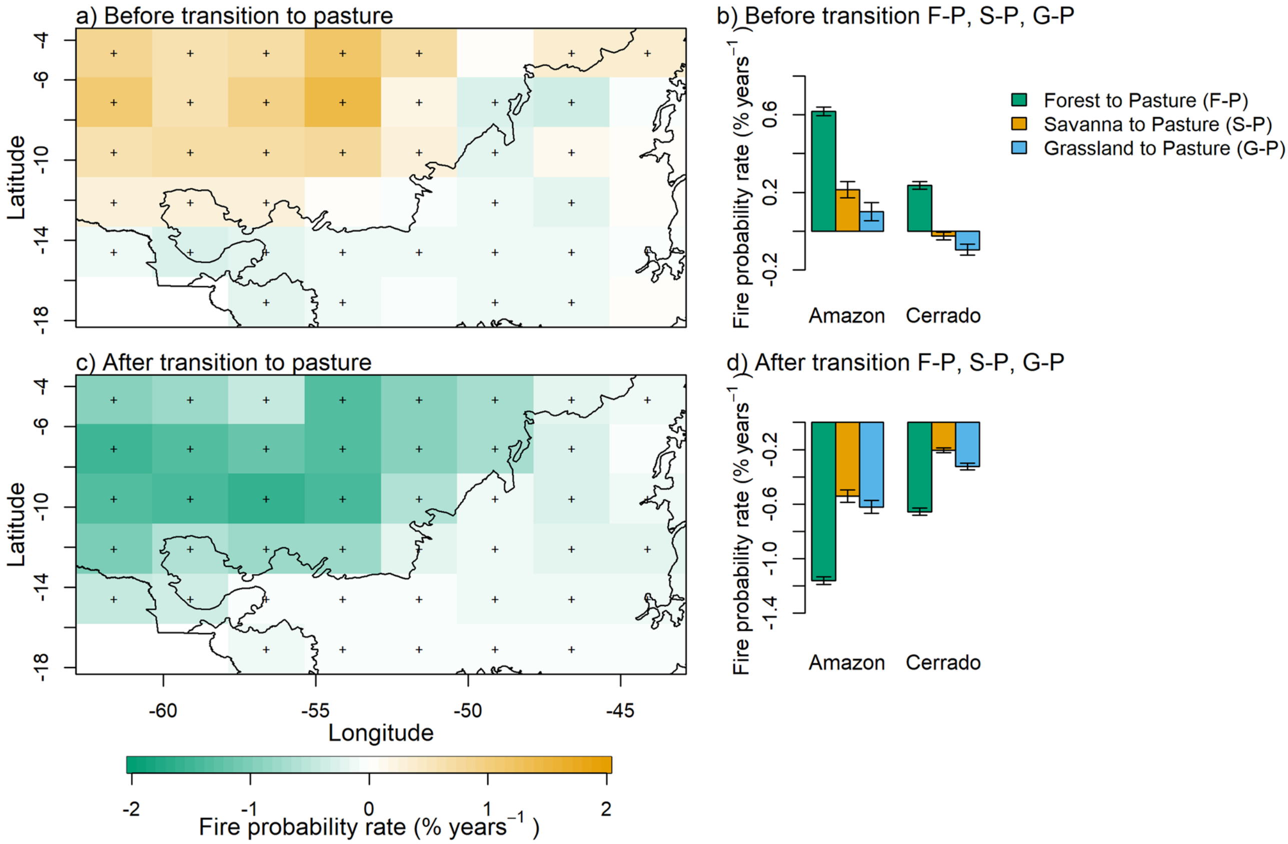

Fig. 4 | Spatial patterns of fire probability pre- and post-conversion to pasture. Fire probability is estimated based on the slope of a linear regression before (**a**, **b**) and after transition (**c**, **d**) from 1986 to 2020 ("Methods"). Crosses indicate statistically significant slopes with 95% confidence (**a**, **c**), and error bars indicate 95% confidence intervals (**b**, **d**). The borders of the biomes are represented in black contour lines, including the Amazon, Cerrado, and northern Pantanal (excluded from the analysis).

conversion, likely associated with fire suppression accompanying agricultural intensification. As the transition to croplands can involve valuable agricultural investments (in terms of machinery, facilities, irrigation, etc.), landholders may take proactive measures to reduce fire risk before the transition or employ mechanized land-clearing methods that minimize the risk of fire spread. These actions could contribute to the decreasing trend in fire probability ahead of the transition to cropland.

To examine the impact of aging over time, we divided the 35-year period into 7-year intervals. Our analysis revealed an overall non-stationarity in fire spikes during the moment of conversion of forest to pasture (age 0, Supplementary Fig. 5). Two main processes could be driving these patterns, aging of the frontier and reductions in deforestation rates. Although both the Amazon and Cerrado regions consistently exhibited spikes in fire probability around the time of forest to pasture conversion, in recent years there has been a decrease in the intensity of these fire spikes. This is in line with reductions in fire activity observed in the time-series of burned area without time-lags between the land-use transition and fire occurrence (i.e., year of transition coincides with the year of fire occurrence) (Supplementary Fig. 6). Hence, this reduction in burned area is not solely attributable to the aging effect but also represents a broader trend reflecting the changes in clearing rates. In contrast, transitions from pasture to cropland displayed relatively lower magnitudes of fire probability spikes over time in both biomes. Interestingly, in the Cerrado, the fire spikes associated with these conversions remained relatively stable over time (Supplementary Fig. 7), while the Amazon experienced slight fluctuations. This indicates that, despite the Cerrado undergoing a greater extent of native vegetation conversion to agriculture (Supplementary Fig. 2), it consistently experiences lower levels of burning due to cropland transitions compared to the Amazon (Supplementary Figs. 6 and 8). Consequently, the decline of fire activity accompanying agricultural intensification has proven to be more effective and less dependent on the age effect in the Cerrado compared to the Amazon. The transitions from pasture to cropland in the Amazon over the past 7 years already suggest a decline in burning prior to conversion, further confirming the suppressed fire activity associated with agricultural intensification. This suggests that improved agricultural management and fire control efforts may have contributed to reducing recent fire occurrences in these croplands, and the age of the frontier becomes a relevant factor in reducing fire occurrence when there is a decrease in overall fire activity within the landscape.

The influence of drought and air dryness on frontier-related fire

In contrast to the drier conditions observed in the Cerrado region, characterized by higher values of vapor pressure deficit (VPD) and more negative values of maximum cumulative water deficit (MCWD) (Supplementary Fig. 9), the Amazon biome exhibits higher humidity levels, indicated by lower VPD values and less negative MCWD values. Despite the distinct regional variations in climate, a recent increase in air dryness (Supplementary Fig. 9) has been observed in both the Amazon and Cerrado during the last decade. This increase would typically be expected to counteract the decreasing trends in burned area (Supplementary Figs. 2, 5 and 8), highlighting how the age of the frontier and highly capitalized land uses reduce fire probability even when weather is very favorable to fire.

While climate conditions alone are not sufficient to initiate fires, our findings reveal a strong association between deforestation, drought, and air dryness (higher classes of MCWD and VPD) with the occurrence of larger extents of burned area associated with the transition, compared to smaller extents of burned areas (Fig. 6). To examine the coupling between land use, climate, and fire, we conducted a comparative analysis of fire probabilities

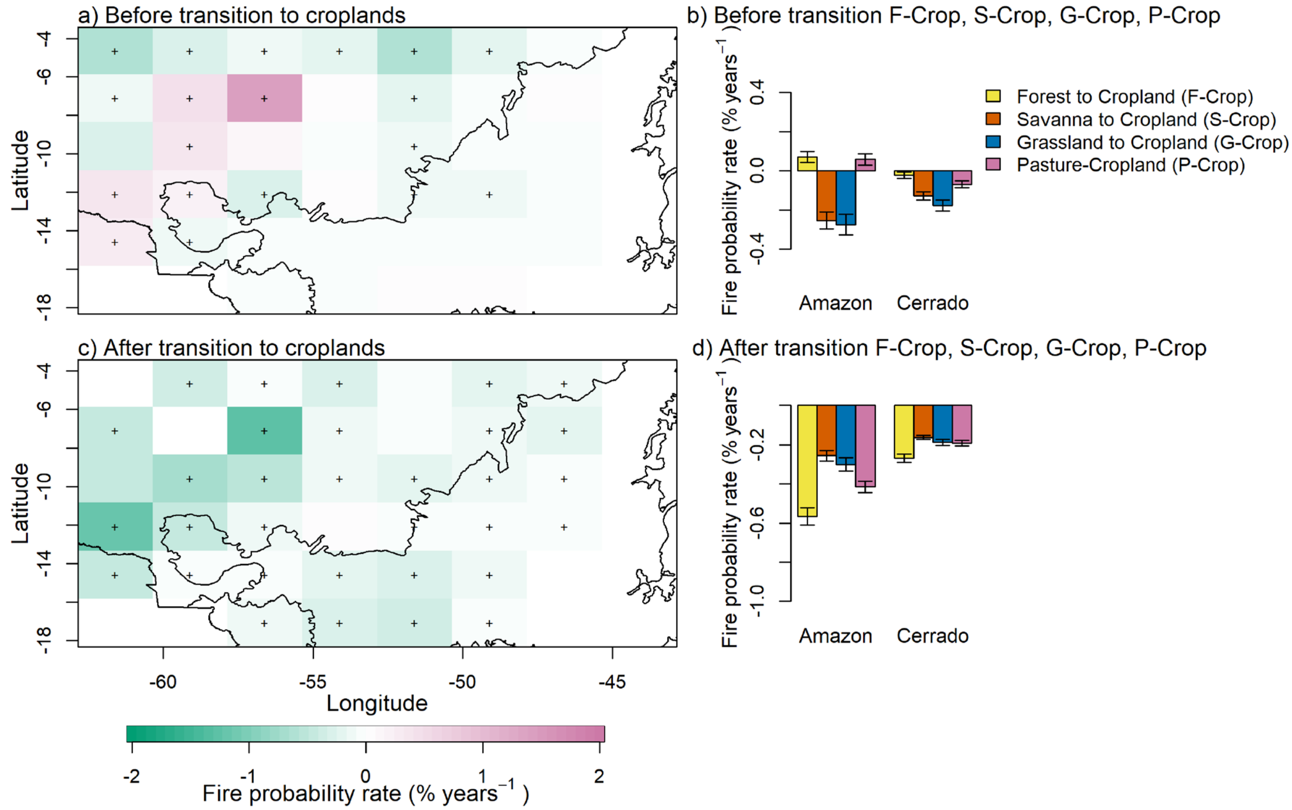

Fig. 5 | Spatial patterns of fire probability pre- and post-conversion to cropland. Fire probability is estimated based on the slope of a linear regression before (**a**, **b**) and after transition (**c**, **d**) during 1986–2020 ("Methods"). Crosses indicate statistically significant slopes with 95% confidence (**a**, **c**), and error bars indicate 95% confidence intervals (**b**, **d**). The borders of the biomes are represented in black contour lines, including the Amazon, Cerrado, and northern Pantanal (excluded from the analysis).

grouped by intervals of annual extents of burned area induced by land clearing, drought levels and air dryness. Conversion of forest to pasture and climate stressors emerged as key drivers of large extents of burned area, whereas small extents of burned area were less influenced by land-use transitions and climate conditions. Higher stress levels of drought and air dryness become increasingly influential as extent of burned area increases, aligning with the notable spike of ~60% in fire probability at the year of conversion. In contrast, smaller extents of burned area are less related to higher climate stress. Nevertheless, even under lower classes of VPD and MCWD, both large and small extents of burned area occur when a transition from forest to pasture occurs, particularly in the Amazon. While the clearing of vegetation during deforestation creates fuel loads that act as catalysts for larger, more intense fires, our results indicate that the lower extents of burned area in fire-dependent ecosystems of the Cerrado had a weaker association with land-use transitions and climate conditions. In contrast, when coupled with drought and air dryness, conversion to pasture further enhances the likelihood of large extents of burned area in both the Cerrado and the Amazon.

In transitions from pasture to cropland, the influence of drought and air dryness on fire probability is negligible, as the probabilities remain consistently low across all classes of burned area extent and climate severity levels (Supplementary Fig. 10). In this type of transition, the extent of burned area is less relevant due to the implementation of fire suppression measures associated with agricultural intensification, even with favorable climate conditions. This suggests a decoupling between climate drivers and land-use changes associated with agricultural intensification. While deforestation and climate drivers have a strong influence on large extents of burned area, the same relationship does not hold for transitions to cropland. Other factors, such as mechanized agricultural practices and modern land management techniques, may play a more prominent role in controlling fire activity within new cropland areas.

Discussion

Previous studies have shown that agricultural expansion and intensification control much of the fire activity in the Amazon[17,31] and Cerrado[4]. Our results show that forest conversion to pasture creates major spikes in burned area (especially during hot and dry conditions), and that the age of the agricultural frontier is another main driver of temporal reductions in burned area. This study expands on previous research concerning the Amazon fire-transition process related to land-use transitions[18] and contrasting responses of fire to human activities in the Amazon and Cerrado[19]. It advances understanding of this topic by showing that, while forest conversion to pasture contributes the most to the region's fire activity (in combination with drought and air dryness), the age of the agricultural frontier and the replacement of pastures and grasslands by mechanized croplands also play substantial roles.

Although the aging of agricultural frontiers and the expansion of croplands markedly reduces fire activity after conversion, a substantial amount of fire activity still precedes and follows the deforestation process, especially in the Amazon, where deforestation fires account for more fire activity than in Cerrado. The magnitude and duration of the peak in fire activity around the transition process contributes to landscape-scale fire risk across this agricultural frontier. Furthermore, the combination of the associated ignition sources, drought, and air dryness, increases the likelihood of large extents of burned area in regions experiencing deforestation. Most importantly, we show that the ongoing widespread process of agricultural intensification taking place along the boundary between the Amazon and Cerrado has fundamentally changed fire regimes in the region.

A striking finding of our study was the large fire activity observed about 4 years before the actual land-use conversion from forest to pasture, followed by a persistently elevated fire probability for ~8 years after conversion. Although burned areas gradually declined over time with frontier aging, this finding underscores the need to address the large fire activity that precedes

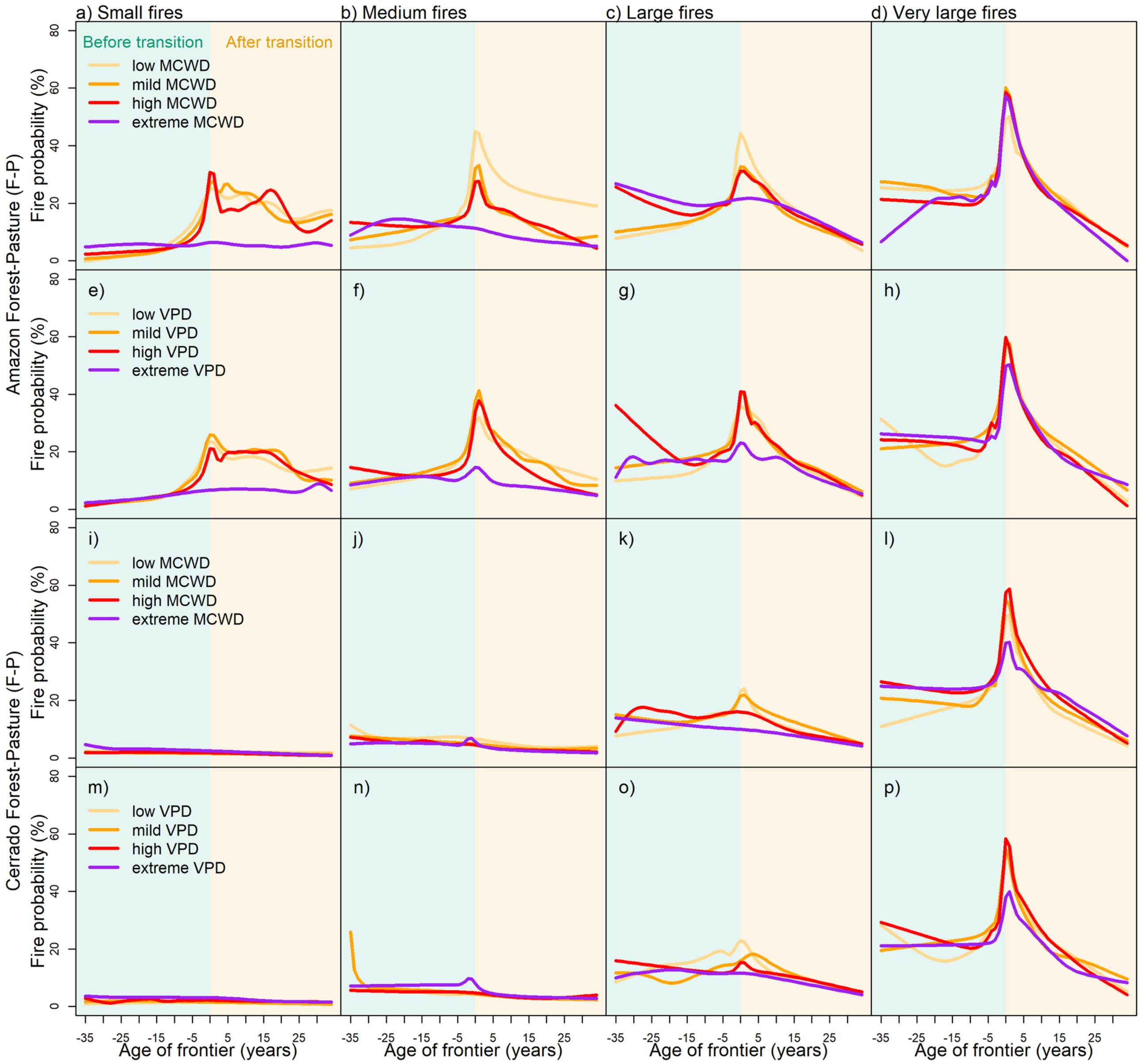

Fig. 6 | Combined effect of age of frontier, drought, and air dryness on frontier-related fire. The influence of MCWD (**a**–**d**, **i**–**l**) and VPD (**e**–**h**, **m**–**p**) on fire induced by conversion of forest to pasture increases with the extent of burned area in the Amazon (**a**–**h**) and Cerrado (**i**–**p**) biomes. The curved response line was estimated based on a GAM using an adaptive Gaussian kernel smoothing method. Extents of burned area, MCWD (drought) and VPD (air dryness) classes are defined by quartile intervals. Supplementary Fig. 9 provides the midpoint value for each quartile of MCWD and VPD in the Amazon and Cerrado, encompassing all classes of burned area extent for each biome (here the class intervals are determined for different subsets by extents of burned area). Note that the classes for MCWD are "inverted" due to its negative values, where more negative values indicate higher levels of dryness.

and follows the deforestation process. In a similar way, a rise in conversion-related fires during the deforestation process in the Amazon has been reported[18] followed by a subsequent decrease in fire occurrence with the implementation of more advanced agricultural practices. Our results advance previous research by modeling fire as a function of frontier age and clarifying how long it takes to eliminate deforestation fires from Amazonian landscapes. Besides the ignitions triggered by deforestation itself, fire is subsequently used to efficiently clear the remaining biomass, which undergoes a drying process over time. The practice of intentionally setting fire to the accumulated woody biomass is employed as a means to clear it, highlighting the dual reliance on fire in the case of deforestation. Our results suggest that intentional forest fires are used as a tool not only for rapid deforestation but also for progressive deforestation, whereby forested areas are gradually degraded and converted over time, rather than being rapidly cleared in a single event.

While one would anticipate a higher level of burning during the forest to cropland transition, compared with transitions from forest to pasture our results revealed a surprising pattern. In previous work, the frequency of active fire detections was found to be higher during the transitions from forest to cropland rather than forest to pasture[31]. Yet, our results are illustrated in terms of time-lagged annual fractions of burned area per converted land (in %/year), allowing us to shed light on the rate at which fire is eliminated from (or remains in) the landscape. Our results suggest that the removal of fire from previously forested landscapes is faster during transitions to cropland compared to pasture, potentially attributable to highly capitalized land uses with better fire management, even when climate conditions are favorable to fire. The overall accuracy of the MapBiomas Fire 1.0 dataset introduces some level of uncertainty in fire detection, particularly related to the potential underestimation of understory forest fires and overestimation of cropland fires ("Methods"), but these limitations do not substantially affect our overall conclusions. Notably, the potential overestimation of fires in land cover types such as annual crop fields[5] suggests that our observation of less burning during forest to crop conversion (compared to forest to pasture conversion) is a conservative result.

Completely eliminating fire in the Amazon also becomes challenging when there are patches of native vegetation scattered within anthropogenic landscapes[20,21,32]. When there is ongoing land-use change or agricultural activities close to these forest edges, the risk of fire spreading and affecting the remaining degraded forest patches becomes higher. In addition, while forest understories typically acts as a natural fire barrier[20], multiple fires weaken forest resilience and regrowth, because burned and fragmented forests dry out more easily[33]. As drought conditions further increase forest susceptibility to fire, forested landscapes are vulnerable to increased deforestation and global warming[27]. Here we provide evidence that despite the overall decrease of fire ignition from agricultural intensification, the Amazon agricultural frontier is still expanding by means of deforestation, and the associated ignition sources are still enough to trigger high-intensity fires, especially in combination with drought and air dryness[26,34]. A major concern is the potential of these modern-era tropical forest fires to push the southeast Amazon into a new lower-biomass state[35], potentially releasing a large part of the carbon stored in these forests and triggering cascading impacts on the rainfall regime[36,37], biodiversity[38,39], and socio-economic development[40]. Reductions in rainfall related with Amazon deforestation would affect the hydrological cycle and other ecological services in the region, threatening the livelihoods of Indigenous people and local communities[41]. While carbon stored in savannas is projected to increase worldwide, this is partly due to the expansion of savannas into forest climate zones[35] and the associated increase in biomass does not offset losses in storage from the replaced forests. In other words, preventing forest ecosystems from transitioning into savanna-like landscapes requires the effective reduction of deforestation fires. Despite decreasing fire rates with frontier age, our analysis revealed that these fires persist in the landscape for a considerable duration following the initial clearing event, underscoring the need for more effective measures to manage fires in these tropical landscapes.

Old-growth Cerrado ecosystems have been historically dependent on a favorable amount and timing of fire[14,15]. Our analysis showed that prior to undergoing conversion to agriculture, Cerrado savannas and grasslands experienced regular burn events in contrast to forests (the probability of forest fires prior to forest conversion is close to zero). Yet, the aging effect of land-use transitions on fire activity observed in our study indicates that the ongoing process of agricultural growth is reducing fire occurrence in most Cerrado regions, consistent with previous studies[4]. While this may have positive implications for fire-sensitive ecosystems like riparian forests, it could potentially lead to biodiversity losses and diminished ecosystem functions in regions with high climatic potential for vegetation encroachment. In addition, fire suppression under agriculture combined with drier and hotter climates, may create regions more prone to severe, high-intensity fires[13–15]. In our study, we observe a stronger association between large extents of burned area, MCWD and VPD, with subsequent nonlinear declines in burned area with the age of the pastureland frontiers. This suggests a weaker association between small extents of burned area and these factors in the Cerrado, where lightning is a natural ignition source and historically a primary driver of frequent fires.

In contrast to the Amazon, the Cerrado is poorly protected and undervalued, leading to widespread vulnerability to anthropogenic pressures. The lack of adequate conservation measures has contributed to an unsustainable expansion of agricultural activities in the region. Predominantly constituted by the Cerrado, the MATOPIBA region represents the greatest expansion area for soybean production, which has advanced primarily through clearing native vegetation rather than by using previously cleared degraded pasturelands. Recent work indicates that this widespread deforestation of the Cerrado is strongly affecting the water cycle and threatening water availability for agriculture[42–44]. Increasing encroachment and poor protection will further incentivize new clearing in natural landscapes with favorable weather conditions and fertile soils, disregarding both long-term environmental sustainability and climatic suitability[3]. Addressing these issues requires the implementation of robust conservation measures, sustainable land-use practices, and policies that prioritize the preservation and proper management of the Cerrado's unique ecosystems. This includes complete elimination of deforestation from the Cerrado and the adoption of double-cropping systems rather than new clearing for single-cropping systems[42,43]. Nevertheless, implementing such changes could require massive irrigation expansion, since much of the region has already been pushed beyond the climatic limits for agriculture[3], potentially leading to future regional water conflicts.

The Amazon-Cerrado agricultural frontier is facing unprecedented pressures. Here we show that, although agricultural growth is reducing burned area as the frontier ages, a large amount of fire activity still precedes and follows the deforestation process. When combined with drought and air dryness, the existing ignition sources are still enough to cause large extents of burned areas. In addition, the long-term ecological consequences of fire suppression in the Cerrado and transitions to croplands have yet to be determined. These findings provide valuable insights on the importance of incorporating the effect of land-use transition ages on ignition probability into fire modeling in combination with climate drivers. Most importantly, we argue that preventing new deforestation and protecting native vegetation is fundamental to ensuring the preservation of forests that regulate regional and global climate.

Methods

Response of burned area fraction to time since land clearing

To capture the response of fire to land-use transitions across the Amazon-Cerrado frontier, we modeled the proportion of burned area associated with conversions as a function of time since land clearing. We investigated annual land-use and associated burned areas (Fig. 1, Supplementary Figs. 1 and 2) based on the MapBiomas 6.0 and MapBiomas Fire 1.0 data, respectively, from 1986 to 2020[5,30]. To optimize the computational performance (by reducing the number of pixels), we regridded the MapBiomas datasets from 30 to 500 m resolution[45] using the default resampling method (nearest neighbor) of the reducer function in Google Earth Engine (GEE). Compared with methods involving statistical transformations of the original data, this approach is a common strategy for resampling categorical datasets such as land-cover[41,45] and enables reliable tracking of pixel transitions, which is critical for understanding the relationship between land-use and fire activity over time. The original 30 m burned area dataset from MapBiomas Fire 1.0 contains potential commission and omission errors in cropland and understory fires, respectively[5]. On one hand, after the harvest, crop fields (e.g., soy, cotton, sugarcane) are often covered with remaining dry plant materials that can exhibit spectral properties similar to burn scars, potentially leading to misclassifications of burned areas in croplands. On the other hand, lower intensity understory fires are notoriously hard to detect and often underestimated within the forest fire class, suggesting a conservative estimation of burned area in our study[5].

To model how fire activity changes with the evolution of land use in the Amazon-Cerrado agricultural frontier, we proceeded as follows: (1) generate land-use transition maps; (2) calculate the fraction of burned area associated with each land-use transition area; and (3) estimate the time interval in years between land conversion and a given burned area (here referred to as the "age" of the frontier). First, we generated land-use transition maps at 500 m resolution by tracking yearly changes from forest to pasture (F-P), savanna to pasture (S-P), grassland to pasture (G-P), forest to cropland (F-Crop), savanna to cropland (S-Crop), grassland to cropland (G-Crop) and pasture to cropland (P-Crop). These land-use transitions represent the dominant pathways of anthropogenic activity across the Amazon-Cerrado agricultural frontier[30]. Next, we overlayed the maps of burned area with the land-use transitions to estimate the fraction of burned pixels occurring in each type of transition. For model regionalization, we created a 2.5-degree spatial surface grid (Fig. 1a), which we used to calculate the fraction of burned area (at 500 m resolution) associated with a given land use transition (at 500 m resolution). To obtain time-lagged fractions of burned area associated with transitions we overlapped each map of burned area with all concurrent and time-shifted land-use transition maps. For each 2.5-degree grid cell, we calculated fire probability, defined as the burned fraction of the total area of converted land. Larger burned areas correspond to higher fire probabilities (a fire probability of 1 means that the area of converted land equals the detected burned area). Finally, for all land-use transitions we estimated the number of years between a given burned area and the initial moment of conversion. The time interval between land conversion and area burned provides a proxy of how frontier age relates to fire activity. The modeling approach (described above) used to generate this dataset was implemented in DinamicaEGO version 5.2.1.

To better illustrate the generation of this dataset, let's consider an example of a random 2.5-degree cell of land-cover information at 500 m resolution, where forests, savanna, and grasslands were present in the year 1994. First, pixels that changed from native vegetation (forest, savanna, and grasslands) to pasture in 1995 were tracked, and a transition map was generated. Second, we overlapped the transition areas with burned areas, identifying the types of transitions that had fire occurrence and the respective fraction of burned area for each land-use transition area. The year 1995 is considered year 0 in this case, (i.e., age of 0 years) and a fire probability associated with the moment of the clearing is determined. One year later (1996), the burned areas of 1996 are overlapped with the 1-year-old transitions (i.e., from 1995) and the probability of burning associated with these 1-year-old transitions is determined. In a similar fashion, the fraction of burned area associated with past transitions is also tracked. One year before (1994), the burned areas of 1994 are overlapped with the transitions that are −1-year-old, and the associated probability of burning is determined. In summary, the analysis consists of tracking different types of transitions and assigning probabilities of fire occurrence to each type of transition at different ages, based on the time interval between a land conversion and a burned area. This database provides insights into the dynamics of fire occurrence and the role of land-cover transitions in shaping these dynamics. To avoid high fire probabilities of 100% for very small clearing areas and very small extents of burned area, we filtered out small areas of land-use transition (below the 15th percentile). The time since transition will be henceforth referred to as the age of the frontier, ranging from −35 years to 34 years (spanning the period from 1986-2020), with the transition occurring at age 0 years. This approach allowed us to understand how the age of the different types of conversion impacts ignition sources and, thus, how it influences fire probability.

Climate drivers

We explored the joint impact of land-use change and climate drivers on fire activity in terms of estimated vapor pressure deficit (VPD) and maximum cumulative water deficit (MCWD), two common measures of flammability and drought impact (Supplementary Fig. 9). MCWD was estimated as the minimum annual value of the cumulative deficit between monthly precipitation and potential evapotranspiration (PET) within a calendar year, representing a simple drought metric based on the climatic water balance:

$$MCWD = \min\left(\sum P - PET,\ 0\right) \tag{1}$$

Precipitation data was derived from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) time series[46] and PET and VPD from the Terra-Climate dataset[47]. MCWD and VPD were resampled to the 2.5-degree spatial surface grid using a median reducer in GEE. Median values of VPD within a calendar year were also estimated using a median reducer in GEE. We restricted our analysis of the influence of drought and air dryness to fire probability induced by conversion of forest to pasture (F-P, Fig. 6) and pasture to cropland (P-Crop, Supplementary Fig. 10).

Statistical analysis

To model the shape of the relationship between fire probability and the age of land-use transitions, we fitted univariate Generalized Additive Models (GAMs) with a Gaussian error distribution and an adaptive Gaussian kernel smoothing method. GAMs allow for smooth nonlinear relationships between dependent y (fire probability) and independent variables x (age of frontier, i.e., time since transition), and are thus adequate to capture curved relationships:

$$y = \mu_0 + f(x) \tag{2}$$

where μ_0 and f denote the intercept and the smooth function of the predictor variable. We used the *gam()* function from the *mgcv* package in R to fit the models, and we used the *s()* function to specify the smoothing function. The adaptive Gaussian kernel smoothing method was selected based on the R-squared for all the transitions and biomes. The aging effect of the land-use transitions on fire probability was captured for all the considered types of transition (F-P, S-P, G-P, F-Crop, S-Crop, G-Crop, P-Crop), during 1986–2020 (Figs. 2 and 3). To capture nonlinearities over time in terms of fire probability induced by the conversion of forest to pasture (F-P, Supplementary Fig. 5) and pasture to cropland (P-Crop, Supplementary Fig. 7), we divided the 35-year period into 7-year intervals (1986–1992, 1993–1999, 2000–2006, 2007–2013, 2014–2020). To help isolate the aging affect from other factors, like environmental governance and fire management, the response curved line based on GAM models was also obtained without time lags between the land-use transition and fire occurrence (Supplementary Figs. 6 and 7).

In addition, we compared with a breakpoint analysis (Supplementary Figs. 3 and 4), using segmented regression based on the *segmented()* R function to identify shifts in the response of fire activity to frontier aging (Supplementary Figs. 3 and 4). The breakpoints τ are used to determine the age of the transition associated with abrupt changes in fire activity, with a maximum of 3 breakpoints in the case of transitions from forest to pasture:

$$y = \begin{cases} \mu_1 + \beta_1 x, & x < \tau_1 \\ \mu_2 + \beta_2 x, & \tau_1 < x \le \tau_2 \\ \mu_3 + \beta_3 x, & \tau_2 < x \le \tau_3 \\ \mu_4 + \beta_4 x, & \tau_3 \le x \end{cases} \tag{3}$$

The number of breakpoints was adjusted manually for a trade-off between model performance and interpretation of the breakpoints. Most of the regression breakpoints occurred in the moment of the transition (with the exception of forest to pasture and croplands with 3 breakpoints and grassland to croplands with 2 breakpoints), or no significant breakpoint was detected, consistent with negative trends of fire suppression before and after transition.

Spatial patterns of fire probability rate pre- and post-conversion (Figs. 4 and 5) were determined based on the slope μ of a linear regression based on *lm()* R function, before and after transition at the 2.5-degree cell level:

$$y = \mu_{pre-conversion} + \beta_{pre-conversion} x \tag{4}$$

$$y = \mu_{post-conversion} + \beta_{post-conversion} x \tag{5}$$

To ensure a reasonable sample size at each grid-cell, all the transitions to pasture (i.e., forest-pasture, savanna-pasture, grassland-pasture) were considered to estimate statistically significant slopes with 95% confidence. Similarly, all the transitions to croplands (i.e., forest-cropland, savanna-cropland, grassland-cropland, pasture-cropland) were aggregated at the grid-cell level for the spatial pattern analysis of fire rates association with cropland expansion. In addition, transition-specific fire rates were estimated before and after clearing, considering all the grid cells, but analyzing each biome individually.

To identify the climate conditions associated with the conversion-induced fires, we divided the database into different subsets by quartile intervals of burned area, drought (MCWD), and air dryness (VPD). Building on the composites of the climate variables by different extents of burned area (small, medium large, and very large), similar GAM models are fitted to capture the shape of the relationship between fire probability and the age of land-use transitions. To ensure a reasonable sample size across each subset, this step was performed for the two dominant types of land-use transition, including transitions of forest to pasture (F-P, Fig. 6) and subsequent transitions of pasture to croplands (P-Crop, Supplementary Fig. 10). This analysis was conducted to illustrate how the coupling between land-use and climate varies with land-use transition and extent of burned area for each biome.

Data availability

The raw data analyzed in this study is openly available in the Google Earth Engine repository[46], including annual land cover maps from MapBiomas 6.0[30], annual burned areas from MapBiomas Fire 1.0[5], precipitation data from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS)[47], potential evapotranspiration and vapor pressure deficit from the Terra-Climate dataset[48]. The dataset of time-lagged fractions of burned area associated with conversions and the number of years since transition that supports the finding of this study is also available from https://doi.org/10.5281/zenodo.10497344.

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Author contributions

A.F.S.R. produced all the figures and wrote the first draft of the manuscript. L.S. conducted the data processing and initial versions of the statistical analysis with A.F.S.R. and P.M.B. supervision. All the authors, A.F.S.R., L.S., J.T.R., M.R.U., A.A.C.A., M.N.M., D.C.M., J.Z., R.A.S., L.R., S.I.S., and P.M.B. contributed to the discussion of the results, reviewed, and finalized the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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