We're building it up to burn it down: Fire occurrence and Fire-related climatic patterns in Brazilian biomes

Luisa Maria Diele Viegas [Corresp., 1, 2] , **Lilian P. Sales** [3] , **Juliana Hipólito** [1, 4] , **Claudjane Amorim** [5] , **Eder J. A. L. Pereira** [6] , **Paulo Ferreira** [7, 8, 9] , **Cody Folta** [10] , **Lucas Ferrante** [4] , **Phillip Fearnside** [4] , **Ana Claudia Malhado** [5, 11] , **Carlos Frederico Duarte Rocha** [12] , **Mariana M. Vale** [13]

[1] Instituto de Biologia, Universidade Federal da Bahia, Salvador, Bahia, Brazil

[2] Fórum Clima Salvador, Salvador, Brazil

[3] Department of Biology, Faculty of Arts and Science, Concordia University, Montreal, Canada

[4] Instituto Nacional de Pesquisas da Amazônia, Manaus, Amazonas, Brazil

[5] Universidade Federal de Alagoas, Maceió, Alagoas, Brazil

[6] Instituto Federal do Maranhão, Bacabal, Maranhão, Brazil

[7] Research Center for Endogenous Resource Valorization, Portalegre, Portugal

[8] Department of Economic Sciences and Organizations, Portalegre Polytechnic Institute, Portalegre, Portugal

[9] Center for Advanced Studies in Management and Economics, Institute for Research and Advanced Training, Universidade de Evora, Evora, Portugal

[10] Department of Biology, University of Maryland at College Park, College Park, Maryland, United States

[11] Research Center in Biodiversity and Genetic Resources, University of Porto, Vairao, Portugal

[12] Departamento de Ecologia, Instituto de Biologia, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

[13] Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

Corresponding Author: Luisa Maria Diele Viegas
Email address: luisa.mviegas@gmail.com

Background. South American biomes are likely to experience a persistent increase in environmental temperature, possibly combined with moisture reduction due to climate change. In addition, natural fire ignition sources, such as lightning, can become more frequent under climate change scenarios, since favourable conditions are likely to occur more often. In this sense, changes in the frequency and magnitude of natural fires can impose novel stressors on different ecosystems according to their adaptation to fires. By focusing on Brazilian biomes, we use an innovative combination of techniques based on satellite-derived climate predictors and fire occurrence time-series data to quantify fire persistence and occurrence patterns over time and evaluate climate risk by considering key fire-related climatic characteristics. **Methods.** We performed a Detrended Fluctuation Analysis to test whether fires in Brazilian biomes are persistent over time. To assess the relationship between climate and fire occurrence, we considered four bioclimatic variables whose links to fire frequency and intensity are well-established. Then, we confronted these climate predictors with a fire occurrence dataset. The climatic conditions associated with each location were assessed with correlative models that related environmental characteristics to fire occurrences. To access climate risk, we calculated the climate hazard, sensitivity, resilience, and vulnerability of Brazilian biomes. Finally, we accessed climate risk by multiplying the Biomes' vulnerability index by the hazards. **Results**. Our results indicate a persistent behaviour of fires in all Brazilian biomes at almost the same rates, which could therefore represent human-induced patterns of fire persistence. We also corroborated our expectations concerning fire occurrence patterns by showing that most fire-dependent biomes presented high thermal suitability to fire, while the fire-independent biome presented intermediate suitability and fire-sensitive biomes are the least suitable for fire occurrence. Our climate-change-related hypothesis was partially corroborated since fire-dependent and independent biomes are likely to increase their thermal suitability to fire, while fire-sensitive biomes are likely to present stable-to-decreasing thermal suitability in the future. Finally, our results indicate that most fire-dependent biomes presented low climate risk, while the fire-independent biome presented a high risk and the fire-sensitive biomes presented opposite trends, thus partially corroborating our climate-risk-related hypothesis. In summary, while the patterns of fire persistence and fire occurrence over time are more likely to be related to human-induced fires, key drivers of burned areas are likely to be intensified across Brazilian biomes in the future.

We're building it up to burn it down: Fire occurrence and Fire-related climatic patterns in Brazilian biomes

Luisa Maria Diele-Viegas[1,2*], Lilian P. Sales[3], Juliana Hipólito[1,4], Claudjane Amorim[5], Eder J. A. L. Pereira[6], Paulo Ferreira[7,8,9], Cody Folta[10], Lucas Ferrante[4], Philip Fearnside[4], Ana Claudia Malhado[5,11], Carlos Frederico Duarte Rocha[12], Mariana M. Vale[13]

[1] Universidade Federal da Bahia, Salvador, Bahia, Brazil
[2] Fórum Clima Salvador, Salvador, Bahia, Brazil
[3] Department of Biology, Faculty of Arts and Science, Concordia University, Montreal, Canada
[4] Instituto Nacional de Pesquisas da Amazônia, Manaus, Amazonas, Brazil
[5] Universidade Federal de Alagoas, Maceió, Alagoas, Brazil
[6] Instituto Federal do Maranhão, Bacabal, Maranhão, Brazil
[7] Research Center for Endogenous Resource Valorization, Portalegre, Portugal
[8] Department of Economic Sciences and Organizations, Portalegre Polytechnic Institute, Portalegre, Portugal
[9] Center for Advanced Studies in Management and Economics, Institute for Research and Advanced Training, Evora University, Evora, Portugal
[10] Department of Biology, University of Maryland, College Park, Maryland, United States
[11] Research Center in Biodiversity and Genetic Resources, University of Porto, Vairao, Portugal
[12] Departamento de Ecologia, Instituto de Biologia, Universidade do Estado do Rio de Janeiro Rio de Janeiro, RJ, Brazil
[13] Departamento de Ecologia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil.

Corresponding Author:
Luisa Maria Diele-Viegas[1]
Av. Adhemar de Barros, s/nº - Ondina, Salvador, Bahia, 40170-110, Brazil
Email address: luisa.mviegas@gmail.com

Abstract

Background.

Terrestrial biomes in South America are likely to experience a persistent increase in environmental temperature, possibly combined with moisture reduction due to climate change. In addition, natural fire ignition sources, such as lightning, can become more frequent under climate change scenarios, since favourable conditions are likely to occur more often. In this sense, changes in the frequency and magnitude of natural fires can impose novel stressors on different ecosystems according to their adaptation to fires. By

focusing on Brazilian biomes, we use an innovative combination of techniques based on satellite-derived climate predictors and fire occurrence time-series data to quantify fire persistence and occurrence patterns over time and evaluate climate risk by considering key fire-related climatic characteristics. ~~In this sense~~, we tested four major hypotheses ~~developed~~ considering the overall characteristics of fire-dependent, fire-independent, and fire-sensitive biomes: The first related to fire persistence over time; the second approaches the relationship between climate and fire occurrence; the third focuses on future predictions of climate change and its potential impacts on fire occurrence; and the last focusing on the climate risk faced by ~~the~~ biomes.

Methods.

We performed a Detrended Fluctuation Analysis to test whether fires in Brazilian biomes are persistent over time. To assess the relationship between climate and fire occurrence, we considered four bioclimatic variables whose links to fire frequency and intensity are well-established. Then, we confronted these climate predictors with a fire occurrence dataset. The climatic conditions associated with each location were assessed with correlative models that related environmental characteristics to fire occurrences. To access climate risk, we calculated the climate hazard, sensitivity, resilience, and vulnerability of Brazilian biomes. Finally, we accessed climate risk by multiplying the Biomes' vulnerability index by the hazards.

Results.

Our results indicate a persistent behaviour of fires in all Brazilian biomes at almost the same rates, which could therefore represent human-induced patterns of fire persistence. We also corroborated our expectations for the second hypothesis by showing that most fire-dependent biomes presented high thermal suitability to fire, while the fire-independent biome presented intermediate suitability and fire-sensitive biomes are the least suitable for fire occurrence. The third hypothesis was partially corroborated since fire-dependent and independent biomes are likely to increase their thermal suitability to fire, while fire-sensitive biomes are likely to present stable-to-decreasing thermal suitability in the future. Finally, our results indicate that most fire-dependent biomes presented low climate risk, while the fire-independent biome presented a high risk and the fire-sensitive biomes presented opposite trends, thus partially corroborating our fourth and last hypothesis. In summary, while the patterns of fire persistence and fire occurrence over time are more likely to be related to human-induced fires, key drivers of burned areas are likely to be intensified across Brazilian biomes in the future, potentially increasing the magnitude of the fires and harming the biomes' integrity.

Introduction

The world is predicted to reach an irreversible climate tipping point if the average global temperature exceeds 1.5°C above pre-industrial levels (IPCC, 2021; Ripple et al., 2019). Consequently, terrestrial biomes in South America are likely to experience a persistent increase in environmental temperature, possibly combined with moisture reduction and changes in wind patterns (Anjos et al., 2021; Burton et al., 2022). In addition, natural wildfire ignition sources, such as lightning, can become more frequent under climate change scenarios, since favourable conditions are likely to occur more often (Clark et al., 2017; Krasovska et al., 2018). Such conditions include fuel availability, a flammable mixture of organic compounds, and cloud cover, whose change can increase the frequency of storm clouds bearing electric charge (Krasovska et al., 2018). As key drivers of naturally burned areas (Burton et al., 2022), these characteristics' changes are prone to affect fire occurrence, with fire intensity and spread likely to increase after the ignition depending on local weather conditions (Clark et al., 2017; Li et al., 2022; Podschwit et al., 2018).

Along with natural fire ignition sources, farmers commonly use human-induced fires as a management tool (Brunel et al., 2021). Such practices have been used in Brazilian grass-dominated lands for centuries (Pivello, 2011), usually ~~aiming~~ to remove excessive dead biomass during the dry season and stimulate the regrowth of high nutritional value grasses for grazing animals (Brunel et al., 2021; da Silva Junior et al., 2020; van der Werf et al., 2008). Although it is an effective practice for improving farm productivity (Laterra et al., 2003), its inadequate application can decrease system resilience (Roberts, 2000). In addition to preparing pasture for the new vegetation period, human-induced fires can also be used to clear new areas for settlements, ranching, agriculture and logging (Barni et al., 2021).

Brazil is among the most biodiverse countries globally and plays a major role in regulating the South American climate system, mainly through the evapotranspiration of the Amazon forest (Convention on Biodiversity, 2021). It also hosts important hotspots of biological diversity that support diverse ecosystem services (Jenkins and Schaap, 2018). The six Brazilian biomes (Amazon, Atlantic Forest, Caatinga, Cerrado, Pampa, and Pantanal) hold large carbon stocks in their forests and soils, besides having the largest freshwater reserve in the world (Souza et al., 2020).

~~Concerning natural fires,~~ Brazilian grassland, savanna and wetland biomes (i.e., Cerrado, Pampa, and Pantanal) are fire-dependent, having coevolved with lightning-driven fires and benefiting from seasonal fires (Hardesty et al., 2005; Pivello et al., 2021). On the other hand, the semi-arid scrub forests of the Caatinga are fire-independent since climatic conditions are not favourable to fire occurrence (e.g., there is a low incidence of lightning events), and the system lacks enough biomass to carry fire (Hardesty et al., 2005; Pivello et al., 2021). Finally, humid tropical forests (i.e., Amazon and Atlantic Forest) are not adapted to fire, being thus fire-sensitive (Hardesty et al., 2005; Pivello et al., 2021).

Fires from human activities are likely to be more intense and can have different effects according to the system's fire susceptibility (da Silva Junior et al., 2020). Therefore, understanding the main sources of fire ignition and its persistence patterns is vital to developing adequate fire management policies and avoid~~ing~~ the loss of biodiversity and ecosystem services (Roberts, 2000). The Detrended Fluctuation Analysis (DFA) is a powerful tool to evaluate long-range dependence in individual time series, which could be applied to identify and measure the existence of autocorrelation in the context of non-stationary time series (Peng et al., 1994). In this sense, it can assess the extent to which trends in fire events observed in the past imply the maintenance of that behaviour in the future, thus evaluating if fire events are random or persistent over time (Murari et al., 2020; Peng et al., 1994; Tong et al., 2019). When fires are persistent, it is likely to occur regularly under natural conditions, and local biodiversity should be adapted to those conditions (Pausas and Bradstock, 2007). Yet, human landscape alterations must be acknowledged, and strategies for fire control must be well organized and consider fire's ecological and cultural role in the landscape

(Santos et al., 2021). On the other hand, if fires are not persistent, emergency fire plans must be designed to combat fire at the appropriate time, considering environmental variables to understand the local potential for fire spread (Santos et al., 2021). Whether fire persists over time or not, its occurrence is recorded in all Brazilian biomes (da Silva Junior et al., 2020). While fires in fire-sensitive and fire-independent Brazilian biomes are frequently attributed to slash and burn farming practices, especially cattle-raising (da Silva Junior et al., 2020; Silva Junior et al., 2021, p. 202), susceptibility to fire is also likely to increase in fire-dependent ecosystems due to such practices (Barbosa and Fearnside, 1999; Barni et al., 2021).

~~Additionally, climate change can contribute to fire weather conditions, improving the chances of fire occurrence (Li et al., 2021). Confronting data of climatic predictors with fire occurrence can be useful to understand the particularities of this relationship in different biomes and their consequences under different climate change scenarios. Correlative models associating environmental (e.g., climatic predictors) and geographic (e.g., georeferenced occurrence points) spaces have been widely used in conservation biology to predict a species' potential occurrence area under different environmental conditions, being traditionally called "ecological niche models" (Guisan and Zimmermann, 2000). By assuming that climatic conditions are at least partially responsible for fire occurrence, it is possible to adapt this method to model fire occurrence by highlighting climatically similar regions where fires were recorded, thus predicting the probability of fire occurrence through time and geographic space.~~

~~The adapted correlative models can be of great importance for understanding potential fire occurrence patterns and developing adequate landscape management to reduce the negative impacts of fires in different biomes. However, climate change is also likely to impact fire-dependent, fire-independent and fire-sensitive biomes (Pivello et al., 2021; Reboita et al., 2022).~~ To understand such impacts, it is important first to understand the biomes' climate risk, which is the result of the interaction between hazard, exposure, and vulnerability (sensu (IPCC, 2018); see (Foden et al., 2019)).

The hazard refers to the potential occurrence of climate-related events or trends that may harm the system, while the exposure is the presence of the system in places potentially affected (Foden et al., 2019). The intensity of droughts ~~has been considered~~

an important hazard related to water availability due to precipitation and soil moisture (Sheffield and Wood, 2008), being also a key driver of burned areas (Burton et al., 2022). Brazilian fire-dependent biomes are likely to present a neutral-to-positive trend concerning soil moisture, indicating a reduction in drought intensity (Lopes Ribeiro et al., 2021). On the other hand, the fire-independent biome ~~can present~~ the most severe trend, while fire-sensitive biomes are likely to present a neutral-to-negative trend (Lopes Ribeiro et al., 2021). Although such predicted trends can potentialize fire spread after ignition, other drivers of burned areas, such as temperature and water availability (from precipitation) during the fire season, have not been evaluated as hazards for Brazilian biomes.

The vulnerability of a system is its propensity or predisposition to be adversely affected and has many components, including sensitivity and resilience (Foden et al., 2019). Sensitivity can be described as the degree to which a system is affected by climate change, while resilience is the capacity of this system to cope with this disturbance and keep its essential functions and structure (IPCC, 2021). The Vegetation Sensitivity Index (VSI) is a useful method to quantify ecosystem sensitivity based on the relative variance of vegetation productivity and air temperature, water availability and cloud cover (Seddon et al., 2016). ~~Since the three climatic variables considered in VSI are key drivers of burned areas, this index can also indicate whether the environment would be sensitive to fire-related climatic conditions. VSI analyses indicate that fire-dependent and fire-sensitive biomes are likely sensitive to temperature and cloudiness, while the fire-dependent biome is most sensitive to water availability (Seddon et al., 2016).~~ However, no study has focused on evaluating each biome’s VSI individually.

Resilience is the system's ability to cope with climate change by maintaining its adaptation and transformation capacities, which can be assessed by quantifying vegetation loss and protected areas (PAs) (IPCC, 2021). Natural vegetation is an essential regulator of ecosystem services, and its destruction ~~has been considered as~~ the leading cause of species extinction (Gonçalves-Souza et al., 2021, 2020). Despite the importance of preserving natural environments, the increasing demand for food, fuel and livestock feed has led to an increase in the conversion of natural habitats to crops and pastures (Gonçalves-Souza et al., 2020). ~~In this sense, agricultural activities are~~

~~currently the major drivers of vegetation loss, undermining the ecosystems' capacity to sustain food production, maintain natural resources and regulate climate and air quality (Foley et al., 2005).~~

~~Brazilian biomes have been constantly threatened by accelerated destruction, mainly caused by deforestation and inadequate environmental management (Diele-Viegas et al., 2020; Silva Junior et al., 2021). Such practices have led~~ fire-dependent biomes ~~to lose~~ over 38% of their natural vegetation since 1985, while the fire-independent biome has lost around 10% and fire-sensitive biomes over 50% (Souza et al., 2020). ~~Protected areas (PAs) are the cornerstone strategy for biodiversity conservation, playing a major role in the maintenance of ecosystem services and adequate environmental conditions for the survival of local species (Bernard et al., 2014). Brazil holds the largest PA network in the world, covering over 250 million ha and 29.4% of the country's territory (UNEP-WCMC IUCN, 2022). However, its coverage is not proportionally distributed among the Brazilian biomes (Oliveira et al., 2017). In this sense,~~ while fire-sensitive biomes ~~present~~ 52% of their area covered by PAs, fire-dependent biomes are only 12.4% covered and the fire-independent has only 1.3% of its area covered by PAs (Oliveira et al., 2017). ~~Concerning resilience, literature indicates that fire-dependent and fire-sensitive biomes are prone to present a high resilience to a gradual increase in climatic stress, while the fire-independent biome is likely to be a low-resilient biome (Anjos and de Toledo, 2018; Pinho et al., 2020).~~ Although these estimates are useful to understand the ecosystems' climatic niche, ~~literature~~ still lacks a comprehensive understanding of Brazilian biomes' resilience based in non-climatic factors such as PAs and vegetation loss.

Finally, it is important to highlight that changes in climate risk, together with fire occurrence and persistence patterns over time, can trigger significant modifications in ecosystem structure and internal feedback and disrupt ecological functions, affecting biodiversity and human livelihoods (Anjos et al., 2021; Diele-Viegas, 2021). However, knowledge gaps on the specificities of these characteristics among Brazilian biomes prevents the development of adequate management policies to minimize such impacts. Therefore, here we aimed to understand fire persistence and occurrence patterns over time and evaluate climate risk considering key fire-related climatic characteristics in

Brazilian biomes, anticipating fire occurrence under different climate change scenarios through an innovative combination of techniques. ~~In this sense~~, we tested four major hypotheses developed considering the overall characteristics of fire-dependent, fire-independent, and fire-sensitive biomes (Fig. 1).

The first hypothesis is related to fire persistence over time; the second approaches the relationship between climate and fire occurrence; the third focus on future predictions of climate change and its potential impacts on fire occurrence; and the last focus on the climate risk faced by the biomes (Fig. 1). We predict that in fire-dependent biomes, fire would be persistent over time (1), since climate would have a major role in fire occurrence (2). Therefore, climate change could increase fire occurrence in the future (3), despite the low climate risk faced by these biomes due to a low hazard associated with low sensitivity and intermediary resilience (4) (Fig. 1). Fire-independent biomes would not present fire persistence over time (1), so climate would have a minor role in fire occurrence (2) and climate change will not be related to fire occurrence in the future (3). However, this biome should present a moderate climate risk (4), since it is likely to present a high hazard associated with high sensitivity and low resilience. Finally, fires in fire-sensitive biomes would not be persistent over time (1), and climate can also play a minor role in fire occurrence (2). However, climate change can have and indirect effect on fire occurrence in the future (3), since these biomes are likely to present high climate risk (4) due to an intermediate-to-high hazard and high sensitivity, even considering their likely high resilience.

Materials & Methods

Persistent fire behaviour

We performed a DFA to test whether fires in Brazilian biomes are persistent over time by considering a time-series of fire occurrences from the reference satellite (AQUA_M-T: MODIS sensor, early afternoon pass), downloaded from the Brazilian National Institute for Spatial Research ~~(INPE in the Portuguese acronym)~~ website (INPE, 2020). The data has a 1-km x 1-km pixel spatial resolution ~~and resolution~~, depicting fires from July 2002 to October 2020. The DFA was calculated for a given time series with *t* equidistant observations. The first step of the analysis consisted of calculating fire profile:

$$X_t = \sum_{i=1}^{t} (x_i - \langle x \rangle)$$

Where ⟨x⟩ is the average observed fire occurrence. Then, this profile was divided into mutually exclusive boxes of equal dimensions *s* (the considered timescale; *N/s*), and a local trend was calculated, using ordinary least squares to detrend the profile:

$$X_s(t) = X_t - z\,(t)$$

Finally, the DFA function was calculated for all *s* values according to the following equation:

$$F(s) = \sqrt{\frac{1}{N}\sum_{t=1}^{N} \left(X_{(s)}(t)\right)^2}$$

The log-log regression was obtained between *F (s)* and *s,* resulting in a power-law given by

$$F(n) \propto n^{\alpha}$$

Through the α exponent obtained from the DFA, it is possible to assess the extent to which the trend observed in the past time series implies the maintenance of that behaviour in the future, indicating a long-term memory effect in the series. Non-correlated series are expected to return $\alpha = 0.50$ and represent a typical case of a random walk. These series are likely to show long-range persistence when $\alpha > 0.50$ and anti-persistent behaviour when $\alpha < 0.50$. Although opposite precipitation anomalies are expected for NE and SE Atlantic Forest (Reboita et al., 2022), we did not separate the Atlantic Forest into NE and SE regions for this analysis since DFA does not consider precipitation patterns in its equation.

Climate and fire occurrence

To assess the relationship between climate and fire occurrence, we considered four bioclimatic variables whose links to fire frequency and intensity are well-established (Oliveira-Júnior et al., 2020): two annual variables (annual mean temperature; BIO1, and annual precipitation; BIO12) and two variables related to the dry (or fire-prone) season (mean temperature of the driest quarter; BIO9, and precipitation of the driest quarter; BIO17). ~~These bioclimatic predictors are derived from monthly temperature and precipitation data and are converted to indices to express annual trends and seasonal variations likely to affect fire occurrence~~. Climatic raster files were obtained from WorldClim version 2.1, ~~a global repository of high-resolution climatic surfaces recorded as gridded raster files~~ (Fick and Hijmans, 2017), ~~downloaded as files with~~ 2.5 arc-minute ~~spatial~~ resolution ~~for land areas. The data results from the interpolation of information from local weather stations and satellite information regarding elevation and distance to the coast, which are included as covariates (Fick and Hijmans, 2017).~~

Climatic predictors were confronted with the fire occurrence dataset available from INPE (INPE, 2020). Each fire source registered from 2002 to 2020 was considered a "fire occurrence", and its georeferenced location was downloaded. The climatic conditions associated with each location were assessed with correlative models that related environmental characteristics to fire occurrences. ~~Traditionally called "ecological niche models", these models were developed to determine species' potential occurrence based on climate and other environmental features (Guisan and Zimmermann, 2000).~~ We adapted this method to fire occurrence, assuming that climate directly influences the phenomena. We, therefore, caution that this method assumes that climate conditions are at least partially responsible for fire occurrence.

The modelled relationship between climate and fire was projected into geographic space to highlight climatically similar regions and relate them to the recorded fires. By assessing the environmental conditions associated with fire events, it was possible to predict the probability of fire occurrence through time and geographic space. ~~Although correlative models are fraught with uncertainty, they help explain and predict the distribution of several biological phenomena. The mathematical algorithms used in these correlative models is often considered the greatest source of variation in modelling exercises (Diniz-Filho et al., 2009). To circumvent this issue,~~ we fitted ~~correlative~~ models using three algorithms: bioclimatic envelopes (BIOCLIM), generalized linear models (GLM), and support vector machines (SVM). ~~These methods have traditionally been used to estimate suitability and occurrence probability surfaces but rely on different approaches. While BIOCLIM estimates a bioclimatic envelope~~

~~associated with occurrences, GLM uses presence-absence data to predict distribution patterns through linear regressions, and SVM is a machine learning approach that recognizes patterns in the occurrence data.~~ We ~~relied on acknowledged modelling standards,~~ considering 10,000 pseudoabsences for BIOCLIM and GLM algorithms while maintaining occurrence prevalence for SVM (Barbet-Massin et al., 2012). A final consensus map was obtained by weighting the cell-based prediction of fire probability by the accuracy of the parent model, as explained below.

We evaluated the accuracy of our model output with a sub-sampling procedure where 30% of fire occurrence records measured the performance of models fitted to the remaining 70% of the records. We run ten replicates for each algorithm (in a total of 30 models) to increase the robustness of the results. The best models were selected based on an Area Under the Curve (AUC) over 0.7 (Hanley and McNeil, 1982), True Skill Statistic (TSS) over 0.3, and Threshold over 0.8. ~~The AUC is a threshold-independent metric and gives a single value of model performance, which varies from 0 to 1. An AUC value of 0.5 indicates random discrimination between presence and absence, values lower than 0.5 imply a discrimination ability worse than expected by chance, and values equal to 1 indicate perfect fit (Fielding and Bell, 1997). The TSS is a suitable discrimination metric once described as independent of prevalence (Allouche et al., 2006) but likely to be dependent and thus showing similar shortcomings as AUC (Leroy et al., 2018).~~ The threshold was calculated as the point at which the sum of the sensitivity (true positive rate) and specificity (true negative rate) is highest (Hijmans et al., 2017; Shabani et al., 2018). Based on the combination of these three accuracy methods, we selected five SVM replicas to proceed with the analyses (See Data Table S1).

We projected our consensus models of fire occurrence based on climate forecasts to predict fire risk into the future. We projected fire occurrence for two time periods (2041-2060, hereafter 2050; and 2081-2100, hereafter 2090) according to two shared socioeconomic pathways (SSP), ~~which examine how global society, demographics, and economics might change over the next century considering different climate change mitigation levels~~ (Riahi et al., 2017). ~~The first scenario,~~ SSP2 45, ~~brings the narrative of medium challenges to mitigation and adaptation, where global and~~

~~national institutions make slow progress in achieving sustainable development goals. This pathway predicts an increase in environmental temperature of 2°C by 2050 and 2.7°C by 2090 (IPCC, 2021). The second scenario,~~ SSP5 85, ~~represents high challenges to mitigation and low challenges to adaptation, with a predicted increase in environmental temperature of 2.4°C by 2050 and 4.4°C by 2090~~ (IPCC, 2021). The future climate projections considered the ensemble (average) of the three general circulation models (GCM) of the Coupled Model Intercomparison Project Phase Six (CMIP6) (Eyring et al., 2016) with particularly good performance in South America (Cannon, 2020): 1) Beijing Climate Center model (BCC-CSM2-MR); 2) Institute Pierre Simon Laplace model (IPSL-CM6A-LR); and 3) Model for Interdisciplinary Research on Climate (MIROC6).

The geographic boundaries of the Brazilian biomes were downloaded from the Brazilian Institute of Geography and Statistics (IBGE, http://ibge.gov.br/). We separated the Atlantic Forest into its northeastern (NE), and southeastern (SE) portions since the predicted changes in precipitation have opposite signs in these areas: reduction in precipitation in the NE and increase in the SE (PBMC, 2014; Reboita et al., 2022). The analysis was performed using the packages *raster* (Hijmans, 2016), *rgdal* (Bivand et al., 2020), biomod2 (Thuiller et al., 2020), and *dismo* (Hijmans et al., 2017) in R 3.5.1 software (R Core Team, 2020).

Climate risk

We assessed Brazilian biomes' climate risk through metrics of climate hazard, sensitivity and resilience (Foden et al., 2019; IPCC, 2021, p. 20). For climate hazard, we first calculated the percentage of change in bioclimatic values between future predictions and the present (See Data Table S2). We considered the same four bioclimatic variables used to assess the relationship between climate and fire occurrence (BIO1, BIO9, BIO12, and BIO17) at the same resolution (2.5 arc-minutes spatial resolution). Future predictions were based on SSP2 45 and SSP5 85 for two time periods (2050 and 2090) and also considered the ensemble of the three GCMs mentioned above (BCC-CSM2-MR, IPSL-CM6A-LR, and MIROC6). Accordingly, the geographic boundaries of the Brazilian biomes were the same used to assess the relationship between climate and fire occurrence (IBGE, http://ibge.gov.br/). Then, we adapted the Regional Climate Change Index (RCCI), developed by Giorgi (2006), to calculate the climate hazard of the fire season in Brazilian biomes. This comparative index was developed to identify the *hotspots* of climate change, ~~i.e., the regions where climate change could be more pronounced considering future scenarios~~ (Giorgi, 2006). The RCCI is defined as:

$$\mathrm{RCCI} = [n(\Delta P) + n(\Delta\sigma_P) + n(\mathrm{RWAF}) + n(\Delta\sigma_T)]_{\mathrm{WS}} + [n(\Delta P) + n(\Delta\sigma_P) + n(\mathrm{RWAF}) + n(\Delta\sigma_T)]_{\mathrm{DS}}$$

Where n is an empirical factor that depends on the magnitude of the involved change (Table 1); ΔP is the percentage of change in BIO12 (annual precipitation) recovered for each biome; $\Delta\sigma_P$ is the interannual variability of precipitation; $\Delta\sigma_T$ is the interannual variability of temperature; and RWAF is the regional warming amplification factor, i.e., the difference between the change in BIO1 (annual mean temperature) recovered for each biome and the mean global temperature change (2°C and 2.7°C in SSP2 45 and 2.4°C and 4.4°C in SSP5 85, considering 2050 and 2090, respectively (IPCC, 2021)). Note that the original RCCI perform these calculations for both wet (WS) and dry (DS) season. However, since we focused our analysis on the dry season, or the fire-prone season, we considered $\mathrm{RCCI}_{\mathrm{DS}} = n(\Delta P) + n(\Delta\sigma_P) + n(\mathrm{RWAF}) + n(\Delta\sigma_T)$ as a proxy of the climate hazard, which was calculated for each biome in each evaluated scenario and time period (See Data Table S3).

The sensitivity of Brazilian biomes was estimated based on VSI (Seddon et al., 2016; See Data Table S4). The index independently compares the relative variance of vegetation productivity with three ecologically important MODIS-derived climate variables (air temperature, water availability, and cloud cover) for each 5 km grid square for the months in which EVI and climate are found to be related. We calculated the sensitivity of the Brazilian biomes by using the packages *raster* (Hijmans, 2016, p. 201) and *rgdal* (Bivand et al., 2020) in R 3.5.1 software (R Core Team, 2020).

Finally, we calculated the Biomes' resilience based on vegetation loss and the area outside PAs (See Data Table S4). The first indicator was calculated from current land-use land-cover data ~~from the Brazilian Institute of Geography and Statistics~~ (IBGE, 2020; see ~~Fernandes et al. for a map figure of the data~~ (Fernandes et al., 2017)), while the second was based on georeferenced data from ~~the Chico Mendes Institute for Biodiversity Conservation~~ (ICMBio, 2020). We considered the resilience status as the arithmetic mean of these two indicators, where the lower the mean value, the greater the resilience status (Lapola et al., 2020).

We then used the sensitivity and resilience metrics to determine the Biomes' vulnerability to climate change. For that, we compared the sensitivity and resilience of each biome and calculated the relative weights for the lower sensitivity and resilience as the difference between the sensitivity/resilience of the biome and the lower sensitivity/resilience value found between biomes. Then, we considered as vulnerability index of each biome the arithmetic mean of the relative weight of sensitivity (ΔS) and the relative weight of resilience ($\Delta \mathrm{R}$). We assessed climate risk by multiplying the Biomes' vulnerability index by the hazards per SSP and year (adapted from Foden et al., 2019).

Results

~~We summarized our findings concerning persistent fire behaviour, fire occurrence, climate hazard, resilience, vulnerability, and climate risk of Brazilian biomes in Figure 2 (See Data Table S5 for details). Each of these topics are detailed below.~~

Persistent fire behaviour ~~(Fig. 2)~~

Over the last ten years, fires in Brazil occurred mainly in the Amazon and Cerrado (Fig. 3). While 2013 and 2018 had the lowest fire occurrence rates in the decade, 2012 and 2020 had the highest rates (Fig. 3). The Pantanal and Pampa biomes were particularly affected in 2020 when they suffered from the highest fire occurrence rates in the decade (Fig. 3).

Our results indicate a persistent behaviour of fires in all Brazilian biomes, with narrow differences among natural-fire dependence classifications (Table 2, Fig. 3). Fire-dependent biomes ~~presented~~ the same persistence behaviour as the Amazon rainforest (α=0.63), but only Cerrado presented the same variation (SD=0.07). The least persistent behaviour was ~~predicted to~~ Caatinga (α=0.61 ± 0.06), the only fire-independent biome. The Atlantic Forest showed the most persistent fire behaviour over the years and therefore is the most foreseeable among the biomes, despite of being fire-sensitive (Table 2, Fig. 3).

Climate and fire occurrence ~~(Fig. 2)~~

The current thermal suitability of the Brazilian biomes to fire occurrence varied from 19% in the Pampa to 88% in the Pantanal (Table 3). Most fire-dependent biomes presented high thermal suitability to fire, while the fire-independent biome presented an intermediate suitability and fire-sensitive biomes are the least suitable to fire occurrence (Table 3).

Although Pampa is currently the least likely biome to burn, it presents the greatest proportional increase in thermal suitability considering future scenarios (Table 3). Thermal suitability to fire is also likely to be greater in the Amazon considering a more optimistic climate change scenario (SSP2 45), but it tends to decrease by the year 2050 considering a more pessimistic scenario (SSP5 85; Table 3). Northeastern Atlantic Forest tends to increase its thermal suitability by 2050 considering SSP2 45, while Southeastern Atlantic Forest tends to decrease its thermal suitability in all forecasts. Caatinga, Cerrado, and Pantanal are likely to present increased thermal suitability to fires in most scenarios, except for SSP5 85 in the year 2050 (Table 3). Overall, fire-dependent and independent biomes are likely to increase their thermal suitability, while fire-sensitive biomes are likely to present stable-to-decreasing thermal suitability to fire in the future (Table 3).

Climate risk ~~(Fig. 2).~~

~~*Climate hazard* (Fig. 2).~~ While Pampa ~~presented~~ the lowest climate hazard in all evaluated scenarios, the Atlantic Forest presented the highest (Table 4). The other biomes varied in their compared positions, but, overall, fire-dependent biomes usually figured among the lower climate hazards, while the fire-independent biome presented the second higher hazard in almost all ~~evaluated~~ scenarios (Table 4).

~~*Vegetation Sensitivity Index.*~~ Despite its low climate hazard, Pampa is predicted to ~~present~~ the ~~higher~~ sensitivity among the Brazilian biomes (Data Table S4). On the other hand, Pantanal ~~presented~~ the ~~lower~~ sensitivity to fire-related climatic conditions (Data Table S4). In this sense, fire-dependent biomes did not seem to present a common pattern of sensitivity, although in average they are likely to present a lower sensitivity than the fire-independent biome (17.3 ± 3.3; compared to 19.6 ± 3.7 from Caatinga). Finally, contrary to expectations, fire-sensitive biomes figured among the lowest sensitivities to fire-related climatic conditions (Data Table S4).

~~*Resilience and Vulnerability* (Fig. 2).~~ The most resilient biome was the Amazon rainforest (Table 4), which presented the lowest rates of vegetation loss added to the greatest proportional area under protection (Data Table S4). On the other hand, the Atlantic Forest and Pampa presented the highest rates of vegetation loss, besides being the least protected biomes (Data Table S4), which led them to be considered the least resilient among the Brazilian biomes (Table 4). Consequently, the vulnerability of Brazilian biomes followed the same pattern of resilience, with the Amazon being the least vulnerable and the Atlantic Forest and Pampa being the most vulnerable biomes (Table 4).

We found no overall pattern of resilience or vulnerability among fire-dependent and fire-sensitive biomes. However, the fire-independent biome presented the greatest resilience (0.70), but the highest vulnerability (10.87) compared to the averaged resilience and vulnerability of fire-dependent (R = 0.72 ± 0.4; Vi = 10.51 ± 3.7) and fire-sensitive (R = 0.73 ± 0.27; Vi = 10.39 ± 12.8) biomes.

~~*Climate Risk* (Fig. 2). Finally, our results indicate that~~ the Atlantic Forest is the most at-risk biome in all evaluated scenarios, while the Amazon and Pampa ~~figure~~ among the least at-risk ~~Brazilian biomes~~ (Table 5). Fire-dependent biomes presented an overall pattern of mid-to-low risk, while the fire-independent biome presented a higher climate risk (Table 5). No pattern was found for fire-sensitive biomes. In average, fire-dependent biomes presented the lowest climate risk in all evaluated scenarios, while the fire-sensitive biomes presented the highest risk for all but the predictions for 2090 considering the SSP2 45 (Table 5).

Discussion

~~In this study~~, we evaluated fire persistence and occurrence over time and climate risk considering fire-related climatic conditions in fire-dependent, fire-independent and fire-sensitive biomes. ~~Natural fires in savannas and grasslands are typically surface fires that consumes the fuel deposited on the litter and the vegetation herb layer, presenting mild ecological impacts on these environments (Pivello et al., 2021). In fact, the recurring fires in these fire-dependent biomes allow the maintenance of their ecosystem structure, favouring fire-adapted organisms (Pausas et al., 2018; Pausas and Parr, 2018; Rosan et al., 2019). Fire-independent biomes, in turn, lack adaptations to frequent fires, since it does not provide flammable fuel from its vegetation and does not present high incidence of natural ignition sources (Althoff et al., 2016; de Queiroz et al., 2017; Pivello et al., 2021). Finally, humid tropical forests present no indication of evolutionary history influenced by fire, having no adaptation favouring species resistance to or resilience after fire events (Pivello et al., 2021). Therefore, the impacts of fires in these fire-sensitive biomes are very detrimental, including consuming the litter that protects the soil from erosion, damaging roots, and killing a variety of plants, thus harming local biodiversity, making the forest susceptible to further fire events and changing ecosystem dynamics and functions (Flores et al., 2016; Sales et al., 2020; Sansevero et al., 2020).~~

~~The~~ first hypothesis ~~we aimed to test~~ was related to fire persistence over time. ~~We expected that fires in fire-dependent biomes would be persistent, while fire-independent and fire-sensitive biomes would not present persistent fires over time. Such inferences were based on the natural conditions expected to influence fire occurrence.~~ However, our results indicate a persistent behaviour of fires in all Brazilian biomes at almost the same rates. Such patterns would only be possible considering the human-induced fires to occur at a recurrent rate, and, in fact, the use of fire in Brazilian crop management is well established for centuries (Maezumi et al., 2018). The recurrence of human-induced fires create a feedback loop, since repeated burned areas are more prone to new fires (Hoffmann et al., 2020). Therefore, our results ~~represents~~ human-induced patterns of fire persistence, instead of ~~representing~~ natural patterns, which is an indicative that human activities have already changed radically the natural fire regimes in Brazilian biomes, mostly concerning frequency and timing of burning (Hardesty et al., 2005; Pivello, 2011).

Our second hypothesis focused on understanding the climatic determinants of fire occurrence, by assuming that climatic conditions are at least partially responsible for it. ~~In this sense, we predicted that fire-related climatic characteristics would play a major role on fire occurrence in fire-dependent biomes, playing a minor role in fire-independent and fire-sensitive biomes since fire occurrence would be more likely to occur due to human-induced sources. Although natural fires caused by lightning in fire-dependent biomes are traditionally expected to occur due to thunderstorms in the beginning of the rainy season (Ramos-Neto and Pivello, 2000), current peaks in active fire detection are strongly related to dryer conditions not only in fire-dependent, but also in fire-sensitive and fire-independent biomes (Aragão et al., 2018; Oliveira-Júnior et al., 2020; Pivello et al., 2021). Therefore, we considered annual mean temperature, annual precipitation, and mean temperature and precipitation of the dry season as fire-related climatic conditions to test this hypothesis (Oliveira-Júnior et al., 2020).~~

Our results corroborated our expectations ~~for the second hypothesis~~ by showing that most fire-dependent biomes presented high thermal suitability to fire, while the fire-independent biome presented an intermediate suitability and fire-sensitive biomes are the least suitable to fire occurrence. Similarly, Oliveira et al. (2022) also demonstrated that climate explain most of the fire variation in the Cerrado and Pantanal biomes, while land-use change explained most of the fire variation in the Amazon. ~~In addition to understanding the current patterns of fire occurrence,~~ in our third hypothesis we aimed to describe its possible tendencies in the future considering different climate change scenarios. ~~In this sense, we predicted that fire occurrence in fire-dependent biomes would be impacted by changes in annual and dry season patterns of temperature and precipitation, while fire-independent would not experience significant effects and fire-sensitive biomes would experience an indirect effect of such changes~~.

Our results partially corroborated ~~our climate change~~ hypothesis by showing that fire-dependent and independent biomes are likely to increase their thermal suitability to fire, while fire-sensitive biomes are likely to present stable-to-decreasing thermal suitability in the future. Specifically, thermal suitability to fire is likely to decrease in all scenarios for the Atlantic Forest, but increase in the Amazon considering the broader scenario of climate change (SSP2 45), while no trend is expected under the most severe scenario (SSP5 85). Extreme drought events are likely to become more frequent under different climate change scenarios (IPCC, 2021), facilitating fire occurrence and spread. In fact, prolonged drought events have already been recorded within the last decade. The lack of rainfall between 2019 and 2020 in Pantanal, caused by the reduced transportation of humid air from the Amazon, has led to a prolonged drought in this fire-dependent biome, which facilitated fire spread, culminating in the extreme fire event that burned over 30% of the biome in 2020 (Libonati et al., 2020; Marengo et al., 2021; Mega, 2020). Similarly, an increased drying effect in fire-sensitive biomes could result in increases in fire incidence, as predicted for the Amazon (Aragão et al., 2018).

~~While climate change is not necessarily the leading cause of the observed fires in fire-independent and fire-sensitive biomes, it is indeed likely to potentialize fire occurrence and spread by creating appropriate climate conditions in these biomes (Clark et al., 2017). In this sense, in~~ our fourth ~~and last~~ hypothesis, we ~~aimed to~~ measure the climate risk of Brazilian biomes considering fire-related climatic variables. ~~Fire-dependent biomes are expected to present low climate risk as a consequence of a low hazard concerning fire-related climatic variables, low vegetation sensitivity and an intermediate resilience. The fire-independent biome, in turn, was expected to present a moderate climate risk due to a moderate-to-high climate hazard, high sensitivity and low resilience. Finally, fire-sensitive biomes were expected to present the highest climate risk, which would be associated to higher hazards and higher vegetation sensitivity, but also high resilience~~.

Our results indicate that fire-dependent biomes presented the lowest hazards, while the fire-independent biome presented high hazards. ~~Concerning fire-sensitive biomes,~~ the Amazon presented a mid-to-high hazard, while the Atlantic Forest presented the highest hazards among Brazilian biomes in all evaluated scenarios. The analysis of climatic predictors also indicated that biophysical conditions conducive to fires (temperature increases and precipitation reduction) are likely to affect all Brazilian biomes (See Data Table S2). However, as showed in our fire occurrence models, such predicted changes could not present the expected results in fire occurrence, which may seem contradictory at first: if flammable conditions are expected to become more widespread and fire frequency is somewhat predictable, fire occurrence should be expected to increase. However, such an assumption would only hold if the primary fire driver across biomes was the climate – which is not true, since human-induced fires are prevalent in all Brazilian biomes (Pivello et al., 2021).

~~Climate change is directly related to changes in the relative variance of vegetation productivity, increasing ecosystem sensitivity, a potential key component of resilience (Seddon et al., 2016). Higher sensitivity rates may indicate that the system is approaching an ecological tipping point (Scheffer et al., 2009). Specifically concerning the VSI, developed by Seddon et al. (2016), it can also indicate sensitivity to fire-related climatic conditions, since the index consider key drivers of burned areas to measure the vegetation sensitivity (Seddon et al., 2016).~~ Our results indicated sensitivity values varying from 14% to 20% across the Brazilian biomes, although no overall pattern was found for fire-dependent biomes. In fact, the Pantanal presented the lowest sensitivity among Brazilian biomes, being the only fire-dependent biome that followed our expectations concerning this metric. Both Cerrado and Pampa ~~figured~~ among the most sensitive Brazilian biomes to the evaluated fire-related climatic conditions, together with the fire-independent biome, Caatinga. In turn, and also contrary to expectations, both fire-sensitive biomes presented the lowest vegetation sensitivities compared to the other biomes. The expected sensitivity of these tropical forests could be operating at different timescales to potential precipitation thresholds identified in these systems (Lenton et al., 2008; Seddon et al., 2016), while the enhanced sensitivity of the Caatinga could indicate a potential relationship between vegetation cover and phenology with precipitation changes (Barbosa et al., 2006; Seddon et al., 2016).

~~We evaluated the biomes' resilience status by quantifying vegetation loss and area under protection. Although PAs are fundamental for environmental conservation and fire prevention (Adeney et al., 2009), people are constantly affecting landscape patterns causing fragmentation and vegetation loss, which has been worsened over the past years (Foley, 2005). According to the theory of ecological stability, changes in environmental conditions that surpass a resilience threshold can lead to catastrophic transitions between stable ecosystems (Scheffer and Carpenter, 2003). Therefore, the conjoined effects of human suppression on vegetation and fire regimes are likely to~~

~~threaten ecosystem structure and stability.~~ Although most of the Brazilian fire-dependent and fire-sensitive biomes are prone to present a high resilience to a gradual increase in climatic stress, and a consequent low vulnerability, Pampa, Atlantic Forest and the fire-independent biome are likely to be low-resilient and highly-vulnerable biomes (Anjos and de Toledo, 2018; Pinho et al., 2020). Consequently, our results indicate that most fire-dependent biomes presented low climate risk, partially corroborating our risk hypothesis. However, the Cerrado biome presented a high risk, which was similar to the recovered for the fire-independent biome, Caatinga. Finally, the fire-sensitive biomes presented opposite trends concerning risk: while the Amazon presented the lowest, the Atlantic Forest presented the highest risk among the Brazilian biomes.

The development of fire and climate management programs to preserve the integrity of Brazilian biomes is paramount to reduce the most severe climate-related and fire-related impacts in these systems. ~~However, despite the importance of public policies to regulate intentional fires and promote environmental preservation, the rapid pace of environmental reversals in Brazil highlights the lack of commitment of the current Brazilian presidential administration to environmental issues (Diele-Viegas et al., 2020; Ferrante and Fearnside, 2019). From destructive environmental policies to the facilitation of illegal activities, government actions have contributed to the inefficiency of protecting ecosystems and populations (Levis et al., 2020). The current economic crisis resulting from the COVID-19 pandemic has been used to justify an indiscriminate increase in the use of natural resources, with Illegal deforestation and deforestation-related fires increasing at appalling rates (Butler, 2020; da Silva Junior et al., 2020; Vale et al., 2021).~~

Although the 2021's 26th Conference of the Parties (COP26) of the United Nations Framework Convention on Climate Change (UNFCCC, a.k.a. "Climate Convention") made clear statements concerning our proximation of reaching dangerous tipping points for the climate system and the maintenance of the Amazon rainforest (Walker, 2021), Brazilian commitment to the convention goals were restricted to general propositions of banning illegal deforestation by 2030 and becoming carbon neutral by 2050, with no proposed action plans (Fearnside, 2021).

While public policies do not protect Brazilian biomes and the government fails to avoid deforestation, related fires, and climate change, Brazil is constantly suffering economic pressure from international traders and consumers to prevent and decelerate environmental destruction (Gibbs et al., 2015). Such pressure occurs mainly in conditions placed on imports of soy and beef, which are usually related to the increase in deforestation rates (Ferrante and Fearnside, 2021; Kehoe et al., 2019). On the other hand, protecting biodiversity should be beyond economic and international markets. Protected biodiverse landscapes create truly regenerative and sustainable systems, enhancing food production while preserving biodiversity (Kremen, 2020). Brazilian biomes' conservation is of global importance since the benefits from its ecosystem services are not only local. Thus, actions must be immediately strengthened to discourage and control intentional fires, stop deforestation, and fight climate change.

Conclusions

Here we present an innovative combination of techniques based on satellite-derived climate predictors and fire frequency time-series data to quantify the relationship between climate and fires in Brazilian biomes and anticipate fire occurrence in the future. Although we focused on fire frequency, other characteristics of fire regimes are also important when evaluating fire impacts on biodiversity and ecosystems. Specifically, the organic matter consumption from fire (i.e., fire severity) can be used as a proxy of how the energy output from fire (i.e., fire intensity) affects ecosystems (Keeley, 2009). In addition, changes in fire season length (the period when fires are prone to spread due to climatic factors) can increase the ignitions occurrence and burn periods, resulting in larger fires that are more likely to spread and negatively impact biodiversity (Riley and Loehman, 2016). Simmilarly, smoke emissions due to fires lead to reduced air quality, directly impacting human health and causing premature adult deaths that could be avoided (Reddington et al., 2015). Future studies on fire regimes in Brazilian biomes should focus on these multiple characteristics to improve the knowledge on Brazilian fire regimes and increase the effectiveness of fire management policies.

In summary, our results showed that, while the patterns of fire persistence and fire occurrence over time are more likely to be related to human-induced fires, key drivers of burned areas are likely to be intensified across Brazilian biomes in the future, potentially increasing the magnitude of the fires and harming the biomes' integrity. Although climate change is not necessarily the leading cause of the observed fires in fire-dependent, fire-independent, and fire-sensitive biomes, it is indeed likely to potentialize fire occurrence and spread by creating appropriate climate conditions in these biomes. Therefore, management actions should go towards the development of programs to preserve the integrity of Brazilian biomes and reduce the most severe climate-related and fire-related impacts in these systems.

Acknowledgements

We thank Alistair Seddon for providing the vegetation sensitivity data.

References

Adeney, J.M., Christensen, N.L., Pimm, S.L., 2009. Reserves Protect against Deforestation Fires in the Amazon. PLoS ONE 4, e5014. https://doi.org/10.1371/journal.pone.0005014

Allouche, O., Tsoar, A., Kadmon, R., 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS): Assessing the accuracy of distribution models. Journal of Applied Ecology 43, 1223–1232. https://doi.org/10.1111/j.1365-2664.2006.01214.x

Anjos, L.J.S., Barreiros de Souza, E., Amaral, C.T., Igawa, T.K., Mann de Toledo, P., 2021. Future projections for terrestrial biomes indicate widespread warming and moisture reduction in forests up to 2100 in South America. Global Ecology and Conservation 25, e01441. https://doi.org/10.1016/j.gecco.2020.e01441

Balch, J.K., Bradley, B.A., Abatzoglou, J.T., Nagy, R.C., Fusco, E.J., Mahood, A.L., 2017. Human-started wildfires expand the fire niche across the United States. Proc Natl Acad Sci USA 114, 2946–2951. https://doi.org/10.1073/pnas.1617394114

Barbet-Massin, M., Jiguet, F., Albert, C.H., Thuiller, W., 2012. Selecting pseudo-absences for species distribution models: how, where and how many?: *How to use pseudo-absences in niche modelling?* Methods in Ecology and Evolution 3, 327–338. https://doi.org/10.1111/j.2041-210X.2011.00172.x

Barbosa, R.I., Fearnside, P.M., 1999. Fires in the Brazilian Amazon: Greenhouse gas emissions from burning of different ecosystems in roraima during the 1997-98 el niño event. Acta Amazonica 29, 513–534.

Barni, P.E., Rego, A.C.M., Silva, F. das C.F., Lopes, R.A.S., Xaud, H.A.M., Xaud, M.R., Barbosa, R.I., Fearnside, P.M., 2021. Logging Amazon forest increased the severity and spread of fires during the 2015–2016 El Niño. Forest Ecology and Management 500, 119652. https://doi.org/10.1016/j.foreco.2021.119652

Bivand, R., Keitt, T., Rowlingson, B., 2020. rgdal: Bindings for the "Geospatial" Data Abstraction Library.

Butler, R.A., 2020. Despite COVID, Amazon deforestation races higher. Mongabay.

Cannon, A.J., 2020. Reductions in daily continental-scale atmospheric circulation biases between generations of global climate models: CMIP5 to CMIP6. Environ. Res. Lett. 15, 064006. https://doi.org/10.1088/1748-9326/ab7e4f
Clark, S.K., Ward, D.S., Mahowald, N.M., 2017. Parameterization-based uncertainty in future lightning flash density. Geophys. Res. Lett. 44, 2893–2901. https://doi.org/10.1002/2017GL073017
Convention on Biodiversity, 2021. Brazil – Main facts.
da Silva Junior, C.A., Teodoro, P.E., Delgado, R.C., Teodoro, L.P.R., Lima, M., de Andréa Pantaleão, A., Baio, F.H.R., de Azevedo, G.B., de Oliveira Sousa Azevedo, G.T., Capristo-Silva, G.F., Arvor, D., Facco, C.U., 2020. Persistent fire foci in all biomes undermine the Paris Agreement in Brazil. Sci Rep 10, 16246. https://doi.org/10.1038/s41598-020-72571-w
Diele-Viegas, L.M., 2021. Biogeography and Climate Change, in: Biogeography: An Integrative Approach of the Evolution of Living, Ecosystems and Environment. ISTE Ltd, pp. 303–320.
Diele-Viegas, L.M., Hipólito, J., Ferrante, L., 2021. Scientific denialism threatens Brazil. Science 374, 948–949. https://doi.org/10.1126/science.abm9933
Diele-Viegas, L.M., Pereira, E.J. de A.L., Rocha, C.F.D., 2020. The new Brazilian gold rush: Is Amazonia at risk? Forest Policy and Economics 119, 102270. https://doi.org/10.1016/j.forpol.2020.102270
Diniz-Filho, J.A.F., Mauricio Bini, L., Fernando Rangel, T., Loyola, R.D., Hof, C., NoguÃ©s-Bravo, D., AraÃºjo, M.B., 2009. Partitioning and mapping uncertainties in ensembles of forecasts of species turnover under climate change. Ecography 32, 897–906. https://doi.org/10.1111/j.1600-0587.2009.06196.x
Durigan, G., Pilon, N.A.L., Abreu, R.C.R., Hoffmann, W.A., Martins, M., Fiorillo, B.F., Antunes, A.Z., Carmignotto, A.P., Maravalhas, J.B., Vieira, J., Vasconcelos, H.L., 2020. No Net Loss of Species Diversity After Prescribed Fires in the Brazilian Savanna. Front. For. Glob. Change 3, 13. https://doi.org/10.3389/ffgc.2020.00013
Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J., Taylor, K.E., 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev. 9, 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016
Fearnside, P.M., 2021. COP-26: Amazonia's Indigenous peoples are vital to fighting global warming (commentary). Mongabay.
Fernandes, G.W., Vale, M.M., Overbeck, G.E., Bustamante, M.M.C., Grelle, C.E.V., Bergallo, H.G., Magnusson, W.E., Akama, A., Alves, S.S., Amorim, A., Araújo, J., Barros, C.F., Bravo, F., Carim, M.J.V., Cerqueira, R., Collevatti, R.G., Colli, G.R., da Cunha, C.N., D'Andrea, P.S., Dianese, J.C., Diniz, S., Estrela, P.C., Fernandes, M.R.M., Fontana, C.S., Giacomin, L.L., Gusmão, L.F.P., Juncá, F.A., Lins-e-Silva, A.C.B., Lopes, C.R.A.S., Lorini, M.L., de Queiroz, L.P., Malabarba, L.R., Marimon, B.S., Junior, B.H.M., Marques, M.C.M., Martinelli, B.M., Martins, M.B., de Medeiros, H.F., Menin, M., de Morais, P.B., Muniz, F.H., Neckel-Oliveira, S., de Oliveira, J.A., Oliveira, R.P., Pedroni, F., Penha, J., Podgaiski, L.R., Rodrigues, D.J., Scariot, A., Silveira, L.F., Silveira, M., Tomas, W.M., Vital, M.J.S., Pillar, V.D., 2017. Dismantling Brazil's science threatens global biodiversity heritage. Perspectives in Ecology and Conservation 15, 239–243. https://doi.org/10.1016/j.pecon.2017.07.004
Ferrante, L., Fearnside, P.M., 2021. Brazil's political upset threatens Amazonia. Science 371, 898–898. https://doi.org/10.1126/science.abg9786
Ferrante, L., Fearnside, P.M., 2019. Brazil's new president and 'ruralists' threaten Amazonia's environment, traditional peoples and the global climate. Envir. Conserv. 46, 261–263. https://doi.org/10.1017/S0376892919000213

Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas: NEW CLIMATE SURFACES FOR GLOBAL LAND AREAS. Int. J. Climatol 37, 4302–4315. https://doi.org/10.1002/joc.5086

Fielding, A.H., Bell, J.F., 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. Envir. Conserv. 24, 38–49. https://doi.org/10.1017/S0376892997000088

Foden, W.B., Young, B.E., Akçakaya, H.R., Garcia, R.A., Hoffmann, A.A., Stein, B.A., Thomas, C.D., Wheatley, C.J., Bickford, D., Carr, J.A., Hole, D.G., Martin, T.G., Pacifici, M., Pearce-Higgins, J.W., Platts, P.J., Visconti, P., Watson, J.E.M., Huntley, B., 2019. Climate change vulnerability assessment of species. WIREs Clim Change 10. https://doi.org/10.1002/wcc.551

Foley, J.A., 2005. Global Consequences of Land Use. Science 309, 570–574. https://doi.org/10.1126/science.1111772

Gibbs, H.K., Rausch, L., Munger, J., Schelly, I., Morton, D.C., Noojipady, P., Soares-Filho, B., Barreto, P., Micol, L., Walker, N.F., 2015. Brazil's Soy Moratorium. Science 347, 377–378. https://doi.org/10.1126/science.aaa0181

González, T.M., González-Trujillo, J.D., Muñoz, A., Armenteras, D., 2021. Differential effects of fire on the occupancy of small mammals in neotropical savanna-gallery forests. Perspectives in Ecology and Conservation 19, 179–188. https://doi.org/10.1016/j.pecon.2021.03.005

Guisan, A., Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. Ecological Modelling 135, 147–186. https://doi.org/10.1016/S0304-3800(00)00354-9

Hanley, J.A., McNeil, B.J., 1982. The meaning and use of the area under a receiver operating characteristic (ROC) curve. Radiology 143, 29–36.

Hannah, L., 2008. Protected Areas and Climate Change. Annals of the New York Academy of Sciences 1134, 201–212. https://doi.org/10.1196/annals.1439.009

Hijmans, R.J., 2016. Introduction to the 'raster' package (version 2.5-8) 27.

Hijmans, R.J., Phillips, S., Leathwick, J., Elith, J., 2017. dismo: Species Distribution Modeling.

ICMBio, 2020. Mapa Temático e Dados Geoestatísticos das Unidades de Conservação Federais.

INPE, 2020. Projeto de Monitoramento do Desmatamento na Amazônia Legal (PRODES).

IPCC, 2021. Summary for Policymakers, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2018. Summary for policymakers, in: Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. World Meteorological Organization, Geneva, Switzerland, p. 32.

Jenkins, M., Schaap, B., 2018. Forest Ecosystem Services 41.

Keeley, J.E., 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. Int. J. Wildland Fire 18, 116. https://doi.org/10.1071/WF07049

Kehoe, L., Reis, T., Virah-Sawmy, M., Balmford, A., Kuemmerle, T., 604 signatories, 2019. Make EU trade with Brazil sustainable. Science 364, 341.1-341. https://doi.org/10.1126/science.aaw8276

Kelley, D.I., Bistinas, I., Whitley, R., Burton, C., Marthews, T.R., Dong, N., 2019. How contemporary bioclimatic and human controls change global fire regimes. Nat. Clim. Chang. 9, 690–696. https://doi.org/10.1038/s41558-019-0540-7

Klein, A.-M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proc. R. Soc. B. 274, 303–313. https://doi.org/10.1098/rspb.2006.3721

Kremen, C., 2020. Ecological intensification and diversification approaches to maintain biodiversity, ecosystem services and food production in a changing world. Emerging Topics in Life Sciences 4, 229–240. https://doi.org/10.1042/ETLS20190205
Leroy, B., Delsol, R., Hugueny, B., Meynard, C.N., Barhoumi, C., Barbet-Massin, M., Bellard, C., 2018. Without quality presence-absence data, discrimination metrics such as TSS can be misleading measures of model performance. J Biogeogr 45, 1994–2002. https://doi.org/10.1111/jbi.13402
Levis, C., Flores, B.M., Mazzochini, G.G., Manhães, A.P., Campos-Silva, J.V., Borges de Amorim, P., Peroni, N., Hirota, M., Clement, C.R., 2020. Help restore Brazil's governance of globally important ecosystem services. Nat Ecol Evol 4, 172–173. https://doi.org/10.1038/s41559-019-1093-x
Mendes-Oliveira, A.C., Santos, P.G.P. dos, Carvalho-Júnior, O. de, Montag, L.F. de A., Lima, R.C.S. de, Maria, S.L.S. de, Rossi, R.V., 2012. Edge effects and the impact of wildfires on populations of small non-volant mammals in the forest-savanna transition zone in Southern Amazonia. Biota Neotrop. 12, 57–63. https://doi.org/10.1590/S1676-06032012000300004
Murari, T.B., Filho, A.S.N., Moret, M.A., Pitombo, S., Santos, A.A.B., 2020. Self-Affine Analysis of ENSO in Solar Radiation. Energies 13, 4816. https://doi.org/10.3390/en13184816
Oliveira, B.F.A., Bottino, M.J., Nobre, P., Nobre, C.A., 2021. Deforestation and climate change are projected to increase heat stress risk in the Brazilian Amazon. Commun Earth Environ 2, 207. https://doi.org/10.1038/s43247-021-00275-8
Oliveira-Júnior, J.F. de, Teodoro, P.E., Silva Junior, C.A. da, Baio, F.H.R., Gava, R., Capristo-Silva, G.F., Gois, G. de, Correia Filho, W.L.F., Lima, M., Santiago, D. de B., Freitas, W.K., Santos, P.J. dos, Costa, M. da S., 2020. Fire foci related to rainfall and biomes of the state of Mato Grosso do Sul, Brazil. Agricultural and Forest Meteorology 282–283, 107861. https://doi.org/10.1016/j.agrformet.2019.107861
Pausas, J.G., Bradstock, R.A., 2007. Fire persistence traits of plants along a productivity and disturbance gradient in mediterranean shrublands of south-east Australia. Global Ecol Biogeography 16, 330–340. https://doi.org/10.1111/j.1466-8238.2006.00283.x
PBMC, 2014. Base científica das mudanças climáticas, Ambrizzi, T., Araujo, M. ed. Universidade Federal do Rio de Janeiro, Rio de Janeiro, COPPE.
Peng, C.-K., Buldyrev, S.V., Havlin, S., Simons, M., Stanley, H.E., Goldberger, A.L., 1994. Mosaic organization of DNA nucleotides. Phys. Rev. E 49, 1685–1689. https://doi.org/10.1103/PhysRevE.49.1685
Pivello, V.R., Vieira, I., Christianini, A.V., Ribeiro, D.B., da Silva Menezes, L., Berlinck, C.N., Melo, F.P.L., Marengo, J.A., Tornquist, C.G., Tomas, W.M., Overbeck, G.E., 2021. Understanding Brazil's catastrophic fires: Causes, consequences and policy needed to prevent future tragedies. Perspectives in Ecology and Conservation 19, 233–255. https://doi.org/10.1016/j.pecon.2021.06.005
Pueyo, S., De Alencastro Graça, P.M.L., Barbosa, R.I., Cots, R., Cardona, E., Fearnside, P.M., 2010. Testing for criticality in ecosystem dynamics: the case of Amazonian rainforest and savanna fire: Criticality in Amazonia. Ecology Letters 13, 793–802. https://doi.org/10.1111/j.1461-0248.2010.01497.x
R Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Reddington, C.L., Butt, E.W., Ridley, D.A., Artaxo, P., Morgan, W.T., Coe, H., Spracklen, D.V., 2015. Air quality and human health improvements from reductions in deforestation-related fire in Brazil. Nature Geosci 8, 768–771. https://doi.org/10.1038/ngeo2535
Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P.,

Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Riley, K.L., Loehman, R.A., 2016. Mid-21st-century climate changes increase predicted fire occurrence and fire season length, Northern Rocky Mountains, United States. Ecosphere 7. https://doi.org/10.1002/ecs2.1543

Ripple, W.J., Wolf, C., Newsome, T.M., Barnard, P., Moomaw, W.R., 2019. World Scientists' Warning of a Climate Emergency. BioScience biz088. https://doi.org/10.1093/biosci/biz088

Roberts, S., 2000. Tropical fire ecology. Progress in Physical Geography 24, 281–288.

Sales, L.P., Galetti, M., Pires, M.M., 2020. Climate and land-use change will lead to a faunal "savannization" on tropical rainforests. Glob. Change Biol. 26, 7036–7044. https://doi.org/10.1111/gcb.15374

Santos, A.C. dos, Montenegro, S. da R., Ferreira, M.C., Barradas, A.C.S., Schmidt, I.B., 2021. Managing fires in a changing world: Fuel and weather determine fire behavior and safety in the neotropical savannas. Journal of Environmental Management 289, 112508. https://doi.org/10.1016/j.jenvman.2021.112508

Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., Held, H., van Nes, E.H., Rietkerk, M., Sugihara, G., 2009. Early-warning signals for critical transitions. Nature 461, 53–59. https://doi.org/10.1038/nature08227

Seddon, A.W.R., Macias-Fauria, M., Long, P.R., Benz, D., Willis, K.J., 2016. Sensitivity of global terrestrial ecosystems to climate variability. Nature 531, 229–232. https://doi.org/10.1038/nature16986

Shabani, F., Kumar, L., Ahmadi, M., 2018. Assessing Accuracy Methods of Species Distribution Models: AUC, Specificity, Sensitivity and the True Skill Statistic 13.

Silva, S.S. da, Oliveira, I., Morello, T.F., Anderson, L.O., Karlokoski, A., Brando, P.M., Melo, A.W.F. de, Costa, J.G. da, Souza, F.S.C. de, Silva, I.S. da, Nascimento, E. de S., Pereira, M.P., Almeida, M.R.N. de, Alencar, A., Aragão, L.E.O. e C. de, Brown, I.F., Graça, P.M.L. de A., Fearnside, P.M., 2021. Burning in southwestern Brazilian Amazonia, 2016–2019. Journal of Environmental Management 286, 112189. https://doi.org/10.1016/j.jenvman.2021.112189

Silva Junior, C.H.L., Pessôa, A.C.M., Carvalho, N.S., Reis, J.B.C., Anderson, L.O., Aragão, L.E.O.C., 2021. The Brazilian Amazon deforestation rate in 2020 is the greatest of the decade. Nat Ecol Evol 5, 144–145. https://doi.org/10.1038/s41559-020-01368-x

Silvério, D.V., Brando, P.M., Balch, J.K., Putz, F.E., Nepstad, D.C., Oliveira-Santos, C., Bustamante, M.M.C., 2013. Testing the Amazon savannization hypothesis: fire effects on invasion of a neotropical forest by native cerrado and exotic pasture grasses. Phil. Trans. R. Soc. B 368, 20120427. https://doi.org/10.1098/rstb.2012.0427

Soberon, J., Peterson, A.T., 2005. Interpretation of Models of Fundamental Ecological Niches and Species' Distributional Areas. Biodiv. Inf. 2. https://doi.org/10.17161/bi.v2i0.4

Souza, C.M., Z. Shimbo, J., Rosa, M.R., Parente, L.L., A. Alencar, A., Rudorff, B.F.T., Hasenack, H., Matsumoto, M., G. Ferreira, L., Souza-Filho, P.W.M., de Oliveira, S.W., Rocha, W.F., Fonseca, A.V., Marques, C.B., Diniz, C.G., Costa, D., Monteiro, D., Rosa, E.R., Vélez-Martin, E., Weber, E.J., Lenti, F.E.B., Paternost, F.F., Pareyn, F.G.C., Siqueira, J.V., Viera, J.L., Neto, L.C.F., Saraiva, M.M., Sales, M.H., Salgado, M.P.G., Vasconcelos, R., Galano, S., Mesquita, V.V., Azevedo, T., 2020. Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat

Archive and Earth Engine. Remote Sensing 12, 2735. https://doi.org/10.3390/rs12172735
Syphard, A.D., Keeley, J.E., Pfaff, A.H., Ferschweiler, K., 2017. Human presence diminishes the importance of climate in driving fire activity across the United States. Proc Natl Acad Sci USA 114, 13750–13755. https://doi.org/10.1073/pnas.1713885114
Thielen, D., Schuchmann, K.-L., Ramoni-Perazzi, P., Marquez, M., Rojas, W., Quintero, J.I., Marques, M.I., 2020. Quo vadis Pantanal? Expected precipitation extremes and drought dynamics from changing sea surface temperature. PLoS ONE 15, e0227437. https://doi.org/10.1371/journal.pone.0227437
Thonicke, K., Venevsky, S., Sitch, S., Cramer, W., 2008. The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model: Fire disturbance and global vegetation dynamics. Global Ecology and Biogeography 10, 661–677. https://doi.org/10.1046/j.1466-822X.2001.00175.x
Thuiller, W., Georges, D., Engler, R., Breiner, F., 2020. biomod2: Ensemble Platform for Species Distribution Modeling. R package version 3.4.6.
Tong, S., Li, X., Zhang, J., Bao, Yuhai, Bao, Yongbin, Na, L., Si, A., 2019. Spatial and temporal variability in extreme temperature and precipitation events in Inner Mongolia (China) during 1960–2017. Science of The Total Environment 649, 75–89. https://doi.org/10.1016/j.scitotenv.2018.08.262
Vale, M.M., Berenguer, E., Argollo de Menezes, M., Viveiros de Castro, E.B., Pugliese de Siqueira, L., Portela, R. de C.Q., 2021. The COVID-19 pandemic as an opportunity to weaken environmental protection in Brazil. Biological Conservation 255, 108994. https://doi.org/10.1016/j.biocon.2021.108994
Walker, R.T., 2021. Collision Course: Development Pushes Amazonia Toward Its Tipping Point. Environment: Science and Policy for Sustainable Development 63, 15–25. https://doi.org/10.1080/00139157.2021.1842711

Figure 1

Hypothetic patterns of fire persistence, fire occurrence, and climate risk in Brazilian fire-dependent (Cerrado, Pampa, and Pantanal), fire-independent (Caatinga) and fire-sensitive (Amazon and Atlantic Forest) biomes.

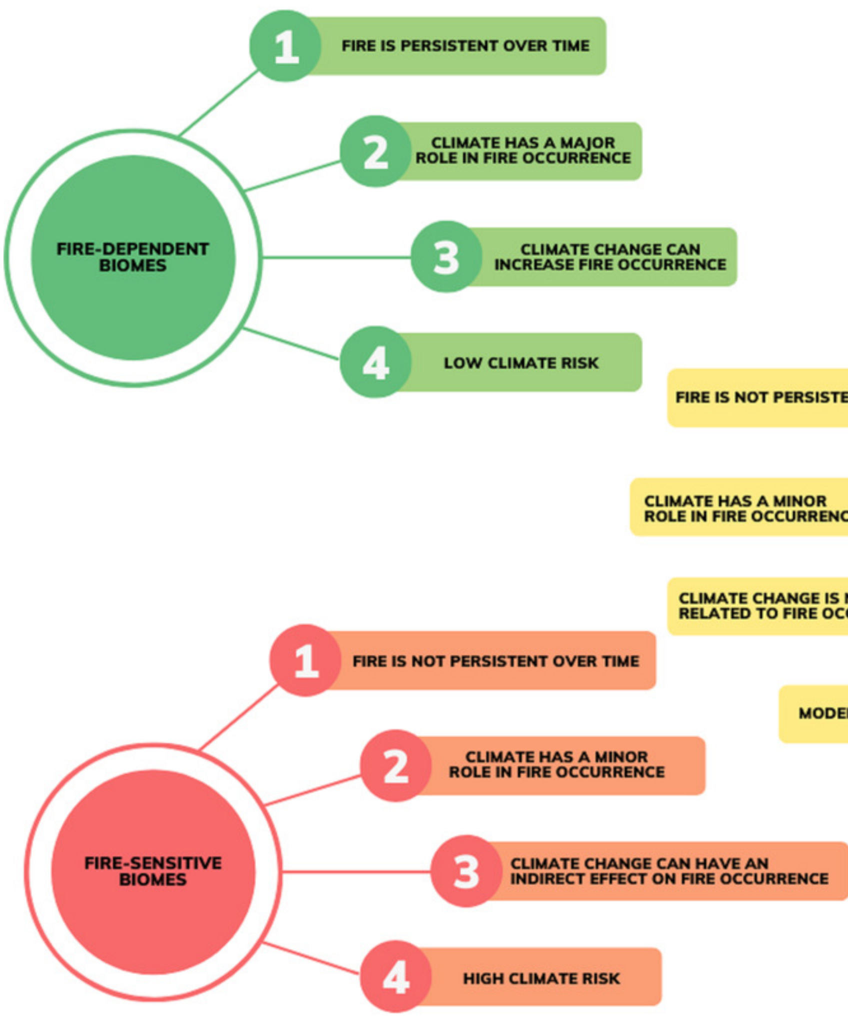

Figure 2

Fire persistence between 2010 and 2020. Source: INPE (2020).

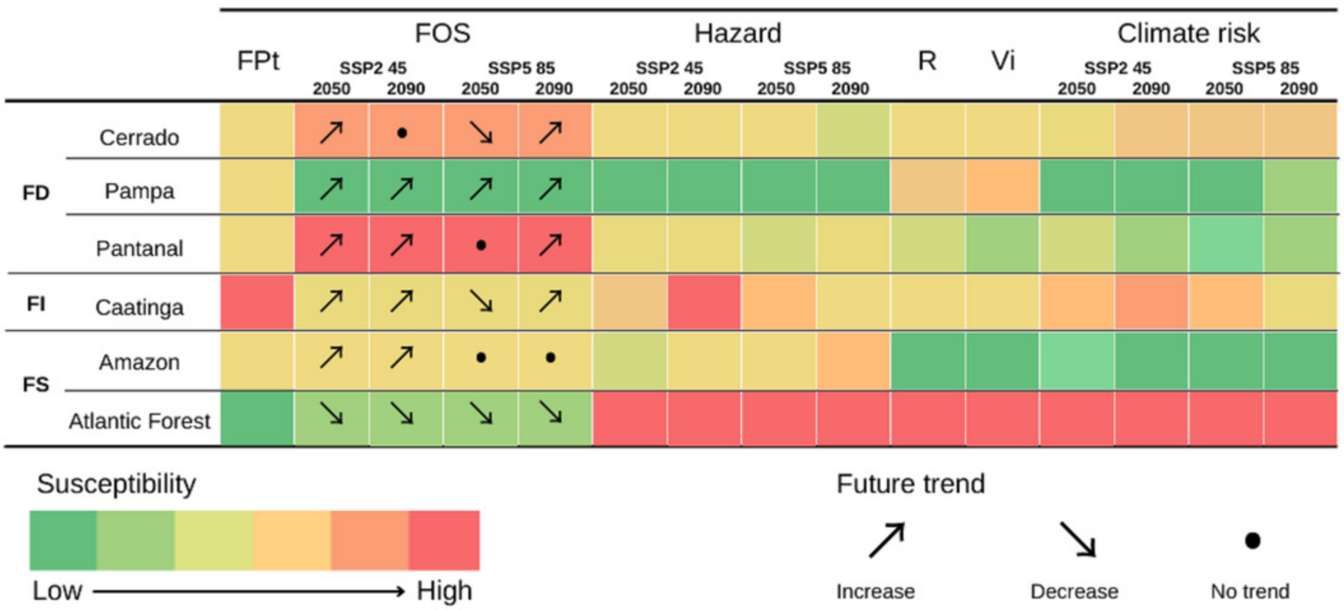

Figure 3

Fire Persistence over time (FPt), Fire Occurrence Suitability (FOS), Climate Hazard, Resilience (R), Vulnerability Index (Vi) and Climate risk of fire-dependent (FD), fire-independent (FI), and fire-sensitive (FS) Brazilian biomes.

Colours represent aspects that make them more (red) or less (green) susceptible to that characteristic than the other biomes. Arrows indicate the future trends in different scenarios of climate change.

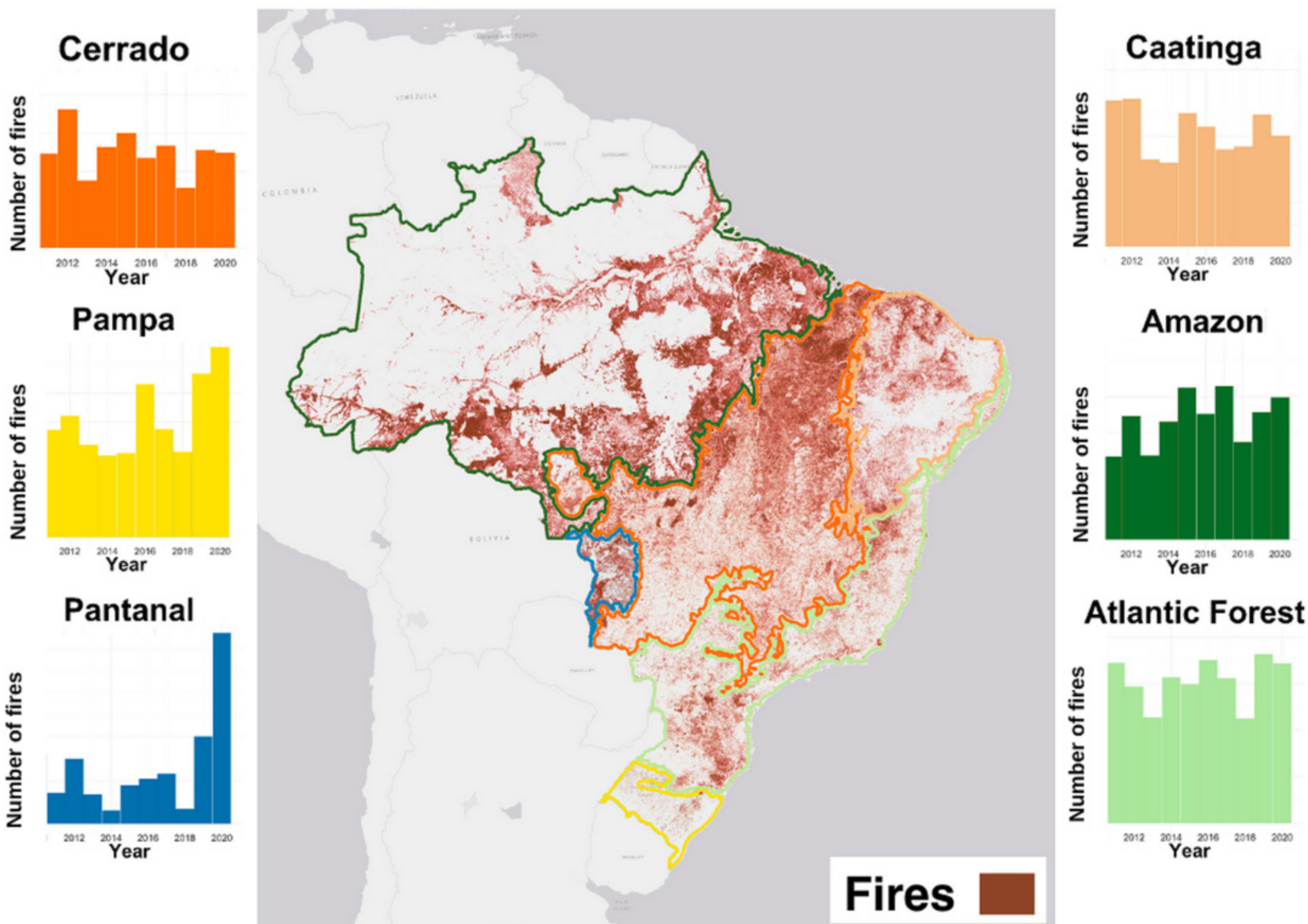

Table 1(on next page)

n values considered in the definition of RCCI, based on Giorgi 2006.

ΔP is the percentage of change in annual precipitation; ΔσP is the interannual variability of precipitation; ΔσT is the interannual variability of temperature; and RWAF is the regional warming amplification factor.

Table 1. ***n*** **values considered in the definition of RCCI, based on Giorgi 2006. ΔP is the percentage of change in annual precipitation; ΔσP is the interannual variability of precipitation; ΔσT is the interannual variability of temperature; and RWAF is the regional warming amplification factor.**

n	ΔP (%)	ΔσP (%)	RWAF	ΔσT (%)
0	<5	<5	<1.1	<5
1	5-10	5-10	1.1-1.3	5-10
2	10-15	10-20	1.3-1.5	10-15
4	>15	>20	>1.5	>15

Table 2(on next page)

Detrended Fluctuation Analysis (DFA) per Brazilian Biome.

NFC = Natural-Fire Dependence Classification; SD = Standard Deviation.

Table 2. Detrended Fluctuation Analysis (DFA) per Brazilian Biome. NFC = Natural-Fire Dependence Classification; SD = Standard Deviation.

NFDC	Biome	DFA ($\alpha \pm SD$)
Fire-Dependent	Cerrado	0.63 ± 0.07
	Pampa	0.63 ± 0.06
	Pantanal	0.63 ± 0.05
Fire-Independent	Caatinga	0.61 ± 0.06
Fire-Sensitive	Amazon	0.63 ± 0.07
	Atlantic Forest	0.72 ± 0.07

Table 3(on next page)

Mean ± Standard Deviation of thermal suitability of the Brazilian biomes (%) to fire occurrence considering different scenarios for climate change (SSP2 45 and SSP5 85) and different years (2050 and 2090).

NFDC = Natural-Fire Dependence Classification.

Table 3. Mean ± Standard Deviation of thermal suitability of the Brazilian biomes (%) to fire occurrence considering different scenarios for climate change (SSP2 45 and SSP5 85) and different years (2050 and 2090). NFDC = Natural-Fire Dependence Classification.

NFDC	Biome	Present	2050 SSP2 45	2090 SSP2 45	2050 SSP5 85	2090 SSP5 85
Fire-Dependent	Cerrado	0.78 ± 0.23	0.80 ± 0.23	0.78 ± 0.23	0.77 ± 0.23	0.80 ± 0.22
	Pampa	0.19 ± 0.09	0.23 ± 0.08	0.25 ± 0.10	0.23 ± 0.09	0.23 ± 0.09
	Pantanal	0.88 ± 0.10	0.90 ± 0.08	0.89 ± 0.08	0.88 ± 0.08	0.89 ± 0.08
Fire-Independent	Caatinga	0.64 ± 0.28	0.66 ± 0.28	0.66 ± 0.28	0.63 ± 0.27	0.65 ± 0.28
Fire-Sensitive	Amazon	0.62 ± 0.34	0.63 ± 0.34	0.63 ± 0.33	0.62 ± 0.33	0.62 ± 0.34
	Atlantic Forest	0.49 ± 0.27	0.50 ± 0.24	0.47 ± 0.23	0.46 ± 0.23	0.45 ± 0.22
	Atlantic Forest NE	0.48 ± 0.25	0.51 ± 0.21	0.46 ± 0.21	0.46 ± 0.21	0.43 ± 0.19
	Atlantic Forest SE	0.50 ± 0.28	0.49 ± 0.26	0.48 ± 0.25	0.46 ± 0.25	0.47 ± 0.25

Table 4(on next page)

Climate-Related Hazard, Resilience and Vulnerability of Brazilian biomes considering different scenarios for climate change (SSP2 45 and SSP5 85) and different years (2050 and 2090).

NFDC = Natural-Fire Dependence Classification.

Table 4. Climate-Related Hazard, Resilience and Vulnerability of Brazilian biomes considering different scenarios for climate change (SSP2 45 and SSP5 85) and different years (2050 and 2090). NFDC = Natural-Fire Dependence Classification.

NFDC	Biome	Hazard SSP2 45 2050	Hazard SSP2 45 2090	Hazard SSP5 85 2050	Hazard SSP5 85 2090	Resilience Status	Vulnerability Index
Fire-Dependent	Cerrado	13.66	32.23	27.37	105.35	0.73	11.73
	Pampa	0.00	6.22	5.07	40.12	0.75	13.43
	Pantanal	14.54	32.98	22.28	112.04	0.67	6.40
Fire-Independent	Caatinga	16.96	49.40	36.26	124.61	0.70	10.87
Fire-Sensitive	Amazon	8.20	33.89	29.88	139.95	0.54	1.33
	Atlantic Forest	28.76	51.02	48.44	188.82	0.92	19.45
	Atlantic Forest NE	42.39	73.64	72.93	267.80	0.92	21.61
	Atlantic Forest SE	15.12	28.40	23.94	109.84	0.93	18.80

1

Table 5 (on next page)

Climate Risk of Brazilian biomes considering their Natural-Fire Dependence Classification (NFDC).

SD = Standard Deviation

Table 5. Climate Risk of Brazilian biomes considering their Natural-Fire Dependence Classification (NFDC). SD = Standard Deviation.

NFDC	Biome	Climate Risk SSP2 45		SSP5 85	
		2050	2090	2050	2090
Fire-Dependent	Cerrado	160.16	377.90	320.91	1235.23
	Pampa	0.00	83.50	68.06	538.61
	Pantanal	93.06	211.07	142.59	717.07
	Average ± SD	84.41 ± 80.4	224.16 ± 147.6	177.19 ± 129.9	830.3 ± 361.8
Fire-Independent	Caatinga	184.36	536.98	394.15	1354.51
Fire-Sensitive	Amazon	10.91	45.07	39.74	186.13
	Atlantic Forest	559.14	992.08	941.82	3671.60
	Average ± SD	285.02 ± 387.6	518..58 ± 669.64	490.82 ± 637.93	1928.87 ± 2464.6
	Atlantic Forest NE	916.05	1591.36	1576.02	5787.16
	Atlantic Forest SE	284.26	533.92	450.07	2064.99

1