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Research article

Protected areas influence fire regimes globally

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ABSTRACT

Protected areas (PAs) aim to support global conservation efforts including the maintenance of fire regimes and mitigation of negative fire impacts. Analyzing data from over 20 million fires worldwide, we found that PAs, along with the various protection levels defined by the International Union for Conservation of Nature (IUCN), significantly influenced burned area (BA) and fire regime attributes across continents and biomes in distinct ways, with varying impacts on fire size, spread, intensity, and duration. In most biomes, the proportion of BA within PAs was smaller than the proportion of PA itself, indicating that PAs were generally less impacted by wildfires. However, in tropical grasslands, tropical dry broadleaf forests and temperate conifer forests, the BA fraction inside PAs was larger. The strictest IUCN protection categories (Ia and Ib) were associated with the lowest BA, compared to National Parks (IUCN II) and other less restrictive protection categories. However, this pattern varied by biome, with mediterranean forests, temperate broadleaf and mixed forests, temperate grasslands and tropical coniferous forests showing increased fire proneness in the strictest IUCN categories and more intense fires. Insights from this research can guide targeted environmental policies to strengthen PA networks to maintain fire regimes.

1. Introduction

Fires have historically shaped landscapes, contributed to global biodiversity, and driven the evolution of ecosystems(Bowman et al., 2011). However, abrupt changes in fire regimes due to human-related ignitions or land use and climate changes may cause undesired effects on ecosystem functioning and services(Pausas and Keeley, 2014). According to the International Union for Conservation of Nature (IUCN), protected areas (PAs) cover territories encompassing vulnerable or valuable regions recognized, dedicated and managed, through legal or other effective means, to uphold long term biodiversity conservation practices and preserve ecosystem services and cultural values. More than 15 % of the world's land area is under some form of protection and this coverage is expected to increase to 30 % by 2030(Shah et al., 2021).

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Understanding PAs' effectiveness in maintaining or restoring ecosystems is key for determining the progress towards achieving the UN Sustainable Development Goals (IUCN). Not all protection strategies are equally effective and factors driving underperformance are poorly understood (Shah et al., 2021). Previous research assessed the effectiveness of PAs as a tool for conserving forest cover and biodiversity, regulating local climate(Duncanson et al., 2023), increasing carbon stock and preserving fire regimes(Duncanson et al., 2023; Resco De Dios et al., 2024; Shah et al., 2021; Spadoni et al., 2023).

PAs may influence fire management strategies through fuel and land management, increased monitoring and early fire detection, and the use of fire for risk mitigation and ecological restoration. The partial or complete restriction of agricultural and forest management practices in PAs may lead to fuel accumulation and landscape connectivity, therefore, boosting fire severity in fire-prone ecosystems such as the Mediterranean(Kreider et al., 2024; Resco de Dios et al., 2025; Resco De Dios et al., 2024). However, it was also proven that PAs contribute to reducing flammability by hampering deforestation and maintaining forest cover in tropical moist forests(Adeney et al., 2009; Nelson and Chomitz, 2011; Cardil et al., 2020). Thus, the effects of PAs on fire regime attributes may change based on nature conservation policies (Adeney et al., 2009; Nelson and Chomitz, 2011), the sensitivity or adaptability to fire within biomes, and the extent of human influence on their ecosystems. These factors collectively influence the structure and composition of vegetation across continents, modulating fire behavior (Bowman et al., 2013). Nonetheless, the degree to which PAs may differentially influence fire regime (FR) attributes such as burned area (BA), fire frequency, and fire behavior characteristics including fire size (FS), duration (FD), rate of spread (FSR) and intensity (FRP) at a global scale remains unknown for most biomes.

Here, we assess how PAs may influence the aforementioned FR attributes at both biome and continent scales globally. We leveraged the latest global remotely sensed fire patch characteristics database, analyzing 20 million fires from 2000 to 2020, considering the main vegetation types and ecoregions. We combined fire information with vector shapes from IUCN, the world's most extensive database on PAs. This analysis, by providing evidence on the differential role of PAs in shaping global FRs, constitutes the backbone information for nature conservation and fire agencies to devise management strategies that minimize the detrimental impacts of fire while maximizing its benefits. The comprehension of these dynamics contributes to the further development and reinforcement of ongoing environmental policies aiming to build the most effective PA network possible, in a context where the increasing severity, spread and intensity of wildfires associated with global change(Grünig et al., 2023) are expected to progressively threaten ecosystems biodiversity and functionality(Zhao et al., 2024), increasing risks to communities worldwide.

2. Materials and methods

2.1. Data

Fire event data were downloaded from the FRYv2.0 global fire patch morphology database which uses the MCD64A1 burned area product (Mouillot et al., 2023), updated from the FRYv1.0(Laurent et al., 2018) by processing the FireCCI51 pixel-level burn dates over the 2000–2020 period. This updated version aggregates neighboring burned pixels with burn date differences lower than a fixed threshold of 24 days, with a multiple ignition identification procedure as in (Oom et al., 2016) allowing for converging fires, frequent in high burning areas as savannas, to be properly separated. Fire regime (FR) attributes (size, median fire radiative power (FRP) as a proxy of intensity, rate of spread (FSR) and duration) were extracted from FRYv2.0. In this database, fire size refers to the area (in m2) of each fire polygone. Median FRP was calculated as the median FRP values delivered in the MC14ML MODIS data. Rate of Spread (in km.day-1) was calculated as the ratio between the length of the longest axis (in km) of the ellipse fitted over the burned pixels and duration (in days) of the fire. Duration was calculated as the time difference (in days) between the latest and the earliest burn dates of the burned pixels within the fire patch. The latitude/longitude coordinates of the ignition point were assessed as the center of the earliest burned pixel or the barycentre coordinates in case of multiple neighboring pixels with the same earliest burndate. The FRYv2.0 fire event database provides a consistent, long-term global record of fire event combining morphological and spreading features, as an essential information for fire regime characterization(Mahood et al., 2022), previously applied across regions and over extended time periods(García et al., 2022). However, we acknowledge certain limitations arising from its relatively coarse spatial and temporal resolution, which may reduce the detectability of very small or low-intensity burns compared to recent sensors(García et al., 2022; Giglio et al., 2025; Ouattara et al., 2024) and smooth fine-resolution patch boundaries, potentially influencing detailed shape metrics. Since the ignition causes (e.g. natural vs anthropogenic) cannot be derived from remote sensing, and are hardly fully assembled globally regarding accidental and arson causes (Ganteaume et al., 2013) or prescribed burning (Hsu et al., 2025), we have not incorporated it into our analysis.

We determined for each single fire, based on its ignition point, whether the fire spread on a protected area or outside, and associated information such as the biome, ecoregion and main vegetation type (tree, shrub, grassland) within the fire perimeter. FRYv2.0 is delivered as yearly global shapefiles of fire polygons at 250m resolution, offering the finest resolution of current fire patch databases(Andela et al., 2019; Artés et al., 2019) and previously used for global fire regime analysis (García et al., 2022).

We used the Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type (MCD12Q1 (Friedl and Sulla-Menashe, 2019)) data product to consider global land cover types at yearly intervals (2001–2020). We always used the pre-fire land cover and distinguished between grasslands, shrublands and forested areas (evergreen and deciduous broadleaf and needleleaf forests, and mixed forests). We removed those fires on areas characterized by non-burnable land uses (permanent snow and ice, barren, water bodies, unclassified) or in agricultural lands.

Fires were also characterized with the most comprehensive global database on terrestrial protected areas, The World Database on Protected Areas (WDPA) from a joint project between the UN Environment and the International Union for Conservation of Nature (IUCN). WDPA serves as a global repository of information on PAs and provides a wealth of data on the extent, location, and management status of PAs across the different countries and regions worldwide. The WDPA database is updated on a monthly basis. We characterized if each fire spread on a PA based on the pre-fire status of that specific area. Further, we analyze whether the FR attributes were influenced by the different IUCN (International Union for Conservation of Nature) PA categories. UICN is a classification system used to define and categorize protected areas based on their management objectives and level of protection. These categories listed below are widely utilized worldwide to standardize the reporting and management of PAs. We summarized the FR attributes grouped by continent, biome and IUCN category SM2, SM3, SM4, SM5, SM6, SM7 and SM8). However, only those groups with more than 25 fires were statistically analyzed and plotted. Here, we list the IUCN categories we used for our analysis.

1. Category Ia: Strict Nature Reserve - Strictly protected for biodiversity conservation and wilderness protection. Generally, there is no human disturbance allowed, except for monitoring and scientific research.
2. Category Ib: Wilderness Area - Similar to Category Ia, but may allow for some human activities or interventions that do not harm the wilderness character.

3. Category II: National Park - Protected area managed mainly for ecosystem protection and recreation. Human activities are allowed, but should not compromise the area's ecological integrity.
4. Category III: Natural Monument or Feature - Protected area managed for the conservation of specific natural features or species. Limited human activities are typically allowed.
5. Category IV: Habitat/Species Management Area - Protected area managed for the conservation of particular species or habitats through active management interventions.
6. Category V: Protected Landscape/Seascape - Protected area where the interaction of people and nature over time has produced a significant landscape/seascape.
7. Category VI: Protected Area with Sustainable Use of Natural Resources - Protected area managed for both conservation and sustainable use of natural resources by local communities.

We summarized and constrained our analysis on how PAs influence FR attributes based on the distribution of the Earth's terrestrial biomes and ecoregions described by (Dinerstein et al., 2017). Biomes and ecoregions are two complementary frameworks for understanding the Earth's ecosystems. Biomes represent broad ecological zones characterized by similar climate, and vegetation, providing a high-level overview of global patterns. Ecoregions offer a more detailed classification, delineating smaller, localized areas within biomes that share similar environmental conditions, species, and ecological dynamics. While biomes serve as broad categories that capture the overarching characteristics of ecosystems, ecoregions provide a finer-scale perspective, highlighting the diversity and complexity of ecosystems within each biome. Together, these frameworks aid in comprehensively categorizing and conserving the Earth's biodiversity and natural resources on both global and local scales.

2.2. Statistical analysis

We searched for statistical differences on FR attributes (fire size, intensity, rate of spread, and duration) mediated by PAs, also considering the different continents, biomes, ecoregions, and vegetation types (i.e., tree, shrubland, or grassland) associated with each fire. PAs have historically influenced land cover and vegetation characteristics in many regions on Earth, subsequently conditioning fire regime attributes (Fig SM9). Consequently, we restricted the statistical analysis across vegetation types, considering the bioclimatic conditions as the confluence of continent, biome and ecoregion. This strategy avoids making meaningless comparisons between different categories (e.g., shrubland versus grassland fires), thus adequately isolating the possible interactions of PAs with land cover and vegetation types. By comparing fire attributes in PAs and non-PAs within the same ecoregion, we indirectly control for large-scale spatial differences in mean climate. Furthermore, this stratification assumes that PAs and adjacent non-PAs, being in the same ecoregion, are subject to the same large-scale weather patterns and interannual anomalies(Cardil et al., 2023; e.g., a severe drought or an El Niño year). We therefore assume that this interannual weather variability impacts both PA and non-PA areas similarly, allowing us to isolate the effect of protection status from the climate signal. In addition, by aggregating fires across more than two decades, our analysis effectively integrates a wide range of climatic conditions.

We evaluated the effect of PAs on FR attributes through a bootstrapping approach using the Mood's median test. The Mood's test is a nonparametric test that compares the medians of two populations, reporting significant differences caused by the shift in their medians. FR attributes were compared in wildfires occurring within and outside PAs. The test was performed with the mood.medtest function of the R package RVAideMemoire(Hervé, 2022). For each FR attribute, only those combinations with at least 200 fire observations were analyzed, thus testing only fire-prone conditions pooled across biomes, continents, ecoregions, and vegetation types. All combinations were then subjected to a bootstrapping procedure by retrieving 1000 random replicates with 10 % of the total number of fires, ensuring that sufficient records were found within and outside PAs. For each replicate, we retrieved the median of the FR attributes inside/outside PAs and the significance level (p-value) of the test. We then summarized each combination as the percentage of replicates where the test found significant differences as a function of PAs. Finally, we also assessed how the different types of PAs (IUCN) may influence FR attributes inside PAs by comparing means and standard deviations of FR attributes.

3. Results and discussion

This study addresses the complex interplay among PAs, vegetation, and fire regimes across biomes worldwide. Our findings reveal that FR attributes were significantly affected within PAs ($P < 0.05$), and that their role was biome-dependent. The fraction of area protected varied across biomes and continents (Fig. 1) along with the annual BA fraction inside and outside these PAs (Fig. 1 and SM1). In most biomes, the BA fraction inside PAs was smaller than the proportion of area protected (Fig. SM1), therefore, indicating that PAs were less affected by wildfires compared to unprotected areas. For instance, this is the case of the tropical moist forest in South America where almost 30 % of its area was under protection, but BA within PAs accounted for less than 15 % of the total BA in the biome (Fig. 1). In contrast, in tropical grasslands, temperate conifer forest and tropical dry broadleaf forests, the BA fraction inside PAs was larger than the proportion of area protected (Fig. SM1).

Globally, the strictest IUCN protection categories (Ia and Ib) were associated with the lowest annual fraction burned compared to other types of PAs (Fig. 2 and SM2). In contrast, National Parks (IUCN II), PAs designated for habitat management (IUCN IV), and those intended for the sustainable use of natural resources by local communities (IUCN VI) were associated with an increased fraction burned area. This is likely due to the increased human footprint associated with these protection categories(Leroux et al., 2010), and lower law enforcement compared to both Ia and Ib IUCN categories. Previous research found a nonlinearity between IUCN categories and fire occurrence, namely showing a high fire susceptibility of National Parks(Nelson and Chomitz, 2011), which also exhibited the highest absolute BA in our analysis (Fig. SM3). However, these patterns varied across biomes, with Mediterranean forests, temperate broadleaf and mixed forests, temperate grasslands and tropical coniferous forests showing increased fire proneness in the strictest IUCN classes (Fig. 2). This could be derived from an increased biomass accumulation from restricted fire use and reduced land management(Pereira et al., 2012). In contrast, tropical moist forests showed reduced fire intensity and burned areas in PAs, probably due to lower deforestation rates and stronger law enforcement among other factors (Cardil et al., 2020). Thus, our analysis underscores the diverse effects of PAs on BA, which may be influenced by land management practices, human footprint(Leroux et al., 2010) and fire policy(Nelson and Chomitz, 2011; Pereira et al., 2012).

Below, we highlight detailed findings by biome and continent to properly analyze the underlying relationships between PAs and FR characteristics.

3.1. Tropical and subtropical moist broadleaf forests

Tropical moist forests (TMF) merit global attention for their role as carbon storage, sequestering around 25 % of the carbon in the terrestrial biosphere (Bonan, 2008), and as biodiversity hotspots, hosting at least two thirds of the world's organisms (Raven, 1988). They are very sensitive to fire, which entail changes in vegetation type and severe degradation of the ecosystem(Cardil et al., 2020). The global percentage of PA in the TMF biome was 16.6 %. However, it varied among continents, being the Americas the region with the highest area protected (26.2 %), followed by Africa (14.6 %), and Asia and Oceania with only

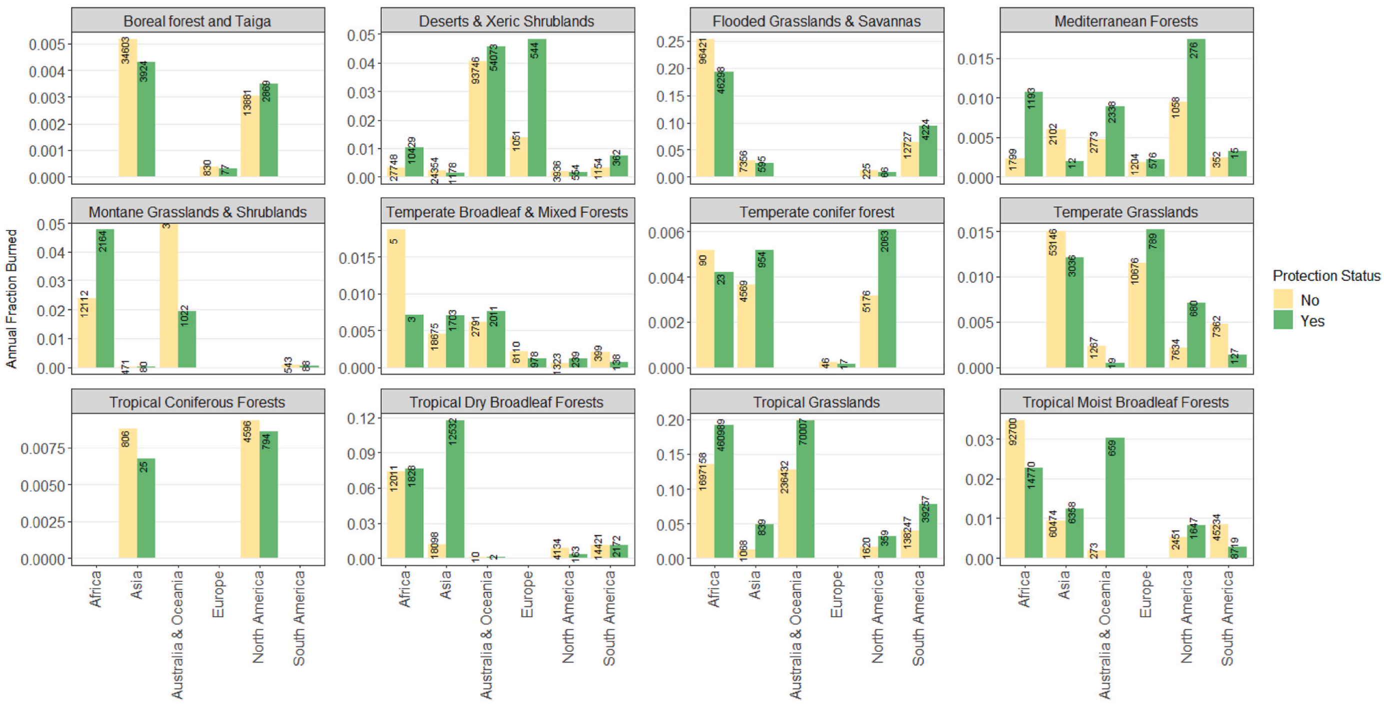

Fig. 1. Annual burned area fraction in protected areas (dark green) and non-protected areas (light yellow) by biome and **continent.** The fraction was calculated by dividing the average annual burned area for PA/non-PAs by the total area protected/non-protected by biome and continent. Labels represent average annual burned area (km^2).

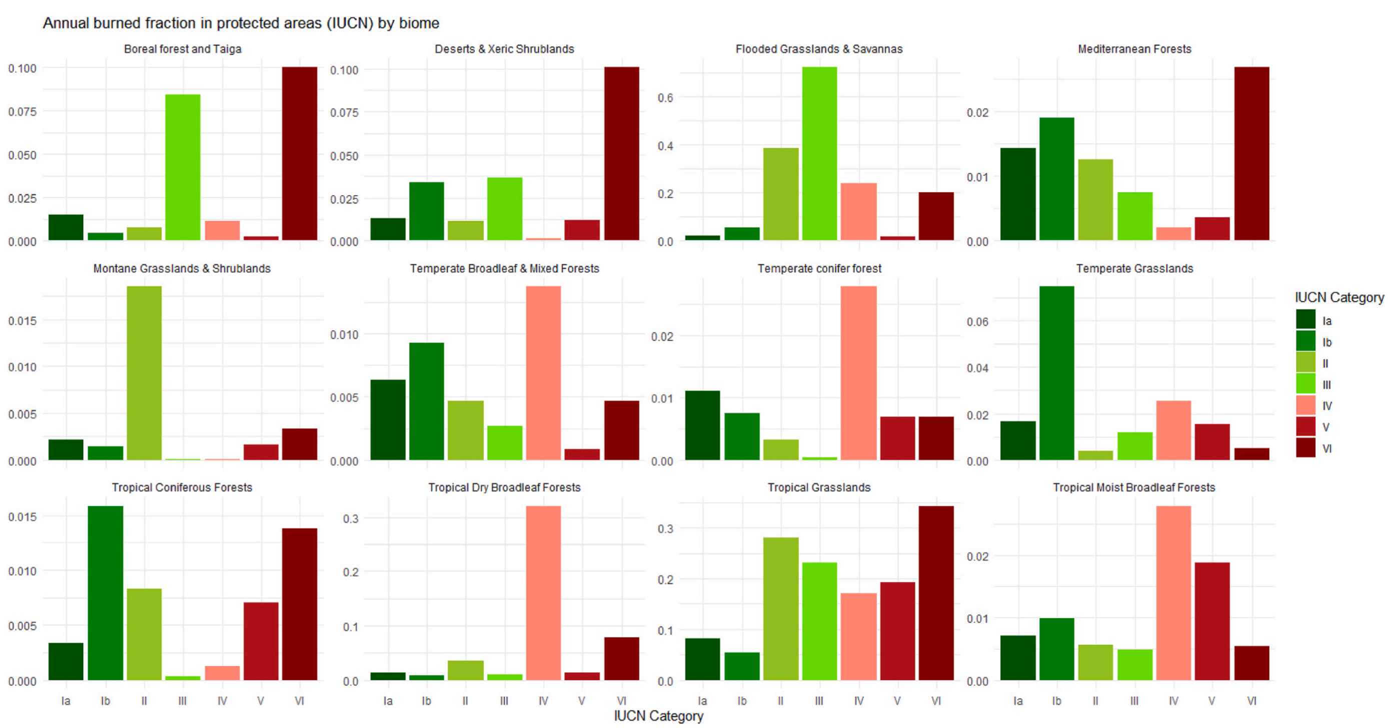

Fig. 2. Annual burned area fraction of protected areas by IUCN category and biome. The fraction was calculated by dividing the average annual burned area for each IUCN category by the total area protected in each category. Category Ia: Strict Nature Reserve; Category Ib: Wilderness Area - Similar to Category Ia, but may allow for some human activities or interventions that do not harm the wilderness character; Category II: National Park; Category III: Natural Monument; Category IV: Habitat/Species Management Area; Category V: Protected Landscape; Category VI: Protected Area with Sustainable Use of Natural Resources.

5.1 % of the territory protected (Fig SM1). The effect of PAs on BA and FR attributes varied across continents. The annual BA fraction within PAs was similar to that of non-PAs area in Asia, Central America and Oceania, while it was significantly lower in Africa (0.033 vs. 0.022, respectively) and South America (0.008 vs. 0.002, respectively), representing the positive effect of PAs in regulating BA in these regions (Fig. 1, SM1). In the Amazon, fires were closely related to deforestation (Cardil et al., 2020) and it has been proved that PAs and law

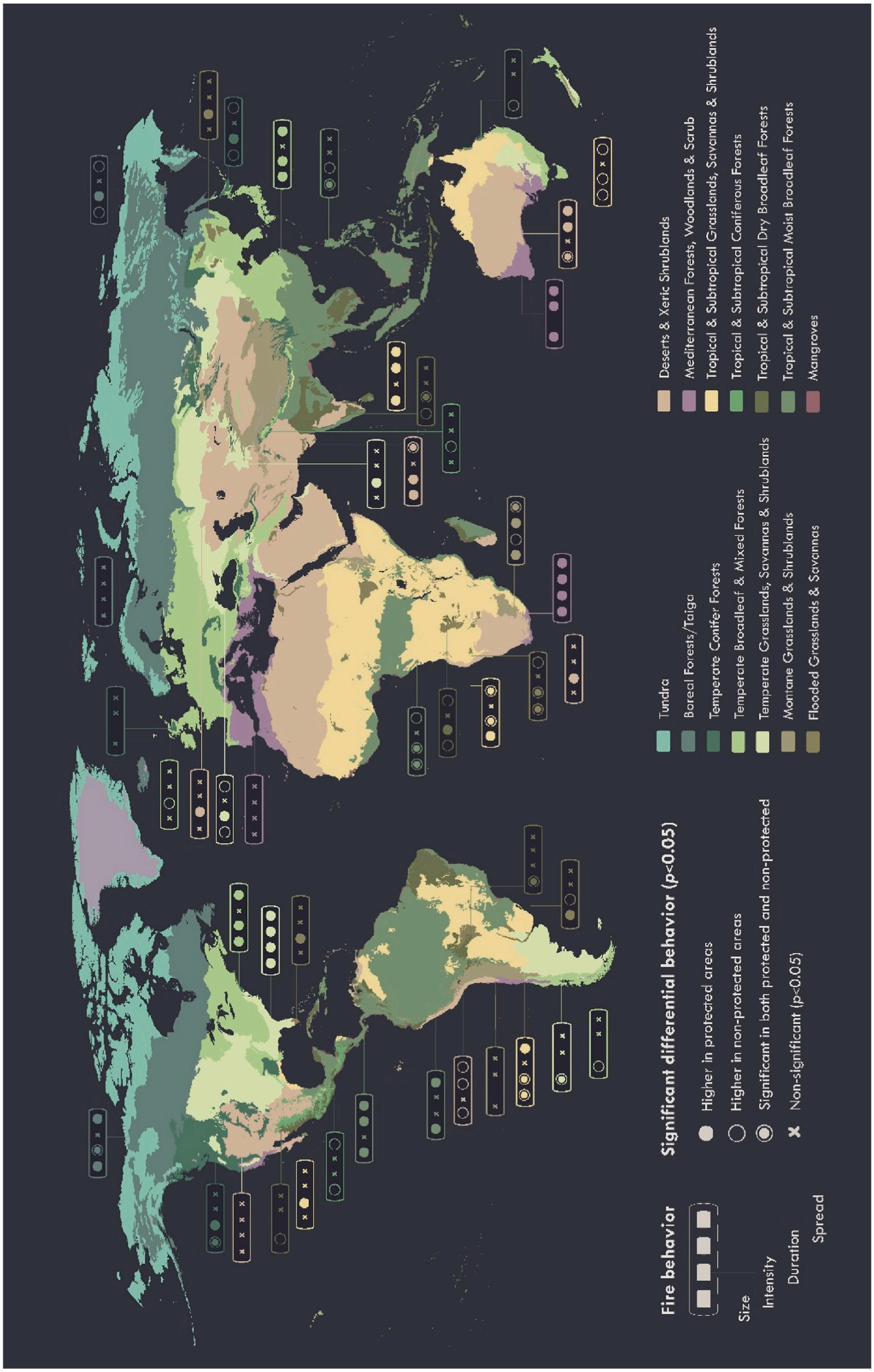

Fig. 3. Effect of protected areas (PA) on fire regime (FR) attributes (fire size, fire spread rate, intensity, and fire duration) by biome and **continent.** The statistical differences in protected vs non-protected areas on FR attributes were conducted through a bootstrapping approach (n = 1000) with a Mood's median test constrained by the biome, continent, ecoregion and vegetation type (grass, shrub, tree) factors.

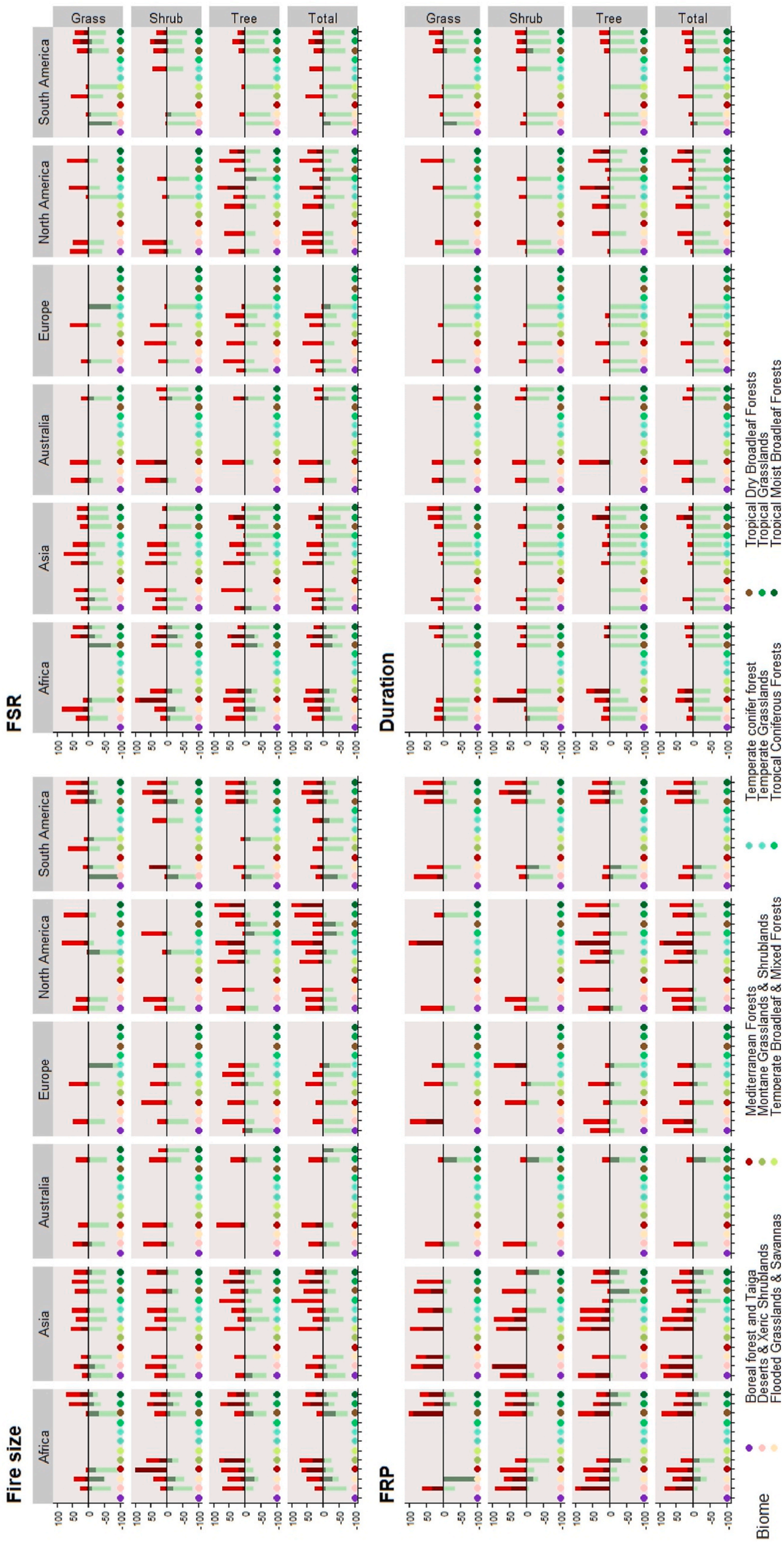

Fig. 4. Influence of protected areas (PAs) on fire regime attributes (a) fire size, (b) fire spread rate (FSR), (c) intensity (Fire Radiative Power, FRP), (d) fire duration (FD), by biome, continent and main vegeta**tion type.** Bars indicate the percent times fires in PAs displayed a median value greater (positive values) or lower (negative values) than fires in non-PAs using a bootstrapping approach (n = 1000) with the Mood's median test. Intense color tone indicates significant ($p < 0.05$) differences.

enforcement support its reduction(Rodríguez et al., 2013). Increased deforestation contributes to the loss of canopy cover, shifts vegetation toward more fire-prone fuel types (e.g., lianas) and promote drier local and windier conditions (Ortega et al., 2023), thereby exacerbating fuel flammability and fire activity(Cardil et al., 2020). Our findings are in line with previous research that pointed out a decrease in fire incidence and BA in PAs by two or three orders of magnitude(Adeney et al., 2009; Nelson and Chomitz, 2011). Within PAs, our results show lower fire incidence in the strictest IUCN categories (Ia, Ib, II and III).

Fires were significantly larger in PAs compared to non-PAs in Africa, Asia and the Americas probably due to a longer fire duration and higher rate of spread (Americas) (Fig. 3). This behavior may have been linked to anthropogenic deforestation, which was more frequent outside PAs and is known to boost fire activity(Adeney et al., 2009) by increasing the number of small fires spreading on the deforested areas(Cardil et al., 2020). Roadlessness and remoteness may also influence the amount of deforestation fires(Adeney et al., 2009; Nelson and Chomitz, 2011) and limit firefighting efforts. Thus, a delayed detection and response to fire together with limited suppression resources may make it challenging to control fires once they start in PAs. A reduction in fire intensity in Asia was found in TMF areas, probably because PAs reduced deforestation and loss of canopy cover, limiting fuel flammability.

3.2. Tropical and subtropical grasslands, savannas and shrublands

Tropical grasslands are among the world's most fire-prone biomes on Earth(Bowman et al., 2009), and fires burned more than 80 % of the total BA in Africa, the continent with the highest fire activity, followed by South America and Oceania (>60 %). This biome has evolved with fire (Beerling and Osborne, 2006; Crisp et al., 2011) and is one of the most flammable biomes of the world, with among the highest fire return intervals(Fig. 1). It also has a relatively low protection percentage (between 15 and 20 %, Fig SM1) and is at the forefront of rapid biodiversity loss (Bond, 2016). After a short vegetative cycle, the prevalence of a long dry season leading to widespread curing of fine fuel and high propensity for both lightning and anthropogenic (agricultural burning, grazing management, accidental fires) ignitions create fire-prone conditions for recurrent fires and high burned-area fractions (van der Werf et al., 2017; Lehmann et al., 2014; Archibald et al., 2010). The importance of fire in maintaining vegetation is well recognized(Archibald et al., 2017). In some places (e.g. South Africa, Australia, and more recently Brazil) fire is used as a management tool for biodiversity conservation and fire-regime regulation(Franke et al., 2024; Price et al., 2012; Russell--Smith et al., 2020; Trollope and Trollope, 2004). Our findings highlight that the annual burned area fraction in PAs was higher compared to non-PAs within the biome in all continents(Fig. 1. In addition, fires in PAs were significantly larger, longer and faster but less intense (Fig. 3). Although the exact drivers are context-dependent, usually outside PA there is extensive fire suppression promoted by policies as well as land use change(Moura et al., 2019). However, many PAs in this biome are very remote and large, difficult for active wildfire suppression. Furthermore, as mentioned above, in many PAs fire is being used as a management tool. These results emphasize the important role of PAs in this biome in sustaining to maintain fire level dynamics that support the unique diversity and ecosystem functioning of these biodiversity-rich hotspots.

3.3. Tropical & subtropical dry broadleaf forests

Tropical dry forests are characterized by a distinct dry season and are subject to various threats, including climate change, population density and human pressures such as deforestation or agricultural conversion. More than half of the tropical dry forest biome is located in South America including Brazil's Caatinga region, Bolivia Chiquitania, Peru's Pacific coast, Ecuador's Tumbes-Chocó-Magdalena region, and Argentina's Chaco region, where we observed notable differences in fire sizes compared to other continents. In general, fires in South America were larger within PAs compared to non-PA whereas the opposite trend was found for Africa and Asia. The effect of PAs in South America on FR attributes was also influenced by vegetation types. Thus, fires in forested areas were larger within PAs, while those in grass and shrub areas were smaller in PAs (Fig. 3). Additionally, fires in IUCN categories I and II were significantly larger, faster and more intense than in other protection categories. This suggests that protection policies and land management practices may lead to increased fire behavior due to higher fuel loads and greater continuity across the landscape. Indeed, Bonilla-Bedoya et al. (2018)(Bonilla-Bedoya et al., 2018) highlighted that certain national parks are under considerable threat from economic interests, natural resource extraction, and the activities of indigenous communities, influencing fire activity as reflected in our findings (Fig. 2 and SM4).

In Africa and Asia, fires in non-PAs were typically larger and faster-spreading but less intense, especially in forested areas (Fig. 4). This aligns with findings from Frappier-Brinton and Lehman (2022) (Frappier-Brinton and Lehman, 2022) in Africa, who reported lower fire frequency within national parks compared to their surrounding areas (Fig. 1). The lower fire intensity in non-PAs may be linked to significant tree loss, as noted by Phelps et al. (2022)(Phelps et al., 2022), leading to a higher prevalence of surface fires. In Asia, a similar pattern was observed, with increased annual BA fraction in PAs and fire sizes likely influenced by factors such as population density, percentage of tree cover loss, and proximity to urban areas(Biswas et al., 2015). In North America, fires were also found to be larger in non-PAs, although further studies are needed to fully understand the interactions between fire, human pressures, and environmental conditions within protected areas (Mansuy et al., 2019).

3.4. Tropical & subtropical coniferous forests

Tropical and subtropical coniferous forests are mostly found in Central America and in submontane elevations throughout much of Southeast Asia. These forests in North America are primarily found in Mexico, particularly in the Sierra Madre mountain ranges and the Trans-Mexican Volcanic Belt where around 20 % of the territory is protected (Fig. 1). The traditional use of fire and its management has been widely boosted in PAs, driven by the Mexican government (CONANP)(Elvira et al., 2011). CONANP manages the national system of PAs and develops fire management programs including training, community engagement, risk assessment and support with essential supplies for firefighting personnel. We found a decrease in BA (Fig. 1), fire size and rate of spread in PAs compared to non-PAs (Fig. 3). Additionally, most of the wildfires analyzed in this biome occurred in areas with IUCN protection II and VI (Fig SM4). Fires in category II were significantly smaller and slower than category VI (Fig SM7), probably indicating that more strict figures of protection may lead to a reduction in the fire activity (Fig. 2; category II versus VI). Timber harvesting and illegal logging in less strict PAs, as well as in areas outside of them, may also explain our findings, as these activities drastically modify fire regimes by increasing fuel loads, which in turn boosts the spread of wildfires(Myers and Rodríguez-Trejo, 2009).

In Asia, this biome is anecdotic as well as its percentage protected (Fig. 1). Tropical coniferous forest can be found in the foothills of the Himalayas where pine forests are usually characterized by open canopies under which grass is maintained by frequent wildfires. More than half of coniferous forests are productive and this fact may explain the more intense fires in non-PAs (Fig. 3) due to increased fuel load after timber harvesting.

3.5. Boreal forest and taiga

The boreal biome represents 27 % of the global forest cover, stores ca. 48 % of the total forest soil organic carbon and contains almost half of the world's remaining intact forests(Potapov et al., 2008). Wildfires are a prevalent natural disturbance driving key ecological dynamics in this biome(Rowe and Scotter, 1973) but are predicted to increase in size, intensity and frequency due to global change(de Groot et al., 2013). Understanding how PAs influence fire regime in this biome is crucial to ensure that these areas are having the desired outcome in terms of fire management. Around 10–15 % of this biome was protected across the three continents (Asia, Europe and North America), but the proportion of BA within PAs was similar or slightly smaller (Fig SM1), especially in the strictest IUCN PAs (Ib and II). However, fire intensity was greater in PAs both in North America and Asia (Fig. 3). Boreal forests in PAs are often older than in non-PAs as the latter tend to be managed in short rotations(Määttänen et al., 2022), which translates into more fuel available to burn and greater fire intensity in older forests(Thompson et al., 2017).

The effect of PAs on fire size and rate of spread, on the other hand, varied across continents. In North American boreal forests, fires tend to be larger and spread faster within PAs (especially in I and II IUCN categories), whereas the opposite is true for Asian boreal forests (they are larger and faster outside PAs) and no significant differences were found in Europe (Fig. 3). These continental differences could stem either from differences in the designation and management of PAs, in fire management approaches and/or from intrinsic differences in fire regimes. Most wildfires in North American boreal forests are high-intensity crown fires, while they tend to be low-intensity surface fires in Eurasia(Kharuk et al., 2021; Rogers et al., 2015). This is likely linked to the distinct adaptations to fire that the dominant tree species have developed(Rogers et al., 2015): in the boreal of North America, the dominant species have evolved to favor spread and be consumed by crown fires (i.e., fire embracers – black spruce, jack pine), whereas in Eurasia forests became fire resistors (e.g., larch and Scots pine)(Rogers et al., 2015). In Europe, fire suppression has been very effective since the 1990's(Mouillot and Field, 2005) both inside and outside PAs, resulting in a small annual BA fraction (Fig. 1). Additionally, forested PAs located in human-transformed areas of Fennoscandia are exposed to their surroundings with the effects being carried over to the PAs themselves (Määttänen et al., 2022), which could explain the lack of differences in fire regime between PAs and non-PAs in this region.

3.6. Montane grasslands and shrublands

The Montane Grasslands and Shrublands biome is characterized by a high diversity and distinct vegetation assemblage that thrives in mountainous regions around the world including the Andes in South America, the Himalayas in Asia, and the East African Highlands (Christmann and Oliveras, 2020). This biome is situated at moderate to high elevations and represents the transition zone between forested areas at lower elevations and the alpine zone, where vegetation is limited by cold temperatures. Grasses and shrubs are the predominant vegetation in this biome. Trees are often sparse or stunted due to the challenging conditions at higher elevations. Human activities, such as agriculture, grazing, and infrastructure development, can impact montane ecosystems. Overgrazing by livestock and conversion of land for agriculture can lead to habitat degradation and loss of biodiversity. We only found significant differences in Africa where PAs burned disproportionately more, much higher than their protected proportion, mainly in National Parks (IUCN II). Fires were larger, lasted longer but less intense than non-PAs. This could be attributed to the fact that most of this biome is highly fragmented and degraded in non-PAs, used for extensive grazing and local crops. Additionally, in South Africa's montane grasslands invasive species have shown to reduce fire spread and burn probability(McGranahan et al., 2018). Thus, in PA's, fires can naturally spread across a more continuous layer of herbaceous and shrub vegetation.

3.7. Mediterranean forests, woodlands and scrub

Fires in the Mediterranean biome are usually fast and intense, occasionally exceeding fire suppression capabilities and becoming large. Most of the BA occurs during the summer season and fire spread is mediated by fuel load and moisture content. Our results show that PAs were affected by fire proportionally to the extent of land they occupy (Fig. 1), similarly to previous research(Resco De Dios et al., 2024). Fires spreading on PAs were more frequent in woodland areas (Fig SM9) compared to areas with no protection, probably because PAs usually forbid the use of fire and restrict human activities. Notice that the strictest IUCN categories (Ia and Ib) showed increased BA compared to other categories (II, III, IV and V; Fig. 2). This results in a dearth of forest management and a change in land uses with an increased biomass available for combustion. Previous research pointed out the exacerbation of the fire paradox in PAs(Pereira et al., 2012), including increased burn severity(Resco De Dios et al., 2024). Our research revealed that PAs increased all FR attributes in Africa (Fig. 3). Similar patterns were observed in Australia where we found increased fire size, rate of spread and duration of wildfires, especially in tree areas (Fig. 4). This highlights the effect of biomass accumulation and extends it to other FR attributes, especially size, duration and spread. However, we did not find significant trends in Europe probably because the mediterranean landscapes are very fragmented and fire suppression capabilities are very strong, which contributes to fading these relationships.

3.8. Flooded Grasslands and Savannas

Flooded Grasslands and Savannas are highly biodiverse open ecosystems(Barbosa da Silva et al., 2016) whose composition and functioning is regulated both by seasonal floods and fires(Damasceno-Junior et al., 2021), which are increasingly altered by rising human pressures and inefficient protection strategies(Marques et al., 2021). PA coverage displayed a strong gradient across this biome that went from over 50 % in North America to around 40 % in Africa and less than 20 % in Asia and South America (Fig. 1). PAs reduced BA on all continents except South America (Fig. 1), where fire size was also higher in PAs, particularly in National Parks (IUCN II; SM5). Flooded grasslands and savannas are characteristic of the Pantanal biome on this continent, which has experienced catastrophic wildfires in recent years, predominantly affecting large continuous grassland and forest patches, many of which were found within PAs, whereas non-PAs are more fragmented and impacted by anthropogenic activities(Correa et al., 2022; de Barros et al., 2022; Marques et al., 2021). However, notice that fires in PAs were less intense and tended to spread more slowly (Fig. 4). Conversely, North America's protected wetlands, primarily in Florida, are managed through effective fire management plans that use continuous prescribed burning to mitigate large wildfire occurrence(Menges et al., 2017), by promoting frequent and low intensity fires favoring herbaceous plant renewal and tree growth(Lugo, 1995). In Africa, shrublands may have been favored in degraded public lands, leading to a higher BA and faster fires in non-PAs. Fire intensity was also higher in grasslands in non-PAs, whereas lower in shrub-tree areas, probably due to the forest management to maintain wetlands commercial plantation's structure(Job et al., 2020; LB Luvuno and Kirkman, 2016). In Asia, the largest flooded grasslands are concentrated in the North East of China, where fire management within PA is overcome, in terms of BA, by consistent agricultural fire practices done outside PAs(Wang et al., 2019). However, fires were more intense in PAs due to fuel accumulation.

3.9. Deserts & xeric shrublands

Deserts and xeric shrublands form the largest terrestrial biome, covering almost 20 % of Earth's land. Fire is a natural regulating factor of this biome, governing the distribution of shrublands and semiarid grasslands(McClaran and Van Devender, 1995). Nonetheless, over the years, fire suppression policies leading to shrubland encroachment, as well as the opening of spaces for fire intolerant species, due to overgrazing, has resulted in a considerable disruption of the natural fire regime(McClaran and Van Devender, 1995). PAs coverage appears low if compared to other biomes, exceeding the threshold of 20 % just in Oceania, and remaining around 10 % in the other continents (Fig. 1). PAs effectively reduce burnt area in Asia, Australia, and North America, while they boost it in Africa, Europe, and South America (Fig. 1).

In Asia, strict protection and fire exclusion within PAs reduced burnt area though leading to fuel accumulation and to higher intensity and larger fire events(Saladyga et al., 2013) (Figs. 1–4). Fires outside PAs are rare and mostly unintentional due to the infrequent use of fire as a tool, while common extensive grazing activities ensure grassland maintenance and reduce fire hazard(Kamp et al., 2016, p. 2015; Saladyga et al., 2013, p. 201). In Africa, we found larger burnt areas within PAs, possibly due to the common use of fire in illegal hunting(Palumbo et al., 2011) (Fig. 1). The higher fire intensity within PAs is not surprising and reported by previous studies(Palumbo et al., 2011). In South America, PAs were correlated with higher fire spread, size and duration (Antongiovanni et al., 2020) (Fig. 3). In North American desert and dry shrublands, mainly present in the west of the United States and in the north of Mexico, the burnt area reduction effect associated with PAs was confirmed by prior research(Mansuy et al., 2019).

3.10. Temperate broadleaf & mixed forests

Temperate broadleaf and mixed forests are characterized by contrasted fire-related functional traits, encompassing both highly fire sensitive ecosystems (e.g., Beech forests(Maringer et al., 2016)) and strongly fire adapted ones (e.g., Australian eucalypts(Adie and Lawes, 2023)). Approximately half of this biome is protected in South America, where it is mainly located at the foothills of the Chilean Andes, while around 30 % is protected in Europe and Oceania (Fig 1; Fig 3). In Asia and North America, where temperate broadleaf and mixed forests cover a considerable area, respectively, in central China and in the eastern USA and Canada, just around 10 % of this biome results under PA (Fig 1; Fig 3). Although previous research showed disproportionate increases in BA in PAs within this biome in Australia, where we did not find this effect(Resco De Dios et al., 2024), our results show that PAs reduced BA in Europe and South America, in line with this research(Resco De Dios et al., 2024) (Fig. 1). Additionally, the most stringent Protected Areas (PAs) exhibited relatively high values of the annual burned fraction (Fig. 2). In Europe BA reduction within PA (Fig. 1) might be explained by the strict protection approaches often adopted for PA management (Pereira et al., 2012; Sebek et al., 2015), and by the low flammability characterizing this biome in this continent, that facilitates fire suppression in highly valued landscapes such as PA (Pezzatti et al., 2009). In South America, fires occurring outside PA were significantly larger. Here, PAs preserve native and fire sensitive vegetation whereas in productive areas outside PAs, *Pinus* and *Eucalyptus* plantations have been spreading, forming a heterogeneous mosaic of vegetation increasing fire behavior. In Asia and North America, fires were larger, more intense and faster in PAs that might be associated with the common fire exclusion practices within PA, that have already been tested to increase fire size and intensity(Chang et al., 2007) (Fig. 3).

3.11. Temperate conifer forests

The temperate conifer forests host some of the most massive forms of terrestrial life such as the coastal redwood (*Sequoia sempervirens*) forests (Waring, 2002), represent 9 % of the terrestrial biomes in North America, and 4 % in Europe and Asia, and their rate of protection ranges between 15 and 40 % across continents (Fig. 1). Proportionally, larger areas were burned within PAs compared to non-PAs in North America, whereas the opposite was found for Europe and Africa (Fig. 1). In North America, the longstanding strategy of aggressive fire suppression since the 1930's(Mouillot and Field, 2005) has, in recent decades, been complemented by allowing wildfires in remote areas to burn under moderate fuel loads and mild weather conditions to reduce hazardous fire behavior(Prichard et al., 2021). These managed wildfires are becoming a common strategy within PAs but remain uncommon outside national parks and wilderness areas due to concerns about fire escapes and potential damage to resources(Huffman et al., 2020). This differential approach to wildfire management between PAs and non-PAs likely explains why proportionally more area is burned within PAs in North America. Conversely, until recently, fire management in Europe has been dominated by suppression and total fire exclusion policies both inside and outside PAs. Since most ignitions in central Europe are deliberate or accidental and tend to occur around urban areas, agricultural zones, and roads, it is not surprising that a proportionally greater burned area occurs outside PAs in Europe.

Considering that this biome is increasingly experiencing a disproportionately high rate of extreme wildfire events(Cunningham et al., 2024), it is crucial to understand how PAs in these temperate conifer forests modulate FR. Fire intensity was greater inside PAs in both North American and Asian temperate conifer forests(Cunningham et al., 2024). Because these forests tend to be intensively managed for timber production outside PAs(Waring, 2002), mechanical fuel reduction could explain why forests outside PAs burned at a lower intensity. However, Parks et al. (2023)(Parks et al., 2023) show that fuel accumulation resulting from historical fire exclusion plays a larger role than logging activities on the prevalence of severe stand-replacing fires in western US conifer forests, concluding that low severity fire begets low severity fire in this biome.

3.12. Temperate grasslands, savannas & shrublands

Temperate grasslands, savannas and shrublands is a biome that includes the Great Plains (United States and Canada), the Pampa and Patagonian grasslands (Argentina, Chile, Uruguay and Brazil), the steppes of Russia and Central Asia (including Mongolia), and the veldt of South Africa and parts of the Sahel. Biome dynamics are largely modulated by land cover changes, agriculture and pasture practices (in some cases overgrazing and pasture abandonment), wildfires and afforestation. Although temperate grasslands are one of the least protected biomes on Earth(Smelansky and Tishkov, 2012), FR attributes were modulated by PAs and the strictest IUCN categories (Ib) showed the highest values of annual burned area fraction (Fig. 2). In North America, fire size, intensity, velocity and duration was higher in PAs due to the effects of increased encroachment by woody vegetation and the long-term practice of fire suppression and exclusion, which has altered the structure and quantity of fuels in the landscape(Parker et al., 2022). Similarly, In Europe, the "zero-fire" policy in PAs could be the cause of its higher fire intensity due to the increased shrub encroachment in grassland areas, thus increasing the fuel load and the probability of more intense fires reducing the fire size and rate of spread(Starns et al., 2019). In Asia, fires inside the most strictly PAs (Ia and Ib) were significantly larger, faster and more intense, probably due to the encroachment effect as well and less grazing pressure compared to the current increasing cattle population(Hao et al., 2021). This is consistent with a reported increase in the number of fires occurring along the Mongolian-Russian border, likely due to prevailing wind direction and the mixed forest and forest-steppe landscape(Kazato and Soyollham, 2022). Additionally, it has been reported that forest loss is higher inside PAs than outside in Mongolia and parts of Central Asia and Europe(Heino et al., 2015), which may suggest that this encroachment effect could alter fire behavior within PAs, potentially leading to significant repercussions.

CRediT authorship contribution statement

A. Cardil: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M. Rodrigues:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **D. Ascoli:** Writing – review & editing, Writing – original draft, Conceptualization. **M. Ortega:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **T. Quiñones:** Data curation. **M. Erdozain:** Writing – review & editing, Writing – original draft. **I. Oliveras Menor:** Writing – review & editing, Writing – original draft. **G.L. Spadoni:** Writing – review & editing, Writing – original draft. **J. Ramírez:** Writing – review & editing, Writing – original draft. **J.R. Molina:** Writing – review & editing, Writing – original draft. **F. Mouillot:** Writing – review & editing, Writing – original draft. **C.A. Silva:** Writing – review & editing, Writing – original draft. **M. Mohan:** Writing – review & editing, Writing – original draft. **C. Martínez-Bentué:** Writing – review & editing, Writing – original draft, Visualization. **S. de-Miguel:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Code availability

The processing codes used in this study are available from the corresponding authors upon request.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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