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Key Points:

- Evaluated burned area, climate, and fuel relationships in temperate desert, shrub, and forest ecoregions in N. & S. America and Europe
- All regions have different patterns of burned areas between the dry fuel-limited and wet climate-limited conditions
- Sizes of individual fires, total burned area, and fraction of area burned have been highest in western N. America and smallest in Europe

Supporting Information:

Supporting Information may be found in the online version of this article.

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Fire, Fuel, and Climate Interactions in Temperate Climates

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Abstract Temperate regions around the world are experiencing longer fire weather seasons, yet trends in burned area have been inconsistent between regions. Reasons for differences in fire patterns can be difficult to determine due to variable vegetation types, land use patterns, fuel conditions, and human influences on fire ignition and suppression. This study compares burned areas to climate and fuel conditions in three temperate regions: the desert, shrub, and forest ecoregions of western North America, west-central Europe, and southwestern South America. In each region the mean annual aridity index (AI, precipitation over potential evapotranspiration) spans arid to humid climates. We examined how the fraction of area burned from 2001 to 2021 varied with mean annual AI, mean aboveground biomass, and land cover type distributions. All three regions had low fractions of area burned for the driest climate zones (AI < 0.5), a sign of fuel limitation to burned area. Fraction of area burned increased with mean aboveground biomass for these dry zones. Fraction of area burned peaked at intermediate AI (0.7–1.5) for all regions and declined again in the wettest climate zones (AI > 1.5), a sign of climate limitation to burned area. Of the three regions, western North America had the highest burned area, fraction of area burned, and fire sizes. Fragmentation of vegetation patches by the high Andes Mountains in southwestern South America and by intensive land use changes in west-central Europe likely limited fire sizes. All three regions are at risk for future wildfires, particularly in areas where fire is currently climate limited.

Plain Language Summary Warmer temperatures around the world are lengthening fire seasons, leading to large wildfires. We compared the burned areas in three regions that have large variations in climate and vegetation: western North America, west-central Europe, and southwestern South America. We found that in the driest parts of each region, very little area burned because the vegetation is sparse, limiting the spread of fire. The area burned was also low in the wettest parts of these regions because the weather conditions were often not conducive to fire. The percent of area burned was highest in the intermediate climates, which have both enough vegetation for fire to spread and dry enough weather for wildfire. Among the three regions, the burned areas have been largest in western North America, which has the largest continuous extents of vegetation to burn. In southwestern South America, the forests and shrublands are broken up by the high Andes Mountains, and in west-central Europe, extensive land use has limited the size of burnable areas. All three regions are at risk for large wildfires in the future, especially in the wettest areas where climate warming will make fire weather more likely.

1. Introduction

As fire weather seasons have lengthened around the world, wildfire has become a widespread and growing concern (Jolly et al., 2015; Jones et al., 2022). Yet despite the global increases in temperature, wildfire area has

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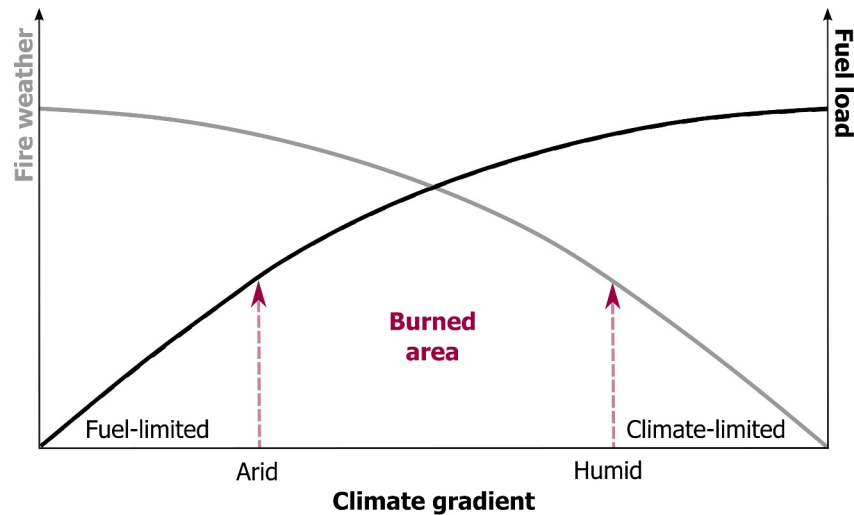


Figure 1. Conceptual model of changes in fire weather, fuel load, and burned area across a climate gradient. The burned area is limited by two factors along a gradient of aridity. On the left side of the graph, burned area is limited by fuel because of low biomass and gaps between vegetation in arid regions. On the right side of the graph, more humid climates rarely have weather conditions conducive to fire, making the burned area climate-limited. In climates that fall between these extremes, a combination of frequent fire weather and sufficient vegetation can lead to large burned areas.

not increased everywhere (Jones et al., 2022), as it is controlled by multiple interacting factors. First, are top-down controls like climate and weather. Some areas, such as western North America (Coop et al., 2022), Europe (Grünig et al., 2023), and Southwestern South America (Carrasco-Escaff et al., 2024; Cordero et al., 2024; Miranda et al., 2023) have experienced increased aridity, which has resulted in increased burned areas and extreme fire behavior. Meanwhile, other locations have seen either an increase in precipitation (Konapala et al., 2020), leading to fuel that can be burned at any time, or desertification (Burrell et al., 2020), leading to less available fuel. The fuel itself is a bottom-up control on burned area (Fernandes et al., 2016; Parks et al., 2012). Larger burned areas are more likely to be possible where vegetation is flammable, dense, and spatially extensive without large gaps that break the continuity of fuel.

A conceptual view of these controls suggests that fire is fuel-limited in the driest climate conditions, climate-limited in wetter conditions (Rego et al., 2021), and peaks in intermediate zones that balance frequent enough fire weather with high fuel loads (Pausas & Bradstock, 2007). In a graphical representation of these broad, regional-scale climate-fuel-fire relationships, the fuel and climate limitations set upper and lower bounds on likely fire extent (Figure 1). Fire ignitions, vegetation structure, understory fuels, invasive species, fuel moisture, size of vegetation patches and gaps, and fire suppression may all alter this relationship (Hessburg et al., 2019; Krawchuk & Moritz, 2011; McWethy et al., 2013; Whitlock et al., 2015). However, the conceptual view of the interaction between fuel and climate controls on burned area is a useful frame of reference for comparing burned areas between regions and anticipating future changes in fire regime.

Globally, wildfires vary greatly across this gradient of fuel limited to climate limited systems (Bowman et al., 2009). In this study, we examine relationships between climate, fuel, and burned area in three temperate regions: the desert, shrub, and forest ecoregions of western North America, western and central Europe, and southwestern South America (Figure 2). Each of these regions has a wide range of climates from arid to humid, as well as a broad range of fuel types including grasses, croplands, shrublands, and forests. All three regions are at temperate latitudes with climate gradients that contribute to the vegetation transitions from shrublands to forests. However, these regions also have varied human histories and accompanying variability in fire regimes.

Western North America has a vast expanse of shrublands in the south transitioning to forests in the north and at higher elevations of mountains (Figure 3). Prior to colonial settlement in the 1800s, many of these landscapes were actively managed with fire by indigenous communities (Long et al., 2021; Roos et al., 2021), and fire regimes varied from short intervals of 2–20 years in low elevation pine woodlands to 100+ year fire return intervals especially in higher elevation, snow bound ecosystems (e.g., Schoennagel et al., 2004). However, over a century

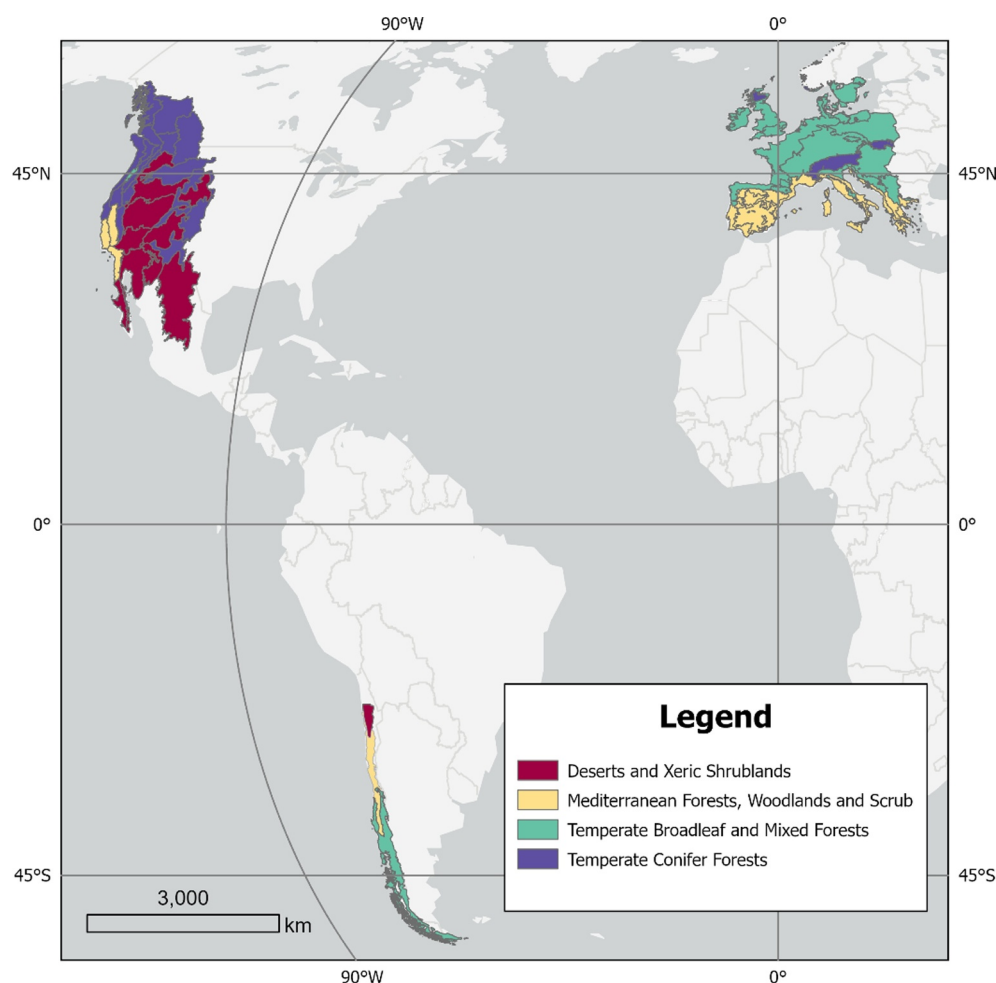


Figure 2. Map of study areas in western North America, west-central Europe, and southwestern South America showing extent of ecoregions (TNC, 2009).

of fire suppression combined with climate change has altered many of these fire regimes (Hessburg et al., 2021). Many ecosystems have seen a lengthening in fire return intervals over the past century (Hessburg et al., 2019), more recently followed by an increase in the amount of fire in the last several decades (Hart et al., 2019; Higuera et al., 2021; Syphard et al., 2009).

West-Central Europe has a long history of intensive human occupation for agriculture, which has led to a large extent of the area being deforested. Shrublands are present only in the southern extent near the Mediterranean coast, and forests are interspersed with deforested areas throughout most of the rest of the region (Figure 3). Land use changes, increases in wildland–urban interface (WUI) areas, and fire suppression activities have significantly altered natural fire regimes across Europe (Ganteaume et al., 2021; Moreira et al., 2020). The highest fire activity is concentrated in less than the 40% of the territory, mostly in the Iberian Peninsula, southern France, Italy, the Adriatic and part of the Balkans (Galizia et al., 2022). Southern Europe experiences frequent and intense wildfires due to its hot, dry summers, episodes of extreme heat and drought, and the considerable fuel loads accumulated over the last decades (San-Miguel-Ayanz et al., 2023). Because the human influence is so large and spatially variable, fire activity can be modified by a high level of intentionality and fire-fighting response in many of those areas.

Southwestern South America includes mainly shrublands in the north transitioning to forests in the south. The central valley west of the Andes from 33° to 42°S is largely used for agriculture and tree plantations. Gradients in latitude and elevation determine distinct transitions in vegetation types; from evergreen to deciduous forests and from deserts to scrublands (Godoy et al., 2019; Nanavati et al., 2022). Lightning frequency is low in this area, and

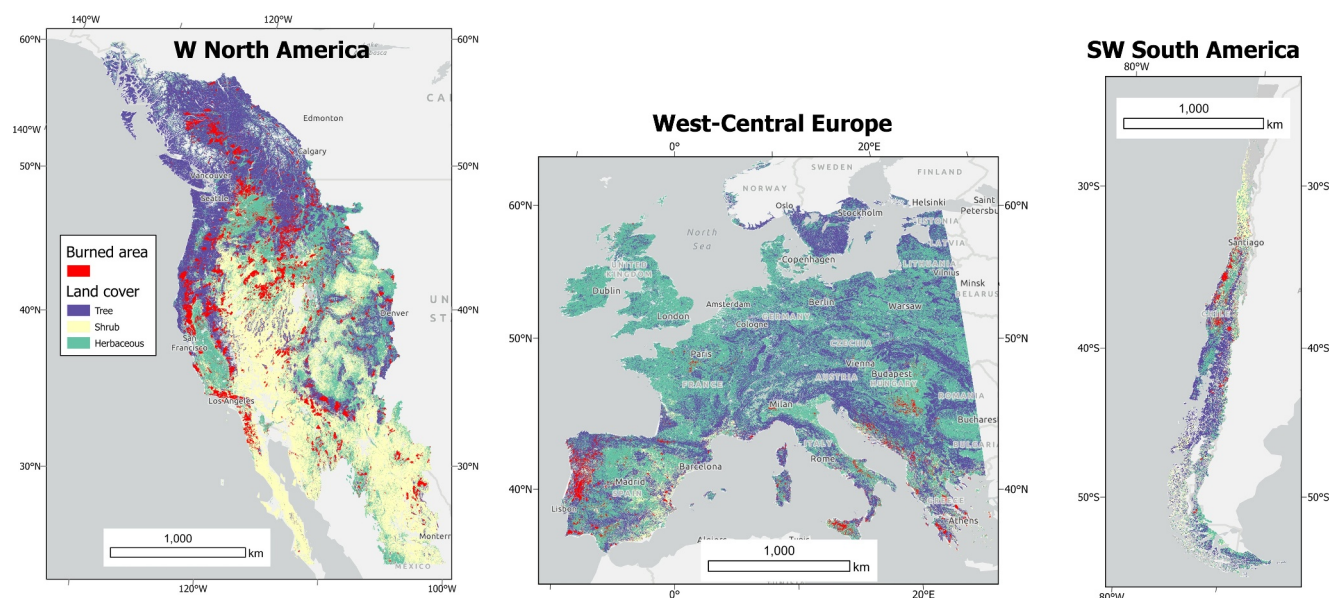


Figure 3. Distribution of major land cover categories in 2000 (GLANCE, Friedl et al., 2022) and wildfires from 2002 to 2021 (GlobFire, Artés et al., 2019).

most fires are human-caused (Úbeda & Sarricolea, 2016). The region's fire regimes have been explained by the interaction between past human activities, which shaped fuel distribution and modified ignition frequency, and climate conditions (Armesto et al., 2009; González et al., 2020; Nanavati et al., 2022).

The unique land use and fire histories of these three regions are likely to affect how their historical burned areas vary across climate gradients. In this study we explore how burned areas vary between these regions and how these burn patterns relate to both climate and fuel.

2. Methods

Temperate regions were selected as a focus for this study because they exhibit gradients in fuel and aridity that may affect fire patterns. The focus regions have experienced both high fire probabilities (Krawchuk et al., 2009) and increasing fire season length (Jones et al., 2022), yet their trends in burned area vary both within and between regions (Jones et al., 2022). We chose three temperate regions with available 30-m land cover type maps from GLANCE (Friedl et al., 2022): western North America, west-central Europe, and southwestern South America (Figure 2). The study area extent in each region are Temperate Conifer Forests, Temperate Broadleaf and Mixed Forests, Mediterranean Forests, Woodlands and Scrublands, and Deserts and Xeric Shrublands (TNC, 2009).

Within each study domain, we obtained fire perimeters from 2002 to 2021 from GlobFire (Artés et al., 2019). For South America, the start and end dates were shifted 6 months in advance (July 2002–June 2022). Using the fire perimeter data, we documented total burned areas, the number of times each location burned over the 20-year time period, and the size distributions of burned areas.

To characterize the climate gradient in each region, we computed the mean annual aridity index (AI) for the same time period. The AI is defined as the mean annual precipitation (P) over the mean annual potential evapotranspiration (PET). These values were obtained from Terra Climate (Abatzoglou et al., 2018), 4 km resolution, monthly precipitation and reference evapotranspiration data. AI values <1 indicate water deficit (dry) conditions, whereas AI values >1 indicate water surplus (humid) conditions. To determine how burned area changes across the climate gradient of each region, we determined the fraction of land area burned for AI increments of 0.2. These AI increments are referred to in the manuscript as aridity zones.

Next, we examined how fuel distributions relate to burned area. We characterized fuel load using both land cover types and aboveground biomass. Land cover types of burned areas (tree, shrub, herbaceous) in 2000 were obtained from GLANCE (Friedl et al., 2022). Since GLANCE does not separate out cropland from other grassland/herbaceous land cover, we obtained the extent of burned area that was cropland in 2000 from another data set

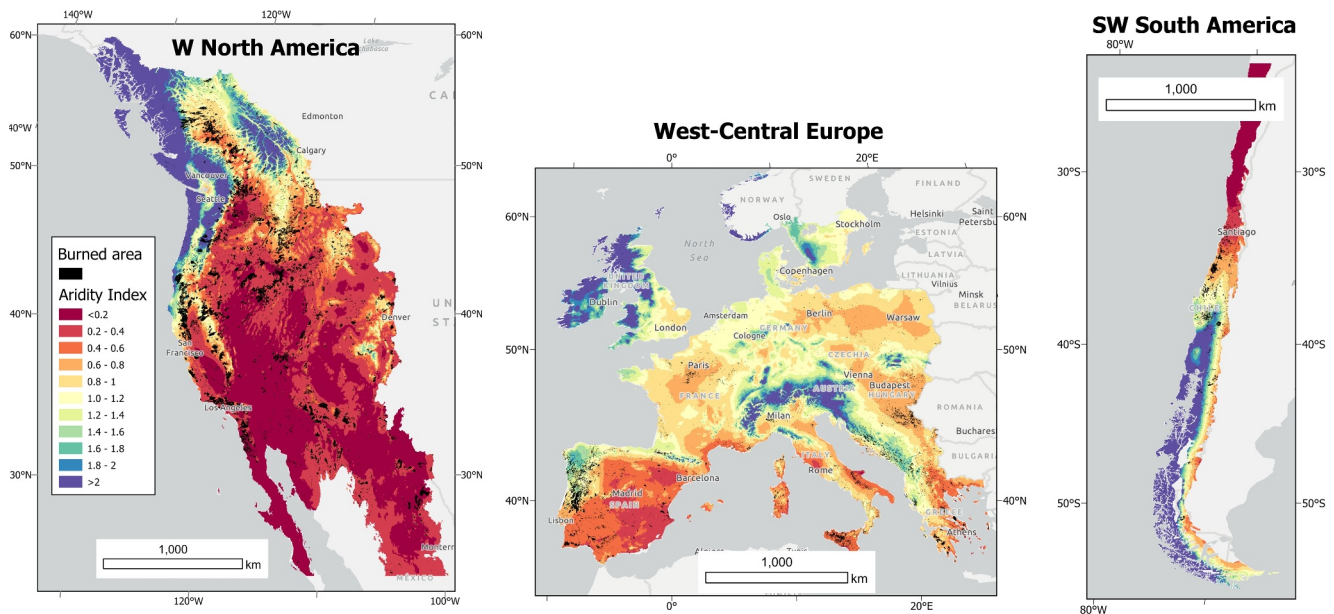


Figure 4. Mean annual aridity index computed from Terra Climate, 2002–2021, and burned areas from GlobFire (Artés et al., 2019) for the same time period.

(Potapov et al., 2021). We computed mean biomass for each AI increment in each subregion using the global map of 2010 aboveground biomass from Spawn and Gibbs (2020) and examined how mean biomass relates to both AI and burned area.

To examine climate effects on burned area, we focused on climatic water deficit (D), a water balance variable that represents potential evapotranspiration minus actual evapotranspiration, using values from Terra Climate (Abatzoglou et al., 2018). We selected this variable because it is effective in capturing the influence of seasonal drying. We computed mean annual D values for each AI increment and subregion, evaluated the range of annual D values experienced at burned areas, and examined how annual burned area relates to annual mean D in water surplus (AI > 1) and water deficit (AI < 1) parts of each subregion.

3. Results

3.1. Burned Area

Of the three regions, western North America has the largest extent of arid conditions and the largest burned area between 2002 and 2021, around 350,000 km², or approximately 9% of the study area (Figure 4). By percent of area, southwestern South America follows, with burn over 5% of the study area, but with the smaller region size, this is only 25,000 km². This is likely an overestimate of burned area because GlobFire maps some fires in the high Andes that were likely affected by volcanoes rather than fire. Europe has the lowest percent of area burned (3%), or around 110,000 km², likely because a large fraction of the Europe study region has sub-humid to humid climate.

Similar to the region-wide burn extents, western North America has the highest burned area fractions over most aridity values, followed by southwestern South America and west-central Europe (Figure 5a). All regions do show indications of fuel limitation in dry conditions (low AI) and climate limitation in wet conditions (high AI), but the patterns of burned area between those extremes vary between the regions. On the fuel-limited side of the aridity axis, burned area fraction is low in both western North America (<0.05) and southwestern South America (<0.01) where AI is <0.2. This aridity zone has low mean biomass (<100 MgC/ha) in both regions. West-central Europe has almost no land area in this driest aridity zone, but it has had low burned area where AI is between 0.2 and 0.4, and aboveground biomass is <100 MgC/ha (Figure 5c).

On the climate-limited side of the aridity axis, all three regions have low (<0.05) fraction burned area where AI > 1.8. These values of AI indicate that precipitation is higher than PET by a factor of 1.8 or more. Within this

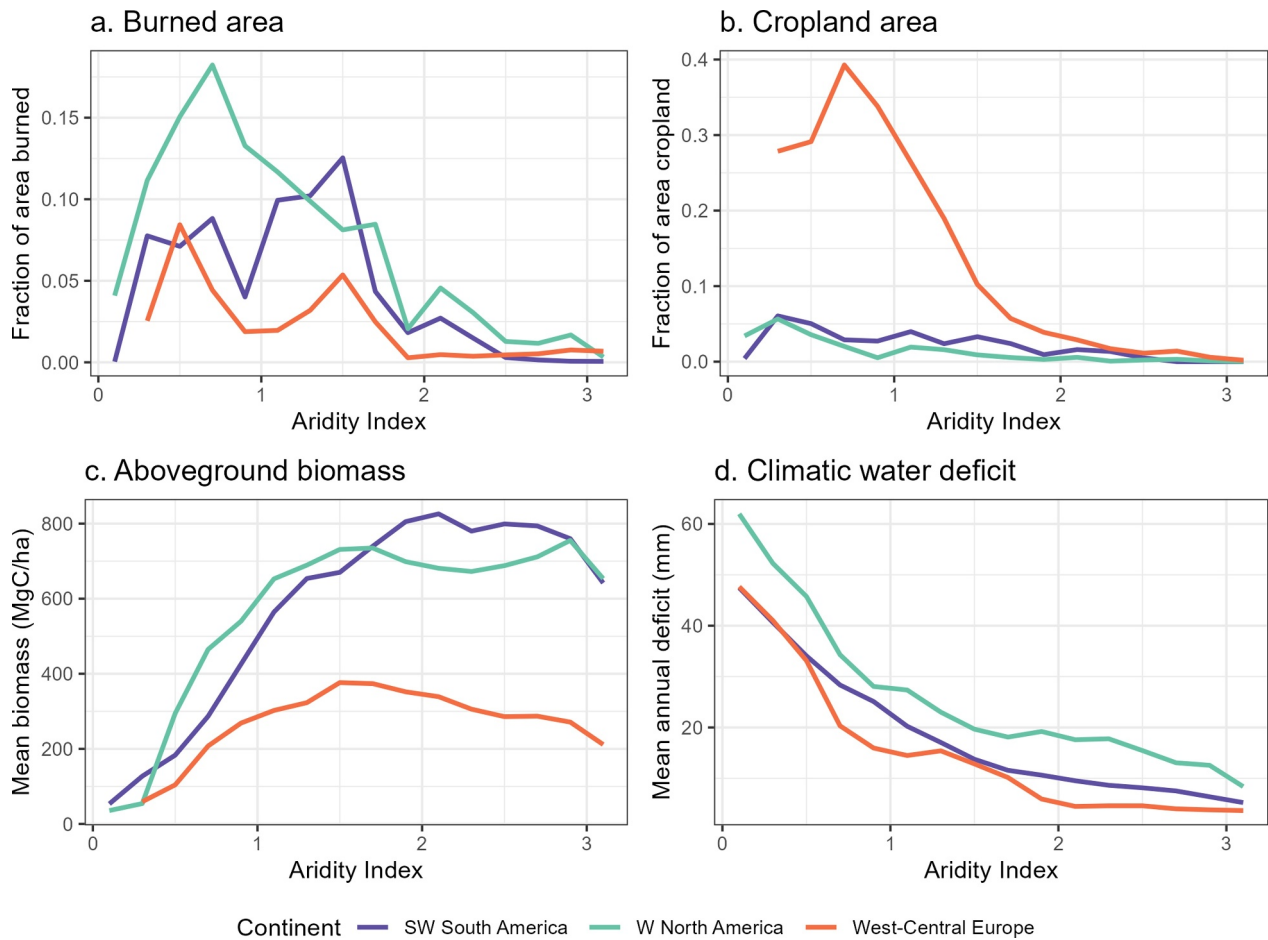


Figure 5. Changes in burned area, fuel load (represented as aboveground biomass), and climate across an aridity index gradient showing (a) fraction of area burned, (b) fraction of area that is cropland, (c) mean aboveground biomass, and (d) mean annual climatic water deficit.

climate-limited zone, western North America again has the highest fraction burned, which may relate to the substantially higher mean climatic water deficit (Figure 5d).

The intermediate aridity space between AI around 0.4–1.8 is where the burned area pattern varies the most between regions. In western North America the peak burned area fraction (0.18) is between AI 0.6–0.8. Locations with this intermediate 0.6–0.8 AI range are spread throughout western North America, including the mountains of California, Oregon, British Columbia, and Idaho. For most of the aridity range from 0 to 2.2, large fires ($>100 \text{ km}^2$) make up the majority of burned areas, with mega-fires ($>1,000 \text{ km}^2$) comprising as much as 63% of the burned area (Figure 6a).

West-central Europe's largest peak in fraction burned area is in relatively dry conditions compared to the other regions, AI 0.4–0.6. This aridity zone includes southwestern Portugal, much of central and southwestern Spain, the southern coast of France, and parts of Italy and Greece. Particularly in Italy, most of the areas in this aridity zone are croplands, where frequent agricultural burning is likely contributing to the peak fraction burned area. A secondary peak in burned area is at AI 1.4–1.6, which is also where mean biomass peaks in Europe (Figure 5c). The areas in this aridity zone include northern Portugal and northwestern Spain, along with some parts of Albania, Bosnia, Montenegro, and Serbia. Some parts of this zone are cropland, but most are forested. Europe also had much smaller fires than North America. Fires $>100 \text{ km}^2$ were only between AI 0.2–1.8 and comprised $<20\%$ of total burned area (Figure 6b). Only one mega-fire ($>1,000 \text{ km}^2$) burned, and this was in the AI 1–1.2 zone in Portugal. However, while this was counted as one fire in GlobFire, the Portugal fire data indicate there were actually five separate fires in close proximity to one another.

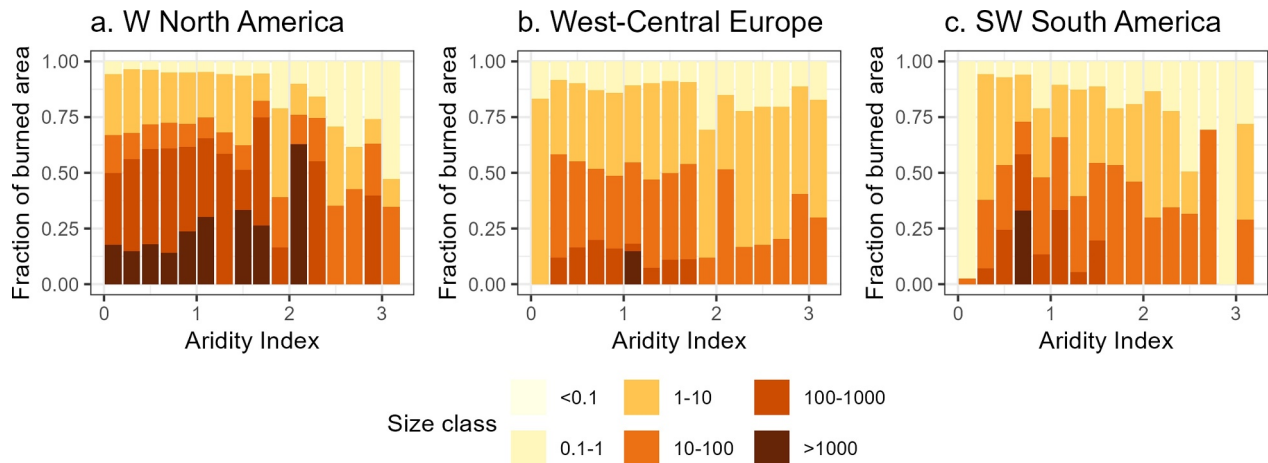


Figure 6. Fraction of total burned areas contributed by different size fires. Fire size class ranges are in square kilometers.

Southwestern South America has two peaks in fraction burned area, one from AI 0.4–0.8 and the other from AI 1–1.6. The fires with AI ranging from 0.4 to 0.8 have been in central Chile between about 33° and 36°S. Those from AI 1–1.6 are in south-central Chile between about 36 and 38°S. The dip in burned area between AI 0.8–1 is a narrow band of land that was mostly missed by the extensive 2017 wildfires that burned large areas to the north and south. For the most part, size distributions of fires are smaller in southwestern South America compared to western North America. Fires >100 km² were confined to AI 0.2–1.6, and the only mega-fire was in AI zone 0.6–0.8 (Figure 6c).

3.2. Fuel

Fuel limitation, particularly more limited spatial connectivity of burnable areas, may partially explain the lower burned area fractions in west-central Europe compared to the other regions. Aboveground biomass is lower across the full aridity range (Figure 5c), and much more of the area is cropland (Figure 5b). The frequent agricultural burning in Europe is partially evident in the land cover distribution in burned areas (Figures 7b and 7c). Herbaceous land cover is the largest land cover type by fraction of area in Europe, and much of the area mapped as herbaceous in the land cover map (GLANCE) is also cropland. The herbaceous land cover makes up an even greater fraction of the total burned land cover: 59% of the areas that burned at least once and 69% of the areas that burned more than once over the 20-year time period. While agricultural burning may increase the frequency of

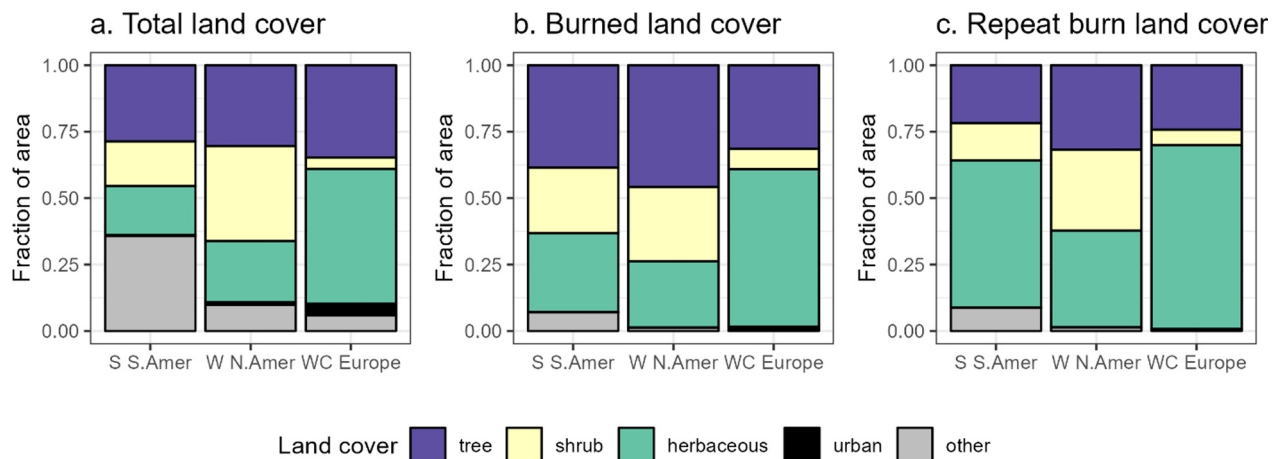


Figure 7. (a) Land cover distribution for full study regions, (b) locations that have been burned, and (c) locations that were burned more than once between 2002 and 2021.

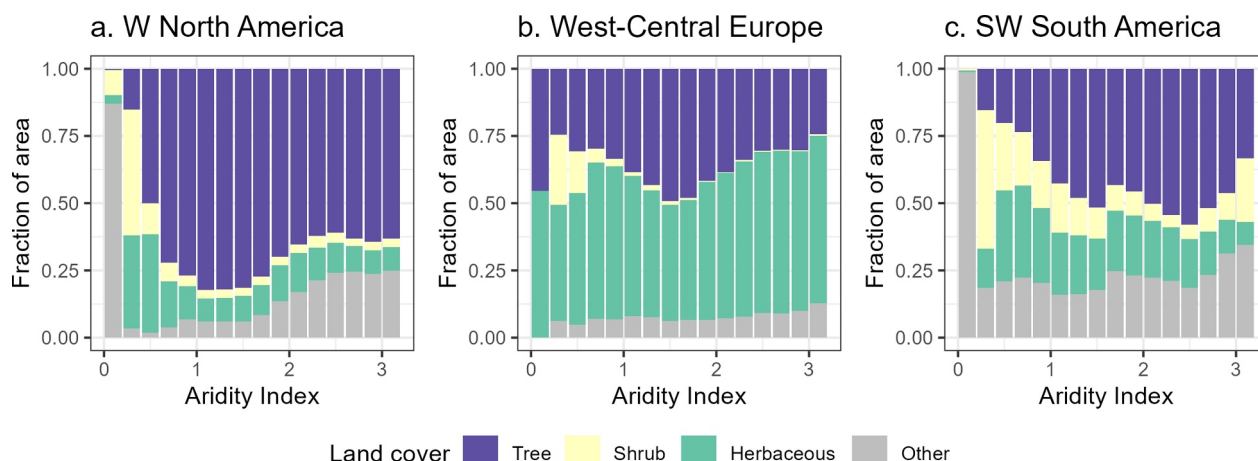


Figure 8. Land cover distribution by aridity index for the three study regions.

burning, this type of burning is typically conducted in small areas. This may partly explain why the majority of the burned areas in Europe were relatively small ($<10 \text{ km}^2$) (Figure 6b).

In southwestern South America mean aboveground biomass increases with AI up to 2 (Figure 5c). However, the aboveground biomass values for high AI zones are over-estimating aboveground biomass compared to field-based estimates from Patagonia (Perez-Quezada et al., 2023), indicating some uncertainty in these values. Geographically, the forested areas in the southern part of the region (south of 36°S) are fragmented between west and east sides of the Andes Mountains, which are covered with bare ground, ice, and lakes (shown as other in Figures 7a and 8c). Although southwestern South America has much less herbaceous land cover than west-central Europe (Figure 8c), some of these herbaceous areas are agricultural zones that experienced frequent burning. Herbaceous vegetation is 18% of the total land cover but makes up 30% of the areas that burned and 55% of the areas that burned more than once in the 20-year period.

Western North America has the highest and most spatially continuous fuel availability of the three regions for AI 0.4–1.6 (Figure 5c). This may be because western North America has a greater fraction of land cover that is forest across much of this aridity range (Figure 8a). These forests cover a much larger surface area than in southwestern South America, contributing to the greater incidence of mega-fires in western North America (Figure 6a). Of the total burned area, 46% was forest in western North America, whereas southwestern South America and west-central Europe had only 39% and 31% of total burned area that was forest (Figure 7b).

One potential indication of fuel limitation in burned area is an increase in fraction of area burned with increasing aboveground biomass, consistent with the expected increase in burned area with increasing fuel load in the conceptual model (Figure 1). This pattern is evident in west-central Europe only from AI 0.2–0.6 (Figure 9b). In both western North America and southwestern South America, the fraction of area burned increases from AI 0–0.8 (Figures 9a and 9c). At higher AI, this relationship between fraction burned area and biomass is no longer evident.

3.3. Climate

The previous analysis of fuel characteristics for the study regions divided each region into aridity zones based on mean annual AI. These mean annual AI values represent the annual water surplus or deficit, whereas the seasonal influences are more evident in climatic water deficit, D. The three study regions each have different ranges of D for the same AI (Figure 5d). Mean annual D values are consistently higher in western North America than in the other two regions across all values of AI, and the median and maximum D values are also highest in western North America (Figure 10a). Lowest mean annual and annual D values are in west-central Europe (Figures 5d and 10a).

A correlation between D and burned area is an indication of top-down, climate control on fire. To determine whether these correlations vary across the study regions, we divided each region into three aridity bins: dry (AI < 0.6), moderate (AI 0.6–1.2), and wet (AI > 1.2). Correlations between D and burned area increase from dry-moderate-wet categories (Figure 10b), indicating greater climate limitation to burned area with higher AI (wetter

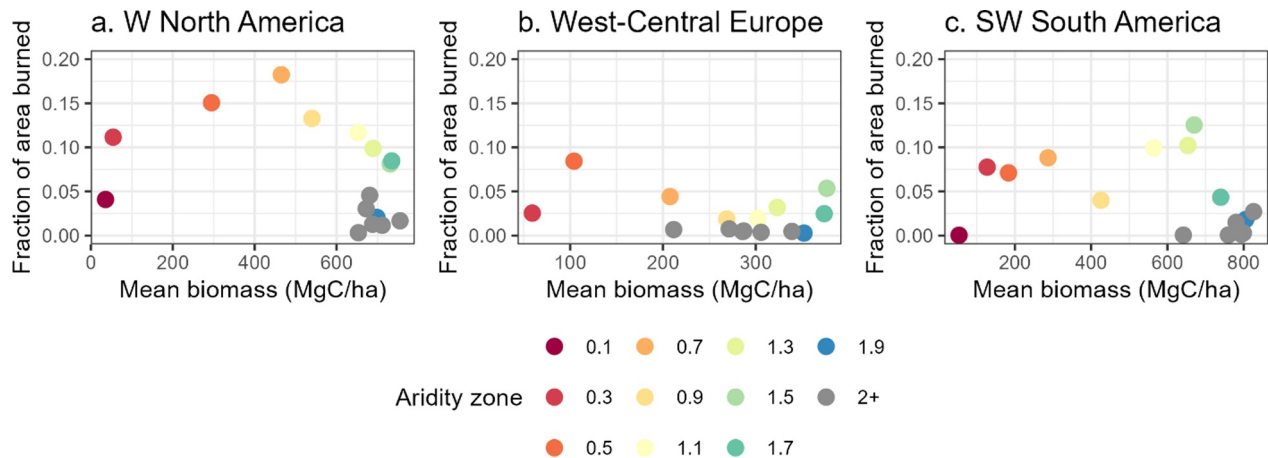


Figure 9. Fraction of area burned versus mean aboveground biomass by aridity zone for each study region.

climates). For the dry category in west-central Europe, the negative correlation coefficient is driven by burned areas in the driest climate zone, where burned areas may be low due to fuel limitation. Otherwise all correlations between D and burned area are positive. The correlation between D and fraction burned area is highest and statistically significant in west-central Europe for both the moderate and wet zones, whereas the correlation is only significant in southwestern South America for the wet zone. Correlations between D and fraction burned area are not significant in western North America.

4. Discussion

Consistent with the conceptual model (Figure 1), burned area fractions in all three study regions peak at intermediate aridity, with some indication of fuel limitations in dry conditions (low AI, <0.8) and climate limitation in humid conditions (high AI, >1) (Figures 5, 9, and 10b). However, there is substantial variability in the patterns of fraction burned area across aridity gradients. This variability is not surprising given the differences in vegetation patterns and land use histories between regions. Extreme wildfires that have an outsized impact on human populations and ecological systems vary regionally (Balik et al., 2024), so we focused more on the fraction of burned area rather than total burned area across these three very different regions.

Western North America has the highest fraction of area burned of all the regions across most of the climate gradient. In the driest parts of this region, high fire activity has been attributed in part to anthropogenic influences,

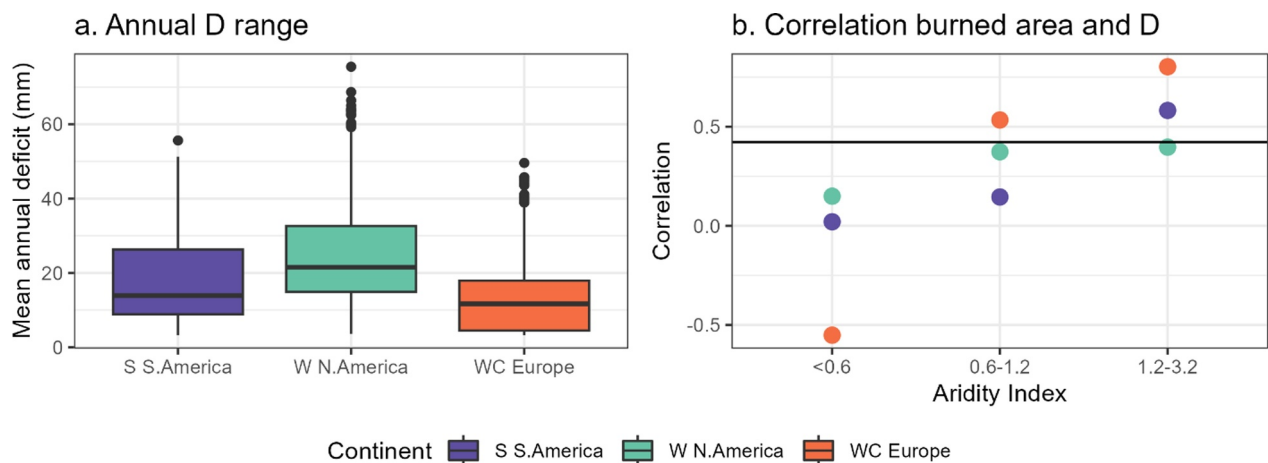


Figure 10. (a) Range of mean annual climatic water deficit (D) in burned areas and (b) Pearson correlation coefficients between annual climatic water deficit and annual fraction of area burned in three aridity zones, dry (AI <0.6), moderate (AI $0.6-1.2$), and wet (AI >1.2). Horizontal line in (b) indicates value above which correlation coefficients are significant at $p < 0.05$.

with some evidence that invasive grasses have increased burn frequency (Syphard et al., 2017). Western North America also has higher forest cover and mean aboveground biomass than the other regions for AI up to 1.6. In part this may be because many decades of fire suppression have led to excess fuel loads (Hagmann et al., 2021). Forests are denser than they would have been prior to fire suppression in some parts of western North America (Steel et al., 2015), and the spatial extent of forests and shrublands is large compared to the other regions (Figure 3). These large expanses of burnable vegetation along with more arid conditions under climate change (Coop et al., 2022) may be responsible for the much greater occurrence of mega-fires in North America compared to the other regions (Figure 6). Some of these mega-fires have also burned in areas historically considered climate limited ($AI > 1.4$, Figure 6a; Hessburg et al., 2019).

At the other extreme of fuel availability, west-central Europe has had the most intensive human occupation history, resulting in the lowest forest cover and by far the highest cropland area of the three regions (Figure 5b). Comparing this with less fragmented regions in western North America offers a deeper understanding of how human land use influences fire regime. The fragmented landscape is associated with the lowest fraction burned areas among the three regions. Peaks in fraction burned area in the drier parts of the region ($AI\ 0.4\text{--}0.6$) are strongly linked to agricultural burning, whereas peak burned areas in wetter parts of the region ($AI\ 1.4\text{--}1.6$) tend to be associated with forests. Many of the forested areas that have burned in Portugal and Spain are introduced plantation forest species, pine and eucalyptus. These areas have experienced some of the larger fires in Europe (Guerreiro et al., 2022; Rego et al., 2019). Shrublands also significantly contributed to the high proportion of fire activity in Southern Europe (Ganteaume et al., 2013), similar to fire activity in chaparral regions of North America (Syphard & Keeley, 2020). Because of the more fragmented landscape in Europe, a large fire is considered any area larger than 100 ha, while extreme wildfire events have been defined as the simultaneous and spatially concentrated occurrence of fires larger than 500 ha (San Miguel-Ayanz et al., 2013). These fires may not be as large individually as some of the fires in the western North America study area, but their simultaneous burning creates high risk for human and ecological values in the region (Acácio et al., 2023). The increasing impacts of climate change, such as rising temperatures and prolonged droughts, are expected to intensify fire activity further, particularly in the Mediterranean (Acácio et al., 2023; Duane et al., 2021; Fernandez-Anez et al., 2021; Grünig et al., 2023). Expected future scenarios also point to an expansion of wildfire activity into regions historically less prone to fires, such as parts of central and northern Europe (Galizia et al., 2023).

The burned area fraction in southwestern South America is intermediate between those in western North America and west-central Europe (Figure 5a). This may be due to smaller contiguous areas of vegetation compared to western North America. Natural fire ignitions, common in regions like California and the Mediterranean Basin, are rare in Central Chile (Ganteaume et al., 2013), due to infrequent thunderstorms. Parts of Chile have undergone substantial land use transformation, including forest clearing for agriculture and replacing native forests with plantations, which has likely affected fire patterns by changing the fuel types, spatial distribution, and flammability (Bowman et al., 2019; Echeverría et al., 2006). Forecasting studies for the region determined that fire risk is highest in areas with a Mediterranean precipitation regime and an expanding WUI, which occurs on both sides of the Andes (Godoy et al., 2019; Miranda et al., 2020). Climate projections indicate with high confidence that drought frequency and severity will increase in this region, further increasing fire weather and fire risk (Castellanos et al., 2022).

Researchers have found relationships between climate and burned area in all of these study regions (Carrasco-Escaff et al., 2024; Coop et al., 2022; González et al., 2018; Grünig et al., 2023; Higuera & Abatzoglou, 2021; Juang et al., 2022), but these studies are difficult to compare to one another because they use different variables, time periods, and geographic areas in their analyses. Here we found evidence that the importance of annual climate conditions to annual burned area fraction is greater for wetter climates than for dry (Figure 10b), as anticipated in the conceptual model. Interestingly, the correlation between annual climatic water deficit and fraction burned area is greatest in west-central Europe, despite the strong apparent role of anthropogenic burning (Figures 7b and 7c), and lowest in western North America despite the more extreme climatic water deficits (Figure 10a). The unexpectedly weak correlation between climatic water deficit and burned area in western North America suggests that additional factors are missed in our analysis. These may include the climate conditions of previous years that enhance or suppress fuel accumulation (Roos et al., 2022); other fire weather factors such as seasonal wind patterns; extreme weather such as heat waves and droughts, density and configuration of fuel; and patterns of human occupation in the landscape. Further analysis of how climate conditions relate to burn areas

could consider these types of climate, vegetation, and social variables in more detail to strengthen the understanding of fire dynamics within each region.

Conducting a regional comparison using consistent data sets for all locations creates limitations in what factors can be examined. We focused here on climate, fuel, and burned area metrics that could be derived from global data sets. This allowed us to have a standard approach for obtaining each variable across all three regions. However, the global data sets will inevitably have some errors because they were created across such a broad geographic area. Each of these data sets was validated against data spread across the globe, but they may have inaccuracies in specific locations.

5. Conclusions

This study has compared the burned area, fuel, climate relationships across the three temperate study regions. Within each region, the mechanisms explaining burned area patterns are complex and include both the interactions of fuel and climate as well as human ignitions and land use dynamics (Hessburg et al., 2019). However, all three regions show some evidence of fuel limitation in the driest conditions and climate limitation in the wettest conditions. Climate limitations are likely declining in all regions, due to both human influences and climate change, making the wetter parts of these regions with high aboveground biomass vulnerable to large fires in the future. Land fragmentation has contributed to different extents of burned areas between these regions and different size distributions of fires, with the largest fires and fraction burned area in western North America and smallest in west-central Europe. However, even though land fragmentation reduces the total area of individual fires in Europe, these fires can have large human impacts due to their proximity to populated areas.

As climate and fire regimes change, forest managers face increasing uncertainty regarding wildfire severity, frequency, and duration. Traditional management goals may become unattainable as ecosystems shift away from desired stable states. To adapt, forest management should consider whether fuel conditions would enable large areas to burn, and potentially reduce fuel loads through prescribed burns or mechanical treatments (Davis et al., 2024; Kalies & Kent, 2016). Management practices must be flexible and regionally specific, ensuring they can adjust to evolving fire patterns and environmental conditions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The base data for these analyses are all publicly accessible data products (Abatzoglou et al., 2018; Artés et al., 2019; Friedl et al., 2022; Potapov et al., 2021; Spawn & Gibbs, 2020). Derived data used in figures are available on Hydroshare (Kampf, 2024).

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