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Increasing aridity causes larger and more severe forest fires across Europe

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Abstract

Area burned has decreased across Europe in recent decades. This trend may, however, reverse under ongoing climate change, particularly in areas not limited by fuel availability (i.e. temperate and boreal forests). Investigating a novel remote sensing dataset of 64,448 fire events that occurred across Europe between 1986 and 2020, we find a power-law relationship between maximum fire size and area burned, indicating that large fires contribute disproportionally to fire activity in Europe. We further show a robust positive correlation between summer vapor pressure deficit and both maximum fire size (R^2 = .19) and maximum burn severity (R^2 = .12). Europe's fire regimes are thus highly sensitive to changes in future climate, with the probability for extreme fires more than doubling by the end of the century. Our results suggest that climate change will challenge current fire management approaches and could undermine the ability of Europe's forests to provide ecosystem services to society.

KEYWORDS
aridity, burn severity, climate change, Europe, fire modelling, fire regime, fire size, forest fire

1 | INTRODUCTION

Forest disturbances are increasing around the globe (McDowell et al., 2020; Seidl et al., 2011, 2017) and forest fires play an important role in this increase (Abatzoglou & Williams, 2016; Curtis et al., 2018; Liu et al., 2019; Westerling et al., 2006). While disturbances are important drivers of natural ecosystem dynamics (Bowman et al., 2009; Viljur et al., 2022), global warming may disrupt natural disturbance regimes and alter post-disturbance forest development trajectories (Bebi et al., 2017; Johnstone et al., 2016; Seidl & Turner, 2022). Increasing summer aridity has been suggested as a main driver of changing forest fire regimes (Huang et al., 2020; Jolly et al., 2015; Williams et al., 2019). For instance, increasing aridity and the resultant dryer fuels led to a fivefold increase in area burned in California over the past 50 years (Williams et al., 2019). Extreme events like the Black Summer of 2019/2020 in Australia are expected to become more frequent (Abram et al., 2021) as increasing temperatures and changing precipitation patterns promote more extreme fire weather (Chiang et al., 2021; Jain et al., 2022; Vicente-Serrano et al., 2020). Increasing forest fire activity could have a number of negative effects on forest ecosystem functions, including a reduction in ecosystem carbon storage (Bowman et al., 2021; Case et al., 2021), a loss of ecosystem service provisioning (Lecina-Diaz et al., 2021), and risks to human health and infrastructure (Bowman et al., 2017; Ganteaume et al., 2021; Keeley et al., 2011; Rosenthal et al., 2021; Wang et al., 2021).

Despite increasing evidence that climate change increases fire activity across the globe (Ellis et al., 2022; Jain et al., 2022; Richardson et al., 2022), area burned has stagnated over the past three decades in Europe, and even decreased in the Mediterranean

(Andela et al., 2017; de Rigo et al., 2017; Jones et al., 2022; Silva et al., 2019; Urbieta et al., 2019). Likely reasons for this trend are successful fire suppression, improved early fire detection and better firefighting capacities (Dupuy et al., 2020; Turco et al., 2016; Urbieta et al., 2019). Nonetheless, extreme fire seasons have been reported for many countries in Europe in recent years. For instance, following a severe drought in 2018, area burned exceeded past long-term averages (reference period 2008–2017) in Sweden (835%), Latvia (827%), Germany (706%) and Norway (372%) (San-Miguel-Ayanz et al., 2019). Also in the Mediterranean basin, extreme fire seasons occurred in the recent past (e.g., 2017 in Portugal or 2021 in Greece; Giannaros et al., 2022; Turco et al., 2019), triggered by longer and hotter drought periods, particularly in more productive regions (Ruffault et al., 2020; Turco et al., 2018). However, continental-scale analyses on the changes in forest fire regimes and their drivers are still missing for Europe. This gap is particularly problematic as most forest fire science in Europe concentrates on the Mediterranean, while the potential effects of climate change on forests that are less fire adapted (e.g. in the temperate biome) and not fuel limited (e.g. in the temperate and boreal biome) remain largely unknown.

Climate change can alter important fire regime characteristics, such as individual fire size (referred to as *fire size* in the following) and burn severity. Evidence from the western United States shows that area burned increases exponentially with summer aridity (Holden et al., 2018; Westerling, 2016; Williams et al., 2019). A reason for the exponential relationship is the disproportional increase of fire lines with increasing fire size, leading to a faster increment of area burned for large compared to small fires (Juang et al., 2022). Increasing aridity might thus expand area burned because of an increase in large fires. Further, aridity has been shown to correlate closely with fuel moisture and has therefore been linked to higher burn severity (Abatzoglou et al., 2017; Huang et al., 2020; Parks & Abatzoglou, 2020). Burn severity is an important indicator for characterizing the impact of fires on ecosystems (Liang et al., 2018; Singleton et al., 2019; Walker et al., 2018) and is linked to the controllability of forest fires (Heward et al., 2013; Lindenmayer et al., 2022). While controllability is influenced by a range of factors (e.g., flame length, spread rate), high burn severity is often associated with crown fires that are difficult to control (Lindenmayer et al., 2022). While low severity fires may have beneficial effects on ecosystems (Hessburg et al., 2015), high severity fires can have numerous negative impacts (Liang et al., 2018). The relationship between aridity and burn severity via effects on fuel moisture might be especially prominent in fire regimes generally not limited by fuel, such as temperate forests (Young et al., 2017). Changing fire size and burn severity might be of particular concern in those regions of Europe where fire management and firefighting capacities are not well prepared to deal with large, catastrophic fires—especially when they occur in parallel in several regions across Europe. A better understanding of the response of fire size and severity to increasing aridity is thus critically needed to make robust projections about future forest fire regimes in Europe and to develop adequate long-term management strategies.

Here, we use a multi-decadal, spatially explicit dataset of 64,448 fire events mapped from satellite data to characterize the fire regimes of Europe, and quantify their sensitivity to past and future summer aridity. First, we investigate trends in area burned, maximum fire size and burn severity between 1986 and 2020, and test the hypothesis that extremely large forest fires contribute disproportionally to total area burned in Europe. Second, we test the hypothesis that summer (June–August) vapor pressure deficit (VPD_s) is positively correlated to maximum fire size and maximum burn severity. We compare competing models to further elucidate the nature of the aridity effect (linear, exponential and power-law) and test whether relationships vary within and among biomes. Third, we investigate how maximum fire size and maximum burn severity could change under future climate conditions, and how this affects the probability of extremely large fires.

2 | MATERIALS AND METHODS

2.1 | Forest fire data

Fire patches were obtained from a remote sensing-based dataset on forest disturbances described in detail in (Senf & Seidl, 2021a, 2021b). The dataset is openly available for download (Senf, 2021). In essence, the dataset depicts where and when forest disturbances caused by fire occurred across Europe at a spatial grain of 30 m and with annual resolution for the period 1986–2020. In order to identify fire patches among pixels flagged as disturbed by fire, we spatially clustered pixels using the DBSCAN algorithm (Ester et al., 1996) via the *dbscan* R-package (Hahsler et al., 2019). We set a maximum clustering distance of 150 m (5 pixels), grouping all pixels that either shared an edge or node in the same year or were in close proximity in the same year (<150 m). This avoided fire patches to be split by roads or small unburnt patches. In a preliminary analysis, we investigated whether using other distances in the spatial clustering (i.e. 3 or 10 pixels) affects the obtained patch size distribution, but found no large differences (see Figure S9). Based on the thus obtained fire patches, we defined a fire complex as the convex hull around all fire patches in one cluster. Our dataset contained 65,283 fire complexes. From these fire complexes we calculated fire size as the total area of the complex polygon (i.e. including burned as well as residual unburned area). We further derived burn severity by calculating the average change in normalized burned ratio (NBR) from pre to post fire of all fire pixels in a fire complex. The NBR is an index combining two spectral infrared bands (4 and 7) to obtain a metric that is sensitive to changes in biomass caused by fire (García & Caselles, 1991; Key & Benson, 2006; Miller & Thode, 2007). Delta NBR (dNBR) is a widely used measure for burn severity and has been shown to capture the severity of fires well across different global ecosystems (e.g. Eidenshink et al., 2007; Mueller et al., 2020; Singleton et al., 2019).

2.2 | Climate data

To characterize historical climate, we used ERA5-Land monthly averaged data (Muñoz-Sabater, 2021), downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store. We obtained monthly temperature and dewpoint temperature for all years between 1986 and 2020 at a spatial resolution of 0.1° (~11 km). We calculated vapor pressure deficit (VPD) with temperature and dewpoint temperature using the August-Roche-Magnus formula (Alduchov & Eskridge, 1996). VPD is a widely used measure of aridity, and it has been shown to be a better predictor of fire size and severity than temperature or precipitation alone (Jain et al., 2022; Mueller et al., 2020). VPD_s was calculated as the mean VPD of the months June, July and August. Because of the annual resolution of the fire data, fires occurring late in the season (i.e. end of August or September) are recorded only in the following year (see also discussion in Senf & Seidl, 2021a). To prevent a temporal mismatch between climate and fire data, we calculated maximum VPD_s for a running 3-year moving window over the climate conditions of the previous and subsequent year. This approach also accounts for potential errors in the attribution of fires to a given year, which were assessed by Senf and Seidl (2021a) to be ±1 year. To test the sensitivity of our results to this moving window approach, we also calibrated models with VPD_s from the focal year only (see Table S2). Finally, we extracted VPD_s values from the 3-year moving window for all fires occurring in our dataset, using the polygons of the fire complexes to obtain the mean VPD_s across the polygon. For polygons that did not align with climate data grid cells, we added a 5 km buffer for VPD_s extraction, followed by a 10 and 20 km buffer (corresponding to two grid cells) if no VPD_s values could be obtained with smaller buffer sizes (e.g. in coastal areas). We further extracted the biome in which fires occurred using the same method. Biomes were obtained from Olson et al. (2001). For the analysis 64,448 fire complexes remained.

To characterize future climate, we used CMIP6 data (O'Neill et al., 2016). We downloaded all monthly near-surface temperatures and near-surface relative humidity variables from the Copernicus Climate Change Service (C3S) Climate Data Store for five different global circulation models (GCMs). We selected CNRM-CM6-1 (Voldoire, 2019a, 2019b, 2019c), EC-Earth3-Veg-LR (Consortium (EC-Earth), 2020a, 2020b, 2020c), FIO-ESM2.0 (Song et al., 2019a, 2019b, 2019c), CMCC-ESM2 (Lovato et al., 2021) and MPI-ESM1-2-LR (Brovkin et al., 2019a, 2019b) from the CMIP6 family, informed by the GCMeval tool (Parding et al., 2020). This tool illustrates the variation of temperature and precipitation projections for different focal regions (see Figures S10–S12). We selected four GCMs that project moderate temperature and precipitation changes across Europe (but note that there is variation between the Mediterranean, central Europe and northern Europe). Further, we added a fifth GCM (CMCC-ESM2) for which all needed outputs were available in the Copernicus Climate Change Service (C3S) Climate Data Store, but could not be assessed in the GCMeval tool. This fifth GCM projects VPD_s similarly to the other four GCMs across the different biomes. Although five GCMs are not sufficient to capture the full uncertainty in future climate projection, our selected GCMs are well able to represent the variation around an intermediate future climate trajectory for the focal region. We obtained model outputs for the historical period (1986–2014) and future projections (2015–2099) at 100×100 km resolution. As dewpoint temperature was not available from CMIP6 data, we calculated it from relative humidity and mean temperature (Anderson et al., 2013), and then derived VPD from the resulting dewpoint temperature and mean air temperature using the August-Roche-Magnus formula as described above. We performed a statistical bias correction for all GCMs by calculating the average VPD_s between 1986 and 2014 for the ERA5-Land dataset and for the historical period of each CMIP6 GCM (i.e. 1986–2014). The difference between the averages over these 28 years was added to VPD_s of each year for future simulations (2015–2099), to account for the bias of CMIP6 GCMs. We then averaged yearly VPD_s over all GCMs for each Shared Socioeconomic Pathways (SSPs). We studied two SSPs to consider uncertainty from different emissions pathways, focusing on the "middle of the road" (SSP245) and "fossil-fueled development" (SSP585) scenarios (Riahi et al., 2017). For the years 2015–2020, we averaged the two SSPs to obtain a time series over the full study period (1986–2020).

2.3 | Analyses

We investigated the effect of VPD_s on maximum fire size and maximum burn severity using Bayesian hierarchical modeling. First, we calculated maximum fire sizes and maximum burn severities, as well as average VPD_s values, per country and biome. That is, we derived maximum fire sizes and maximum burn severities at the country level, but if a country included several biomes, we calculated maxima for each biome-country combination. This allowed us to simultaneously model variations among biomes and countries nested within biomes. We specifically included countries as random mixed effect in our model, because countries are an important proxy for differences in forest management regimes throughout Europe (Schelhaas et al., 2018). Maximum fire size and maximum burn severity were modelled using VPD_s as an independent variable, with random intercepts and slopes among countries nested within biomes. We used a Gaussian error distribution and tested three competing patterns of VPD_s influence: linear, log-linear and log–log (i.e. power-law model). All competing models were compared sequentially (i.e. linear vs. log-linear and log-linear vs. log–log) using Bayes factors (Kass & Raftery, 1995). If the logarithm of the Bayes factor was >2, we considered this to indicate strong support for the competing model (Beard et al., 2016). All models were fitted using the *brms* package in R (version 2.16.3; Bürkner, 2017). We used standard priors implemented in *brms*. Joint posterior distributions were sampled with four chains à 2000 draws, of which half were dropped as warm-up. Model performance was estimated by conditional and marginal R^2. Posteriors of all effects were summarized by means of their median and 95% credible interval. Using the fitted model, we simulated 4000 random posterior draws of maximum fire size and maximum burn severity under historical and projected future climate

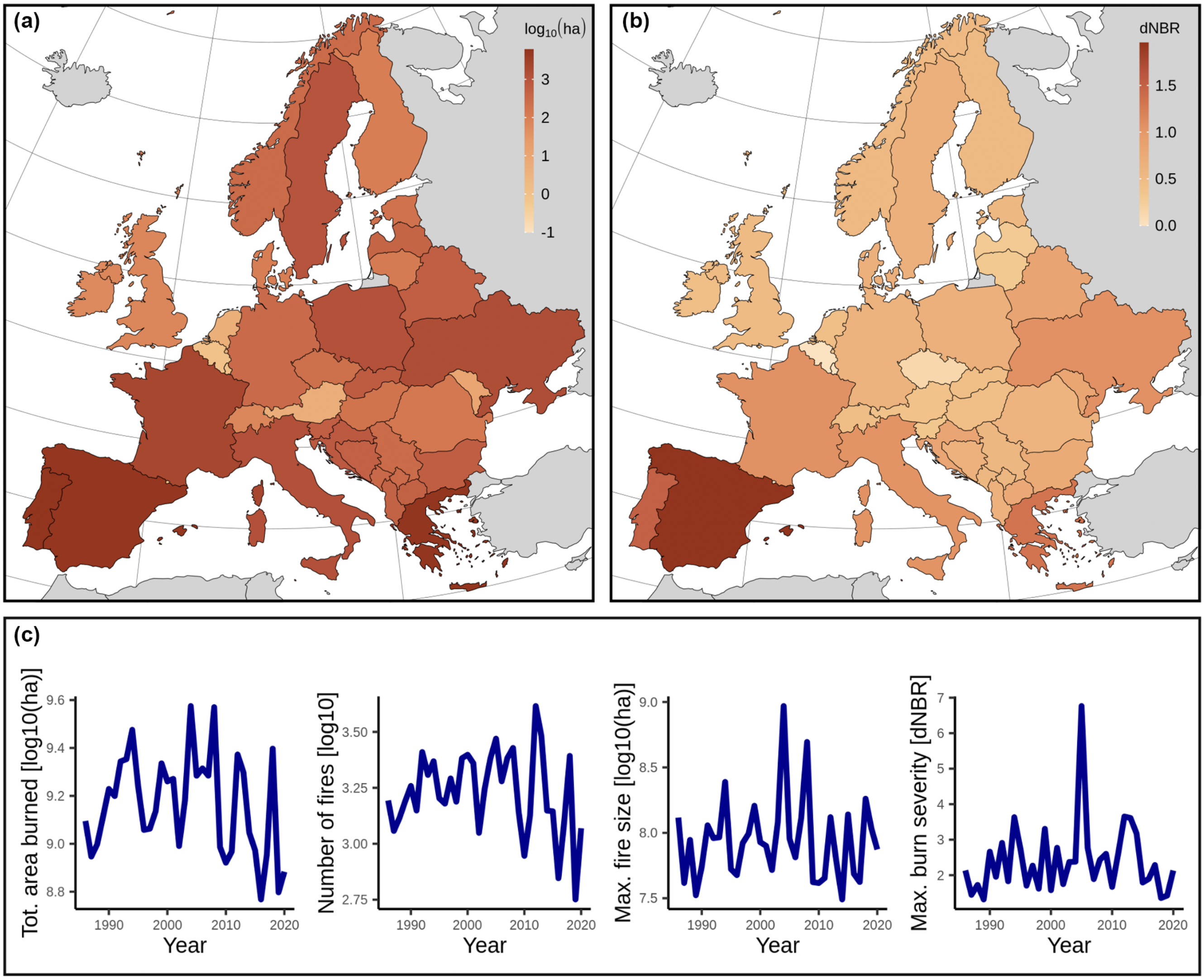


FIGURE 1 Average maximum fire size (a) and average maximum burn severity (b) per country over the period 1986–2020. Values for maximum fire size are presented in hectares on a log10 scale. Map lines delineate study areas and do not necessarily depict accepted national boundaries. Panel (c) shows total area burned, number of fires and absolute maxima for fire size and burn severity across Europe. Total area burned, maximum fire size and number of fires are shown on log10-scale. Values at the level of biomes are given in Figure S1.

conditions in order to investigate the climate sensitivity of the fire regime. Specifically, we calculated the annual maximum fire size for each draw per biome, and subsequently derived the median and 95% credible interval across all draws. Finally, we calculated the probability of maximum fire sizes exceeding 2500 ha per year, representing extremely large fires in the context of European forest fire regimes (Fernandes et al., 2016).

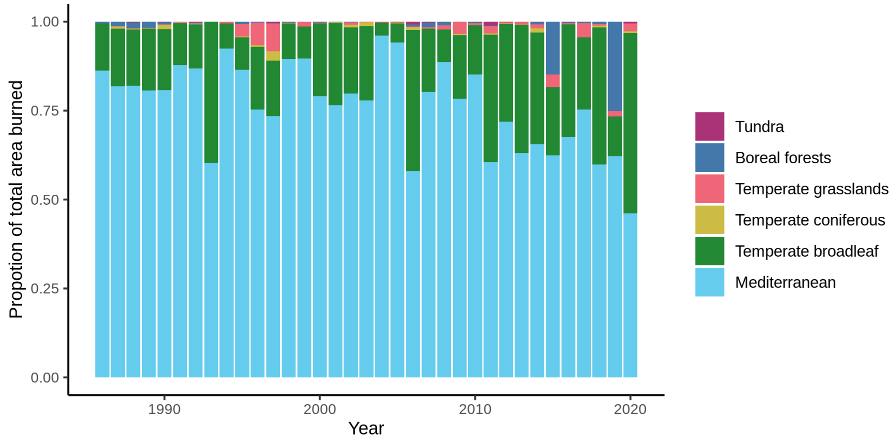
3 | RESULTS

3.1 | The forest fire regimes of Europe

Area burned, maximum fire size and maximum burn severity varied strongly from year to year since 1986, with no evidence for an increasing trend over time (Figure 1 and Figure S1). Our data thus confirm the overall stagnating trend of area burned previously reported for Europe. The largest area burned was found in the Mediterranean biome, which accounted for 79% of the total area burned in Europe. This pattern changed, however, in recent years, with increasing area burned in temperate and boreal forests (Figure 2). In 2018 and 2020, for instance, less than 60% of the total area burned occurred in the Mediterranean biome, and fires in temperate broadleaved forests dominated total area burned in Europe in 2020 (51%).

Total area burned was strongly driven by maximum fire size. Maximum fire size is here defined as the largest forest fire occurring annually per country × biome. Average maximum fire size was 11,676 ha (1986–2020) in the Mediterranean, 3120 ha in temperate broadleaf forests, 1006 ha in boreal forests, 839 ha in temperate grasslands, 318 ha in temperate coniferous forests and 129 ha in the Tundra. Average maximum burn severity was highest in the Mediterranean with 2.4 delta normalized burn ratio (dNBR). We

FIGURE 2 Proportion of total area burned in Europe by biome between 1986 and 2020.



also found considerable variation between countries (Figure 1a,b), with largest average maximum fire size recorded for Portugal (6072 ha) and highest average maximum burn severity for Spain (2.2 dNBR). Comparing maximum fire size to annual area burned, we found a robust power-law relationship between maximum fire size and total area burned across all biomes (Figure 3; mixed effects model; R^2 = .95). The global exponent of the power law was 1.05 [0.99–1.10; 95% credible interval], with little variation among biomes (see Figure S2). In other words, with a doubling of maximum fire size area burned increased by 207 [199–214]% on average. The power-law relationship further indicated that large fires contribute disproportionally to total area burned. In fact, the largest 10% of all fires make up 71% of the total area burned in Europe, and the largest 1% of all fires still contribute 36% to the total area burned. There was, however, substantial variation among biomes, with the largest 1% of all fires resulting in 27% of the total area burned in forests of the Tundra and 48% in the boreal forest (Table S1).

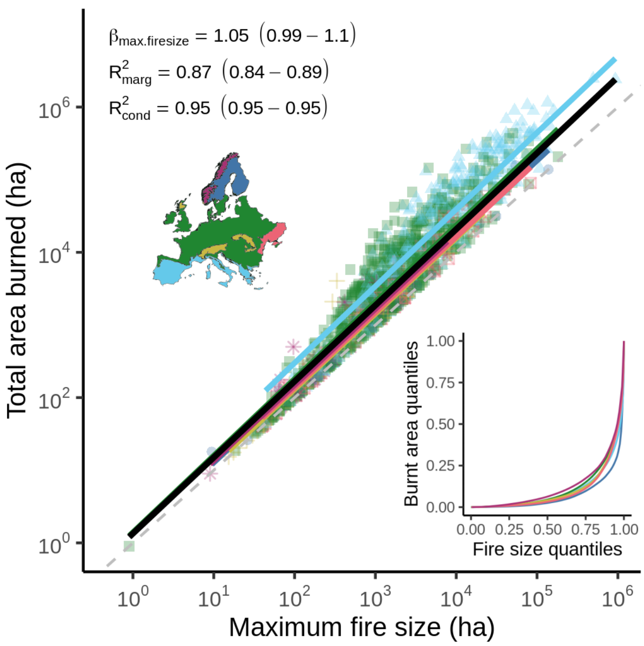


FIGURE 3 Power-law relationship between maximum fire size and total area burned. We find a strong relationship (R^2 = .95) between the two metrics (black line shows correlation at continental scale) which is consistent across all biomes (colored lines, colors according the map insert). The grey dashed line marks the 1:1 line. Both axes are on log10 scale. The insert on the bottom right shows the contribution of different fire size quantiles to total area burned, indicating that the largest fires contribute disproportionally to total area burned.

3.2 | Aridity effect on maximum fire size and burn severity

We found strong support for a positive relationship between VPD_s and maximum fire size as well as maximum burn severity (Figure 4; mixed effect models; conditional R^2 = .19 [0.03–0.38] for size and R^2 = .12 [0.01–0.24] for severity). In addition to VPD_s explaining temporal variability in fire size and burn severity, we found strong evidence for high spatial variability in average fires size and burn severity among countries and biomes. In fact, the marginal R^2 including both the temporal VPD_s effect and spatial variation among countries and biomes increased to 0.52 for [0.50–0.55] for size and 0.55 [0.52–0.58] for burn severity. We modelled the relationship of VPD_s and both fire regime metrics considering linear, exponential and power-law relationships, and compared the three competing models using Bayes factors. For both metrics, we found that the power-law model was more likely than the linear and exponential models (logarithm of Bayes factor ≫2). For maximum fire size, the exponent of the power-law was 1.77 [0.76–3.07], indicating that size increases by 341 [169–840]% with each doubling of VPD_s. For maximum burn severity (i.e. yearly maximum burn severity per country nested within biome), the exponent of the power-law was 0.39 [0.17–0.64], indicating that with each doubling of VPD_s maximum burn severity increases by 131 [113–156]%. For both models, there was considerable variation among biomes. The effect of VPD_s and maximum fire size was strongest in boreal forests and weakest in temperate coniferous forests (Table 1). The effect of VPD_s and maximum burn severity was strongest in the Mediterranean and weakest in the temperate broadleaf biome (Table 1). We also found considerable variation among countries within biomes (Figures S3 and S4).

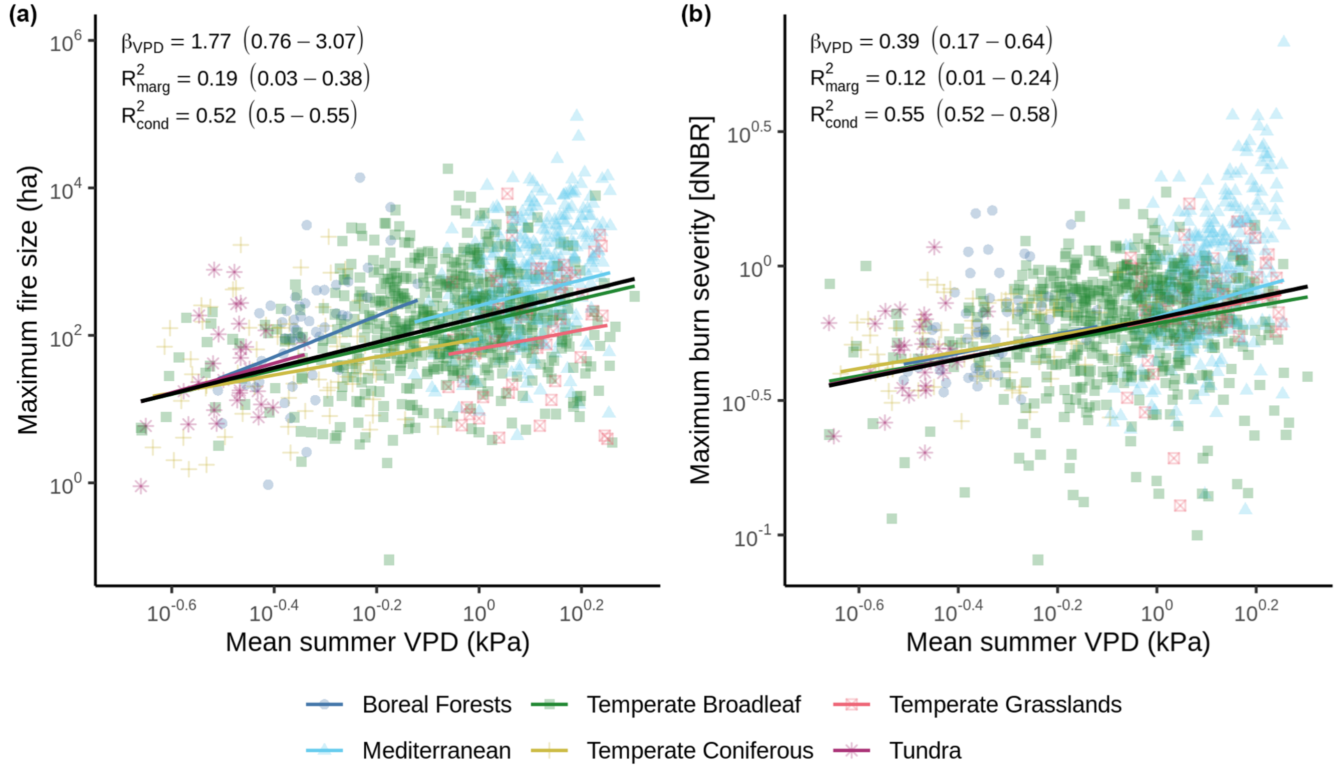


FIGURE 4 Correlation of summer vapor pressure deficit (VPD_s) with maximum fire size (a) and maximum burn severity (b). For both metrics, power-law models were more likely than linear and exponential models. For maximum fire size, the exponent of the power-law was 1.77 (95% CI 0.76–3.07). We assessed model performance with marginal R^2 and conditional R^2. VPD_s alone explained 19% of the variance in maximum fire size, while the entire model explaining 52%. For maximum burn severity, the exponent of the power-law was 0.39 (0.17–0.64) and VPD_s alone explained 12% of the variance, with the overall model explaining 55%.

TABLE 1 The effect of summer vapor pressure deficit on maximum fire size and maximum burn severity in Europe and for different biomes, expressed as the power law exponent. Mean and 95% confidence intervals (2.5% and 97.5% quantiles) were derived from the joint posterior of each effect

	Maximum fire size			Maximum burn severity		
	Mean	Lower CI	Upper CI	Mean	Lower CI	Upper CI
Europe	1.77	0.76	3.07	0.39	0.17	0.64
Boreal forests	2.79	1.24	5.22	0.38	0.09	0.71
Mediterranean	1.74	0.92	2.54	0.54	0.28	0.85
Temperate broadleaf	1.62	1.07	2.15	0.32	0.18	0.46
Temperate coniferous	1.19	−0.02	2.15	0.31	0.08	0.52
Temperate grasslands	1.28	−0.09	2.46	0.38	0.07	0.68
Tundra	2.03	0.58	4.13	0.39	0.10	0.68

3.3 | Sensitivity to future climate conditions

Under future climate conditions, potential maximum fire size and maximum burn severity increased across all biomes of Europe (Figure 5). Based on the above-described models, we projected average maximum fire size and maximum burn severity for the climate of the years 1986–2099 under two different climate scenarios (SSP585 and SSP245) and an ensemble of five global circulation models (GCMs). Average maximum fire size was most sensitive to climate change in the Mediterranean, increasing from 14,537 ha in 2020 to 57,019 ha under the climate expected for 2099. Forests in the tundra biome were least sensitive, yet maximum fire sizes still more than doubled under the scenarios considered here (127 ha in 2020 to 314 ha in 2099). With regard to average maximum burn severity, the Mediterranean biome (+1.12 dNBR between 2020 and 2099) and temperate broadleaf forests (+0.56 dNBR) were most sensitive to future changes in aridity. In boreal forests and the tundra biome, however, due to stationary VPD_s projections until the end of the century, maximum burn severity remained stable under both scenarios (+0.12 dNBR and +0.24 dNBR). While those values are based on the SSP585 emission pathway, we observed clear differences between the two SSPs considered here, which were particularly pronounced towards the end of the 21st century, and which

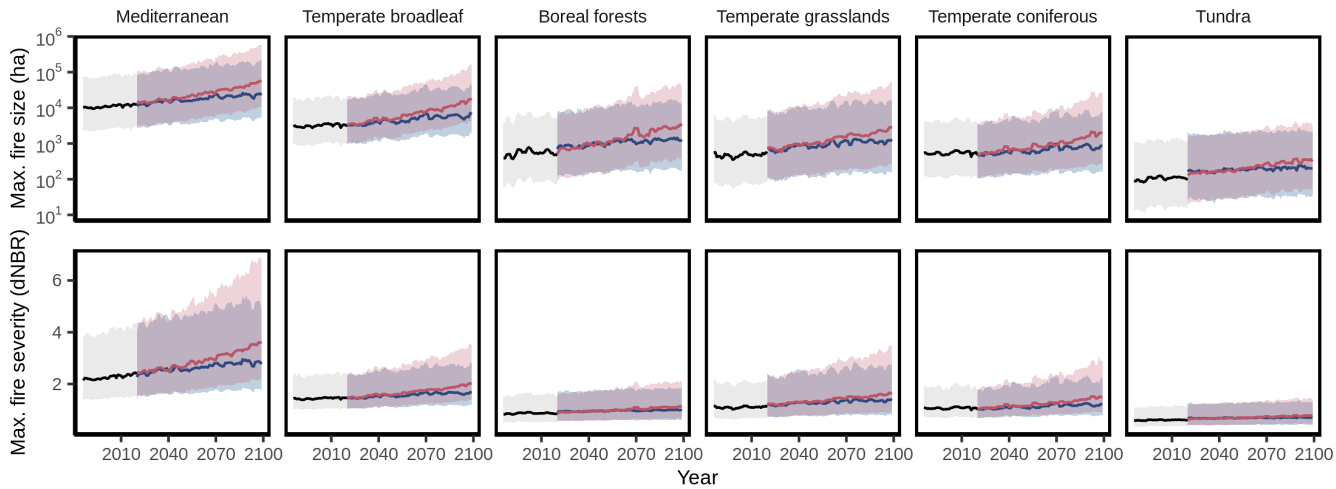


FIGURE 5 Climate sensitivity of maximum fire size (upper panels) and maximum burn severity (lower panels) across biomes based on climate projections under the SSP585 (red) and SSP245 (blue) scenarios. Maximum fire size and burn severity models were used to project climate sensitivity under the conditions expected for the 21st century based on CMIP6 GCMs. Black lines show the modeled values under historical conditions (1986–2020). Shaded areas indicate the 95% confidence interval derived from posterior prediction of the model, and solid lines show the median model predictions for the SSP585 (red) and SSP245 (blue). Projections were made for an average climate trajectory based on five GCMs. Projections for the conditions simulated by individual GCMs are shown in the supplementary material (Figure S5).

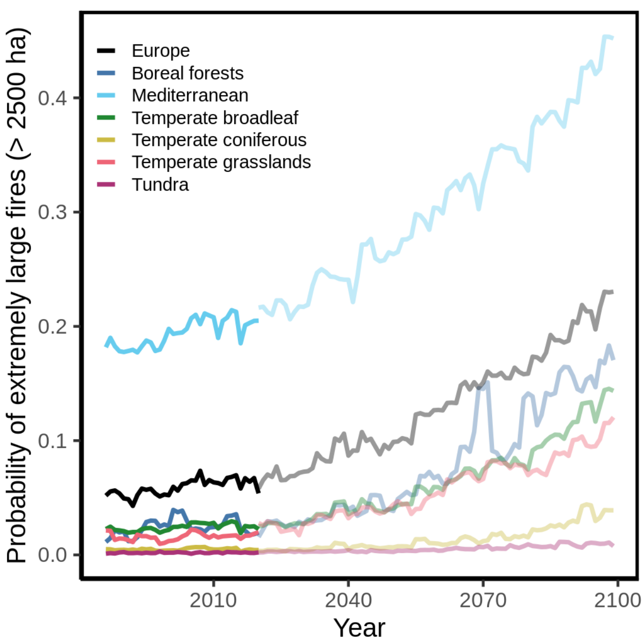


FIGURE 6 Probability of maximum fire sizes exceeding 2500 ha for future climate conditions. Solid colors indicate probabilities for historical conditions (1986–2020), shaded colors indicate future scenario analyses under SSP585. The probabilities of extremely large fires under SSP245 are shown in Figure S6.

showed a considerably stronger changes under SSP585 compared to SSP245.

We found an increasing probability of extremely large fires under future climate conditions. Extremely large fires were defined as fires exceeding 2500 ha, a commonly used threshold that marks the 99.9th percentile of fires in Portugal between 2003 and 2013 (Fernandes et al., 2016; Resco de Dios et al., 2022). Based on the climate scenarios investigated here, the annual probability for extremely large fires across Europe increased from 0.06 under historical climate conditions to 0.24 for conditions expected at the end of the 21st century (SSP585) (Figure 6). We found that Mediterranean forests were most sensitive to a climate-induced increase in large fires, with probabilities for extremely large fires reaching 0.45 by the end of the century (compared to 0.19 in the historical period). Temperate grasslands, temperate broadleaf forests and boreal forests also were highly sensitive to projected future increases in aridity, with probabilities of extremely large fires reaching 0.12–0.18 at the end of the century. While extremely large fires were largely absent in the past in these biomes, they could become considerably more likely (~15% of the largest fires) in the future. In contrast, the likelihood of extremely large fires increased only moderately in temperate coniferous forests (up to 0.05 at the end of the century) and remained close to zero for forests of the tundra.

4 | DISCUSSION AND CONCLUSIONS

We here present evidence for a strong positive relationship between summer aridity and forest fire activity across Europe's forests. While such a relationship has been reported previously at the regional scale (Ruffault et al., 2020; Turco et al., 2018), we here show that it is generalizable across all forest biomes of Europe. Going beyond area burned we show that maximum fire size and maximum burn severity—two important indicators in the context of social-ecological fire impact—are also strongly driven by aridity. The fact that we found consistent climate sensitivity of forest fire regimes across biomes (cf. also Seidl et al., 2020) is noteworthy because it indicates that fire could become a major driver of the European disturbance regime also outside the Mediterranean basin. We in fact found that temperate and boreal forests increasingly contributed to the total area burned in Europe already in recent years. Temperate and boreal forests of Europe are less fuel-limited than most Mediterranean ecosystems (Verkerk et al., 2019), and experienced strong increases in summer VPD in recent years (Jain et al., 2022). This, in turn, increases fuel aridity (Gudmundsson et al., 2014; Pausas & Paula, 2012), making large fires increasingly likely also in temperate and boreal forests of Europe. Furthermore, both lightning ignitions (Chen et al., 2021) and forest productivity (Piao et al., 2020; Zhu et al., 2016) are expected to increase in mid to high latitudes of Europe, which—in combination with increasing fuel aridity—could lead to considerable increases in fire activity. This is particularly noteworthy as many ecosystems in Europe (e.g., in the temperate biome) are not well adapted to high fire activity (i.e. lacking important fire resistance and response traits, such as thick bark, serotiny and the ability to resprout after fire; Keeley et al., 2011; Pausas, 2022). Likewise, societies are not yet well-prepared to live with fire in many temperate and boreal regions of Europe, suggesting that social-ecological adaptation measures are needed.

We here show that climate change could substantially alter forest fire regimes in Europe in the 21st century. The decade between 2011 and 2020 included the nine most extreme years for global VPD maxima on record (Jain et al., 2022), and aridity is expected to further increase in the future. However, despite the strong link between summer aridity and fire activity reported here, there is currently no significant positive trend of area burned across Europe, and even a declining trend in the Mediterranean basin (Dupuy et al., 2020; Jones et al., 2022; Turco et al., 2016). This pattern is in stark contrast to studies from similarly fire-driven ecosystems, such as the western United States (Abatzoglou & Williams, 2016) and southeastern Australia (Canadell et al., 2021), where area burned has sharply increased in recent decades. The particular pattern of area burned in Mediterranean Europe can be explained by improved fire management (Turco et al., 2016) and underlines that human activities are a particularly important element in the forest disturbance regimes of Europe. Yet, our findings of high climate sensitivity of forest fire regimes suggest that changes in aridity could increasingly challenge the relative success of recent fire management in Europe. Specifically, our analyses indicate that increasing aridity could lead to increased maximum fire size and maximum burn severity, and elevate the probability of extremely large fires by at least a factor of two for most parts of Europe. This will render future fires less controllable (Fernandes et al., 2016), because larger fires have more extensive fire lines that are more difficult to control (Juang et al., 2022). Similarly, an increase in burn severity could considerably challenge the ability to control fires (Jolly et al., 2019; Parks et al., 2018; Podur & Wotton, 2010). Current fire management and firefighting strategies might thus become increasingly ineffective for controlling area burned in the future. This will require new paradigms of disturbance management in which not all fires are managed equally: Limited resources should be used to fight dangerous fires while accepting fires as a part of natural ecosystem dynamics in areas with limited impacts on humans (e.g., Resist—Adapt—Direct; Schuurman et al., 2022). Furthermore, firefighting capacities need to be increased particularly in areas of Europe that have experienced limited forest fires in the past. Pan-European coordination and sharing of available resources (such as planes for aerial firefighting) can further help to efficiently address the growing risk from wildfires, but needs to consider that it is increasingly likely to have multiple active large fires in parallel under climate change.

We here present the first European-scale analysis of fire activity in response to increasing summer aridity, yet some caveats need to be considered when interpreting our results. First, we based our analyses on gridded climate reanalysis and simulation data that might underestimate both past and future VPD extremes. Additionally, we here focus on the effect of summer VPD, disregarding the potential contribution of lengthening fire seasons on forest fire regimes (Jain et al., 2022; Jolly et al., 2015; Jones et al., 2022; Westerling et al., 2006). While historically most fires in Europe occurred during the summer months (June, July, August), longer fire seasons may cause more spring and autumn fires (EFFIS; see https://effis.jrc.ec.europa.eu/apps/effis.statistics/seasonal-trend). The climate sensitivity reported here is thus a conservative estimate, as the effects of increasing VPD in spring and fall were not considered. Furthermore, climate change will also alter the forest vegetation of Europe, and could lead to a reassembly towards broadleaved communities in some areas (e.g. Thom et al., 2022), which could alter flammability. Such dynamic feedbacks between climate, vegetation, and fire were not considered here and should be the focus of future research. Finally, we did not explicitly include human-fire interactions in our analyses. The role of humans is the greatest source of complexity in predicting fire patterns (Ford et al., 2021; Jones et al., 2022), particularly in densely populated and intensively managed areas that are characteristic for many parts of Europe. We addressed social factors by means of country-level random effects in our modelling, finding that random variation among countries was large and contributed substantially to the overall variance explained (Figures S7 and S8). Hence, it is important to note that the relationship between summer aridity and fire activity reported here is only one of many drivers that will shape the future fire activity in Europe. Nonetheless, our study provides robust evidence for a strong link between summer aridity and maximum fire size as well as maximum burn severity across Europe. As continued increases in summer aridity are projected for Europe (Balting et al., 2022), we conclude that the stable development of area burned observed for Europe over the past decades will likely change to increased fire activity in the near future. Forest management and policy in Europe thus need to prepare for a future with larger and more severe fires, and develop strategies to mitigate fire-related impacts on forest carbon (Carnicer et al., 2022), resilience (Turner et al., 2022) and biodiversity (Palm et al., 2022).

AUTHOR CONTRIBUTIONS

Marc Grünig, Rupert Seidl and Cornelius Senf contributed to the conceptualization of the study. Investigation, formal analysis and coding were done by Marc Grünig with support from Cornelius Senf. Marc Grünig prepared the original draft and all authors contributed to writing and editing.

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CONFLICT OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data and code that support the findings of this study are openly available at https://doi.org/10.5281/zenodo.7386862. The European forest disturbance map dataset is available at https://doi.org/10.5281/zenodo.7080016.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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