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The effectiveness of past wildfire at limiting reburning is short-lived in a Mediterranean humid climate

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Abstract

Background The study of wildfire interactions (i.e., spread limitation and reburns) is gaining traction as a means of describing the self-limiting process of fire spread in the landscape and has important management implications but has scarcely been attempted in Europe. We examined to what extent previously burned areas restricted the development of individual large wildfires (> 500 ha) in mainland Portugal.

Results For the 1984–2021 period, we (1) modeled the proportion of large wildfire perimeters coinciding with transitions to shorter time since fire (TSF), i.e., locations where fire spread ceased upon encountering assumedly less flammable fuels, and (2) characterized the prevalence of different TSF in the composition of the area burned by large wildfires in relation to available TSF. Only 4% of the large wildfires did not comprise edges intersecting past wildfires. Low TSF (especially up to 8 years) resulted in large-wildfire perimeter limitation at TSF transitions. This effect was further enhanced by high historical burn probability and proximity to roadways and watercourses. Perimeter limitation did also increase under high (but not very high or extreme) fire danger, benefiting from maximum seasonal firefighting preparedness. TSF prevalence in the composition of large-wildfire area was extremely variable and thus an overall weak pattern emerged, with minimum and maximum prevalence respectively at TSF < 2 years and TSF ≥ 6 years.

Conclusions Large wildfire limitation in Portugal is hampered by fast fuel build-up after fire, indicating a short-lived fire-hazard reduction effect under the prevailing Mediterranean humid climate of the study region. Nonetheless, such effect should be considered when planning fuel-reduction treatments and can be used opportunistically during large-wildfire suppression operations.

Keywords Fire-on-fire interaction, Fire regime, Fuel management, Large wildfire, Portugal, Shrubland, Time since fire

Resumen

Antecedentes El estudio de las interacciones de incendios forestales (es decir, limitación de propagación y requemado) está cobrando relevancia como una forma de describir los procesos de autorregulación en la propagación de incendios en el paisaje, y tiene importantes implicaciones de gestión. Sin embargo, apenas se ha intentado en Europa. Examinamos hasta qué punto las áreas previamente quemadas restringieron el desarrollo de incendios grandes (> 500 ha) en Portugal continental.

Resultados Para el período de 1984 a 2021, (1) modelamos la proporción de perímetros de incendios grandes que coincidieron con transiciones a un menor tiempo desde el último incendio (TSF), es decir, lugares donde la

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propagación del fuego cesó al encontrarse con combustibles presumiblemente menos inflamables, y (2) caracterizamos la prevalencia de diferentes valores de TSF en la composición del área quemada por incendios grandes en relación con los valores de TSF disponibles. Solo el 4% de los incendios grandes no incluyeron bordes que se cruzaran con incendios anteriores. Un TSF bajo (especialmente hasta 8 años) resultó en la limitación del perímetro de incendios grandes en las transiciones de TSF. Este efecto se vio amplificado por una alta probabilidad histórica de incendios y la proximidad a rutas y cursos de agua. La limitación del perímetro también aumentó en condiciones de alto riesgo meteorológico de incendio (pero no muy alto o extremo), beneficiándose de la máxima preparación estacional para la lucha contra incendios. La prevalencia de diferentes valores de TSF en la composición del área de incendios grandes fue extremadamente variable y, por lo tanto, se obtuvo un patrón general débil, con una prevalencia mínima y máxima, respectivamente, en TSF.

Conclusiones La limitación de incendios grandes en Portugal se ve obstaculizada por la rápida acumulación de combustible después de un incendio, lo que indica un efecto de reducción de riesgo de incendio de corta duración bajo el clima mediterráneo húmedo predominante en la región de estudio. Sin embargo, este efecto debe considerarse al planificar tratamientos de reducción de combustibles y puede aprovecharse oportunamente durante las operaciones de supresión de incendios grandes.

Background

In Mediterranean-type ecosystems (MTE), similarly to other terrestrial biomes, fire (either planned or unplanned) is an important ecological process that plays a vital role in driving landscape heterogeneity and ecosystem resilience (McKenzie et al. 2010; McLauchlan et al. 2020). Many species and species assemblages are resilient to a given fire regime through passive resistance or by being able to easily resprout or germinate from a seed bank, but may disappear if the fire regime changes (Pausas et al. 2008; Pausas and Keeley 2014). Most common key characteristics of fire regimes to be addressed are fire size, frequency, intensity, season, and extent (Archibald et al. 2013; Pereira et al. 2022a, b). Fires in MTE have the highest intensity and recurrence among European ecosystems and are only surpassed in extent by those occurring in steppes (Pausas 2022). More acutely, from a societal perspective, wildfires in MTE can result in extreme socioeconomic damage, including loss of human lives and livelihoods (Bowman et al. 2017).

Although typically occurring under different fire weather conditions, prescribed burning and wildfire disturb the quantity, composition, and structure of vegetation, from local- to landscape-scales, producing vegetation mosaics reflecting the spatial patterns of past fires. The fuel mosaic is a fundamental characteristic of the landscape as it affects wildfire propagation, but is itself shaped by wildfire propagation through pattern–process feedbacks (Turner 1989, 2010). This includes enduring effects or legacies embedded in the landscape matrix as an ecological memory (Peterson 2002; Johnstone et al. 2016). For example, the loss of the rural mosaic with its inherent fuel discontinuities promotes the spread of large wildfires, which in turn contribute to increase landscape homogeneity (Loepfe et al. 2010). Landscapes can be more or less readily reburned by subsequent wildfires, depending on the severity and extent of prior fire events, and also on climate, topography, and vegetation recovery rates after disturbance (Collins et al. 2009; Price and Bradstock 2010, 2011; Parks et al. 2013; Buma et al. 2020). Thus, from the perspective of planning fuel management and fire suppression strategies, it makes sense to consider past wildfires as fuel treatments that can opportunistically contribute to fire control operations (Regos et al. 2014; Parks et al. 2015).

MTE landscapes are prone to wildfires and Portugal is no exception, namely under the current situation where large wildfires have increased in frequency and extent (Davim et al. 2022). The bottom-up (topography and fuels) drivers of wildfire spread exert local scale control, whereas top-down (climate-weather and land use) prevail at larger scales of analysis (Viedma et al. 2009; Parks et al. 2012; Fernandes et al. 2016b). At the intermediate scale level, wildfire behavior is affected by an intricate and irregular play of interactions between bottom-up and top-down variables where the legacy of previous wildfires may play a decisive role (McKenzie et al. 2010).

Empirical studies show direct or indirect worsening of fire behavior with time since last fire (TSF), e.g., McCaw et al. (2012), following structural changes that increase fuel continuity, height and load (Fernandes 2015) and explain why a wildfire is more likely to be contained when intersecting a recently burned area. Fire-on-fire interactions, whereby a wildfire encounters an area burned in the past, are understood as part of a self-regulating mechanism where past burned areas limit subsequent wildfire occurrence, spread, and severity (Collins et al. 2009; Parks et al. 2013, 2016) and may provide suppression opportunities that otherwise might not exist (Belval et al. 2019).

Multiple studies have directly or indirectly addressed fire-on-fire interactions in the western USA (Collins et al. 2009; Parks et al. 2012, 2013, 2015, 2016; Price et al. 2012; Belval et al. 2019; Yocom et al. 2019, 2022) and Australia (Boer et al. 2009; Price et al. 2015b) but are scarce elsewhere (Price et al. 2015a). Previous work in southern Europe was based on simulation and dealt with the effects of past burned area (prescribed fire and wildfire scars) and firefighting (Piñol et al. 2005, 2007; Regos et al. 2014) or modeled how past burned area influenced subsequent burned area (Price et al. 2015a; Duane et al. 2019; Davim et al. 2021, 2022). However, analyses of fire-on-fire interactions based on individual wildfires are missing from the European literature.

Overall, current results show TSF as a central driver in the self-limiting process, its effect decaying over time, and that extreme fire weather increases reburn probability, while topography effects vary across sites. Collins et al. (2009) found that fuels younger than nine years have low reburn probability under low to moderate fire weather in the Sierra Nevada of California. Teske et al. (2012) report that less than 3% of wildfire edges were intersected by subsequent wildfires, but around 80% of those edges were breached, resulting in reburns. Some authors (Parks et al. 2012, 2013, 2015, 2016; Yocom et al. 2022) indicate that past wildfires reduce future wildfire occurrence, severity, and extent, with the effect decaying as fuels build-up. Others (Fernandes et al. 2012, 2016a, 2016c; Oliveira et al. 2012; Price et al. 2015a) also note that wildfire size and burn likelihood correlate positively with long-unburnt fuels. Frequent fire can decrease fire size and enhance past fire leverage, i.e., the effect that past burned area has on reducing wildfire growth (Price et al. 2015a; Davim et al. 2022).

Landscape features such as roads, water (and moist topographic positions), and other unvegetated areas can also diminish wildfire size by acting as fuel breaks and anchor points for fire suppression operations (Syphard et al. 2011; Yocom et al. 2019). Davim et al. (2021; 2022) considered prescribed burning – wildfire interactions in Portugal, but wildfire-on-wildfire interactions remain to be studied. Studies on the prevalence of land cover classes burned by wildfires are popular in southern Europe (Nunes et al. 2005; Bajocco and Ricotta 2007; Barros and Pereira 2014; Oliveira et al. 2014). The concept can be extended to analyze how prevalent are different TSF in the composition of the area burned by large wildfires, thus providing an overall landscape-level assessment of reburn likelihood.

Integrated fire management benefits from characterizing and evaluating wildfire as a self-regulating mechanism in the landscape, as it should facilitate decision making regarding the planning of fuel treatment and suppression operations. We examined individual fire-on-fire interactions in mainland Portugal and assessed the effect of past wildfires on limiting the spread of subsequent large wildfires. We addressed the following research questions: (1) to what extent previous wildfire limits subsequent large wildfire, considering distinct firefighting preparedness and suppression difficulty levels and the presence or absence of putative barriers, namely roads and water? and (2) how does TSF varies in its contribution to the area burned by large wildfires? We hypothesized that recently burned areas are likely to hinder fire spread, especially where past burn probability is higher, and that such likelihood increases under lower fire danger, higher fire suppression preparedness, and when TSF transitions coincide with physical barriers such as roads and water. Likewise, we expected that higher TSF would be more prevalent in the composition of the area burned by large wildfires.

Methods

Study area

Mainland Portugal (89,100 km^2) is located in the western Iberian Peninsula, facing the Atlantic Ocean (Fig. 1a). With an elevation ranging from 0 to 2000 m above mean sea level (Fig. 1b), it has two distinct climate regions. According to the Köppen-Geiger Climate Classification (Peel et al. 2007), Portugal has a Mediterranean climate classified as Csa (hot summer, i.e., at least 1 month's average temperature above 22 °C) in the south and Csb (warm summer, i.e., all months with average temperatures below 22 °C) in the north and center. The southern part of the country is mostly a lowland dominated by farmland and evergreen oak (*Quercus suber*, *Q. rotundifolia*) woodlands, where grass is the main fire propagation carrier. The northern section of Portugal is more rugged and is dominated by forest in its western part and at lower elevations, mainly pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) plantations, and by shrublands in the eastern part and at higher elevations, with fragments of deciduous oak forests (Tonini et al. 2017). In general, vegetation features adaptations to frequent and severe fire and persists through sprouting and (or) germination but obligate seeders such as pines are vulnerable to short-interval stand-replacement fire (Paula et al. 2009).

The fire regime varies regionally depending on climate, land cover, topography, and ignition density (Fernandes et al. 2019; Pereira et al. 2022a,b; Bergonse et al. 2023). The median fire return interval in Portugal is 28 years, and 1.2% of the country burns every year (Oliveira et al. 2012), but wildfire activity is unevenly distributed (Fig. 1c), with a higher prevalence of particularly large and severe wildfires in central Portugal mountains (Fernández-Guisuraga et al. 2023). The

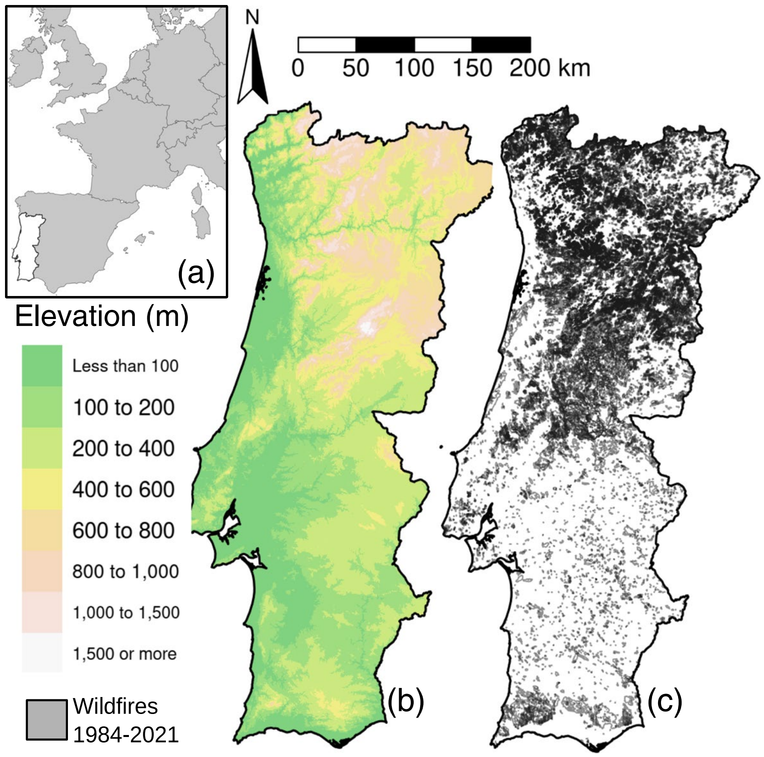

Fig. 1 Mainland Portugal as the study area: **a** location; **b** spatial distribution of the elevation classes, resulting from the *elevatr* package (Hollister et al. 2021) in *R software enviroment* (R Core Team 2021); **c** wildfires ≥ 20 ha between 1984 and 2021

Portuguese fire management policy is similar to the rest of the southern Europe and follows a fire-suppression centered paradigm (Moreira et al. 2020). Nonetheless, fuel treatments and prescribed burning to reduce large wildfire occurrence and extent have been expanding in the last decade (Davim et al. 2022). Managing wildfire spread under mild fire weather, which has been proposed for southern Europe (e.g., Regos et al. 2014), is possible under the Portuguese legislation, and pastoral (non-institutional) burning is tolerated to some extent (Oliveira and Fernandes 2023).

Data sources and processing

We compiled a wildfire atlas from burned-area shapefiles downloaded from the Portuguese Forest Service Geocatalogue (https://geocatalogo.icnf.pt/catalogo_tema5.html). Although available records go back to 1975, satellite imagery sources and wildfire mapping methodology changed over time. Thus, we restricted wildfire data to 1984–2021 to ensure that all burned area measurements were made using Landsat TM and Enhanced TM Plus with a 30-m spatial resolution and a 5-ha minimum mapping unit (Neves et al. 2023). We separated wildfires into two data subsets: wildfires ≥ 20 ha that occurred during 1984–2021 (Fig. 2) as the "past wildfires" candidates to be encountered by "large wildfires" and wildfires ≥ 500 ha that occurred in the period 2001–2021 as the "large wildfires" (Fig. 2). The 20-ha threshold was selected because it is a reasonable size limit below which recently burned patches are unlikely to disturb large-wildfire spread (Davim et al. 2021). Past prescribed burning interactions with wildfire were previously studied (Davim et al. 2021) and were not considered, also because prescribed fires seldom exceed 20 ha in size, are scarce and very unevenly distributed in Portugal, and tend to be located in pastoral burning landscapes where large wildfires are infrequent or even absent (Fernandes et al. 2016b; Davim et al. 2021).

To analyze how past wildfires limited future large wildfires, we iterated through each large wildfire (Fig. 2) and used the *sf* (Pebesma 2018) package in *R software enviroment* (R Core Team 2021) to select from the "past wildfire candidates" those that were partially or totally reburned or had a section of their edge located within 100 m of the large wildfire edge (positive fire-on-fire interaction). We assumed this distance as the most adequate, considering satellite imagery resolution (30 m) and the associated classification uncertainty along fire edges, as well as the distances reported in fire-on-fire interaction studies (Teske et al. 2012; Parks et al. 2015; Macauley et al.

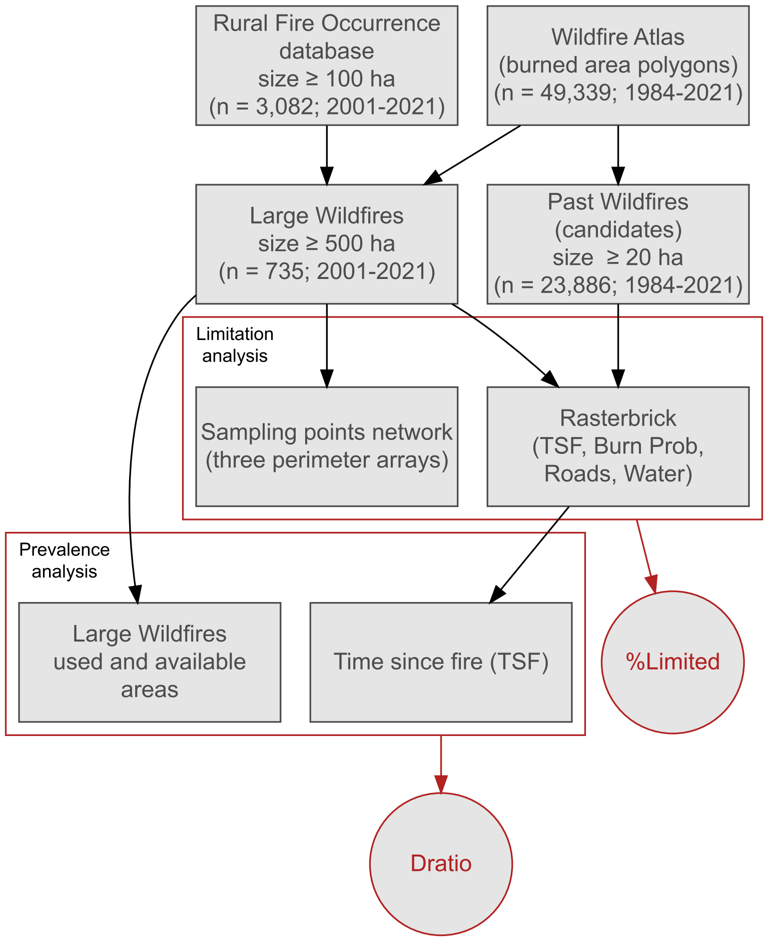

Fig. 2 Flowchart of data processing to obtain %Limited as the proportion of large-wildfire edge that was limited in spread at fuel patches with time since fire (TSF) transitions and to obtain Dratio as the burn prevalence by TSF

2022). We used the *terra* (Hijmans 2022) package to rasterize past wildfires and their intersections (reburns) to identify the last time each pixel (30×30 m) burned. We calculated the TSF of each pixel as the number of years elapsed between the previous wildfire and the large wildfire event. Large wildfires in Portugal are typically stand-replacing, owing to the nature of the vegetation, i.e., shrubland, low-stature oak woodlands, and forests plantations prone to crowning or complete canopy scorch. Additionally, as it could influence fuel build-up rate, we calculated burn probability (Burn Prob) by dividing the number of times a pixel burned by Y-1984, where Y is the year of the large wildfire in question.

We identified roadways (Roads) and watercourses, i.e., streams and rivers (Water) in the vicinity of each large wildfire using Open Street Maps data from the Geofabrik's server (http://download.geofabrik.de/europe/portugal-latest-free.shp.zip). The data was converted from vector to raster and classified into binary maps where each pixel coincident with a road or with water and the respective 100-m buffer was classified as Yes (presence) and the remaining pixels as No (absence). All rasters were stored into a rasterbrick (Fig. 2) representing the large-wildfire landscape.

Fire danger rating in Portugal and at pan-European level is based on the Canadian Forest Fire Weather Index System (Van Wagner 1987) which has been successfully linked to fire activity in southern Europe (e.g., Fernandes 2019; Dupuy et al. 2020). The Fire Weather Index (FWI) and the other indices in the system are calculated daily by the Portuguese Institute for Sea and Atmosphere and are available for each wildfire record in the Rural Fire Occurrence (RFO) database curated by the Portuguese Forest Service (https://www.icnf.pt/florestas/gfr/gfrgestaoinformacao/estatisticas). Missing FWI were obtained from the Copernicus Emergency Management Service historical data (https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-fire-historical?tab=overview). We matched each large wildfire polygon (on the basis of year, location and size) with the corresponding wildfire record in the RFO to obtain its date of occurrence. Each wildfire was then assigned a fire danger class following Palheiro et al. (2006): Low (FWI ≤ 8.4), Moderate (8.5 ≤ FWI ≤ 18.1), High (18.2 ≤ FWI ≤ 24.5), very high (24.6 ≤ FWI ≤ 38.2), or extreme (FWI > 38.2); these thresholds define fire suppression difficulty levels as determined by fireline intensity in maritime pine stands. Likewise, each wildfire was assigned a preparedness level. Fire suppression in Portugal considers four seasonal preparedness levels (DECIR I to IV) signifying increasingly higher availability of firefighting resources (Comando Nacional de Emergência e Proteção Civil 2021): I (1 January to 14 May), II (15–31 May and 16 October-31 December), III (1–30 June and 1–15 October), and IV (1 July to 30 September).

Wildfire limitation at TSF transitions

We used the whole extent of the edge of each large wildfire (*n* = 735) to anchor a network of sampling points to evaluate whether fire spread ceased upon encountering lower TSF, noting also if this TSF transition coincided with roads or water. In *QGIS* (QGIS Development Team 2021), we drew 240-m transects perpendicular to the wildfire perimeter and spaced at 30-m intervals to match the wildfire data resolution (Fig. 3). We placed three points in each transect: midway (wildfire edge) and at its extremities, i.e., 120 m inside and outside the burned area. At each transect, the wildfire edge point was dichotomously classified as limited (1) or not limited (0), depending on whether TSF changed (decreased) from the inside to the outside, resulting in a whole perimeter classification similar to that of Parks et al. (2015). The dataset was truncated at a TSF of 15 years, the approximate threshold for steady-state fuel loading and modeled fire spread and intensity in Portugal (Rosa et al. 2011; Fernandes et al. 2014, 2016c; Botequim et al. 2015).

For each large wildfire, we grouped the observations corresponding to all combinations of TSF, Roads, and Water, calculated the corresponding proportions of "limited = 1" events, and used it as the dependent variable (%Limited) in a generalized linear model (GLM). This grouping process was expected to minimize, if not override, the serial and spatial correlation of the 30-m observation points along wildfire edges. Model fitting considered TSF, Roads, Water, Fire Danger, Burn Prob, and their first-order interactions as putative predictors, weighted by the number of observations (equivalent to the whole perimeter). Firefighting preparedness was not retained for the GLM, as most wildfires coincided with maximum seasonal availability of suppression resources (Table S1). We assumed the binomial family with the logit link function through the *glm* function of the *stats* package and considered zero-inflated (due to the high percentage of zeros in the dependent variable) and mixed effects (with the wildfire identification as a random effect) models.

We assessed model performance with the Akaike's information criterion, AIC (Burnham and Anderson

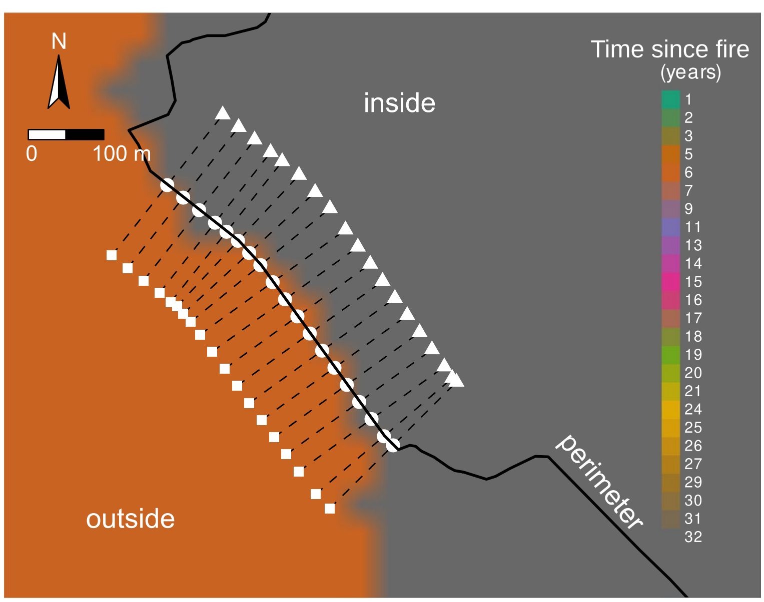

Fig. 3 Example of a section of a large-wildfire edge limitation analysis. Solid black line, large wildfire perimeter; dashed lines, sampling transects; triangles are located 120 m inside the large wildfire perimeter; squares are located 120 m outside the large wildfire perimeter; circles coincide with the large wildfire edge. This analysis was done for the whole extension of the large wildfire perimeters (*n* = 735)

2004), and pseudo-R^2 (Nagelkerke 1991). We inspected the residuals for autocorrelation and influential observations that could bias model estimates. We analyzed the predictors effect through the analyzes of deviance of the best model. We compared the predictors effect size by computing the odds ratio and robust confidence intervals (95%) of the model coefficients and plotted them using the *sjPlot* (Lüdecke 2022) package.

Differential prevalence of TSF within large wildfires

The overall effect of TSF on wildfire size reflects near-immediate fire spread limitation when TSF changes but also wildfire containment within the perimeter of a previous fire, i.e., partial reburn, which can be tackled by a resource selection function framework (Manly et al. 2002; Barros and Pereira 2014; Moreira et al. 2009). We used a type III study design (Manly et al. 2002) for assessing large-wildfire areal prevalence by TSF. We considered the large wildfire burned area as the "used area" and enlarged it through a 5-km distance buffer to define the "available area" (Fig. 4). We calculated Dratio = (u-a)/(u + a − 2ua), i.e., the Jacobs selectivity index ratio (Jacobs 1974), where u is the proportion of TSF i used by large wildfire j and a is the proportion of TSF i available to fire j. Dratio approaches 1 for maximum areal prevalence and −1 for minimum areal prevalence. Dratio = 0 expresses perfect indifference, i.e., a given TSF burn in the exact proportion of their presence in the landscape. We modeled Dratio as a function of ln(TSF) and with Fire Danger as covariate, since a power function should approach how fuel dynamics change over time, e.g., Marsden-Smedley et al. (2022).

Results

Wildfire limitation at TSF transitions

From the compiled wildfire atlas (n = 49,339 and 4,699,272 ha, 1984–2021), 42% of the wildfire polygons were ≥ 20 ha, accounting for 96% of the total burned area. Large wildfires (≥ 500 ha, n = 735) burned 1,853,529 ha (39% of the total burned area) in 2001–2021, mostly during Very High to Extreme Fire Danger (95%) and DECIR IV days (90%) (Table S1). The median TSF of large-wildfire edges was 7 years with a 4–11 inter-quartile range (IQR). Fire spread cessation within 100 m of the wildfire edge coincided mostly with the presence of roadways (52%) or watercourses (32%). The median %Limited was 3% with an IQR of 0–22%. The overwhelming majority (96%) of large wildfires intersected at least one past wildfire. The number of past wildfires intersected by a large wildfire ranged from 0 to 295, with a median of 14 and an IQR of 6–24. Central Portugal was the hotspot of fire-on-fire interactions, especially due to the extremely large wildfires of 2017.

Fixed effects logistic regression had better fit (lowest AIC) than zero-inflated and mixed effects models. First-order interactions between variables were discarded from selected models due to statistical non-significance and high collinearity with the main effects. TSF alone explained 51% of the variability in %Limited (Table 1). Adding Burn Prob, Roads, Water, or Fire Danger as main effects to TSF increased, in small increments, model

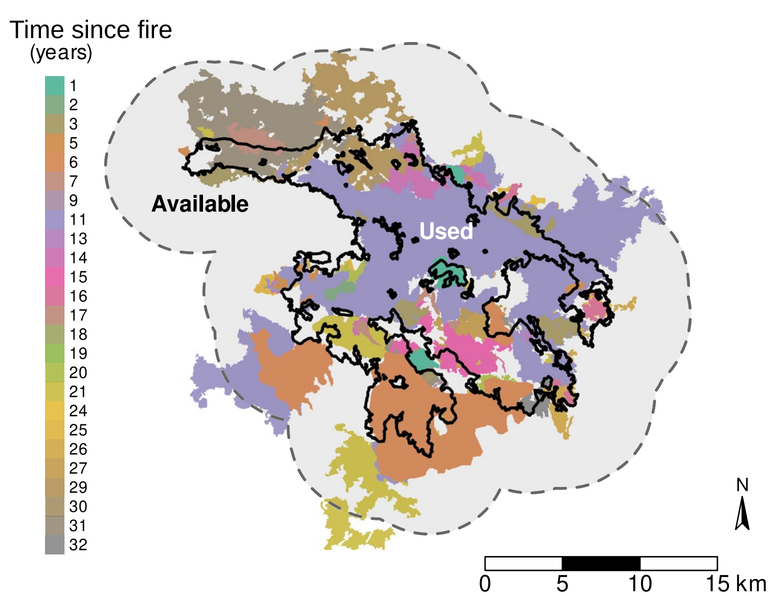

Fig. 4 Example of the areas considered for the burn prevalence analysis. The solid black line delimits the used area (large-wildfire area) and the dashed line delimits the available area, corresponding to a 5-km buffer

Table 1 Goodness-of-fit of models to predict the proportion of wildfire edge (%Limited) coinciding with time since fire (TSF) transitions and covariates. Nagelkerke pseudo-R^2 (Nagelkerke 1991); Model1 is the null model; Number of observations = 11,745

Model	Formula	Pseudo-R^2	AIC	Deviance	Df
Model1	%Limited = 1	0	157,422	137,349	11,744
Model2	%Limited = TSF	0.51	149,134	129,059	11,743
Model3	%Limited = TSF + Burn Prob	0.51	148,931	128,854	11,742
Model4	%Limited = TSF + Roads	0.52	148,885	128,808	11,742
Model5	%Limited = TSF + Water	0.51	149,128	129,052	11,742
Model6	%Limited = TSF + Fire Danger	0.53	148,583	128,546	11,738
Model7	%Limited = TSF + Burn Prob + Roads + Water + Fire Danger	0.55	148,073	127,985	11,729

Table 2 Analysis of deviance of Model7. See the "Methods" section for description of variables and Tables 1 and S2 for model goodness-of-fit and coefficient estimates respectively

Predictor	Df	Deviance	Residual Df	Residual deviance	*p*-value
Null			11,744	137,349	
TSF	1	8,290	11,743	129,059	< 0.001
Burn Prob	1	205	11,742	128,854	< 0.001
Roads	1	303	11,741	128,551	< 0.001
Water	1	27	11,740	128,524	< 0.001
Fire Danger	4	539	11,736	127,985	< 0.001

performance. Among the partial models (Model2 to 6), the highest pseudo-R^2 and lowest AIC was from Model6 where TSF and Fire Danger explained 53% of %Limited. Model7 provided the best fit and combined all variables of the partial models, accounting for 55% of the variability in %Limited.

Analysis of Model7 residuals plots showed no pattern in residuals versus fitted values, i.e., no autocorrelation. However, the residuals versus leverage plot revealed some outliers (Fig. S1), requiring the robust estimation of confidence intervals (Table S2). TSF was the overwhelming important variable in Model7, as assessed by deviance reduction, followed by Fire Danger, Roads, Burn Prob, and Water (Table 2).

TSF had a negative and near-linear effect on %Limited (Fig. 5), which is to say that the likelihood of large wildfire limitation decreases as TSF increases and fuel grows older. %Limited decreased from 15% at TSF = 1 year to 10% at TSF = 8 years. The Burn Prob effect was positive, showing that high fire recurrence increases the probability of subsequent large wildfire limitation. The presence of Roads (Fig. 5c) or Water (Fig. 5d) increased %Limited, but the effect of the later was inconsequential. %Limited under Extreme Fire Danger (reference level, 70% of the observations) was lower than under Very High and High Fire Danger (28% of the observations) but higher than under Moderate to Low Fire Danger (2% of the observations).

Differential prevalence of TSF

Dratio approaches 1 for maximum areal prevalence and −1 for minimum areal prevalence. Dratio = 0 expresses perfect indifference, i.e., a given TSF burn in the exact proportion of their presence in the landscape. TSF prevalence in the composition of large-wildfire area (Dratio) was extremely variable (Fig. 6), resulting in an overall weak pattern across the TSF range. The minimum prevalence was for TSF = 1, but if a less strict criterion is followed, e.g., considering the 25th percentile of Dratio, some degree of burning in a proportion lower than presence in the landscape persists for 5 years after fire (Fig. 6). Mean Dratio increased with TSF up to 6 years, and then the corresponding plateau was maintained, as indicated by both the median and the mean values.

The model describing burn prevalence, Dratio = $a + b\ln(\text{TSF}) + c$Fire Danger (Fig. 7), indicates that Dratio increases weakly ($b = 0.153$) with TSF (Table 3). We could not unequivocally quantify a Fire Danger effect on TSF prevalence in the areal composition of large wildfires, as the confidence intervals of most classes were overlapped. Nonetheless, Low Fire Danger results in low burn prevalence (as defined by negative Dratio) for ~ 6 years since the last fire.

Discussion

Large-wildfire limitation by TSF

The overwhelming majority (96%) of large wildfires occurring in mainland Portugal (2001–2021) overlapped at least once with an area burned by a previous wildfire. This intersection rate is considerably higher than reported elsewhere, namely in the USA, where it ranged between 3 and 50%, conditional on time-frame and spatial-scale of analysis (Teske et al. 2012; Belval et al. 2019; Yocom et al. 2019). Davim et al. (2021) also reported a markedly higher intersection rate between wildfires and

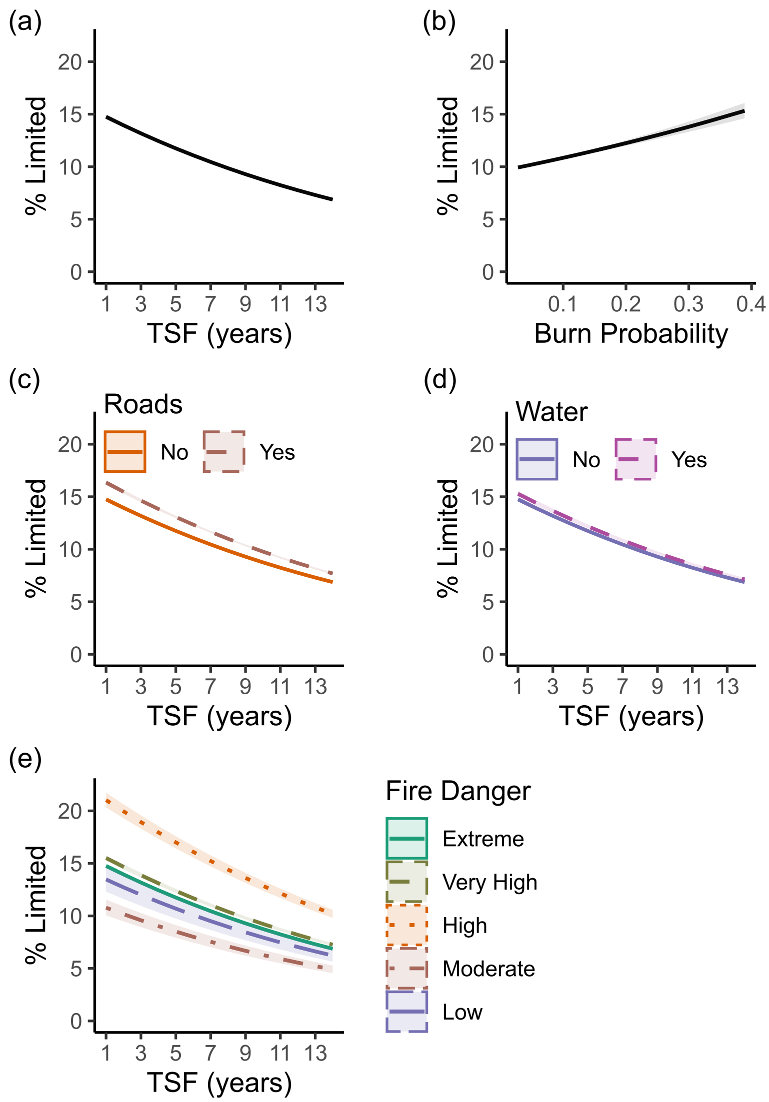

Fig. 5 Model7 prediction of %Limited as a function of: **a** TSF (time since fire); **b** Burn Prob (burn probability); **c** TSF and Roads; **d** TSF and Water; **e** TSF and Fire Danger. Other covariates were set to reference (Roads = No, Water = No, Fire Danger = Extreme) and median values (TSF = 7, Burn Prob = 0.07)

prescribed burning treatments in Portugal compared to the USA and Australia, justified by the fact that in some regions the combination of ignition density, topography, and flammable fuels leads to a higher frequency of large wildfires, which increases the likelihood of fire interactions.

While the median TSF of the wildfire limits is just 7 years, the median fire return interval in Portugal varies regionally between 23 and 52 years (Fernandes et al. 2012) with a country-wide median of 28 years (Oliveira et al. 2012). This is suggestive of a fuel effect on wildfire spread beyond the barriers posed by TSF transitions, i.e., within reburns. The typical percentages of the wildfire perimeter that are limited by TSF transitions may seem modest, but the corresponding burned area decrease is substantially higher, because fire size is roughly dependent on the square of its perimeter, as per elliptical fire growth models (Forestry Canada Fire Danger Group 1992). For example, the perimeter of one fourth of the large wildfires was decreased by > 22%, which translates into a burned area reduction of > 39%.

Wildfire limitation by TSF class transitions was mostly concurrent with the presence of roads or water, indicating the repetition of previous spread cessation events. Our coincidence of large wildfire edges with roads doubled the 26% figure reported by Yocom et al.

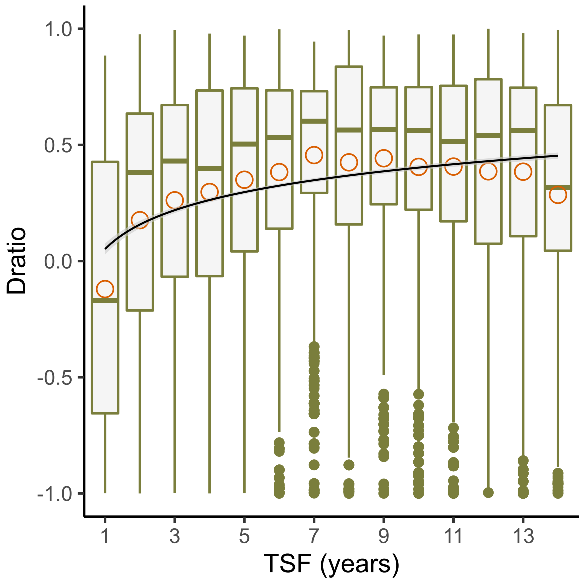

Fig. 6 Burn prevalence (Dratio) distribution by TSF (time since fire). Hollow circles and thick lines inside the boxplots are the mean and median values, respectively. The model Dratio = ln(TSF) (black curve with confidence intervals) is superimposed

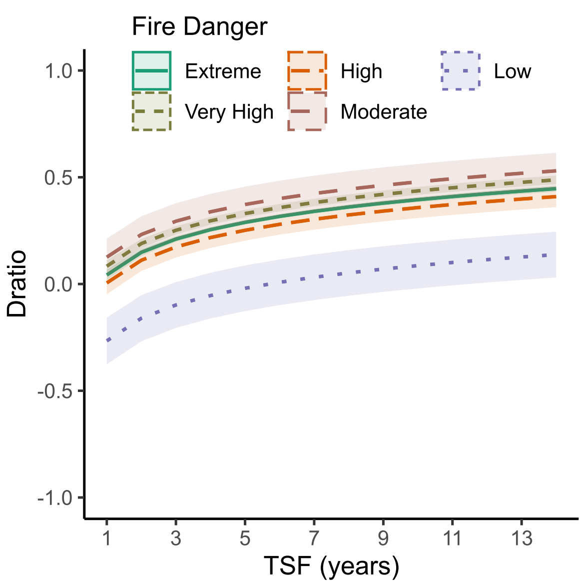

Fig. 7 Prediction curves for burn prevalence (Dratio) as a function of TSF (time since fire) and Fire Danger

(2019). This may be attributed to the fact that Portugal is a more densely populated country and consequently has higher density of roads within forests and shrublands compared to the western USA. Price and Bradstock (2010) also noted that the presence of roads increases the chances of wildfire spread stopping in the vicinity.

Table 3 Coefficient estimates for the Dratio (burn prevalence) model

Predictor	Coefficient (95%CI)	*p*-value
Intercept	0.042 (0.018 to 0.067)	0.001
ln(TSF)	0.153 (0.141 to 0.165)	< 0.001
Fire danger		
Extreme		
Very high	0.041 (−0.021 to 0.062)	< 0.001
High	−0.037 (−0.087 to 0.012)	0.140
Moderate	0.083 (−0.001 to 0.168)	0.053
Low	−0.309 (−0.416 to −0.201)	< 0.001

Bottom-up variables, including those that pertain to fuels, can override top-down influences as drivers of large wildfire likelihood and growth (Parks et al. 2012; Fernandes et al. 2016b). Our finding that %Limited decreases when TSF increases is consistent with other studies (Collins et al. 2009; Fernandes et al. 2012; Parks et al. 2015; Prichard et al. 2017; Yocom et al. 2019). Aging shrubland has higher dead-to-live fuel ratio and therefore decreased mean fuel moisture content (Baeza et al. 2002; Rossa 2017; 2018; Rossa and Fernandes 2018), making these fuel complexes more likely to burn under most fire weather conditions, even though young fuels are not fire-free under severe burning conditions (Davim et al. 2021; Fernandes et al. 2012). Additionally, fire spread and intensity are expected to be enhanced by increases in fuel loading, height and continuity with time since the last disturbance (e.g., Marsden-Smedley and Catchpole 1995; McCaw et al. 2012; Fernandes 2015).

TSF explained half of the existing variability in %Limited. A manifest limitation of using TSF in the analysis as a proxy for fuel conditions is that substantial variation in fuel structure and loading is expected depending on climate, vegetation type, and site productivity, e.g., Rosa et al. (2011). Past fire severity may also play a role in such uncertainty, although its effect on fuel recovery has been shown to be weak in Mediterranean shrublands (Keeley et al. 2008). Minor model improvements resulted from individually adding the other variables to TSF. Considering TSF together with Fire Danger resulted in a relevant increase in %Limited. The scarce representativeness of Fire Danger levels Low, Moderate, and High, collectively accounting for 5% of the number of observations, warrants a cautious interpretation. Nevertheless, %Limited was distinctively higher for High Fire Danger, a probable combined outcome of maximum preparedness level, non-extreme fire behavior, and the annual peak of live fuel moisture content (an influence not depicted by the FWI) in late spring and early summer.

The presence of roadways resulted in higher %Limited than watercourses, possibly because the latter are located mostly in valleys and are not expected to anchor fire suppression operations, due to difficult access and poor safety conditions. While wildfire edges and roads often coincided, the presence of a road increased %Limited by less than 10% compared with its absence. This suggests that the influence of roads is essentially physical—a fuel discontinuity—rather than effectively assisting with fire containment operations. Multiple influences can be at play here, including absence of firefighting crews, extreme fire behavior precluding direct control, unattempted or ineffective indirect attack, and spotting over roadways. Opportunities for large-fire control, including those related with fuels, are known to be insufficiently explored in Portugal (Fernandes et al. 2016c).

Increased historical burn probability substantially increased the likelihood of wildfire perimeter limitation at TSF transitions. Repeated wildfire events can decrease site productivity through soil erosion and subsequent higher rockiness, but also result in high pyrodiversity in terms of the spatial patterns of fire recurrence, which has been shown to decrease subsequent wildfire size (Fernandes et al. 2016b). Moreover, high pyrodiversity can indirectly mitigate the effects of large wildfires, as in the "treatment shadow effect" described by Collins et al. (2013).

In Portugal, a burn prevalence categorically lower than what would be expected from landscape presence is limited to TSF < 2 years, with low dependence on Fire Danger. The maximum burn prevalence is attained and stabilizes at 6 years after the previous fire, i.e., a higher presence of TSF < 6 years in the landscape increases the chances of restraining large-wildfire size. This is different from the results of the %Limited analysis, which indicate a TSF effect that extends beyond 6 years. Thus, the period during which burn prevalence is lower as a consequence of recent fire is shorter within the reburned area, i.e., beyond locations where TSF transitions coincide with roads. This is the expected outcome of the prevailing fire suppression model where the heavy reliance on fire engines (rather than on hand crews) is dependent on the road network for accessing an approaching fire.

Our results are consistent with those pointing to a short-lived effect of TSF on wildfire extent in Portugal (Price et al. 2015a; Fernandes et al. 2019), Spain (Duane et al. 2019), and in temperate warm to hot summer climates elsewhere (Boer et al. 2009; Price et al. 2012). Previous work reports that the area treated with prescribed fire and not reburned by a subsequent wildfire was 1.5 times greater for fuels < 3.5 years old (Davim et al. 2021) and that the effect of prescribed burning in decreasing wildfire extent lasted for about 5 years, whereas the corresponding effect of wildfire lasted 7 years (Davim et al. 2022). The longer lasting effect of wildfire may be because it burns at higher intensity and therefore more severely than prescribed burning. In addition, wildfire burns a larger proportion of the landscape than prescribed burning, so a subsequent fire is more likely to encounter areas previously burned by wildfire that limit its spread.

Management implications

Among the options for fuel treatments, prescribed burning is considered the most cost-effective, and although its use is often limited by socio-political, ecological, and environmental reasons (Miller et al. 2020), it is being reinforced in Portugal to reduce large wildfires. Our results provide additional support for the design of integrated fire management strategies aiming at reducing fire hazard, since the notion of wildfire being a self-limiting process in landscapes (Parks et al. 2015) was further supported, albeit during a shorter period of time than in less productive ecosystems elsewhere. Davim et al. (2022) highlight that wildfire area is notably higher than prescribed burning in Portugal and so is its leverage. Thus, the fuel-reduction effects of past wildfires should be recognized as a component of the fire management tool box. Using prescribed burns and managing wildfire spread under mild fire weather conditions as complementary strategies for limiting large wildfires (Piñol et al. 2007; Regos et al. 2014) can promote healthier ecosystems and maintain resilient landscapes able to withstand the impacts of future wildfires.

Fire management actions should follow a philosophy of anticipation rather than of reaction to wildfires. Our results on the effectiveness of previously burned areas and proximity to roads and water as barriers to fire spread can inform the design of spatial simulations of fire behavior aimed at planning the strategic placement of fuel treatments (Benali et al. 2021; Aparicio et al. 2022; Sá et al. 2022) and used in planning to increase the effectiveness of wildfire control operations (Belval et al. 2019). Integrated fire management will greatly benefit from the holistic use of fire, i.e., managing ongoing wildfires sharing principles and practices with prescribed burning, namely a prescription and assessment following objective criteria (e.g., "restoration fire," Barros et al. 2018). This approach to fire management can result in higher burned area, but a trade-off is expected whereby severe large fires contribute less to the fire regime and lower-severity and smaller fires, either planned or unplanned, expand. This is in line with the idea that, rather than the overall burned area, evaluation of wildfire campaigns should acknowledge the reduction of areas burned at high severity (Tubbesing et al. 2019; Moreira et al. 2020) and the corresponding avoided ecological and socioeconomic impacts and embrace the ecosystem services associated to low-severity fire.

Conclusion

Large wildfires in Portugal often intersect areas burned by previous wildfires. The edge of a spreading wildfire is more likely to be limited when it encounters younger fuel resulting from recent wildfires, particularly when it coincides with the existence of roads or water. The extent of perimeter limitation is also influenced by annual burn probability and fire danger. The likelihood of large-wildfire limitation increases with lower TSF and where historical burn probability is high, showing the importance of fuel discontinuity and pyrodiversity for wildfire containment. Large wildfires occurring when the seasonal availability of suppression resources is maximum are more limited if spreading under high fire danger conditions but not under very high to extreme fire danger. This reflects the technological limits to wildfire control in face of extreme fire behavior but presumably also a firefighting system based on fire engines and dependent on the road network for access. Burn prevalence in relation to TSF availability in the landscape was less marked and shorter-lived than wildfire spread cessation at TSF transitions, a further indication of firefighting efforts concentrated along roads, hence not taking advantage of low-flammability conditions beyond them.

A fire management approach that combines improved management of wildfire events, either suppressing them more effectively when fuel conditions allow it or "using" them as a fuel management tool under mild fire weather and supplementing prescribed burning and other fuel treatments would diminish large wildfire occurrence and promote more fire-resilient landscapes.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-023-00227-x.

Additional file 1: Table S1. Observed wildfire distribution (%) by combinations of firefighting preparedness (DECIR) and Fire Danger classes. **Table S2.** Predictor effects of %Limited models in the form of odds ratios (and robust 95% confidence intervals). See methods for description of predictor variables. **Figure S1.** Model7 residuals diagnostic plots.

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Authors' contributions

DD: formal analysis, investigation, methodology, writing—original draft, review and editing. CR: supervision, formal analysis, writing—review and editing. JP: supervision, writing—review and editing. NG: methodology, writing—review and editing. PF: conceptualization, supervision, writing—review and editing. The authors read and approved the final manuscript.

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author, D.A. Davim, upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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