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Fuel build-up promotes an increase in fire severity of reburned areas in fire-prone ecosystems of the western Mediterranean Basin

José Manuel Fernández-Guisuraga[1,2*] and Leonor Calvo[2]

Abstract

Background Fire-vegetation feedbacks can modulate the global change effects conducive to extreme fire behavior and high fire severity of subsequent wildfires in reburn areas by altering the composition, flammability traits, and spatial arrangement of fuels. Repeated, high-severity wildfires at short return intervals may trigger long-term vegetation state transitions. However, empirical evidence about these feedbacks is absent in fire-prone ecosystems of the western Mediterranean Basin, where the response of fire activity has been enhanced by contemporary socioeconomic and land-use changes. Here, we evaluated whether fire severity differs between initial burns and subsequent wildfires in reburn areas (fire-free periods = 10–15 years) of maritime pine and Aleppo pine forests, holm oak woodlands, and shrublands in the western Mediterranean Basin, and whether there is a relationship between the severity of such interactive wildfire disturbances. We also tested how the type of ecosystem and changes in vegetation structure after the initial wildfires influence these relationships. We leveraged Landsat-based fire severity estimates for initial and last wildfires using the Relativized Burn Ratio (RBR) and Light Detection and Ranging (LiDAR) data acquired before the last wildfire.

Results Fire severity of the last wildfire was significantly higher than that of the initial wildfire for each dominant ecosystem type in reburn areas. These differences were very pronounced in maritime pine forests and shrublands. For consistency, the same patterns were evidenced for the fire severity in reburn and first-entry areas of the last wildfire for each dominant ecosystem type. Fire severity of the last wildfire in forests and woodlands (particularly maritime pine-dominated) raised with increasing severity of the previous wildfire to a greater extent than in shrublands. Pre-fire fuel density in the lower vegetation strata (up to 4 m high in maritime and Aleppo pine forests, as well as in shrublands, and up to 2 m high in holm oak forests) was significantly higher in reburn than in first-entry areas of the last wildfire.

Conclusions Our results suggest that land managers should promote more fire-resistant landscapes to high fire severity by minimizing fuel build-up and thus fire hazard through pre-fire fuel reduction treatments such as prescribed burning.

Keywords Interacting disturbances, LiDAR, *Pinus*, RBR, Reburning, Shrubland

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Resumen

Antecedentes Las retroalimentación entre el fuego y la vegetación puede modular los efectos del cambio global que conducen al comportamiento extremo del fuego y a una alta severidad de fuegos subsiguientes en áreas de interacción entre incendios. Esto se puede producir mediante alteraciones en la composición, características de inflamabilidad, y la disposición espacial del combustible. Los incendios repetidos, de alta severidad en intervalos de tiempo cortos, pueden producir transiciones a largo plazo sobre el estado de la vegetación. Sin embargo, la evidencia empírica sobre estas retroalimentaciones está ausente en los ecosistemas propensos al fuego en la cuenca oeste del Mediterráneo, donde la respuesta a la actividad del fuego ha aumentado por las actividades socioeconómicas y el cambio en los usos del suelo. En este trabajo, evaluamos si la severidad del fuego difiere entre incendios iniciales y subsiguientes en áreas con fuegos recurrentes (período libre de incendios de 10–15 años), en bosques de pino marítimo y pino de Alepo, en bosques de encinas y en matorrales de la cuenca oeste del Mediterráneo, y si existe una relación entre la severidad de estas perturbaciones interactivas. Testeamos asimismo cómo el tipo de ecosistema y cambios en la estructura de la vegetación después de los incendios iniciales influencian esas relaciones. Potenciamos las estimaciones de severidad basadas en LANDSAT para los incendios iniciales y finales, usando el Ratio Relativoa de Quema (Relativized Burn Ratio o RBR en inglés), y datos LIDAR adquiridos antes del último incendio.

Resultados La severidad del último incendio fue significativamente más alta que la del fuego inicial para cada tipo de ecosistema dominante en áreas de interacción de incendios. Estas diferencias fueron muy pronunciadas en bosques de pino marítimo y en matorrales. Consistentemente, los mismos patrones fueron evidenciados para la severidad de los incendios en áreas de interacción de incendios y en aquellas en que el fuego entró por vez primera durante el último incendio para cada tipo de ecosistema. La severidad del último incendio en bosques (particularmente los dominados por pino marítimo) aumentó con una la severidad del incendio anterior en mayor grado que en matorrales. La densidad del combustible pre-incendio en los estratos de vegetación bajos (hasta 4 m de altura en bosques de pino marítimo y de Alepo, como también en matorrales, y hasta 2 m de altura en bosques de encinas), fueron también significativamente más altos en las zonas de interacción de icnendios que en la primera entrada del fuego durante el último incendio.

Conclusiones Nuestros resultados sugieren que los gestores del territorio deben promover paisajes más resistentes a la alta severidad, minimizando el aumento de la carga de combustible y por lo tanto el riesgo de incendio, mediante tratamientos de reducción del combustible, como por ejemplo quemas prescriptas.

Background

Terrestrial ecosystems of Mediterranean-type climate regions worldwide are subject to frequent wildfires for millennia (Pausas et al. 2008; Catry et al. 2013; Xofis et al. 2020). Under historical fire disturbance regimes, wildfires have shaped mosaic-like patterns of landscape diversity (i.e., pyrodiversity; Jones and Tingley 2022) and species adaptive traits from the ecological memory of past disturbances in fire-prone ecosystems of these regions (Keeley et al. 2012; Johnstone et al. 2016). Fire-adaptive traits, including resprouting response, serotiny, or heat-triggered germination (Lamont et al. 2019), are likely a result of different evolutionary pathways (Keeley et al. 2011; Pausas and Keeley 2017) and foster resilience to fire in Mediterranean plant communities (Fernández-Guisuraga et al. 2021). However, wildfire trends in recent decades evidence that strong fire regime shifts are occurring in fire-prone ecosystems of Mediterranean-type climate regions worldwide (Marlon et al. 2008), namely an increase in the area burned, frequency and severity of wildfires (Moreira et al. 2020; Ruffault et al. 2018).

Unprecedented impacts on adaptive resilience mechanisms to the next disturbance and ecosystem functions can be expected under rapid fire regime shifts in the context of global change (e.g., agricultural land abandonment and anthropogenic climate warming) (Johnstone et al. 2016; Morán-Ordóñez et al. 2020), particularly in southern European countries (Moreira et al. 2011). Specifically, these shifts may involve (i) novel interacting wildfire disturbances (Walker et al. 2018), (ii) transitions to alternate ecosystem states due to altered disturbance legacies (Franklin et al. 2000; Seidl et al. 2014), and (iii) cascading consequences for the provision of ecosystem services to the society, such as carbon sequestration and storage, timber production, or erosion protection (e.g., Huerta et al. 2022). In particular, there is heightened concern about the potential cumulative ecological impacts of unusually, large stand-replacing wildfire disturbances that begin to interact to past wildfire disturbances in reburn areas (Buma et al. 2020), with associated risk of ecosystem collapse (Tepley et al. 2018; Steel et al. 2021). In this context, fire-vegetation feedbacks can modulate the global change effects conducive to extreme fire behavior and high fire severity of subsequent wildfires in reburn areas (e.g., Parks et al. 2014a; Tepley et al. 2018) by altering the composition, flammability traits, and spatial arrangement of fuels (Lydersen et al. 2019; Collins et al. 2021). Remarkably, a repeated, high-severity wildfire at short return intervals may perpetuate high-severity patches due to long-term vegetation state transitions (van Wagtendonk et al. 2012) conducive to the degradation of ecosystem functioning and service provisioning (Steel et al. 2021). Therefore, understanding fuel dynamics and fire severity variability in areas of overlapping wildfire disturbances could provide valuable insights for managing Mediterranean fire-prone landscapes towards the maintenance of ecosystem resistance and resilience to fire, and the restoration of natural disturbance regimes in light of global change (Holden et al. 2010; Lydersen et al. 2019).

Much has been learned from previous research in reburn areas in temperate regions of the USA and Australia. In general, reburn areas in these regions have been reported to experience lower fire spread and severity than first-entry wildfire areas, indicating that previous wildfires moderate the fire behavior of subsequent wildfires, particularly on very short return intervals as a consequence of the reduction in fuel availability (Miller et al. 2012; Parks et al. 2015; Buma et al. 2020). Indeed, this is the main principle underpinning prescribed burning treatment to reduce fire hazard (Parks et al. 2014a). Specifically, self-regulating processes (i.e., negative feedbacks) in which low-to-moderate fire severity constrains fire spread and severity of subsequent wildfires can be expected if the initial wildfire consumes surface and ladder fuels leaving the canopy almost unaffected (Larson et al. 2013). Conversely, positive fire feedbacks may arise from high-severity wildfires that promote early seral vegetation types with high continuity of dry surface fuels, shrubs, and regenerating trees (van Wagtendonk et al. 2012; Tepley et al. 2018; Collins et al. 2021), as well as charred dead wood (Lydersen et al. 2019), readily available to subsequent wildfires. Indeed, downed branches and standing snags contribute to ground and elevated surface fuel loads, as well as to canopy torching of live trees in conifer forests (Stevens-Rumann et al. 2012; Ritchie et al. 2013; Coppoletta et al. 2016). Post-fire management after initial burns targeted at selectively removing snags can be effective in moderating the severity of subsequent wildfires (Coppoletta et al. 2016), bearing in mind the risks to the ecosystem that post-fire salvage logging may entail in some cases (Thompson et al. 2007; Castro 2021).

There is no empirical evidence about fire severity feedbacks in fire-prone ecosystems of the western Mediterranean Basin, where (i) the response of fire activity to fire weather has been enhanced by fuel build-up linked to contemporary socioeconomic and land-use changes (Moreira et al. 2011) and (ii) there is a high prevalence of flammable vegetation types coupled with high site productivity (Fernandes 2019). Similarly, fuel drivers of high-severity reburn trends in this region, including those related to vegetation composition and structure, remains completely unexplored.

Maritime pine (*Pinus pinaster* Ait.) and Aleppo pine (*Pinus halepensis* Mill.) forests are the most widely distributed fire-prone conifer ecosystems in the lowlands of the western Mediterranean Basin (Tapias et al. 2004). Both species are intrinsically flammable obligate seeders (Pausas et al. 2008) which have high crowning potential due to the common presence of a well-developed shrubby understory with a high fine-fuel load (Castedo-Dorado et al. 2012; Fernández-García et al. 2019). Woodlands dominated by the resprouter holm oak (*Quercus ilex* L.) tree species are also widely distributed in the Mediterranean Basin (de Rigo and Caudullo 2016). The abandonment of traditional management practices in these woodlands has led to shrub encroachment and, therefore, to an increase in fire hazard (Hinojosa et al. 2021). Altered disturbance regimes and the subsequent increase of interacting wildfires in maritime pine and Aleppo pine forests, holm oak woodlands, and shrublands in the western Mediterranean Basin in recent years (Fernández-García et al. 2019; Urbieta et al. 2019) provide a key opportunity to explore the ecological impact of reburning trends in this region. To this end, we leveraged satellite-based fire severity estimates and the uncharacteristically availability of pre-fire Light Detection and Ranging (LiDAR) data to analyze reburn severity patterns in two large wildfires of the western Mediterranean Basin with similar fire-free periods (10–15 years). Specifically, we tried to answer the following questions: (i) Are there differences between the severity of initial and last wildfires in reburn areas of distinct Mediterranean ecosystems? (ii) Does the severity of initial burns influence the severity of subsequent wildfires? (iii) How do ecosystem types and changes in vegetation structure after the initial wildfire modulate these relationships, if present? We hypothesize that fire severity in reburn areas would be lower than in first-entry areas due to the fuel consumption by the initial wildfire under relatively short fire-free periods (Parks et al. 2014a; Buma et al. 2020). However, high fuel build-up in productive, post-fire landscapes of the western Mediterranean Basin, including in the very short-term after fire (Fernández-Guisuraga et al. 2023a), may obscure this process. We also expect that the increase in the connectivity of hazardous surface and elevated fuels after initial burns, including downed and standing deadwood available to burn, can induce positive fire severity feedbacks in reburn areas (Tepley et al. 2018), particularly in ecosystem dominated by the most flammable vegetation types.

Materials and methods

Study sites

The study sites are located in the Iberian Peninsula (western Mediterranean Basin; Fig. 1). We focused on 2012 Sierra del Teleno and 2022 Bejís wildfires due to (i) the presence of large reburn areas within the wildfire scars with similar fire-free periods (10–15 years), (ii) the availability of immediately pre-fire National Forest Inventory and LiDAR data, and (iii) the dominance of typical Mediterranean forests and shrublands. The Sierra del Teleno wildfire ignited in August 2012 and burned 11,602 ha, including 54% (1934 ha) of a wildfire occurred in August 1998. The Bejís wildfire ignited in August 2022 and burned 18,058 ha, including 31% (7127 ha) of a wildfire occurred in June 2012. Within the perimeter of the Sierra del Teleno and Bejís fires, we focus on (i) areas only affected by the last wildfire since 1984 (year of Landsat 4–5 Thematic Mapper (TM) data availability to verify wildfire occurrence) and (ii) reburn areas only affected since 1984 by the initial wildfire and the last wildfire (Fig. 1). Topography of both study sites is mountainous, with steep slopes and wide valleys. The altitude ranges from 836 to 1499 m and 547–1579 m a.s.l. in Sierra del Teleno and Bejís sites, respectively. The climate is Mediterranean temperate, depicting cool and wet winters, and warm and dry summers, with precipitation ranging from 600 to 800 mm in Sierra del Teleno and from 400 to 600 mm in Bejís. Vegetation prior to the 2012 Sierra del Teleno wildfire (including reburn areas) was dominated by fire-prone, native maritime pine (*Pinus pinaster* Ait.) forests with a well-developed shrubby understory composed of fine-fuel rich species, as well as open shrubland formations dominated by *Erica australis* L., *Pterospartum tridentatum* (L.) Willk., and *Halimium lasianthum* subsp. *alyssoides* (Lam.) Greuter. In the 2022 Bejís

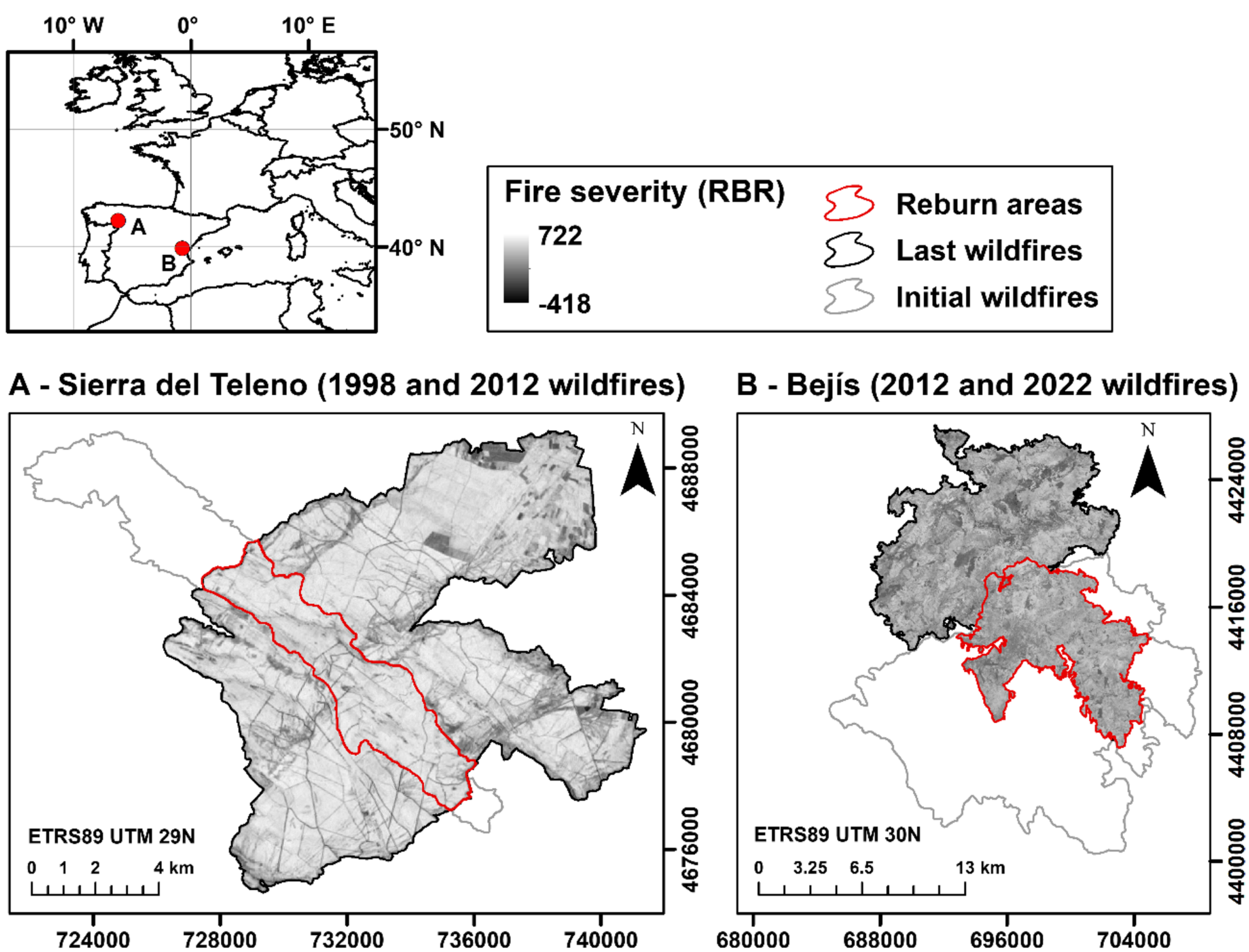

Fig. 1 Location of 2012 Sierra del Teleno and 2022 Bejís wildfires in the western Mediterranean Basin. For each wildfire, the reburn areas of previous wildfires (1998 Sierra del Teleno and 2012 Bejís) and the severity in terms of the Relative Burn Ratio (RBR) index are shown

wildfire, both non-overlapping and reburn areas were also dominated by fire-prone native vegetation, including Aleppo pine (*Pinus halepensis* Mill.) forests with a tall and dense understory, holm oak (*Quercus ilex* L.) woodlands and *Quercus coccifera* L., *Ulex parviflorus* Pourr., and *Rosmarinus officinalis* L. shrubland formations. Maritime and Aleppo pine forests in these regions have nearly 100% serotinous trees which ensures an effective seedling recruitment, and both species reach the reproductive maturity at 6–10 years (Tapias et al. 2001, 2004). Holm oak trees have a vigorous resprouting ability after wildfire disturbances (Espelta et al. 1999). Also, the seeder and resprouter species of the abovementioned Mediterranean shrubland formations feature a good post-fire establishment and recover quickly to the pre-fire state (Calvo et al. 2012; Santana et al. 2018). These adaptive traits, together with fire-free periods of 10–15 years, should be enough to ensure the reestablishment of similar pre-fire vegetation communities and avoid transitions to alternative stable states in Mediterranean ecosystems of these regions (e.g., Broncano et al. 2005; Fernández-García et al. 2019).

After the initial wildfires in Sierra del Teleno and Bejís, salvage logging of the burned *Pinus pinaster* and *Pinus halepensis* stands was implemented by the regional Forest Services, with high harvest intensity (more than 80% of merchantable deadwood removed) throughout the entire wildfire scars (personal communication). The operation was conducted immediately following fire (< 1 year). Dead trees were cut by sawyers with mechanical chainsaws with the branches being lopped off and left on the forest floor. Then, logs were manually dragged to firebreaks and forest tracks. Only unmerchantable burned trees were left onsite. In Bejís site, *Quercus ilex* woodlands were not salvage logged, probably because of the strong post-fire resprouting responses of the dominant species in the community (Broncano et al. 2005).

Data acquisition and processing

Fire severity estimation

Satellite-based fire severity estimates for initial and last wildfires were computed in Google Earth Engine (GEE; Gorelick et al. 2017) using the Relativized Burn Ratio (RBR; Parks et al. 2014b) index calculated from Landsat Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager (OLI) Level 2 (Collection 2, Tier 1) surface reflectance products at 30-m grid size. Pre- and post-fire imagery acquisition dates were selected based on the availability of cloud-free Landsat scenes as close as possible to the start and extinction dates for both wildfires (Table 1). In this study, we selected a relativized fire severity metric (i.e., the RBR) for its potential higher sensitivity in sparsely vegetated areas and enhanced performance in heterogeneous landscapes encompassing multiple vegetation types as compared to absolute change metrics (Miller and Thode 2007). The relative differenced Normalized Burn Ratio (RdNBR; Miller et al. 2009), operationally used in the Monitoring Trends in Burn Severity (MTBS) program (Picotte et al. 2020), was discarded because of anomalous fire severity estimates emerging in our study sites from its lower numerical stability with small or negative values of the pre-fire Normalized Burn Ratio (NBR; López-García and Caselles 1991) as compared to the RBR (Parks et al. 2014b). We accounted for vegetation phenology variations between the pre- and post-fire Landsat scenes to improve comparability between wildfires by considering an offset term (Miller and Thode 2007; Parks et al. 2014b) in the differenced NBR (dNBR; Key 2006) index involved in the RBR calculation. The offset for each wildfire was calculated from the average dNBR value of 1% of the pixels in unchanged areas within a 1-km buffer of the wildfire scars following Saberi and Harvey (2023).

Table 1 Acquisition dates of Landsat imagery used for fire severity estimation

Wildfire	Sensor	Acquisition date
1998 Sierra del Teleno		
Pre-fire	Landsat TM	August 23, 1998
Post-fire	Landsat TM	November 27, 1998
2012 Sierra del Teleno		
Pre-fire	Landsat ETM+	September 20, 2011
Post-fire	Landsat ETM+	September 6, 2012
2012 Bejís		
Pre-fire	Landsat ETM+	May 22, 2012
Post-fire	Landsat ETM+	July 17, 2012
2022 Bejís		
Pre-fire	Landsat OLI	August 8, 2022
Post-fire	Landsat OLI	September 27, 2022

Vegetation type characterization

The distribution of the dominant ecosystem types before the initial and final Sierra del Teleno and Bejís wildfires (see the "Study sites" section) was assessed using the Spanish Forest Map (SFM) at scale 1:50,000 and 1:25,000 developed in coordination with the third and fourth Spanish National Forest Inventory (NFI), respectively. The SFM is the basic forestry cartography at the state level and was developed from the photointerpretation of aerial imagery at very high spatial resolution provided by the National Plan for Aerial Orthophotography (PNOA), combined with pre-existing maps and NFI data (Alberdi et al. 2017). The SFM has been used in numerous previous forest ecology studies to reliably map the distribution of Spanish forest ecosystems (e.g., Gil-Tena et al. 2007;

Adame et al. 2022). We ascertained that there have been no changes in the dominant vegetation types between the dates of the initial and final wildfires in both study sites (Fig. 2), confirming the absence of transitions to alternative stable ecosystem states with fire-free periods of 10–15 years as expected in the "Study sites" section.

LiDAR data processing

Pre-fire LiDAR data for the 2012 Sierra del Teleno and 2022 Bejís wildfires were acquired from the PNOA 2 years before each fire using a Leica ALS60 sensor onboard a fixed-wing aircraft. The mean point cloud density was 0.76 m^{-2} (pulse spacing of 1.15 m) and 0.94 m^{-2} (pulse spacing of 1.03 m) for Sierra del Teleno and Bejís sites, respectively. The vertical accuracy ($RMSE_Z$) of the point cloud reported by the PNOA was lower than 0.2 m for both sites. Despite the time-lag between LiDAR acquisitions and wildfire dates, we assumed that LiDAR data was representative of immediately pre-fire vegetation structure (Fernández-Guisuraga et al. 2022a). We used the MCC-LIDAR 2.1 software to classify the point clouds into ground points and non-ground points using the multiscale curvature classification algorithm (MCC; Evans and Hudak 2007). We used LAStools software (rapidlasso GmbH, Germany) to compute a digital terrain model (DTM) with 2-m grid size from the MCC-classified ground returns. The height-normalized point clouds were used to compute several area-based LiDAR density metrics for a grid coincident to the fire severity product, and ecologically related with the fuel arrangement in vertical vegetation strata. We implemented a 0.2-m height threshold (same as vertical accuracy of the point cloud) following Fernández-Guisuraga et al. (2022a). The calculation of LiDAR density metrics for each stratum was based on the ratio of LiDAR returns in the stratum to the total number of returns in that stratum and below (Kane et al. 2013). We considered the 0.2–2 m, 2–4 m, 4–7 m, and >7 m strata, in order to discriminate the density of near-surface and elevated understory fuels (i.e., potential ladder fuels), as well as the density of subcanopy and overstory fuels, respectively (García-Llamas et al. 2019; Fernández-Guisuraga et al. 2022a).

Data analysis

We generated a 100-m point sampling grid across both the reburn and first-entry (i.e., non-overlapping) wildfire areas in Sierra del Teleno and Bejís sites. Sampling and analysis were limited to the dominant ecosystem types (maritime pine, Aleppo pine and holm oak forests, and shrublands) prior to the last wildfires in both sites. At each sampled point, we extracted fire severity data of the initial and last wildfires, the ecosystem type, and fuel LiDAR density metrics prior to the last wildfire.

We fitted ordinary least squares (OLS) linear regression models (one-way ANOVA) to determine the significance of the differences in mean fire severity (i.e., the

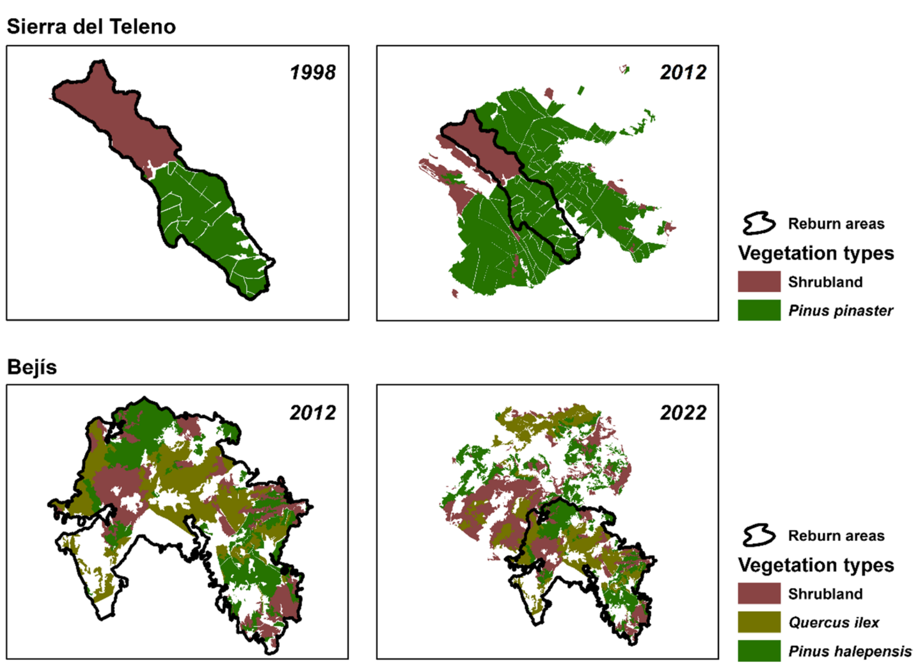

Fig. 2 Distribution of the dominant vegetation types before the initial (reburn areas) and final wildfires in Sierra del Teleno and Bejís sites assessed using the Spanish Forest Map (SFM)

RBR) between the initial and last wildfires in reburn areas for each dominant ecosystem type. The same procedure, together with Tukey HSD post hoc tests, was used to assess the differences in mean fire severity between ecosystem types. Data from the two sites were pooled together in all analyses. We explored how the fire severity of the initial wildfires influences the severity of subsequent wildfires in reburn areas using an OLS linear regression model. We also considered the interaction between initial wildfire severity and ecosystem type. The coefficient of determination (R^2) was used to assess model fit.

Due to the limited availability of LiDAR data only immediately before the last wildfire, we first evaluated whether there were significant differences in the mean fire severity of the last wildfire between reburn and first-entry wildfire areas for each dominant ecosystem type using OLS linear regression models. We assume that first-entry areas in the last wildfires may be representative of pre-fire fuel arrangement before the initial wildfires in reburn areas. Indeed, the successional stage and fuel accumulation patterns of pre-fire communities over the landscape were similar in both scenarios according to previous research (Calvo et al. 2008) and first to fourth Spanish National Forest Inventories and derived Spanish Forest Maps (Álvarez-González et al. 2014; Alberdi et al. 2017). The comparison of pre-fire fuel characteristics between first-entry and reburn areas may be of utmost importance to provide scientific basis for managers to meet restoration goals in the context of the increasing frequency of extreme wildfire events (Huffman et al. 2018). Accordingly, we fitted OLS linear regression models to test differences in pre-fire fuel density metrics computed from LiDAR data between reburn and first-entry wildfire areas.

Despite the straightforward ecological interpretation of the OLS model outputs (Schielzeth 2010), and the typical little effects of spatial autocorrelation in the assessments of fire effects in many forest ecosystems worldwide (van Mantgem and Schwilk 2009; *and references therein*), we tested for the potential presence of spatial autocorrelation in our dataset. A distance of 100 m between samples was found to be appropriate in our study sites, with a Moran's $I < 0.1$ for each of the dependent variables indicating a lack of significant spatial autocorrelation patterns (Diniz-Filho et al. 2012).

Statistical significance was determined at the 0.05 level in all analyses, which were implemented in R (R Core Team 2021).

Results

Fire severity was greatest within maritime pine forests as compared to other ecosystems for both the initial and the last wildfires (*p-values* < 0.001) in reburn areas. Mean fire severity of the last wildfire was significantly higher ($F > 62.71$; p-values < 0.001) than that of the initial wildfire for each dominant ecosystem type in reburn areas (Fig. 3). These differences were much more pronounced in maritime pine and shrub-dominated ecosystems than in those dominated by holm oak and Aleppo pine.

Fire severity of the initial wildfire ($F = 590.78$; p-value < 0.001) and ecosystem type ($F = 124.81$; p-value < 0.001), as well as their interaction ($F = 5.29$; p-value < 0.001), explained fire severity of the last wildfire in reburn areas (Table 2) with a R^2 equal to 0.42. Fire severity of the last wildfire in forest and woodland

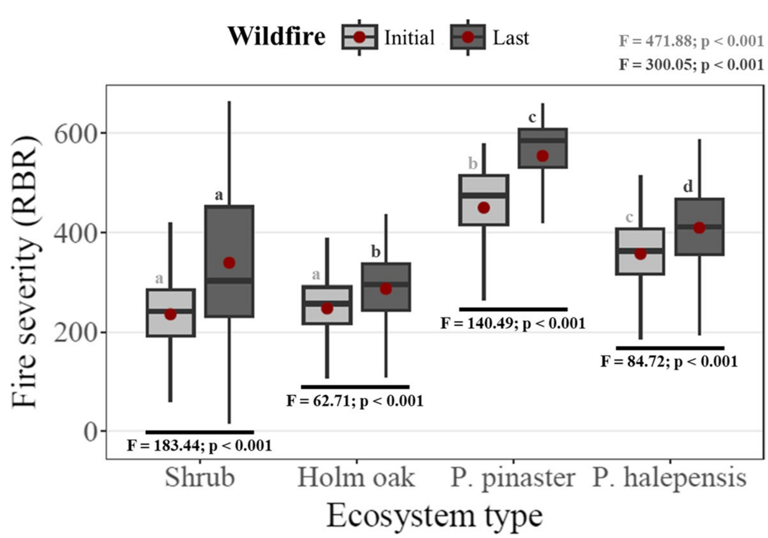

Fig. 3 Fire severity (RBR) of initial and last wildfires for each dominant ecosystem type in reburn areas. We show ordinary least squares (OLS) linear regression models results. Lowercase letters denote differences in mean fire severity between ecosystem types for initial and last wildfires

Table 2 ANOVA table of the ordinary least squares (OLS) linear regression model explaining fire severity of the last wildfire in reburn areas

Parameter	Df	Sum Sq	Mean Sq	*F*	Pr(> *F*)
Initial wildfire severity (RBR)	1	6.43E+06	6.43E+06	590.78	< 0.001
Ecosystem type	3	4.07E+06	1.36E+06	124.82	< 0.001
RBR:Ecosystem type	3	1.40E+05	4.66E+04	5.29	< 0.001
Residuals	1456	1.58E+07	1.09E+04		

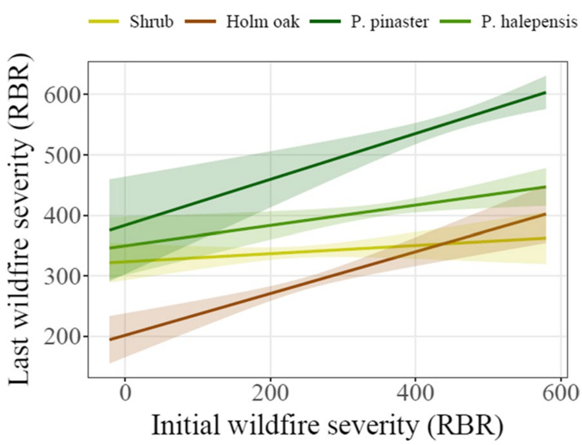

Fig. 4 Mean predicted fire severity of the last wildfire in relation to fire severity of the initial wildfire and ecosystem type, as well as their interaction, in reburn areas

ecosystems (particularly maritime pine-dominated) raised with increasing severity of the initial wildfire to a greater extent than in shrubland ecosystems (Fig. 4).

Mean fire severity of the last wildfire was significantly higher ($F > 13.85$; p-values < 0.001) in reburn than in first-entry areas for each dominant ecosystem type (Fig. 5), which is consistent with previous analyses. We can then assume that pre-fire fuel arrangement in first-entry areas of the last wildfires may be representative of vegetation structure before the initial wildfires without expecting differential driving conditions among ecosystem types. However, the magnitude of fire severity differences between first-entry and reburn areas for the last wildfires was smaller than in the comparison analyses for all ecosystems between initial and last wildfires (Fig. 3).

Fuel density showed clear differences among ecosystem types, with the greatest differences being observed in the lower vegetation strata. In maritime and Aleppo pine forests, pre-fire fuel density up to 4 m high was significantly higher in reburn than in first-entry areas of the last wildfires (Fig. 6). The opposite behavior was observed for the upper strata. In holm oak forests, there were no differences between fuel density by strata, except in the 0.2–2-m stratum, where density was greatest in reburn areas (Fig. 6). The density of existing strata in shrubland ecosystems (< 4 m) was also significantly higher in reburn than in first-entry areas (Fig. 6).

Discussion

The understanding of how fire regime attributes modulate future fire behavior is of utmost importance for predicting ecosystem responses to future land-use and climate scenarios in the context of global change (Bowman et al.

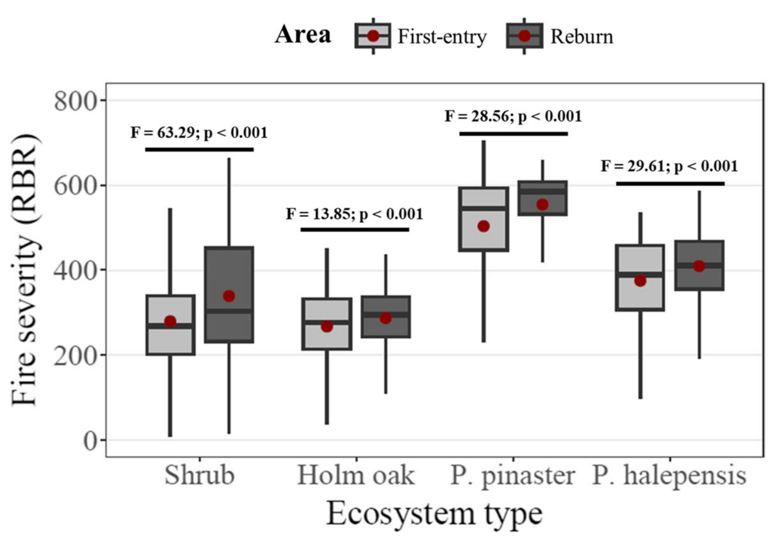

Fig. 5 Fire severity of first-entry and reburn areas in the last wildfires for each dominant ecosystem type. We show ordinary least squares (OLS) linear regression models results

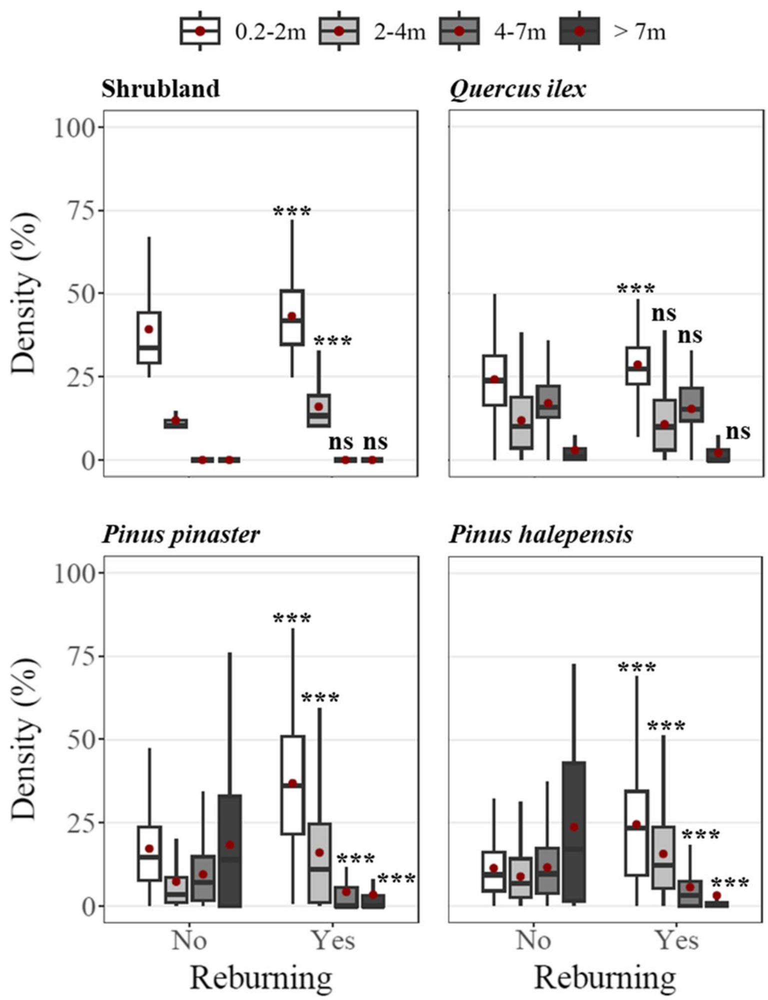

Fig. 6 LiDAR density metrics for each vegetation stratum in first-entry and reburn areas in the last wildfires for each dominant ecosystem type. We show ordinary least squares (OLS) linear regression models results. The significance of differences in pre-fire fuel density between first-entry and reburn areas is represented by ***(*p*-value < 0.001), **(*p*-value < 0.01), *(*p*-value < 0.05), and ns (*p*-value > 0.05)

2014; Archibald et al. 2018; Lydersen et al. 2019). This will provide integrated insights on long-term management strategies tailored to secure the provision of multiple functions and ecosystem services threatened by global change feedbacks conducive to high-severity wildfire disturbances (Keeley 2009; Fernandes et al. 2016; Taboada et al. 2021). However, few insights on the ecological impact of interacting wildfire disturbances are currently provided in fire-prone ecosystems of the western Mediterranean Basin. This study represents a first attempt to shed light on reburn severity patterns in this region.

A key finding of our study is that areas of interacting wildfire disturbances (reburn) in all the most widely distributed fire-prone ecosystem types in the western Mediterranean Basin experienced higher fire severity in the last wildfire than in the preceding wildfire, contrary to expectations according to previous research in temperate ecosystems. For example, Parks et al. (2014a) evidenced that reburn areas across two wilderness areas in the western United States encompassing more than one hundred wildfires from 1984 onwards experienced lower fire severity than areas of no-reburn, the effect being still evident up to fire intervals of 22 years. The same behavior was reported by Holden et al. (2010) in ponderosa pine (*Pinus ponderosa* C. Lawson) forests within the Gila National Forest in New Mexico. Collins et al. (2009) found no significant differences in the mean proportion of high-severity patches between initial and subsequent wildfires in reburn areas of Sierra Nevada in California. However, they reported that areas reburned under more adverse fire weather conditions experienced a shift toward increased fire severity. These studies attributed the lower fire severity in reburn areas to (i) the consumption of vegetation and downed dead fuel in the forest floor by the initial wildfire (Parks et al. 2014a) and (ii) the insufficient fuel accumulation and thus reduced fuel availability for subsequent wildfires until landscape regenerates enough biomass (Holden et al. 2010).

Our results, pertaining to fuel accumulation periods of 10–15 years in the western Mediterranean Basin, are unlikely to be associated with more extreme fire weather conditions at the time of the last wildfires, since their severity was also higher in reburn than in first-entry areas for each dominant ecosystem type. Indeed, great fuel build-up in productive post-fire landscapes of the western Mediterranean Basin and changes in microenvironmental conditions after high-severity wildfires (Fernández-García et al. 2019; Fernández-Guisuraga et al. 2023a) could explain the trends observed here.

First, early post-fire successional pathways in this region are characterized by the dominance of highly-flammable regenerating seeder shrub species favored by heat-shock triggered germination (Santana et al. 2018) and resprouter shrub species that feature strong competitive abilities and quickly recolonize the space occupied before the fire from belowground surviving tissues (Calvo et al. 2003; Pausas and Keeley 2014). Also, seedling recruitment of Mediterranean pine species after the initial wildfire under long fire-free periods is very strong (Fernández-García et al. 2019). Altogether, the dominant vegetation in early post-fire seral stages in the western Mediterranean Basin may support hazardous, dense surface, and understory fuel accumulations that dry out quickly in the absence of tree canopy (Clarke et al. 2014), and which are then prone to be reburned at high fire severity. The higher pre-fire fuel density in the lower vegetation strata (up to 4 m high in maritime and Aleppo pine forests, as well as in shrublands, and up to 2 m high in holm oak forests) in reburn than in first-entry areas of the last wildfire evidenced in our study can support the above assumptions regarding fuel build-up after initial high-severity wildfires.

Second, high-severity wildfires may yield a high post-fire abundance of charred downed branches and standing snags, as well as burned cones in pine-dominated ecosystems (Donato et al. 2016; Taboada et al. 2018). Consequently, fine and coarse charred woody debris may add to surface fuels available for subsequent wildfires and affect fire behavior by increasing fire residence times (Coppoletta et al. 2016) and stand flammability when decayed in the medium-term after the initial wildfire (Stevens-Rumann et al. 2012). Also, the abundance of downed medium and heavy dead fuel in the forest floor is usually negligible in fire-prone ecosystems of the western Mediterranean Basin before the initial wildfire (Fernández-García et al. 2018; Fernández-Guisuraga et al. 2023b). This can contribute to the differences in fire severity between the initial and subsequent wildfires, the latter having downed and standing charred woody debris available to burn. Despite salvage logging operations conducted in burned conifer stands of our study sites after the initial wildfire, the relocation of fine and coarse deadwood to the forest floor during the removal operation may still have promoted high severity fire in subsequent wildfires by increasing surface fuel load (Thompson et al. 2007).

The highly flammable early successional vegetation with dense and dry surface and understory fuels, together with charred woody debris availability, can support the increase in reburn severity with the severity of the initial wildfire (i.e., positive severity feedback), as previously evidenced in Mediterranean-type ecosystems elsewhere (e.g., Parks et al. 2014a; Coppoletta et al. 2016; Collins et al. 2021). In this study, the positive feedback was stronger in forests, particularly maritime pine-dominated, than in shrublands. The explanation could lie with (i) the unleashed shrub species' competition and productivity by increased resource availability, e.g., more light levels reaching the understory through severe canopy cover reduction (Fernández-Guisuraga et al. 2022b; Khayati et al. 2023); (ii) the promotion of high dead fuel loads by severe burns in forests (Odion et al. 2004); and (iii) the fine dead fuel accumulation close to the forest soil of Ericaceae species regenerating vigorously after high-severity wildfires in the understory of maritime pine forests (Quintano et al. 2019). Then, high load of live and dead surface and understory fuels provide favorable conditions for subsequent severe burns (Parks et al. 2014a). These results are coherent with ecological expectations in which a high fire severity regime could be perpetuated by a positive feedback loop conducive to alternate ecosystem states dominated by persistent shrubland formations before the development of fire-resistant trees (Coppoletta et al. 2016; Tepley et al. 2018). For example, we observed during field visits in the study sites 4 years after the last wildfires that pine seedling densities were insufficient for the pine forests to naturally recover in the reburn areas (Fernández-García et al. 2019).

Our results do not contradict the fuel reduction effectiveness of prescribed burning treatments to moderate the severity of subsequent wildfires. For example, we found that prescribed burning was particularly effective at mitigating fire severity at the first wildfire encounter in the western Mediterranean Basin for around 5 years (Fernández-Guisuraga, under review) (a much shorter fire-free period than the 10–15 years analyzed here), as also found by Collins et al. (2023) in temperate shrublands of southeastern Australia. Our results also suggest that management efforts in fire-prone ecosystems of the western Mediterranean Basin should be tailored to moderate fuel build-up and thus fire hazard and high fire severity not only prior to the initial wildfires, but also before subsequent reburns occur (Coppoletta et al. 2016) to avoid long-term ecosystem state changes in areas of interacting wildfire disturbances. The fire severity patterns of reburn areas evidenced here should be confirmed at broader scales in the western Mediterranean Basin in the face of the predicted increase in the frequency of high-severity wildfires in this region. Moreover, the processes driving these trends should be further investigated. Although not evaluated here, fire weather variables may have a major influence on the fine dead fuel moisture content and fuel availability (Sharples et al. 2009) and thus on fire spread and fire severity (Collins et al. 2007; Dillon et al. 2011). In this sense, it would also be relevant to evaluate in future studies the potential interaction of bottom-up (fuel and topography) and top-down (fire weather) environmental drivers of fire behavior with temporal attributes of the fire regime in Mediterranean reburn areas at large spatial scales.

Conclusions

Our results give light for the first time on reburn severity patterns in fire-prone ecosystems of the western Mediterranean Basin under rapid fire regime shifts in the context of accelerating global change. Reburn areas in all the most widely distributed fire-prone ecosystem types in this region experienced higher fire severity in the last wildfire than in the preceding wildfire due to great fuel build-up of highly-flammable early seral vegetation. Our results also suggest that a high fire severity regime could be perpetuated by a positive feedback loop linked to the high load of live and dead surface and understory fuels after initial wildfires, including downed and standing charred wood available to burn, providing favorable conditions for subsequent severe burns and precluding forest autosuccession. The implementation of management strategies targeted at controlling fuel build-up prior to initial and reburning wildfires may be of utmost importance to avoid long-term ecosystem state changes in the face of changing fire regimes in the western Mediterranean Basin.

Abbreviations

dNBR	Differenced NBR
DTM	Digital terrain model
ETM+	Enhanced Thematic Mapper Plus
GEE	Google Earth Engine
LiDAR	Light Detection and Ranging
MCC	Multiscale curvature classification
MTBS	Monitoring Trends in Burn Severity
NBR	Normalized Burn Ratio
NFI	National Forest Inventory
OLI	Operational Land Imager
OLS	Ordinary least squares
PNOA	National Plan for Aerial Orthophotography
RBR	Relativized Burn Ratio
RdNBR	Relative differenced Normalized Burn Ratio
SFM	Spanish Forest Map
TM	Thematic Mapper

Authors' contributions

J.M.F.G. and L.C. conceived and designed the experiment. J.M.F.G. analyzed the data. J.M.F.G. wrote the manuscript. L.C. revised the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated and used during the current study are available from the corresponding author on 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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