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The loss of ecosystem multifunctionality in Pinus pinaster forests as one of the main footprints of large wildfires

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Keywords

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Abstract

The main objective of this study was to analyse the effect of recurrence and burn severity on ecosystem multifunctionality in Pinus pinaster forests. We selected a large wildfire that occurred in the Sierra del Teleno in 2012 (NW Spain), where we differentiated two recurrences and two burn severity situations. As a result, four scenarios were identified: low recurrence plus low severity, low recurrence plus high severity, high recurrence plus low severity, high recurrence plus high severity. In each one, a number of 1 m x 1 m plots proportional to the burned area were established. Three years after the wildfire we evaluated in each plot: (1) percentage of covered soil, (2) total percentage cover of herbaceous species, (3) percentage cover of each woody species, (4) total plant species richness. Also, a composite soil sample was collected from each plot. Chemical (total organic carbon, total nitrogen and available phosphorus) and microbiological (microbial biomass carbon) properties were analysed in each soil sample. The following variables were used as indicators of ecosystem functions: percentage of covered soil, total cover of herbaceous species, Pinus pinaster cover, total plant richness, total organic carbon, total soil nitrogen, available phosphorus and microbial biomass carbon. Another indicator of ecosystem functions was calculated: floral colours of shrub species diversity using the Shannon index. The values of each ecosystem function indicator were standardized. The indicators/functions of regulating ecosystem services were: Climate regulation (indicator: total % of organic soil carbon) and Erosion protection (indicator: covered soil %). The functions/ indicators of supporting ecosystem services were: soil fertility (indicator: total nitrogen and available phosphorous) and soil quality (indicator: microbial biomass C). The indicators/functions of cultural ecosystem services were: species diversity (indicator: plant species richness) and aesthetic value (indicator: the Shannon index of floral colours). The functions/indicators of provisioning ecosystem services were: grass for livestock (indicator: % cover of herbaceous species) and timber production (indicator: % cover of Pinus pinaster). The results indicated that all scenarios apart from low recurrence plus low severity negatively affected the multifunctionality of the ecosystems.

1. Introduction

In the Mediterranean Basin dramatic shifts in fire regime have been detected during recent decades, driving an increase in large and severe wildfires, with significant consequences on ecosystems and societies at different scales (Singleton et al., 2019). Impacts include loss of lives and infrastructures, alterations in functional processes (e.g. erosion, vegetation dynamics or carbon cycle) and reduction in ecosystem service provision (e.g. food, timber or fresh water stocks) (Taboada et al., 2021). In general, these alteration of the ecosystem services are related not only to fire severity but also to fire recurrence that modify ecosystem resilience, due to damage to vegetation and soil characteristics.

In recent decades, rural depopulation and agricultural land abandonment have favoured the expansion of shrublands and forests to the detriment of open areas such as pasturelands and croplands. Consequently, fuel amount and its connectedness increase, leading to a simplification of the landscape mosaic associated with an increase in the risk of extreme wildfires that are more dangerous to people and ecosystems. In this context, increase in drought periods and thermal anomalies associated with climate change are favouring fuel ignition (Stephens et al., 2014). Indeed, according to global change predictions, Spain will be included in a primary climate change hotspot, where warming will be above the global average. Both changes in climatic conditions and land use contribute to the increase in new wildfire regimes, with more frequent catastrophic fires causing abrupt changes in the functioning of ecosystems and in the delivery of ecosystem services to society. In general, ecosystem functioning is inherently multidimensional and so, multifunctionality measures can summarise the ability of an ecosystem to deliver multiple functions or services simultaneously (Manning et al., 2018).

Mediterranean ecosystems largely affected by megafires are those dominated by *Pinus pinaster*, which provide relevant provisioning, regulating, cultural and supporting ecosystem services. A new and innovative approach to evaluate the status of the forest ecosystem and interruption of multifunctionality by fire is currently being implemented. This approach of studying the modifications in biotic and abiotic processes that determine the provision of ecosystem services in *Pine* forest, represent an integrated analysis of the footprints of large recurrent and severe wildfires. Thus, the knowledge acquired in this integrated analysis would help in the implementation of novel solutions to promote landscapes and socio-ecological contexts less susceptible and more resilient to recurrent high burn severity wildfires (Moreira et al., 2020).

The main objective of this work was to analyse the effect of recurrence and burn severity on ecosystem multifunctionality in *Pinus pinaster* forests in Northwest Spain.

2. Material and methods

The study area (Figure 1) is located in Sierra del Teleno (NW Spain), within the perimeter of a megafire (11,600 ha) that occurred in August 2012, affecting a forest dominated by *Pinus pinaster*, with the understorey community dominated by *Pterospartum tridentatum* (L.) Willk., *Halimium lasianthum* (Lam.) Spach and *Erica australis* L. (Calvo et al., 2008). The climate in this region is temperate with dry warm summers. The orography is heterogeneous, ranging from flat to mountainous areas. Soils are developed over siliceous lithologies.

Prior to the fire in 2012, the area had suffered another large fire in 1998 of around 3000 ha. Therefore, within the perimeter of the 2012 fire, we defined two recurrent scenarios: low recurrence (a single fire in the last 15 years) and high recurrence (two fires in the last 15 years). Additionally, based on a dNBR (differenced Normalized Burn Ratio) index derived from Landsat pre-fire and post-fire images (September 20th, 2011 - September 6th, 2012) and CBI (Composite Burn Index) field measured values (Key and Benson, 2006), we established two severity scenarios within the perimeter of the 2012 fire: low severity (dNBR between 220-550) and high severity (dNBR between 550-1400). Overlaying the recurrence and severity classes, we identified four scenarios (low recurrence-low severity (LR-LS), low recurrence-high severity (LR-HS), high recurrence-low severity (HR-LS) and high recurrence-high severity (HR-HS). Within the fire perimeter, we selected a 3000 ha study framework where the four scenarios of recurrence and severity were represented (Figure 1) to collect field data. A total of 88 1 m x 1 m plots were established: 20 in LR-LS, 20 in LR-HS, 20 in HR-LS and 28 in HR-HS. Three years post-fire, we evaluated in each plot the visual percentage cover of each plant species and the bare soil. In addition, a composite soil sample (consisting of 4 subsamples) was collected from each plot. Chemical (total organic C, total N and available P) and microbiological (microbial biomass carbon) properties were analysed in each soil sample.

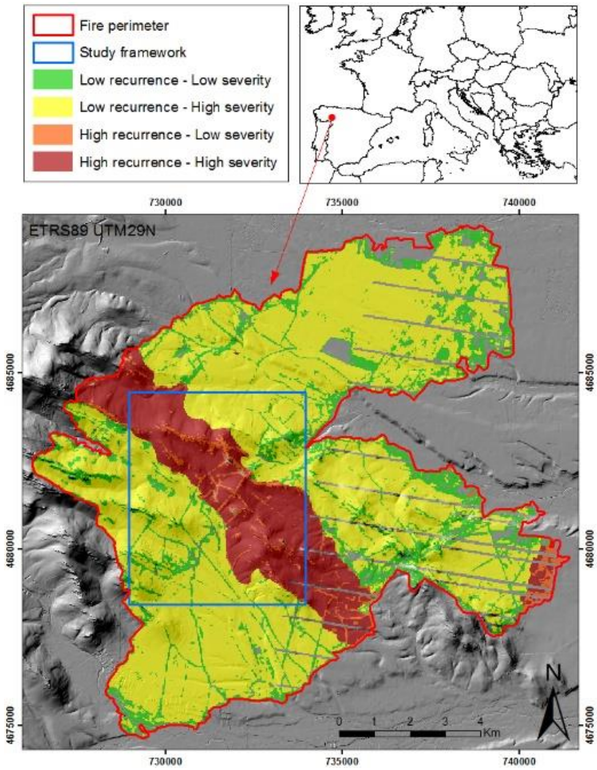

Figure 1- Study framework within the perimeter of the Sierra del Teleno megafire which occurred in 2012, and the considered recurrence-severity scenarios

Soil organic C was obtained by Walkley-Black dichromate oxidation (Nelson and Sommers, 1982). Total N was determined by the Kjeldahl method (Bremner and Mulvaney, 1982) and available P was analysed following the Olsen *et al.* (1954) procedure. Microbial biomass C was determined by the fumigation-extraction method (Vance *et al.*, 1987).

The variables used as indicators of ecosystem functions were (Table 1): percentage of covered soil, total cover of herbaceous species, *Pinus pinaster* cover, total plant richness, total organic carbon, total soil nitrogen, available phosphorus, microbial biomass carbon and % of floral colours of shrub species diversity using the Shannon index (Shannon, 1948). The values of each ecosystem function indicator were standardised according to the following procedure: Standardized value = (Unstandardized value – Minimum value) / (Maximum value – Minimum value).

Minimum and maximum values correspond to the lowest and highest unstandardized values of each indicator, respectively. Consequently, a set of standardized data was obtained for each indicator, ranging from 0 (minimum value) to 1 (maximum value).

The indicators of regulating ecosystem services were: climate regulation (indicator: total % of organic soil carbon) and erosion protection (indicator: covered soil %). The indicators of supporting ecosystem services were: soil fertility (indicator: total N and available P) and soil quality (indicator: microbial biomass C). The indicators of cultural ecosystem services were: species diversity (indicator: plant species richness) and aesthetic value (indicator: Shannon index of floral colours). The indicators of provisioning ecosystem services were: grass for livestock (indicator: % cover of herbaceous species) and timber production (indicator: *Pinus pinaster* percentage cover).

In the soil fertility function, in which we used more than one indicator, the average value of these indicators was calculated. In the same way, ecosystem multifunctionality was calculated by averaging the values of regulating, supporting, cultural and provisioning ecosystem services.

Generalized linear models (GLMs), with a quasi-Poisson error distribution (log link function) to account for overdispersion, were applied to evaluate the effects of recurrence and burn severity on ecosystem functions, services, and multifunctionality. Data analyses were carried out with R (R Core Team, 2021).

Table 1. List of functions for regulating, supporting, cultural, and provisioning ecosystem services, and indicators used to define these functions.

Ecosystem functions		**Function indicators**
Regulating ecosystem service		
Climate regulation	Carbon sequestration	Total organic soil C (%)
Erosion protection		Covered soil (%)
Supporting ecosystem service		
Soil fertility	Soil nutrient storage capacity	Total N (mg kg-1)
		Available P (mg kg-1)
Soil quality		Microbial biomass C (μg C g^{-1} dw soil)
Cultural ecosystem service		
Species diversity		Plant species richness
Aesthetic value		Shannon index of floral colours of shrub species
Provisioning ecosystem service		
Grass for livestock		Total cover of herbaceous species (%)
Timber production		Total cover of *Pinus pinaster* (%)

3. Results and discussion

The significant negative effects of recurrence and burn severity in the regulation of ecosystem services, even three years after wildfire (Figure 2), are a consequence of the impact on climate regulation and erosion protection functions. Recurrent and severe fires are characterized by the elimination of vegetation cover and therefore, the soil is non-protected, and could be affected by erosion processes after rain events. However, in low recurrent plus low severe fire scenarios, a higher level of survival of vegetation, which facilitates the protection of the soil, is observed. Another ecosystem service negatively affected by burn severity is provisioning (Figure 2), as grass for livestock and timber production functions had higher values in low recurrent and severe scenarios, decreasing with increased severity or recurrence. González-De Vega et al. (2018) also observed a lower presence of herbaceous species with increasing burn severity. In the same way, high recurrence and severity affect reducing the probability of regeneration of *Pinus pinaster* (Fernández-García et al., 2019).

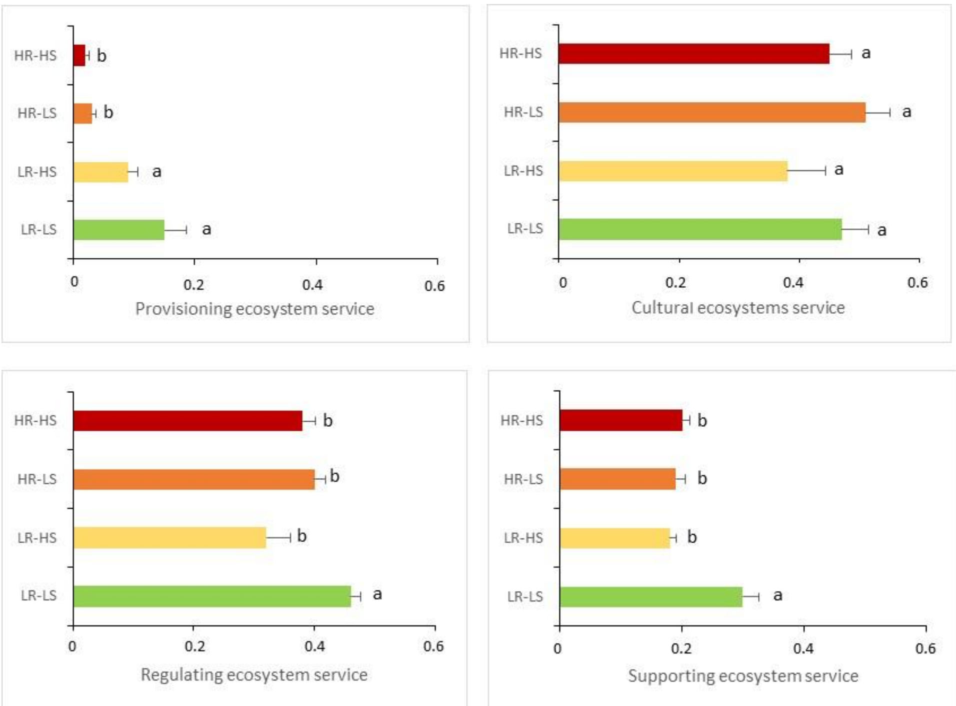

Figure 2. Average value and standard error of provisioning, cultural, regulating and supporting ecosystem services for each scenario: Low recurrence and low severity (LR-LS), low recurrence and high severity (LR-HS), high recurrence and low severity (HR-LS) and high recurrence and high severity (HR-HS). Different letters indicate significant differences ($p < 0.05$) between scenarios.

High recurrence and/or high severity negatively modify nutrient availability due to the reduction in soil organic matter content (Hedo et al., 2015). These patterns determine the reduction in supporting ecosystem services observed in these scenarios of high recurrence plus low and high severity (Figure 2).

Three years after fire, we only detected a significant decrease in plant richness after high recurrence and burn severity. However, the recovery of woody species with different flower colours showed an opposite pattern, as the elimination of the dominant tree species favoured colonization by other understory shrub species. These two opposing patterns mean that the cultural ecosystem services do not show significant effects among recurrence and burn severity scenarios.

As a result of the effects of fire recurrence and severity on plant community and soil properties, which act as indicators of functions, and modulate post-fire ecosystem multifunctionality (Lucas-Borja et al., 2021), showed a clear reduction in those scenarios different to low recurrence plus low severity (Figure 3).

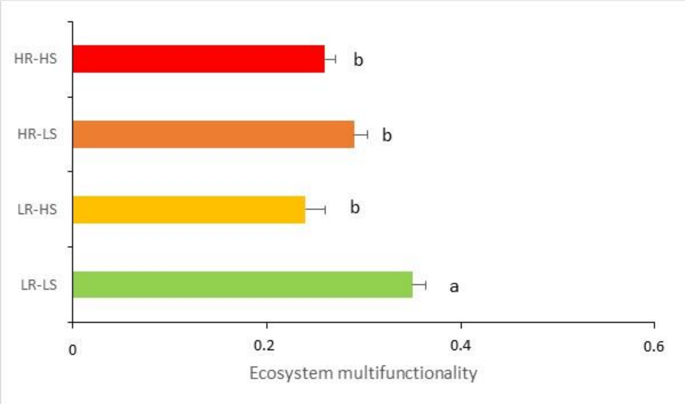

Figure 3. Average value and standard error of ecosystem multifunctionality for each scenario (Low recurrence and low severity (LR-LS), low recurrence and high severity (LR-HS), high recurrence and low severity (HR-LS) and high recurrence and high severity (HR-HS). Different letters show the presence of significant differences ($p < 0.05$) between burn severity categories.

4. Conclusions

The footprint of a megafire, three years after, is very evident through the reduction of ecosystem multifunctionality under those scenarios of high recurrence plus low or high burn severity. This integrated approach to the study of the effects of large wildfires on the functioning and provisioning of ecosystem services in fire prone ecosystems represents an outstanding advance in the design of adequate post-fire recovery strategies to minimise the impact and accelerate the recovery of the vegetation and soil.

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