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FIRE RISK ASSESSMENT IN THE WILDLAND-URBAN INTERFACE OF IBERO-ATLANTIC HETEROGENEOUS LANDSCAPES

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ABSTRACT. Forest fires cause major environmental and socio-economic impacts, with the greatest risk for people occurring in the wildland-urban interface (WUI). In Ibero-Atlantic landscapes, where dispersed settlements are expanding into wildlands and vegetation is encroaching on populated areas, both the frequency and severity of WUI fires are rising sharply. The objective of this study was to develop a new methodological approach to assess fire risk in the WUI of Ibero-Atlantic heterogeneous landscapes under the assumption that fire impacts on population entities may occur by direct or indirect exposure to different types of vegetation. Based on landscape configuration analysis, expert knowledge of fire behaviour across vegetation types and on-site observations of fire impact on buildings and other infrastructures, we developed a multi-ring system around different types of population entities to characterize pre-fire vegetation patterns and fire severity across zones of influence (rings) within the WUI. The relationships between vegetation and severity (estimated with the Relativized Burn Ratio –RBR– spectral index derived from Sentinel-2 satellite imagery) were evaluated using multivariate linear regression models, with a backward stepwise procedure, at two levels: WUI and ring. This framework was tested in the large forest fire of Foyedo (Asturias, NW Spain) that affected more than 10,000 ha in the spring of 2023. Vegetation changed across the WUI, reflecting a land-use gradient from more managed vegetation near settlements to less managed and more natural types in outer zones, with fire severity increasing outward. The main drivers of fire severity at WUI level were vegetation type and vertical complexity. At ring level, the pattern was similar, with the percentage of heathlands and shrublands being the best predictor of fire severity in all rings. In the outermost ring, pine and eucalyptus plantations were also directly related to fire severity. Our findings underscore the need to develop spatially complex analytical frameworks accounting for different exposures across the WUI in order to guide effective vegetation management for forest fire prevention in the Atlantic landscapes of the Iberian Peninsula.

Evaluación del riesgo de incendio en la interfaz urbano-forestal de paisajes heterogéneos Ibero-Atlánticos

RESUMEN. Los incendios forestales producen multitud de impactos ambientales y socioeconómicos, identificándose el mayor riesgo para las personas en la interfaz urbano-forestal (IUF). En los paisajes Ibero-Atlánticos, donde los asentamientos dispersos se expanden hacia las zonas forestales y la vegetación avanza hacia las áreas habitadas, está aumentando la frecuencia y severidad de los incendios de IUF. El objetivo de este estudio fue desarrollar un enfoque metodológico para evaluar el riesgo de incendio en la IUF de paisajes heterogéneos Ibero-Atlánticos bajo el supuesto de que el fuego puede impactar en las entidades de población por exposición directa o indirecta a diferentes tipos de vegetación. Tomando como base el análisis espacial de la configuración del paisaje, el conocimiento de experto sobre el comportamiento del fuego en distintos tipos de vegetación y las observaciones in situ sobre el impacto del fuego en edificios y otras infraestructuras, se ideó un sistema multi-anillo en torno a distintos tipos de entidades de población que permitió caracterizar los patrones espaciales de la vegetación pre-incendio y la severidad del fuego en áreas de influencia (anillos) dentro de la IUF. Las relaciones entre vegetación y severidad (estimada con el índice espectral de área quemada relativa –RBR– derivado de imágenes de satélite Sentinel-2) se evaluaron utilizando modelos de regresión lineal multivariante a dos niveles: IUF y anillo. Esta aproximación se probó en el gran incendio forestal de Foyedo (Asturias, noroeste de España) que afectó a más de 10.000 ha en primavera de 2023. La vegetación cambió a lo largo de la IUF, reflejando un gradiente de uso del suelo, desde tipos de vegetación más gestionados cerca de los asentamientos hasta otros menos gestionados y más naturales en zonas periféricas, con un aumento de la severidad del fuego hacia el exterior. Los impulsores más importantes de la severidad fueron el tipo de vegetación y su complejidad vertical. A nivel de anillo, el patrón fue similar, siendo el porcentaje de matorrales el mejor predictor de la severidad. En el anillo más externo, el porcentaje de pinares y eucaliptares también se relacionó directamente con la severidad. Se evidencia la necesidad de desarrollar marcos analíticos espacialmente estructurados que integren los diferentes tipos de exposición al fuego en la IUF, con el fin de guiar estrategias más eficaces de gestión de la vegetación para la prevención de incendios forestales en los paisajes atlánticos de la Península Ibérica.

Key words: Burning embers, fire exposure, fire severity, Foyedo large forest fire, RBR spectral index, WUI.

Palabras clave: exposición al fuego, gran incendio de Foyedo, índice espectral RBR, IUF, paveseo, severidad del fuego.

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1. Introduction

Over the past few decades, the Atlantic landscapes of the Iberian Peninsula have undergone profound socio-economic and environmental transformations. Population shifts from rural to urban and coastal areas have reshaped local economies and lifestyles (Serra *et al.*, 2014; Gómez-Sal *et al.*, 2024), reorienting the rural economic model from self-consumption to market-oriented systems aligned with the Common Agricultural Policy (CAP). This process has triggered rapid and complex changes in land use and landscape structure (Moreira *et al.,* 2011; García-Llamas *et al.*, 2020). On the one hand, land-use intensification has heightened environmental pressures on more accessible and productive lands; on the other, land abandonment has promoted the expansion of dense and continuous stands of heathlands and shrublands on formerly cultivated lands, driven by mild temperatures and high humidity (Reyes and Casal, 2008; Morán-Ordóñez *et al.*, 2013). A notable example is the restructuring of livestock farming systems, which has led to the disappearance of small farms and the expansion of larger ones, where higher animal densities aimed at maximizing profitability are generating more concentrated impacts on the landscape (Blanco-Fontao *et al.*, 2011). In parallel, forestry intensification has converted large tracts of land (primarily pasturelands, grasslands, heathlands, shrublands and native forests) into monospecific plantations of fast-growing species for timber, such as pines and eucalyptus (López-Sánchez *et al.,* 2021), resulting in greater landscape homogeneity (Teixido *et al.*, 2010). Furthermore, the expansion of other land uses, such as tourism, dependent not only on local resources and policies, but also on broader-scale institutional and market dynamics, has driven new infrastructure development (Serra *et al*., 2014), becoming a source of conflicts at different levels. Concurrently with this land use reorganisation, anthropogenic climate change is increasing the frequency and intensity of drought and heat waves, particularly in spring and summer (Hernández, 2020; Jeffries and Perry, 2020; Calheiros *et al.,* 2021). These climatic shifts in temperature and precipitation are altering soil moisture regimes, vegetation productivity and dryness and species composition.

The synergistic effects among global change drivers have profoundly altered the forest fire regime in the Ibero-Atlantic region (Castañeda and Reyes, 2014). In this area, ignition events, mostly of human origin (Ganteaume *et al.,* 2013), show an increasing probability of developing into large fires of high severity (Flannigan *et al.*, 2000; Alvarez *et al.,* 2024). In fact, recent evidence indicates that fire severity is rising relatively more under Atlantic than under Mediterranean conditions (Beltrán-Marcos *et al.,* 2024), making this region a new frontline for severe fires. This shift is exemplified by recent extreme events, as the fire outbreak occurred in northern Spain in August 2025. Fire severity is expected to increase further due to repeated burns (Fernández-García *et al*., 2018; Rodrigues *et al.,* 2020) along the progressive lengthening of fire season (Turco *et al*., 2017), reinforcing positive fire-vegetation feedbacks that perpetuate vegetation types prone to severe fires (Povak *et al.,* 2023). As a result of these dynamics, the probability of larger and more extreme forest fire events could double in the region by the end of the century, similar to projections for other parts of Europe, posing a major challenge for risk management (Elmqvist *et al.*, 2025). Given the strategic relevance of these trends, further research will be crucial to anticipate risks in emerging fire-prone regions of western Europe, where fuel availability is high and fire risk is expected to become a major concern (Dupuy *et al.*, 2020).

In the Ibero-Atlantic landscapes, the highest risk of forest fire occurs in the complex wildland-urban interface (WUI) areas (Chas-Amil *et al.,* 2013), where towns, cities or isolated buildings directly adjoin agricultural lands and forest ecosystems. In these landscapes, settlements are generally scattered and surrounded by dense vegetation, often dominated by monospecific plantations of fast-growing species, such as pines and eucalyptus (Modugno *et al.*, 2016; Chas-Amil *et al*., 2020). In recent decades, the WUI has expanded due to the aforementioned socio-economic and environmental changes, with urban development advancing toward wildlands and suburban agropastoral lands transitioning into heathlands, shrublands, forests and tree plantations. As vegetation encroaches into populated areas, new fuel corridors emerge, facilitating fire spread and increasing the frequency with which fire perimeters affect these zones (Calviño-Cancela *et al.,* 2016; Guo *et al.,* 2024). Consequently, both the probability and magnitude of fire damage in the WUI are rising sharply, regulated by interacting geographic, climatic, topographic, land use and social variables that operate in a context-dependent manner (Hernández, 2018). Improved understanding of these interactions in local contexts is therefore essential to inform strategies that minimise fire impacts in the WUI by reducing hazard, exposure of goods and services and susceptibility of exposed elements.

Fire risk in the WUI has been widely characterized based on fire occurrence, pre-fire vegetation and settlement patterns (Lampin-Maillet *et al.*, 2011; Beltrán-Marcos *et al.*, 2024), which is crucial for advancing forest legislation and planning in fire-prone regions. Nevertheless, there is still a lack of comprehensive methodologies to classify WUI areas across heterogeneous landscapes, such as those of the Ibero-Atlantic region, considering the exposure generated by the surrounding vegetation types on human infrastructures and communities (Caton *et al.*, 2017). In this sense, it is remarkable that most studies evaluating the link between fire regime, pre-fire vegetation and human infrastructures in the WUI rely on single analytical units of fixed size (e.g. buffers of 600-meters radius; Bar-Massada *et al.*, 2023) that not necessarily capture the full range of exposure conditions in heterogeneous landscapes.

Moreover, fire severity has often been overlooked, despite its critical role in determining the degree of damage to ecosystems and infrastructures. Therefore, incorporating more complex and spatially structured analytical frameworks that integrate both exposure and fire severity is essential to better represent vegetation–fire dynamics in the WUI in the face of global change.

In this study, we developed a novel methodological framework to assess fire risk in the WUI of heterogeneous Ibero-Atlantic landscapes, under the assumption that fire impacts on settlements depend on their exposure to surrounding vegetation types. The innovation of this approach lies in: (i) the development of a concentric multi-ring system around population entities as the analytical unit to characterize vegetation features influencing fire severity across zones (hereafter rings) of direct and indirect exposure in the WUI, in contrast to traditional single-ring methods; (ii) the spatial analysis of fire risk through two key components: hazard, determined by fire severity, and vulnerability, linked to vegetation susceptibility to fire, which is influenced by structural factors such as vertical continuity, fuel quantity or vegetation density (Keeley, 2009; Lecina-Diaz *et al.,* 2021). Specifically, we intend: (i) to establish a typology of population entities based on their spatial pattern; (ii) to characterise the WUI associated to these entities according to pre-fire vegetation features; and (iii) to identify the pre-fire vegetation characteristics most prone to high fire severity and susceptible to intervention by managers and local population across different WUI influence areas (Radeloff *et al.,* 2005; Lampin-Maillet *et al.*, 2011). This framework was tested in the large Foyedo forest fire that occurred in the Ibero-Atlantic region in 2023, which primarily affected tree-dominated ecosystems, reached significant levels of fire severity and led to the evacuation or confinement of numerous inhabited areas (Suárez-Seoane *et al*., 2024).

2. Study area

The Foyedo forest fire was the largest event ever reported in the Principality of Asturias (NW Spain; Fig. 1) since official records began in 1968. The fire, located in the Ibero-Atlantic biogeographical region (González-García *et al.*, 2024), affected 10,096 ha distributed along an elevation gradient ranging from the sea level up to 896 m a.s.l. Despite fires generally affect heathlands and shrublands in this area, only 20% of the burned surface in the Foyedo forest fire was covered by this type of ecosystems, with the remaining 80% occupied by the next tree-dominated ecosystems: (i) pine plantations (*Pinus pinaster, P. radiata* and *P. sylvestris*) for timber harvesting (52.81%); (ii) native broadleaf forests, mainly mixed forests, birch forests dominated by *Betula* spp., chestnut groves of *Castanea sativa* and oaklands of *Quercus robur* (15.72%); (iii) commercial eucalyptus plantations (mainly of *Eucalyptus globulus*) (6.96%); and (iv) a mixture of the previous types (2.49%). Climate is Oceanic, with an average annual temperature of 11 - 15 °C, mild winters and moderate summers. The cumulative rainfall is 1200 - 1800 mm evenly distributed throughout the year, being more frequent in autumn and winter, which helps to keep the vegetation green and lush. The fire affected mostly individual private lands, the dominant type of ownership. Areas burnt up to six times were identified within the fire perimeter for the period 1984 - 2020. The fire started on March 27th and was extinguished on the 31st, with a reproduction on April 8-9th, 2023. The wind played a key role in the rapid advance of fire (average wind speed of 16.42 km/h, with maximum gusts of 73.44 km/h), along with the conditions of temperature (20.15ºC) and dryness (relative humidity of 38.8%) that were extremely high for the time of year (data from the Spanish Meteorology Agency). See Suárez-Seoane *et al*. (2024) for more details on the general features of the fire event.

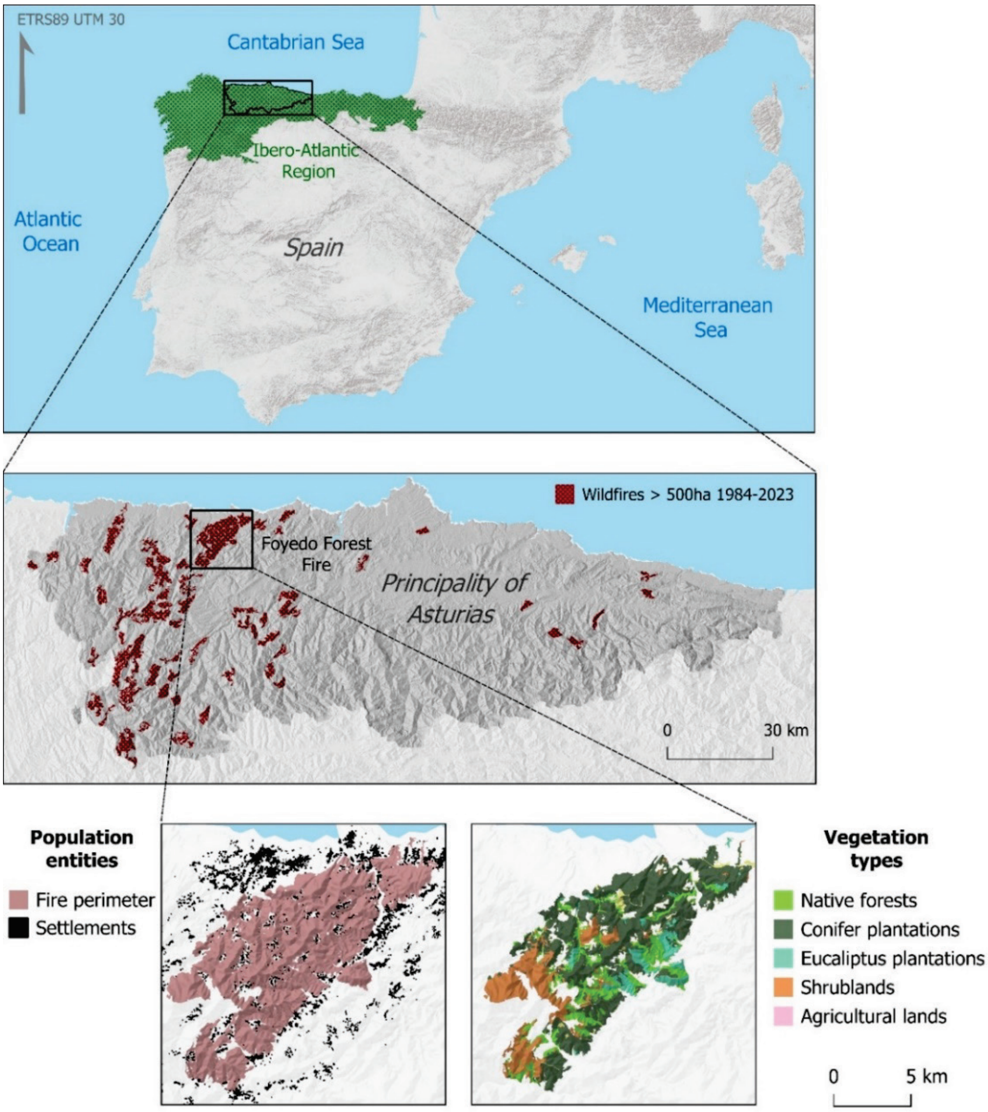

Figure 1. Location of the Foyedo forest fire in the Principality of Asturias (NW Spain). The perimeter was obtained from the European Forest Fire Information System EFFIS (San-Miguel-Ayanz et al.*, 2012) and revised in the field. Vegetation types were derived from the Forest Map of Spain at 1:25,000 (MITECO, 2012)*

3. Methods and materials

3.1. Analytical framework for fire risk characterization in the WUI: a multi-ring system

The methodological approach developed here is based on the understanding that fire risk across the WUI of heterogeneous landscapes depends on the exposure of infrastructures to different fire spread mechanisms. Two classes of exposure were considered (Tecnoma, 2010; Caton *et al*., 2017): (i) direct exposure, linked to fire spread by radiative and convective heating, which occurs when large flames are close to exposed structural elements as buildings (Calkin *et al.*, 2014), or by direct flame contact, which occurs when flames from small fires contact with adjacent structural elements as litter or wood; (ii) indirect exposure, related to fire spread via the aerial transport of burning embers generated either by the main fire front, flammable vegetation or nearby burning structures (Mell *et al.,* 2010).

The analytical framework was then designed as a system of concentric rings arranged around population entities with the objective of unravelling pre-fire vegetation features linked to fire severity across different areas of influence (rings) in the WUI (Fig. 2). The specific characteristics of this multi-ring system were defined considering: (i) Expert knowledge from researchers, forest managers and firefighters on fire spread mechanisms across vegetation types. (ii) On-site observations of fire damage to buildings and other infrastructures. Up to 78% of the buildings affected by the Foyedo forest fire were located in areas with low direct impact risk (Fig. 3) and were destroyed by long-range smouldering embers carried over 1 km (Personal Communication), as also observed in other large forest fires, such as the Pedrógão Grande (Portugal) fire complex of 2017 (Ribeiro *et al.,* 2020). (iii) Spatial analysis of landscape configuration. The mean distance between buildings and the nearest boundary of the vegetation polygon containing each building was 51.5 m, indicating that most buildings are located close to the edges of vegetation units. Additionally, the mean distance between buildings and the 20 nearest vertices of those vegetation polygons was 105.27 ± 17.76 m (range: 75.20 - 130.28 m), suggesting a heterogeneous and fragmented landscape pattern where settlements are interspersed within a mosaic of vegetation types. These values are consistent with the thresholds established in the regional regulation on WUI fire prevention in Asturias, which regulated the use of fire, approved burning instructions and defined prevention measures in force at the time the fire occurred (Resolution of July 17th, 2023). This resolution established the obligation to maintain a strip in the 50 m closest to the buildings, in which a total absence of contact between horizontal and vertical vegetation fuel must be achieved by total clearing of heathlands and shrublands and high intensity thinning of the trees, with pruning to a Fractional Vegetation Cover (FVC)<20%. In the following 75 m, horizontal and vertical continuity of vegetation should be avoided by selective clearing of heathlands and shrublands to achieve FVC<15% and a reduction of tree vegetation to FVC<40% (Fig. 4).

Based on the above criteria, six rings were defined around each population entity. Levels 1 and 2 represent areas of direct exposure of buildings to fire due to their proximity to forest stands, where impacts would result from direct flame contact or nearby radiant heat. Levels 3 and 6 reflect indirect exposure of buildings to flames or embers projected from forest stands in the peripheral rings. (i) Level 1: population entity. (ii) Level 2: A 50-m wide ring drawn from the edge of the population entity. (iii) Level 3: A 75-m ring defined from the edge of the previous one (i.e., 50 - 125 m from the population entity). (iv) Level 4: A 125-m ring extending from the edge of the previous one (i.e., 125 - 250 m from the population entity). (v) Level 5: A 250-meters ring from the edge of the previous one (i.e., 250 - 500 m from the population entity). (vi) Level 6: A 500-m ring from the edge of the previous one (i.e., 500 - 1000 m from the population entity).

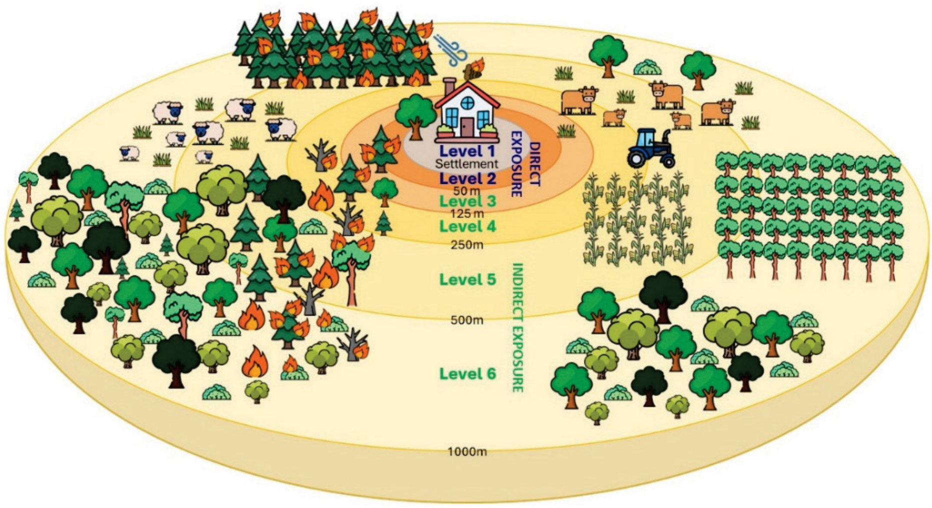

Figure 2. Analytical framework for WUI characterisation across a concentric multi-ring system. At level 1 (population entity) and level 2 (50-m strip from the edge of the population entity), the exposure of the population entity to fire is direct. At level 3 (75-m strip, 50 - 125m from the population entity), level 4 (125-m strip, 125 - 250m from the population entity), level 5 (250-m strip, 250 - 500m from the population entity) and level 6 (500-m strip, 500 - 1000m from the population entity), the exposure is indirect.

Figure 3. Buildings with a low risk of direct exposure to forest fire but damaged by the arrival of burning embers from nearby pine plantations (indirect exposure) during the Foyedo forest fire. Locality of Lago (council of Valdés, Principality of Asturias, Spain).

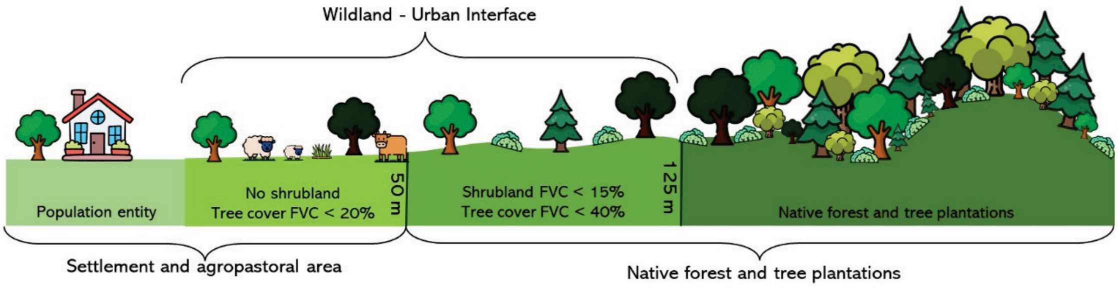

Figure 4. WUI zonation according to the Resolution of 17 July 2023 of the regional government of Asturias.

3.2. Input data: settlements, pre-fire vegetation and fire severity

All buildings within the perimeter of the Foyedo forest fire were individually mapped, including those located within an additional buffer of 500-m to avoid edge effects in subsequent analyses. Three sources of data were used: (i) the topographic base at 1:10,000 scale from the Territorial Information System and Spatial Data Infrastructures of Asturias; (ii) the cadastral cartography at 1:5,000 from the Directorate General for Cadastre (DGC); and (iii) the Geographical Information System for Agricultural Plots (SIGPAC) at 1:5,000. These datasets were integrated into a single layer, in which 5,350 buildings were identified. Since there was no full correspondence among the three sources (i.e., some buildings appeared in only one dataset or were partially represented in another), a geometric union of all layers was performed. Overlapping features were then dissolved to avoid multiple counting and to ensure completeness and consistency in the final building inventory.

A typology of population entities was established based on building distribution and density. We considered that, in the study area, the basic unit of rural settlement is the “caseria” that is typically made of four buildings, including the domestic space (housing) and three productive annexes for agricultural and livestock uses, as granaries, stables, cellars or other auxiliary buildings (Rodríguez, 2025). According to this, the next three classes of population entities were defined (Fig. 5): (i) nuclei: at least four buildings spaced up to 50 m; (ii) mixed: less than four buildings spaced up to 50 m or more than one building spaced 50 - 100 meters from the nearest building; and (iii) isolated: one building at more than 100 m from the nearest. Each building was labelled according to one of these types of population entities. Contiguous buildings sharing the same label were then aggregated using minimum convex polygons into 658 population entities: 168 nuclei, 189 mixed and 301 isolated.

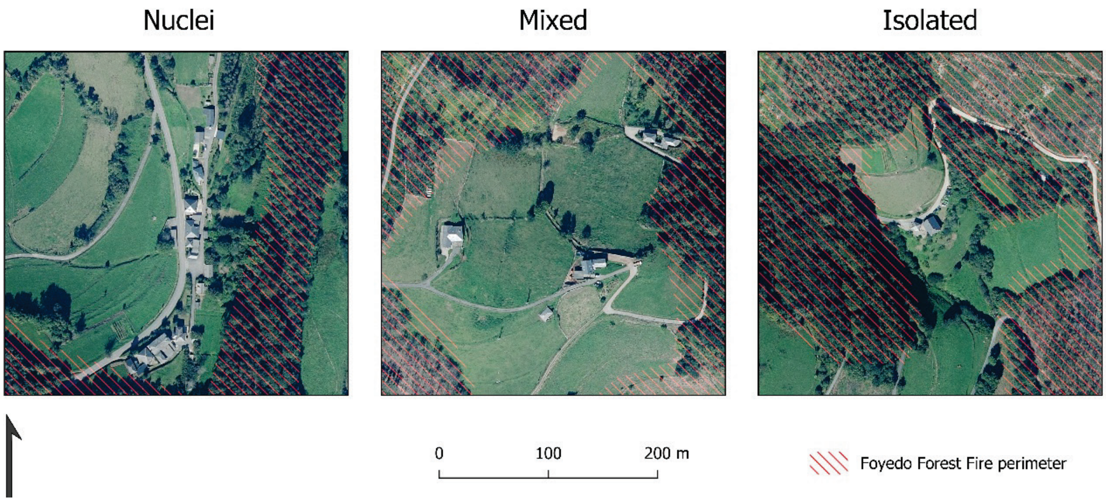

Figure 5. Examples of the three basic types of population entities (nuclei, mixed and isolated) defined in the study area to characterize the WUI.

These polygons were used as the reference geometry for creating the multi-ring buffer system. Rather than generating buffers around individual buildings, the rings were produced from the outer boundary of the 658 aggregated polygons, enabling the characterization of pre-fire vegetation patterns surrounding each population entity. A set of eight variables was compiled at 20 m of spatial resolution to account for vegetation features potentially related to fire severity (Table 1): (i) Vegetation type (% surface covered by heathlands and shrublands, native deciduous forests, eucalyptus plantations and pine plantations), recorded from the Forest Map of Spain at 1:25,000 (MITECO, 2012). (ii) Horizontal continuity of fuel amount and productivity, assessed through the FAPAR (Fraction of Absorbed Photosynthetically Active Radiation by plants) parameter (Baret *et al.*, 2013). FAPAR was derived from a Sentinel-2 image immediately prior to fire (from March 15th, 2023) using the biophysical processor integrated in the Sentinel Application Platform (SNAP) that applies an artificial neural network pre-trained with PROSAIL radiative transfer model (RTM) simulations to retrieve biophysical properties of vegetation (Xie *et al.,* 2019). (iii) Vertical structure of vegetation, evaluated as the cover of both the understory and the tree canopy strata (the most relevant strata influencing the spread and control of surface and crown fires; Corona *et al*., 2015), as well as the vertical complexity of vegetation across all strata. These variables were derived from LiDAR data following the methodology of García-Llamas *et al.* (2019) and Fernández-Guisuraga and Fernandes (2023). LiDAR data (second coverage) were collected from November 2020 to July 2021 by the Spanish National Plan for Aerial Orthophotography (PNOA; https://pnoa.ign.es), with a density of 1 point per square meter and an RMSE of 0.3 m (xy) and 0.15 m (z). Point clouds were normalized with a Digital Elevation Model (DEM) with a spatial resolution of 2 m, created from the ground returns filtered using the multiscale curvature classification (MCC) algorithm. The height of LiDAR returns above ground surface was then obtained through DEM subtraction. The set of LiDAR metrics defined to explain the vertical structure of vegetation was calculated from all non-ground LiDAR returns at 20-m grid size using a height threshold of 0.2 m to exclude noise caused by misclassified ground returns and non-target ground features. The cover of the understory and the tree canopy were evaluated as the proportion of LiDAR returns in the strata of <2 m and >10 m height, respectively, divided by the total number of returns within that stratum and below. The vertical complexity of vegetation was calculated as the diversity of LiDAR returns by strata (<2 m, 2-4 m, 4-10 m, >10 m) using the Shannon - Wiener index (Shannon, 1948). To avoid subsequent problems of multicollinearity and overfitting in further models, we applied a bivariate Pearson correlation analysis between the eight vegetation predictors described above, which revealed no highly correlated groups of variables (i.e., pair correlations were always lower than 0.5).

Table 1. Variables used to assess the role of pre-fire vegetation as a predictor of fire severity in the WUI. Variables were derived at a spatial resolution of 20 m and LiDAR return heights were measured in meters.

Family	**Code**	**Description**	**Source**
Vegetation type	Perc.shrub	Heathlands and shrublands (% cover)	Forest Map of Spain at 1:25,000 (MITECO, 2012)
	Perc.natfo	Native deciduous forests (% cover)	
	Perc.euc	Eucalyptus plantations (% cover)	
	Perc.pine	Pine plantations (% cover)	
Horizontal continuity of vegetation	FAPAR	Fraction of photosynthetically active radiation absorbed by plants that reflects fuel amount and plant productivity	Sentinel-2 satellite image (March 15th, 2023)
Vertical structure of vegetation	LiDAR2m	Understory cover measured as the density of LiDAR returns in the stratum <2 m height	LiDAR data (second coverage), National Aerial Orthophotography Plan (PNOA) (November 2020 to July 2021)
	LiDAR10m	Tree canopy cover measured as density of LiDAR returns in the stratum >10 m height	
	DivLiDAR	Vertical complexity of vegetation calculated as the diversity of LiDAR returns by strata (<2m, 2-4m, 4-10m, >10m) using the Shannon- Wiener index (Shannon, 1948)	

Fire severity was remotely assessed using the Relativized Burn Ratio (RBR; Parks *et al.*, 2014) derived from two Sentinel-2 satellite images: pre-fire (March 15th, 2023) and post-fire (April 19th, 2023). As typical in this kind of studies, the values of the spectral index were validated in the field using the composite severity index (CBI; Key and Benson, 2006) that was quantified with a set of visual indicators of fire damage on soil and vegetation strata. On the basis of the linear relationship between the CBI and the RBR (R^2 value of 0.49), three severity classes were established according to the following thresholds: low severity (RBR< 343), moderate severity (343-520) and high severity (> 520). A more detailed description of the data and the methodological approach can be found in Suárez-Seoane *et al.* (2024).

3.3. Pre-fire vegetation features most prone to fire severity in the WUI

To investigate the relationship between pre-fire vegetation variables (Table 1) and fire severity (RBR spectral index) across the multi-ring system, we ran a multivariate linear regression analysis, with a backward stepwise procedure to select the variables to be included into the final model. The goodness-of-fit of the models was assessed using the coefficient of determination (R^2) and the predictive ability with the root mean squared error (RMSE). The predicted effect of each pre-fire vegetation variable included in the multivariate model was also plotted. Analyses were performed at three spatial levels: (i) global, considering the whole dataset, (ii) by population entity type, considering all rings as a whole, (iii) by ring class, combining all population entity types. All analyses were performed using R-studio 2024.12.0 and QGIS 3.40 (Bratislava).

4. Results

4.1. Characterization of the wildland-urban interface based on pre-fire vegetation

All types of vegetation analysed (heathlands and shrublands, native forests, eucalyptus plantations and pine plantations) increased their presence from the inner to the outermost rings defined for WUI characterization. Pine plantations were the most frequent vegetation type across all rings, with their presence being particularly important in the two innermost levels (1 and 2), where the percentage of occupation of the other vegetation types was less relevant. Eucalyptus plantations were almost absent in all rings, apart from the outermost ring. On the other hand, fuel amount and productivity (estimated by the FAPAR parameter) decreased and became less variable from the surroundings of the population entities towards the peripheral rings. Regarding the vertical structure of the vegetation (assessed from the density of the LiDAR point cloud returns), the cover of both the tree canopy (>10 m) and the understory (< 2 m) strata, as well as the vertical complexity through all strata increased towards the outmost rings. It should be highlighted the high level of variability identified for the last two LiDAR-derived parameters in the innermost ring, indicating a heterogeneity of vegetation types and structures. The lower variability identified at the outermost rings is compatible with the pattern of growing homogenization (Fig. 6).

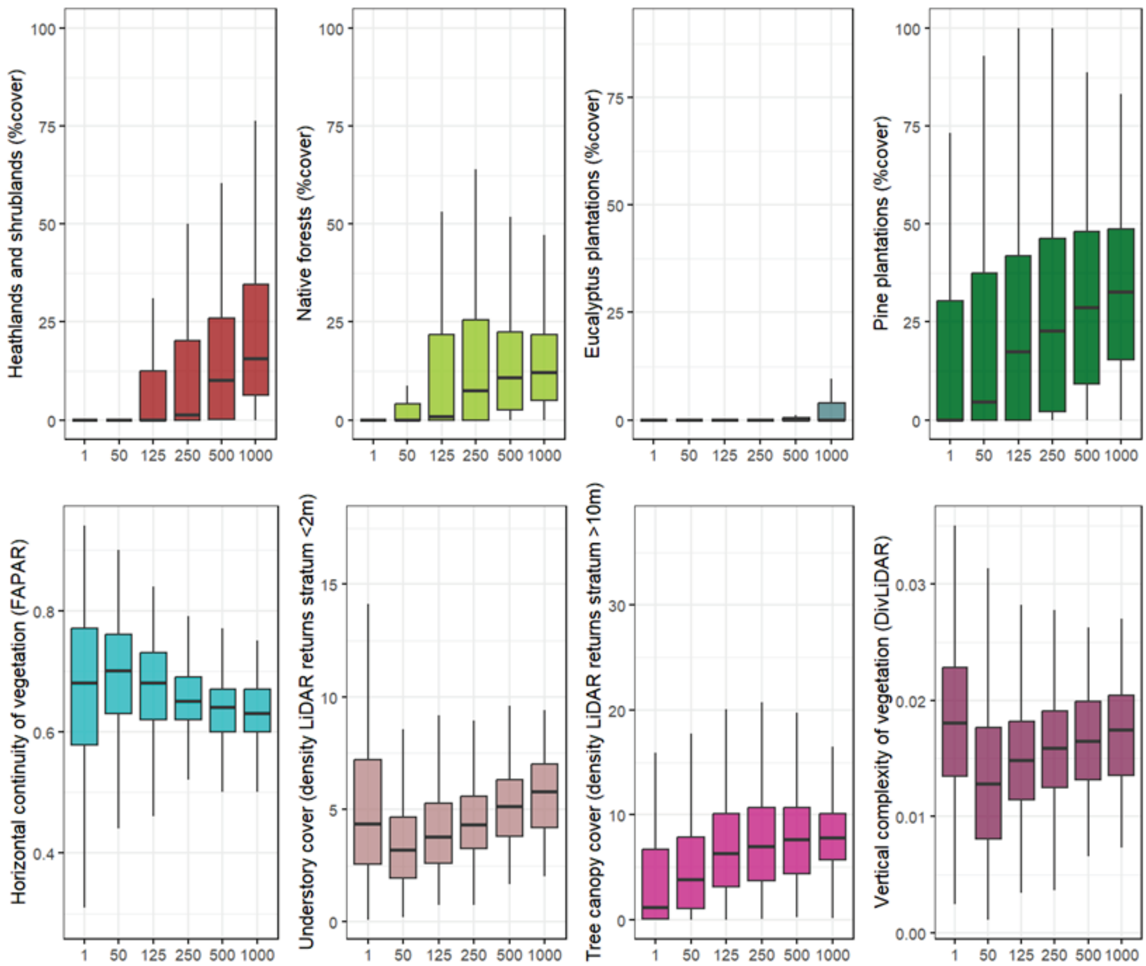

Figure 6. Percentage occupied by the four dominant vegetation types across the multi-ring system defined to characterize the WUI affected by the Foyedo forest fire. The horizontal (FAPAR) and vertical structure of vegetation (density of LiDAR returns) are also shown. The value 1 on the abscissa axis corresponds to the population entity and the rest of the values define the distance from the edge of the population entity to the outer part of each ring. Average values are plotted for 658 population entities (168 nuclei, 189 mixed and 301 isolated), with a total of 3290 rings.

4.2. Relationship between pre-fire vegetation features and fire severity

Fire severity varied significantly among the rings defined for WUI characterization (F=182.90, df=5, p<0.001), with a sound increase from the inner towards the outermost rings (Fig. 7). This pattern was consistent across the different types of population entities, with the lower levels of fire severity observed in the two innermost rings across all types of entities and the highest values of fire severity being recorded in the outmost ring of mixed entities.

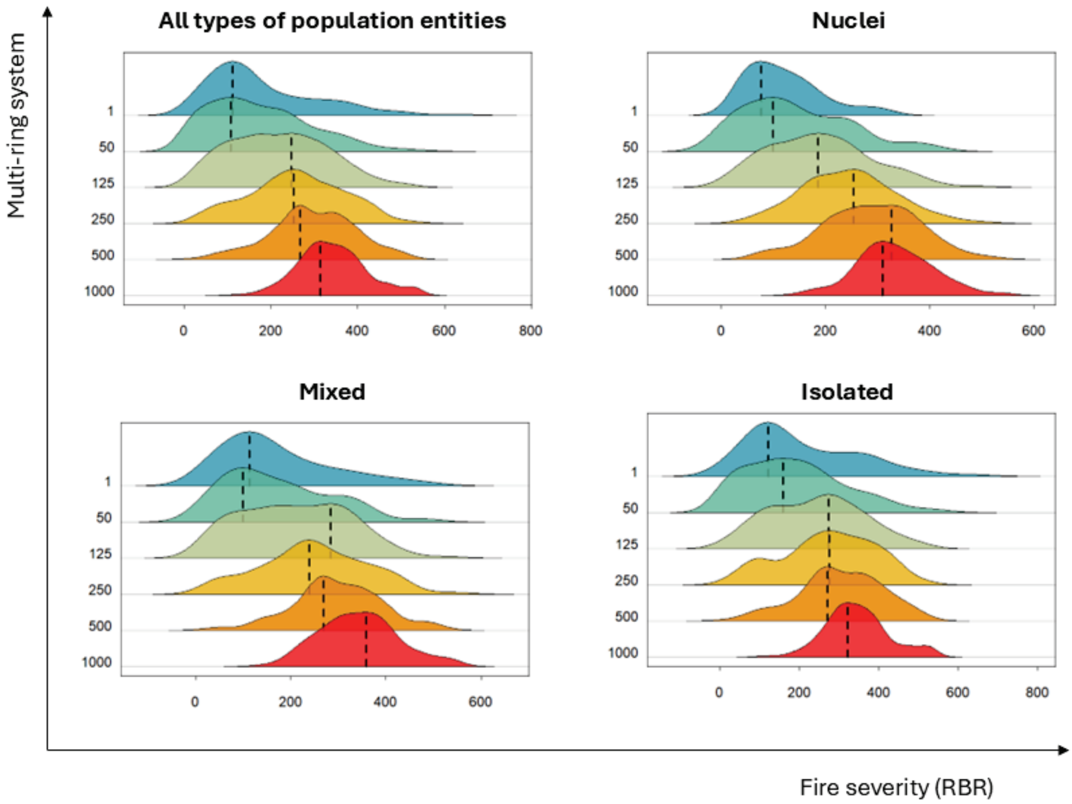

Figure 7. Fire severity (RBR index derived from Sentinel-2 satellite images) in the multi-ring system defined to characterize the WUI affected by the Foyedo forest fire. The value 1 on the ordinate axis corresponds to the polygon encompassing the population entity and the rest of the values define the distance from the edge of the population entity to the outer part of each ring. Averaged values correspond to 658 population entities (168 nuclei, 189 mixed and 301 isolated). The median is also shown for each ring.

Five of the eight pre-fire vegetation variables introduced in the model significantly predicted fire severity. According to F-values, the most important driver of fire severity in the WUI was the percentage of heathlands and shrublands. The second driver was the cover of the understory (density of LiDAR returns in the stratum <2 m) and the third, the area occupied by pine plantations. The presence of eucalyptus plantations and vertical complexity of vegetation (DivLiDAR) were also significant predictors, but of lower relevance. All pre-fire variables included in the model increased positively with fire severity, except for vertical complexity that followed the opposite trend. No significant effect on fire severity was identified for the area occupied by native forests, the horizontal continuity of vegetation cover (FAPAR) or the cover of the tree canopy (LiDAR10m). The variance explained by the model was 42.32% (R^2=0.42) and the residual standard error was 90.71 for 2796 degrees of freedom (Table 2, Fig. 8).

The multi-ring analysis yielded a similar pattern of results. Across all rings, the percentage of heathlands and shrublands was the best predictor of fire severity (Table 3). The understory cover and the area occupied by pine plantations were both important drivers in almost all models, with the latter playing a more relevant role in the outermost ring. In that specific ring, eucalyptus plantations also explained significantly fire severity. The vertical complexity of vegetation was negatively related to severity in the inner rings, while tree canopy cover was in the peripheral rings. The most parsimonious model corresponded to the 500m ring and the less parsimonious (more complex) to the peripheral one. The explained variance was similar for different rings, with the minimum at 35.3% (50m ring) and the maximum at 41.9% (1000m). The relationships between fire severity and pre-fire vegetation variables were more complex in isolated buildings than in other two types of population entities, with the highest data dispersion, specifically in the inner rings (Fig. 9).

Table 2. Global model. Results of the multivariate regression analysis implemented for the evaluation of pre-fire vegetation variables as drivers of fire severity in the WUI.

Variable	df	Sum Sq	F-value	Relation y~x	p-value
Perc.shrub	1	11864336	1441.86	+	***
Perc.pine	1	1659892	201.73	+	***
Perc.euc	1	469092	57.01	+	***
LiDAR2m	1	2933092	319.11	+	***
DivLiDAR	1	297093	39.43	-	***
Residuals	2795	22998580			

*(n.s. no significant; * p <0.05; ** p<0.01; *** p< 0.001)*

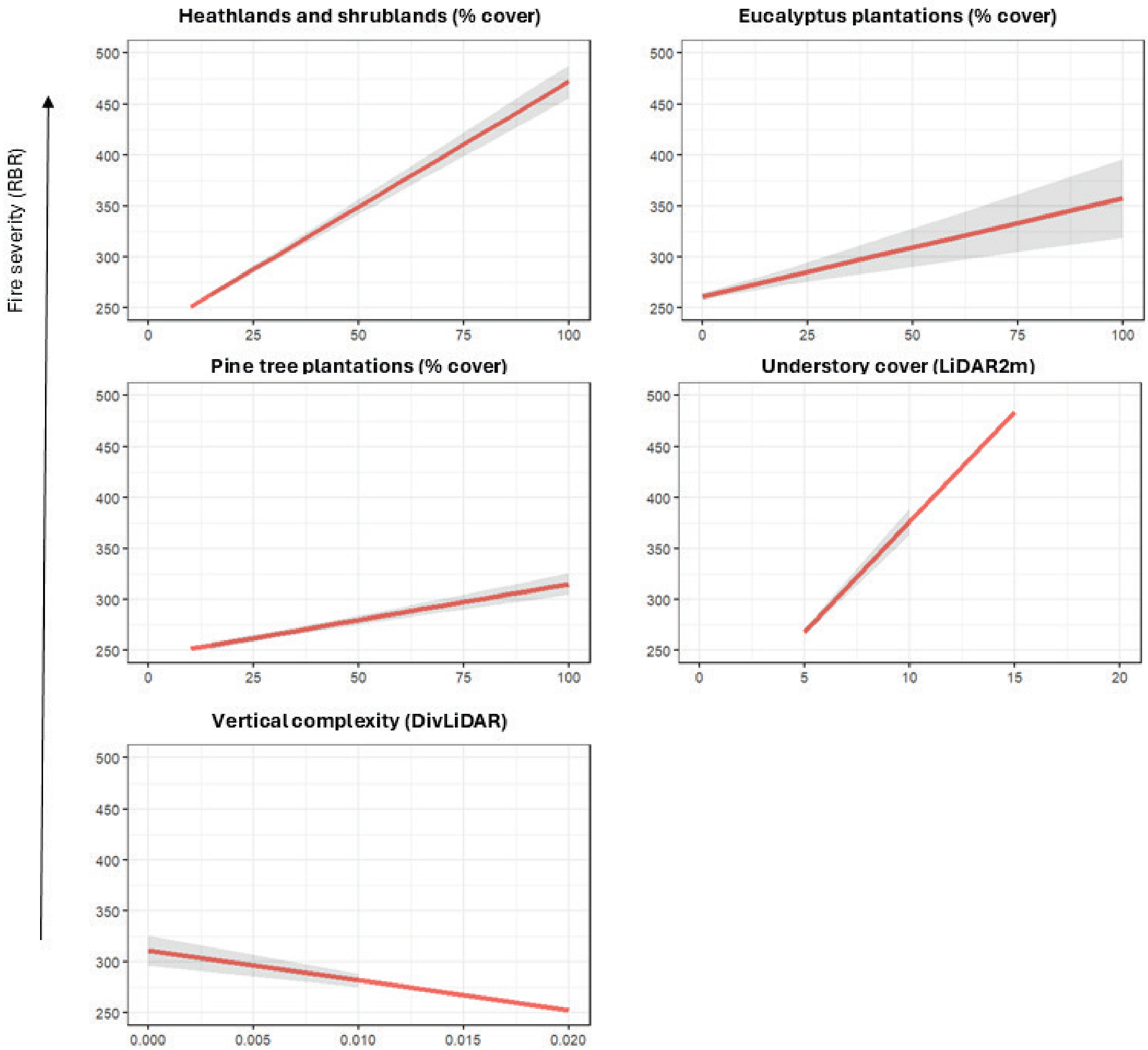

Figure 8. Predicted effect of each pre-fire vegetation variable included in the multivariate model on fire severity.

Table 3. Multi-ring models. Results of the multivariate regression analyses implemented for the evaluation of pre-fire vegetation variables as drivers of fire severity across the concentric ring system defined to characterize fire risk in the WUI. Each column corresponds to a different model. The cells in the table show the F-value and p-value (level of significance) achieved by each variable in each ring model. The orange colour represents a positive relationship between the variable response and the predictor. The blue colour represents a negative relationship. The table also shows the adjusted R-squared, the residual standard error and the explained variance (%) for each model.

	Ring 1	**Ring50**	**Ring 125**	**Ring 250**	**Ring 500**	**Ring1000**
Perc.shrub	1413.02***	1286.922***	1430.618***	1419.47***	1370.91***	1431.71***
Perc.natfo	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Perc.euc	n.s.	n.s.	n.s.	n.s.	n.s.	24.40***
Perc.pine	197.69***	180.05***	200.15***	198.59***	n.s.	232.51***
FAPAR	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
LiDAR2	349.33***	n.s.	353.68***	350.92	446.35	316.86
LiDAR10	n.s.	n.s.	n.s.	13.76	n.s.	19.46
DivLiDAR	n.s.	68.54***	35.82***	n.s.	n.s.	n.s.
Adj. R^2	0.4114	0.3537	0.4186	0.4141	0.3933	0.4191
Res. SE	91.63	96.02	91.07	91.42	93.03	91.03
Exp. var.	41.14%	35.37%	41.86%	41.41%	39.33%	41.91%

*(n.s. no significant; * p <0.05; ** p<0.01; *** p< 0.001)*

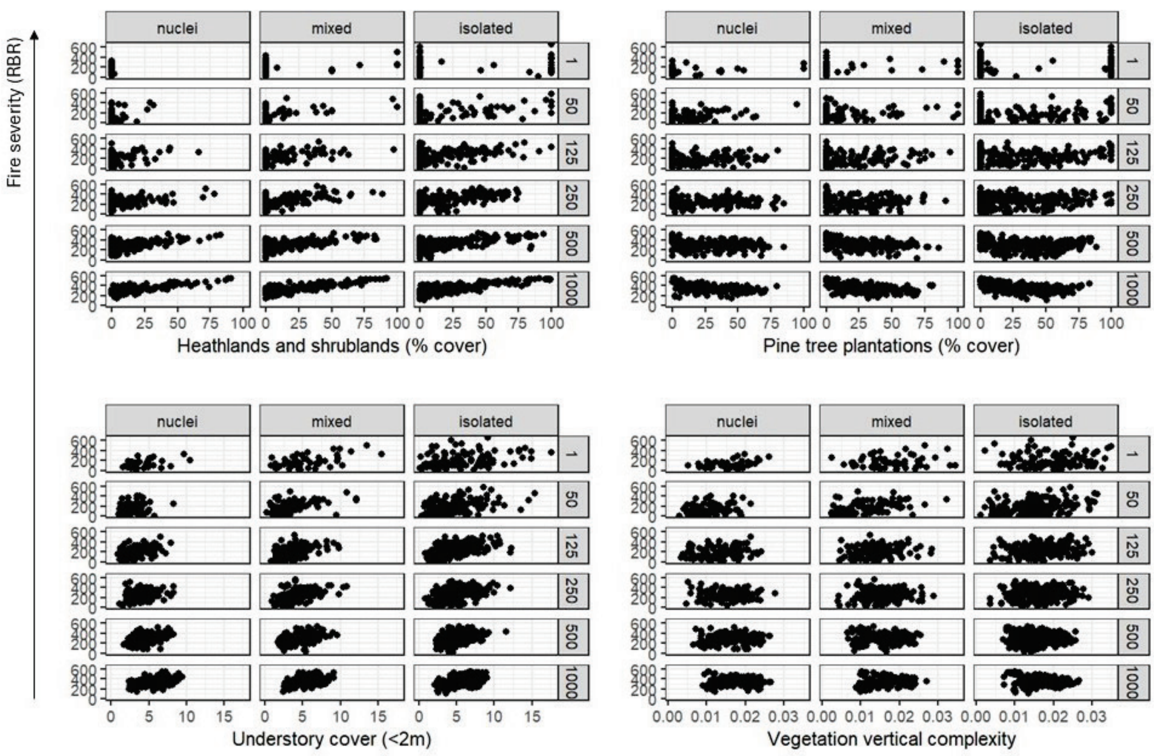

Figure 9. Relationship between fire severity and the most relevant vegetation pre-fire predictors included in the multi-ring models across types of entities and rings.

5. Discussion

5.1. Relevance of the multi-ring approach

The multi-ring analytical framework developed in this study allowed the characterization of pre-fire vegetation features related to fire severity in the WUI of heterogeneous landscapes of the Ibero-Atlantic biogeographical region, while facilitating the assessment of fire risk across different types of population entities. In overall, the pattern of increasing fire severity from the core area to the peripheral of the WUI was consistent and did not reveal major differences among the three types of settlements defined. Our approach, based on a system of concentric rings extending up to 1,000 m from inhabited areas, allowed us to assess fire risk in terms of both direct and indirect exposure, the latter becoming increasingly relevant under extreme weather conditions. In fact, in areas where pine and eucalyptus plantations are present in the surroundings of the WUI, fire surveillance, suppression and prevention measures should not be limited to the inner rings. In the context of global change and widespread land use reconfiguration in rural areas, the development of effective strategies to mitigate fire risk in the WUI is increasingly critical (Bento-Gonçalves and Vieira, 2020). However, the diversity of WUI typologies and associated environmental conditions requires regionally and locally tailored approaches. Spatially explicit, multi-scalar methodologies, such as the one proposed in this study (see also Barbosa *et al.,* 2024, for a comparable approach in Portugal, Carlson *et al.,* 2022 in U.S.A., or Kaim *et al.,* 2023 in Poland), are particularly valuable for assessing fire risk in heterogeneous and dynamic landscapes, such as those found in the Ibero-Atlantic region.

5.2. Characterization of the wildland-urban interface based on pre-fire vegetation

The presence of forest ecosystems generally increased within the WUI as ring size expanded, which is consistent with the findings of previous studies (e.g. Kaim *et al.,* 2023). Our results revealed a growing proliferation of heathlands, shrublands and tree-dominated ecosystems from the rings closest to the settlements toward the periphery. This pattern likely reflects land-use gradients commonly found in the WUI, where intensive human activity and fuel management near settlements progressively give way to less managed and more natural vegetation types in outer zones. This spatial transition is consistent with the observed decrease in plant productivity (FAPAR) and the increase in vegetation structural variability, as reflected by greater vertical complexity (DivLiDAR), and higher cover of both tree canopy (>10 m) and understory (<2 m). Pine plantations (*Pinus pinaster*, *P. radiata* and *P. sylvestris*) were by far the most widespread forest ecosystem across all rings. In contrast, heathlands, shrublands and native deciduous forests were less prevalent, whereas eucalyptus stands occupied a relatively small area. Therefore, the outer rings exhibited the highest vegetation cover and vertical structural complexity, while the innermost ring (corresponding to the residential core) showed considerable variability in these structural descriptors, likely reflecting heterogeneous land uses and management practices typical of peri-urban environments.

5.3. Relationship between pre-fire vegetation features and fire severity

In the inner rings of direct exposure (levels 1 and 2), average fire severity was relatively low. These areas were generally located outside the main fire perimeter, partly due to landscape configuration (i.e., settlements are often surrounded by areas of lower biomass) and the effectiveness of fire suppression efforts. Nevertheless, in the context of very large forest fires, as the Foyedo fire (see also the Pedrógão Grande fire, Portugal 2017; Ribeiro *et al.,* 2020), these inner zones remain susceptible to spot fires ignited by windborne embers, a risk that strongly depends on the dominant vegetation in the outer rings. Fire severity tended to be higher in areas farther from population entities, echoing the findings of Guo *et al.* (2024), who reported that the most intense fire hotspots worldwide are often located at greater distances from WUI cores. This pattern is likely related to the higher amount of plant biomass in the outermost rings, which provides a greater amount of available fuel.

However, not all vegetation types contributed equally to fire severity. Model results indicated that the presence of heathlands and shrublands was the strongest driver of fire severity in the WUI of the Foyedo fire, despite their relatively low prevalence across all rings. This result aligns with previous research done in both Mediterranean and Atlantic Iberian bioclimatic regions and, specifically, in northwestern Atlantic WUI areas, where this type of vegetation is related to high fire recurrence (Beltrán-Marcos *et al.,* 2023; Fernández-Manso *et al.,* 2024). Nonetheless, the relevance of pine plantations should not be underestimated. In the Ibero-Atlantic bioregion, high fire severity associated with these plantations has been linked to fuel structure, extreme weather conditions (Fernández-Guisuraga and Calvo, 2025) and terrain morphology (Fernández-Alonso *et al.,* 2017), likely due to differences in fire behaviour. For instance, in this bioregion, conifer and eucalyptus plantations have been shown to produce higher fireline intensity than broadleaf forests (Fernandes *et al.,* 2019), with their presence identified as a major driver of fire risk in WUIs areas (Calviño-Cancela *et al.,* 2016). In contrast to the significant role of heathlands, shrublands and pine plantations as drivers of fire severity in the WUI, the absence of such effects in native broadleaf forests is noteworthy. This finding is consistent with previous research (Calviño-Cancela *et al.,* 2016; Fernández-Guisuraga and Calvo, 2025) and complements other evidences of the greater post-fire resilience of native broadleaf forests in this biogeographical region compared to pine and eucalyptus plantations (Cruz *et al.,* 2024). In the current context of global change, in which society faces challenges related to multiple stressors, native broadleaf forests hold potential as a nature-based solution for mitigating fire impacts in the WUI and, more broadly, across the landscapes of the Ibero-Atlantic region (Lecina-Díaz *et al.,* 2023; Oliveira *et al.,* 2023; Regos *et al.,* 2023).

Furthermore, we found negative correlations between vegetation vertical complexity and fire severity. Although this relationship may be context-dependant and should be interpreted with caution, it agrees with prior evidence on Iberian forest fires (García-Llamas *et al.,* 2020), suggesting that more structurally diverse and complex forest stands may contribute to reduce fire severity. Conversely, monospecific plantations with lower vertical diversity, typically composed of younger and more homogeneous trees, tend to accumulate more continuous and flammable biomass, making them more susceptible to burning at higher severity. This finding also supports the broader view of structurally complex forest ecosystems as nature-based solutions to other global change stressors, such as droughts or biological invasions (Verheyen *et al.,* 2024).

5.4. Limitations of the study

Although the results were robust and consistent, some limitations should be acknowledged. First, the vegetation data used to analyse the relationship between fire severity and vegetation type were derived from a dataset published more than a decade before the fire, despite vegetation distribution may have changed during that time. Additionally, the spatial resolution of this dataset (scale 1:25,000) might be too coarse for detailed analysis within rings as narrow as 50 meters. Second, there was a slight temporal mismatch (approximately two years) between the period of the LiDAR flight (November 2020 - July 2021) and the fire event (March - April 2023). Although this temporal difference may have introduced some discrepancies between the observed and predicted relationships regarding stand structure and fire effects, particularly for fast-growing species (e.g., Eucalyptus), these differences are not expected to be large enough to affect the results significantly. Third, fire severity estimates were derived from remote sensing data. Although these estimates are based on widely validated methods, they primarily capture changes at the top of canopy level and may not fully reflect the range of ecological impacts. This limitation is particularly relevant in Atlantic environments where fire impacts can vary significantly across vertical strata, as observed in this fire event (Fernández-Guisuraga *et al.,* 2024).

6. Conclusions and recommendations

The results of this study highlight the importance of developing differentiated and spatially structured strategies to characterize fire risk in the WUI of heterogeneous landscapes, such as those of the Ibero-Atlantic bioregion, by considering different areas of influence and exposure to fire. Our findings revealed a clear spatial pattern of vegetation across the WUI, reflecting a land-use gradient in which intensive human activity and fuel management near settlements progressively give way to less managed and more natural vegetation types in outer zones. Accordingly, pine plantations and, to a lesser extent, heathlands and shrublands increased their presence from the inner to the outermost rings, in parallel with a consistent rise in fire severity across all settlement types. Heathlands and shrublands were identified as the main drivers of fire severity, along with understory cover and pine plantations, whereas vertical structural complexity showed a negative relationship with fire severity. In the inner rings of direct exposure, fire severity was relatively low due to landscape configuration and the effectiveness of fire suppression efforts. Nevertheless, under very large forest fires, these inner zones remain susceptible to spot fires ignited by windborne embers, a risk strongly influenced by the dominant vegetation in the outer rings. These findings emphasize the need to account for spatial variations in vegetation composition and structure when assessing fire risk in the WUI. Such approaches are crucial for guiding effective vegetation management, improving the allocation of firefighting resources and enhancing the efficiency of prevention and mitigation efforts in fire-prone regions.

The following recommendations are made: (i) To promote WUI assessment at both regional and local scales, which are the most appropriate scales for the design and development of effective forest fire prevention actions. (ii) To establish new methodologies to characterize fire risk in the WUI considering explicitly fire spread mechanisms, either by direct or indirect exposure. Vegetation management actions aimed at preventing forest fires in the WUI should not only be undertaken in the inner rings, but also in the outer rings, depending on the types of vegetation present and the threat from fire-breathing. However, in Atlantic landscapes, where settlements are widely dispersed, this issue is extremely complex because of the overlapping of the influence rings defined around the multiple population entities. (iii) When a large wildfire occurs, it is strongly recommended to analyse in depth the mechanisms of fire spread in the WUI, as well as to inventory the affected structures, identifying the role that the spatial configuration of the vegetation has played in the damage. Lessons learned from past catastrophes can be used to improve defence options and ensure the safety of the inhabitants.

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