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# Characterising land cover—wildfire interactions in Catalonia and their implications for resilience

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## Abstract

**Background** In recent years, wildfire events have become increasingly challenging in many regions around the world. In Mediterranean Europe, wildfires are a natural part of the ecosystem. However, in recent decades, such fires have become more impactful due to years of land abandonment, fire suppression, and climatic changes. Characterizing the interactions between wildfires and land cover is important for understanding which land cover type is most likely to burn, and how this can be used to guide future landscape management.

**Results** We quantified land cover extents for wildfires in Catalonia, northeast Spain, from 2009 to 2022, looking at the fire interior, fire edge, and fire refugia. We found over 70% of burnt areas were forest, shrub, and grasslands, while over 50% of the fire refugia was cultivated land. Shrub and grasslands burned disproportionately more than forested areas when compared to average land cover values. Around fire edges, roads, watercourses, and cultivated areas were more prevalent than on average in Catalonia. The results show that agricultural activity is important for providing fire refuges as well as helping contain fires.

**Conclusions** These results emphasize the importance of maintaining current agricultural landscapes and investing in rural livelihoods to enhance landscape resilience to fire. Conversely, the predisposition of forest and shrublands to burn decreases the Catalonia's resilience to wildfire events, indicating that more management is needed in these areas.

**Keywords** Wildfires, Land cover, Resilient landscapes, Catalonia, Fire suppression

## Resumen

**Antecedentes** En años recientes, los eventos de incendios están siendo incrementalmente desafiantes en muchas regiones alrededor del mundo. En la Europa Mediterránea, los incendios de vegetación son parte natural de los ecosistemas. Desde luego, en décadas recientes, estos incendios se han transformado en más impactantes debido al abandono de los campos, la supresión de los incendios, y el cambio climático. La caracterización de las interacciones entre incendios de vegetación y la cobertura vegetal es importante para entender cual tipo de vegetación es más propenso a quemarse, y cómo esta puede ser usada para guiar el manejo futuro de los paisajes.

**Resultados** Cuantificamos la extensión de la cobertura de incendios de vegetación en Cataluña, en el este de España, desde 2009 a 2022, observando el interior de los incendios, el perímetro del fuego, y los refugios de fuego. Encontramos que más del 70% de las áreas quemadas eran bosques, arbustales y pastizales, mientras que el 50% de

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los refugios de fuego eran tierras cultivadas. Los pastizales y arbustales se quemaron desproporcionadamente más que los bosques cuando se compararon con el promedio de las áreas cubiertas de vegetación. Las quemaduras alrededor de los perímetros de incendios, rutas, cursos de agua y áreas cultivadas, fueron más prevalentes que en el promedio de Cataluña. Los resultados muestran que las áreas agrícolas son importantes como refugios de fuego como así también para contener estos incendios.

**Conclusiones** Estos resultados enfatizan la importancia de mantener los actuales paisajes agrícolas e invertir en los asentamientos rurales para aumentar la resiliencia al fuego. Contrariamente, la predisposición de los bosques y arbustales a arder decrece la resiliencia a eventos de fuego, indicando que es necesario un mayor manejo en esas áreas.

## Background

Wildfires are a growing risk across the world (UNEP 2022). While fire is a natural process, large wildfire events with significant negative impacts are becoming increasingly common in European countries such as Spain, France and Portugal (Higuera and Abatzoglou 2021). Temperate regions such as north-west Europe are also experiencing more extreme events (Arnell et al. 2021; Cardil et al. 2023). While some of these changes can be attributed to global climate change (Costa et al. 2020; Dupuy et al. 2020), regional and local transformations on a landscape level also have repercussions in terms of wildfire management (Moreira et al. 2020). Enhancing landscape resilience to wildfire events, including accepting fire within the landscape, has become a popular topic to investigate (Higuera et al. 2019; Magalhães et al. 2021; McWethy et al. 2019; Newman Thacker et al. 2023). Interactions between wildfires and land cover are an important element of landscape resilience, as land cover ultimately dictates what fuel is present. Fuel is the only element of the fire behavior triangle (fuel, weather, topography) that can be reliably anthropogenically managed in the near-term, and so forms a significant factor in wildfire resilience (Bajocco and Ricotta 2008; Moreira et al. 2011).

Interactions between wildfire events and land cover types have been studied globally within different contexts, such as Chile (Carrasco et al. 2021), the USA (Hanberry 2020; Zhong et al. 2021) and Canada (Marchal et al. 2017). Alongside these broad interactions, particular elements of land cover and wildfire events have been investigated. In the USA and Australia, landscape features, e.g., roads and watercourses, and their influence on wildfire cessation has been researched (Narayanaraj and Wimberly 2011; Parks et al. 2015; Yocom et al. 2017, 2019; Fisher et al. 2022). These studies conclude such features can impact wildfire events, acting as control points or decreasing the rate of spread. Wildfire refugia, unburned 'islands' within the fire interior (Collins et al. 2019), have been studied from a land cover perspective as changes in fuel type can contribute to their formation

(Meigs and Krawchuk 2018; Martinez et al. 2019). The studies examining the relationship between particular land cover elements (landscape features and refugia) are mainly constrained geographically to the US and Australia. The results are thus not fully translatable to European landscapes, due to Europe's higher average density population, a more fragmented landscape with differing land/fire management strategies (Tedim et al. 2016), and alternative fire regimes (Prichard et al. 2017).

While much research exploring landscape features and fire refugia is located outside of Europe, within Mediterranean Europe, the relationship between wildfires and overall land cover has been moderately investigated. Moreira et al. (2011) and Oliveira et al. (2014) examine fire selectivity within the context of Southern Europe. Fire selectivity refers to the tendency of a fire to burn through a particular vegetation type, and in both studies shrubland was identified as the land cover most likely to burn.

Studies on the relationship between wildfire events and land cover selectivity have been conducted within regional contexts in Sardinia (Bajocco and Ricotta 2008), Portugal (Moreira et al. 2009; Carmo et al. 2011; Barros and Pereira 2014) and several areas of Spain (Ruiz-Mirazo et al. 2012; Montiel-Molina et al. 2019). Julio Camarero et al. (2019) also examined historical connections between land use change and fire regimes in central Spain, suggesting a relationship between the transition to a fragmented shrub and pine landscape and a peak in historical fire occurrence. Land cover transitions after wildfire events have been studied in a Mediterranean context. Post-fire transitions from forest to grassland have been shown to occur on both a temporary (Ojeda et al. 1996; Capitanio and Carcaillet 2008) and permanent basis (Eugenio et al. 2006), depending factors including fire severity and fire return intervals (Eugenio and Lloret 2004). Land cover change is not the only factor shaping wildfire outcomes in Mediterranean climates. Viedma et al. (2017) indicated that land cover in the Turkish study region between 1975 and 2010 did not become more hazardous in regard to wildfire, and yet the time period also

coincided with the region's largest wildfire in 2008, attributed to extreme fire weather.

This study concentrates on Catalonia, Spain, because of this region's longstanding fire history, the existence of a wildfire-specific firefighting force and the presence of reliable datasets for examining wildfire and land cover interactions. Previous research has examined land cover wildfire interactions within two municipalities of Catalonia (Lloret et al. 2002) or throughout earlier time periods, 1978–1995 (Díaz-Delgado et al. 2004) and 1986–2002 (González and Pukkala 2007), concluding that predominantly dense forests and shrublands interact the most with wildfires. However, land cover changes are ongoing in Catalonia (Badia et al. 2019) and land abandonment has slowed in recent years (Otero et al. 2015; Cervera et al. 2019). Following natural succession pathways, sites that were abandoned decades ago will now have matured into forests (Poyatos et al. 2003). Thus, these 20–50-year-old findings may not reflect more recent wildfire-land cover interactions. Furthermore, fire suppression strategies have altered and Catalan approaches toward wildfires are beginning to shift away from fire exclusion and suppression (Otero and Nielsen 2017). Fire suppression strategies play an important role in characterizing burn patterns from wildfires, depending on the characteristics of the firefighting teams amongst other factors such as fire weather (Harris et al. 2024). In lieu of shifting wildfire regimes and firefighting strategies, climatic changes and alterations in land cover, it is vital that knowledge about fire selectivity and land cover reflect current events. Working within the fire service in a transdisciplinary collaboration also offers insights into practical fire suppression techniques—knowledge which often goes undocumented in academic research.

We derived four research questions: (1) To what extent do landscape features interact with fire edges in Catalonia? (2) What is the relationship between land cover and wildfire events in Catalonia? (3) What are the characteristics of post-fire land cover transitions in Catalonia? And (4) How do landscape features and land cover interactions influence Catalonia's resilience to wildfire events?

This research was conducted within the context of a PhD project analysing fire resilient landscapes, and contributes to furthering understanding about how such landscapes (Newman Thacker et al. 2023) can be assessed. Within this research we focus on wildfires from 2009 to 2022 and their interactions with land cover for three different contexts of each fire: the fire edge, interior and fire refugia. Using a Geographic Information System (GIS) based methodology we investigated the relationship between land cover and what does or does not burn during a wildfire. We examined the influence of landscape features and their prevalence around the fire edge,

alongside characterizing overall land cover type around the fire edges. Land cover within the fire interior, the area which was burnt, was analyzed, alongside the fire refugia within the fire interior. We also characterized post-fire land cover transitions that occurred after the studied fires. To place this analysis in the context of fire management, we interweave place-based knowledge from GRAF (Catalan acronym for Support Group of Forest Interventions), the specialized wildfire-fighting taskforce within the Catalan Fire and Rescue Service (CFRS). We aimed to understand the implications of this research in terms of the resilience of Catalonia's landscape to wildfires. This research offers an analysis of the relationship between land cover and wildfire events and links this relationship to the how, where, and why of fire suppression activities, providing a nuanced interpretation of the results.

## Methodology

### Experimental design

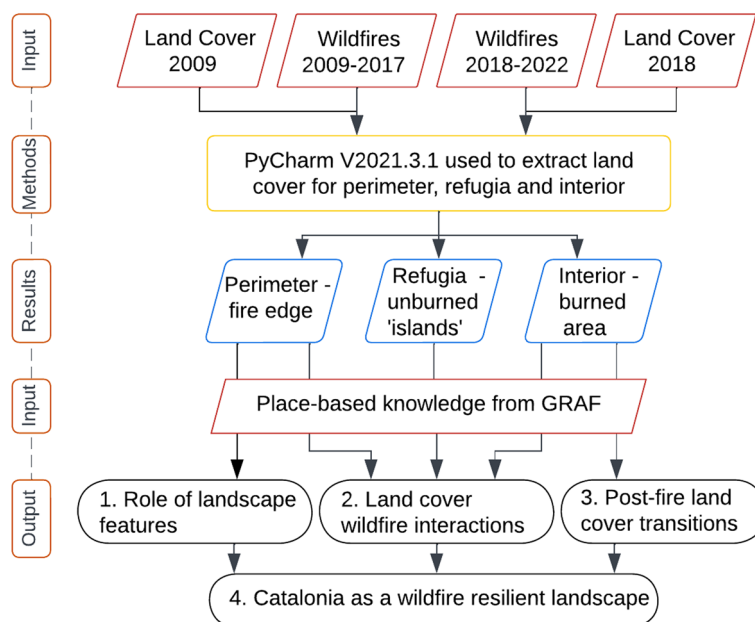
We used open access data to analyze wildfire perimeter datasets and land cover interactions. The overall workflow is shown in Fig. 1, indicating the use of two GIS-based datasets (wildfire perimeters and land cover data) as inputs alongside PyCharm Version 2021.3.1 (JetBrains 2019) to extract land cover for the fire edge, refugia and interior. Integrating place-based knowledge from GRAF, we used these outputs to answer the four research questions as outlined in the “Background” section.

### Study area

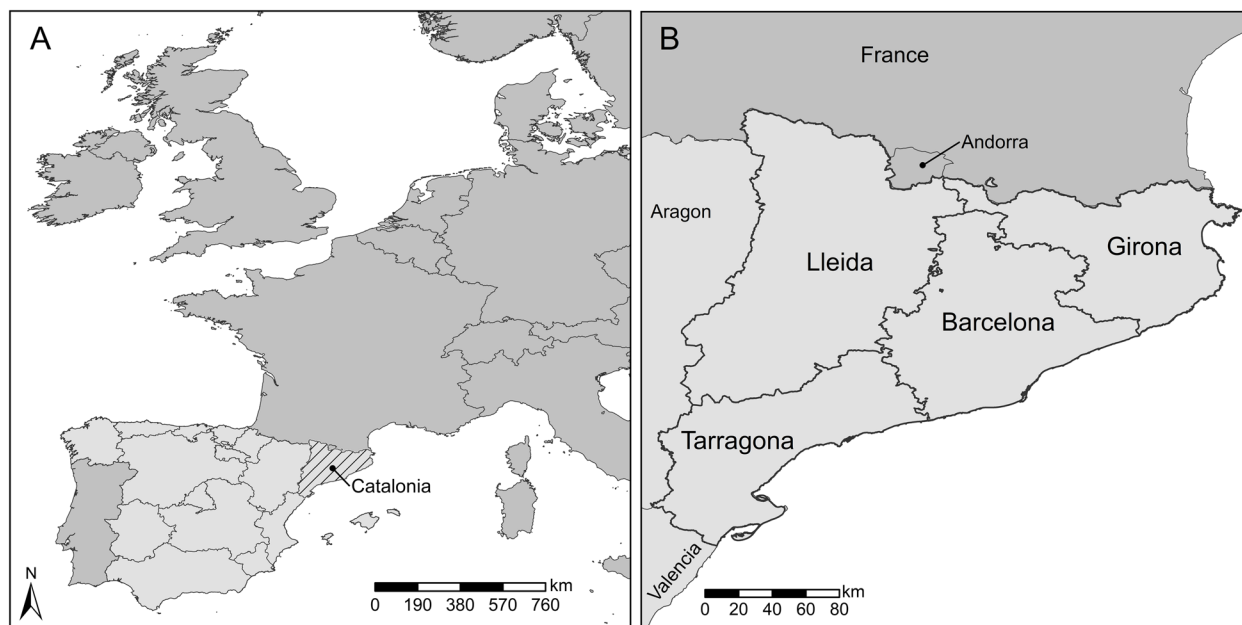
Catalonia is an autonomous region in north-eastern Spain (Fig. 2). The area has a Mediterranean climate with hot, dry summers, which are becoming more extreme due to climate change (Loepfe et al. 2012; Otero and Nielsen 2017). Catalonia experiences frequent wildfire events, partially fueled by the continuing conversion of agricultural land to forests and scrublands due to mass land abandonment (Badia et al. 2002, 2019; Cervera et al. 2019). Catalonia's population is predominantly urbanized, with over 60% of people living in the metropolitan area of Barcelona (Otero and Nielsen 2017). With increased urban sprawl, the wildland-urban interface (WUI) has also been expanding, creating an intermix of housing and abandoned vegetation (Badia et al. 2019). The combination of increased high fire danger days due to climate change, the expansive unmanaged, poor-quality forests, and the rise in WUI dwellings, has made Catalonia increasingly vulnerable to wildfire events (Serra et al. 2013; Alcasena et al. 2019).

### Firefighting operations in Catalonia

In 1986, wildfires were placed at the top of the Catalan governmental agenda when over 6000 ha burnt,



**Fig. 1** Schematic diagram showing workflow used to answer research questions 1–4 (“output”)



**Fig. 2** **A** Location of Spain relative to Europe, with Catalonia labeled, and **B** Catalonia and its respective four provinces, along with its bordering autonomous communities (Aragon, Valencia) and countries (Andorra, France)

including the site of the Montserrat mountain, an area of significant cultural heritage in Catalonia (Fernández-Blanco et al. 2022). Subsequently, wildfires became an increasing concern, leading to the formation of the Forest Defence Group volunteer force, who work on wildfire prevention and suppression (Fernández-Blanco et al.

2022). Firefighting operations altered after 1998, when the Catalan Ministry of Interior formed a new taskforce for fighting forest fires, following a year of particularly severe fire events (Otero and Nielsen 2017). GRAF was initiated in 1999 as a sub-group within the Catalan Fire and Rescue Service (CFRS), and has been responsible

for wildfire events since, working alongside the broader CFRS when a wildfire ignites. Currently GRAF has around 80 members. The unit is increasingly irreplaceable as climate changes increases the length of the wildfire season in Catalonia alongside the number of high fire risk days (Loepfe et al. 2012). GRAF uses techniques such as the creation of Strategic Management Points to analyze landscapes and identify areas which could be used in fire management (Otero and Nielsen 2017; Oliveres et al. 2025). These areas include those which have been managed to reduce fuel load, through strategies such as prescribed burning, thinning or grazing, along with cultivated areas.

### Datasets

Three sources of data were used within this research: land cover maps from the Institut Cartogràfic i Geològic de Catalunya, wildfire perimeters from the Generalitat de Catalunya Department d'Interior and place-based knowledge from GRAF (Table 1).

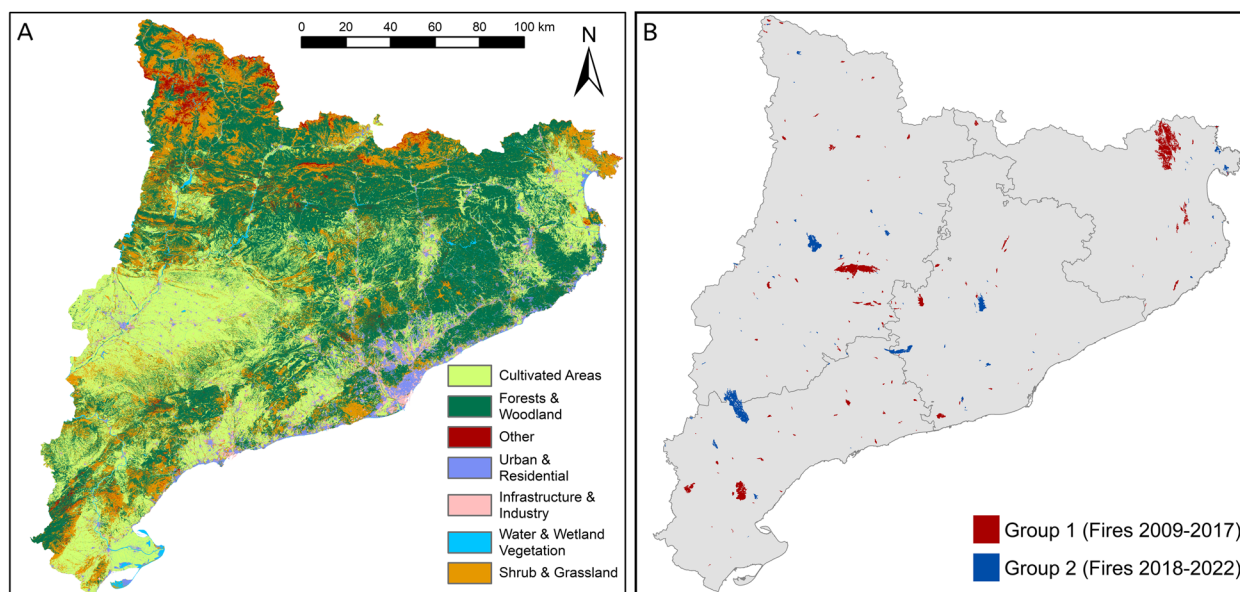
Land cover data was taken from the Institut Cartogràfic i Geològic de Catalunya (Institut Cartogràfic i Geològic de Catalunya 2023). The land cover was pre-classified at 1-m resolution, with 41 different land cover classes (Table S2). Land cover maps were available for 2009 and 2018 (Fig. S2) and were matched with wildfire events as explained below. The original 41 land cover classes (Appendix 2.1) were used in the wildfire analysis. To make the analysis more indicative of trends in overall land cover type, and to better summarize the findings, these were distilled into seven classes post analysis for both 2009 (Fig. 3A) and 2018 (Fig. S2): cultivated area, forests, infrastructure and industry, shrub and grassland, urban and residential, water and wetland vegetation and

“other” (which comprised of two classes; rocky outcrops and burned areas). The distillation of these 41 classes (Table S1) was undertaken according to the ecological characteristics of the land cover type (for example, all those described as ‘forest’ were placed into the category ‘forest and woodland’). This was determined using the accompanying technical specifications for the land cover maps (Generalitat de Catalunya 2016), alongside discussions across co-authors.

Fire perimeters were taken from the Generalitat Catalunya Department d'Interior, and are available from 1986 to 2022 (Generalitat de Catalunya 2023). The perimeters are collected by the government alongside the Institut Cartogràfic i Geològic de Catalunya for fires over 5 ha (Fig. 3B). Satellite imagery is used to observe transformations in the Normalized Difference Vegetation Index (NDVI), locating and measuring burned areas through reflectance changes (Generalitat de Catalunya 2023). As these perimeters use the most developed satellite data, the resolution of the perimeters improve as new satellite missions are launched (e.g., moving from Landsat 5 to Sentinel 2). Burned area extent assessment through remote sensing has a long history in scientific research (Kurbanov et al. 2022) and Sentinel-2 data has been useful for delineating fire perimeters in Mediterranean land cover (Llorens et al. 2021). While fire data was available from 1986 onwards, high resolution land cover data was only available from 2009 to 2018 at the time this manuscript was prepared. Thus, fires before 2009 could not be included as the land cover would not indicate vegetation burnt in the historical fires. We did not include fires below 10 ha, as it is expected that land cover and landscape features have less influence on fires which are suppressed at this small size (Rodrigues et al. 2020). Consequently, we conducted our analysis on the 222 fire

**Table 1** Three sources of data form the basis for this study. NA is used to indicate that temporal availability did not apply to the place-based knowledge in the context of this research

| Data type                           | Description  | Temporal availability | Reference   | Methodology for derivation  |
|-------------------------------------|--|-----------------------|---|---|
| Land cover maps (Raster)            | Land cover across Catalonia at 1 m resolution                                    | 2009 and 2018         | Institut Cartogràfic i Geològic de Catalunya, 2023. Accessible at: <a href="https://www.icgc.cat/en/Sustainable-territory/Land-cover">https://www.icgc.cat/en/Sustainable-territory/Land-cover</a>  | Photointerpretation of relevant orthophotos   |
| Wildfire perimeters (Shapefile)     | Perimeters of wildfires in Catalonia over 10 ha in size                          | 2009—2022             | Generalitat de Catalunya 2023, accessible at: <a href="https://agricultura.gencat.cat/ca/serveis/cartografia-sig/bases-cartografiques/boscoss/incendis-forestals/">https://agricultura.gencat.cat/ca/serveis/cartografia-sig/bases-cartografiques/boscoss/incendis-forestals/</a> | Processing of satellite imagery using NDVI transformation and principal component analysis, followed by digital classification of pixels corresponding to the burned area |
| Place-based knowledge (Qualitative) | Interpretation of results from a wildfire suppression and management perspective | NA                    | GRAF, subgroup of CFRS  | Lead author joined GRAF for a period of 4 months, conducting informal interviews and discussions surrounding the research topic   |



**Fig. 3** **A** Example of distilled land cover map used from 2009. Source: Cartogràfic i Geològic de Catalunya. **B** Wildfires > 5 ha, from 2009 to 2022, split by age in order to pair with appropriate land cover dataset. Source: Generalitat Catalunya Department d'Interior

perimeters over 10 ha in the dataset from 2009 to 2022, to ensure that the land cover data was indicative of pixels present before the fires occurred. The fires were then split into two groups, to use with the appropriate land cover dataset.

- Group 1:  $n = 139$  fires, 2009–2017 (land cover year 2009)
- Group 2:  $n = 83$  fires, 2018–2022 (land cover year 2018)

Qualitative data was gathered in the form of place-based information, collected through a close collaboration with the Catalan Fire and Rescue Service. The first author worked embedded in the GRAF team, shaping the research design, analyzing and interpreting the data jointly, alongside joining the team to prescribed fires, wildfires and training events. Place-based knowledge from GRAF was gathered to understand current strategies surrounding suppression of wildfires, alongside present and future challenges facing the team. The place-based knowledge was utilized for results interpretation and discussion. There is a wide diversity of agencies and stakeholders active in fire management in Catalonia and working directly with GRAF offered meaningful opportunities to link our findings to their work within wildfire suppression.

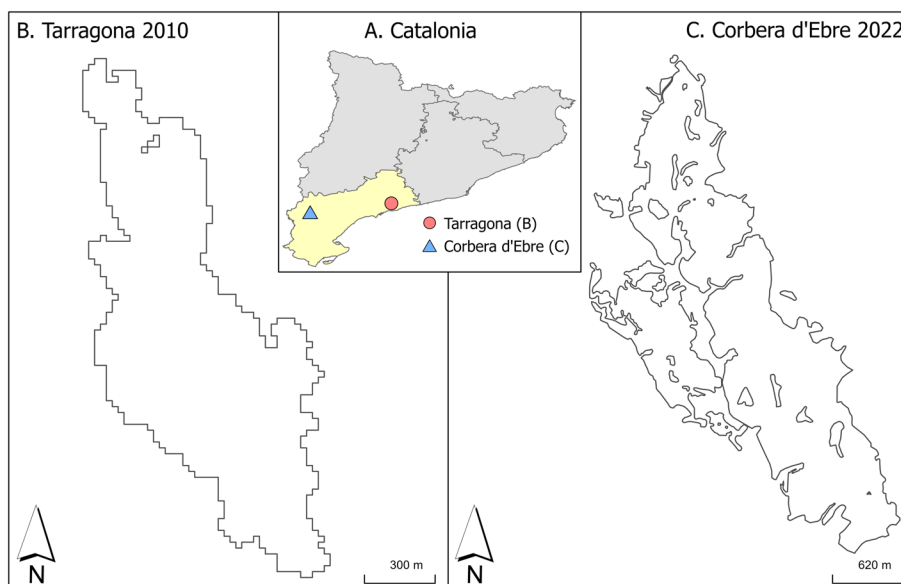
#### Interactions between wildfire events and land cover

##### *GIS analysis of fire edges, interiors and refugia*

Alongside splitting the fires by year of ignition, we also divided the fires according to size. We split the fires

between 10 and 50 ha, 50–200 ha, and fires over 200 ha, as shown in the Table S1. The fires were separated by size to allow for appropriately sized buffers within the analysis of the fire edge. Buffer zones were used to analyze the fire edge due to the potential inaccuracy of recording the initial fire perimeters (Parks et al. 2015). This inaccuracy is likely to be higher in the older fires within group 1 (2009–2017), particularly in the years before the launch of Sentinel 2 in 2015. An example of the difference between perimeter recordings is shown in Fig. 4. This figure indicates how the detail surrounding the fire perimeter has improved over time, further reaffirming the use of buffers to account for potential inaccuracies.

Buffers are utilized across similar research focusing on interactions between wildfire perimeters and other landscape characteristics (Teske et al. 2012; Parks et al. 2015; Yocom et al. 2019). We split the fires into three groups to ensure the buffer area remained proportional to the fire size. Smaller fires require a smaller buffer to ensure the analysis was constrained to the fire edge, rather than including the majority of the interior. This smaller buffer then covered proportionally little of the larger fires, which can also contain more inaccuracies in their recording. From explorative analysis and previous literature (Yocom et al. 2019), we used a buffer of 200 m (100 m inside, 100 m outside) for fires over 200 ha, a buffer of 60 m (30 m inside, 30 m outside) for fires between 50 and 200 ha, and a buffer of 30 m (15 m inside, 15 m outside) for fires 10–50 ha. We used the buffer inside and outside the fire, as inaccuracy in perimeter collection can



**Fig. 4** Two example fires: **B** Tarragona in 2010 and **C** Corbera d'Ebre in 2022, both situated within Tarragona province **A**, indicating how the level of detail of the wildfire perimeter recording has improved the resolution of the perimeter over time

occur in both directions. To create the buffer, the wildfire polygon was first filled using “eliminate polygon part,” an ArcGIS Pro tool which removed the fire refugia from each wildfire polygon. This ensured that only the outside boundary edge of the fire polygon was buffered, rather than including internal boundaries from the refugia.

Once the buffers were created, a custom python-based script using PyCharm Version 2021.3.1 extracted pixel count per land cover type for each fire buffer zone. The use of PyCharm means that this methodology could be easily transferred to another geographical area for future research, and on any scale, provided the right datasets are available. We made our script available within a public access data repository (see the “Data availability” statement) for this purpose. We used the buffer zones to examine the presence of landscape features around the fire edge, focusing on canals, ponds, lakes and lagoons, watercourses and roads, relevant landscape features identified in previous studies (Brzuszek et al. 2010; Narayanaraj and Wimberly 2011; Yocom et al. 2019).

Land cover within fire interiors was also extracted using the PyCharm script. The original fire polygons, prior to the use of polygon part were used, ensuring fire refugia were not counted as burnt area. The PyCharm script masked the area around the fire polygon and extracted pixels that were only within the perimeter boundary. Subsequently, land cover in the refugia was determined by subtracting the original fire polygon from the polygon which had been filled for the buffer analysis.

#### **Interactions between burn patterns and land cover**

Once the land cover pixels had been extracted for each element of the fire (fire edge and landscape features, interior and refugia) these were grouped together to produce overall values and compared against the average land cover values per class from the relevant year, either 2009 or 2018 (RQ2). These average land cover values were used as a control, to indicate the degree to which land covers are present within the different areas of the fire when compared to an average.

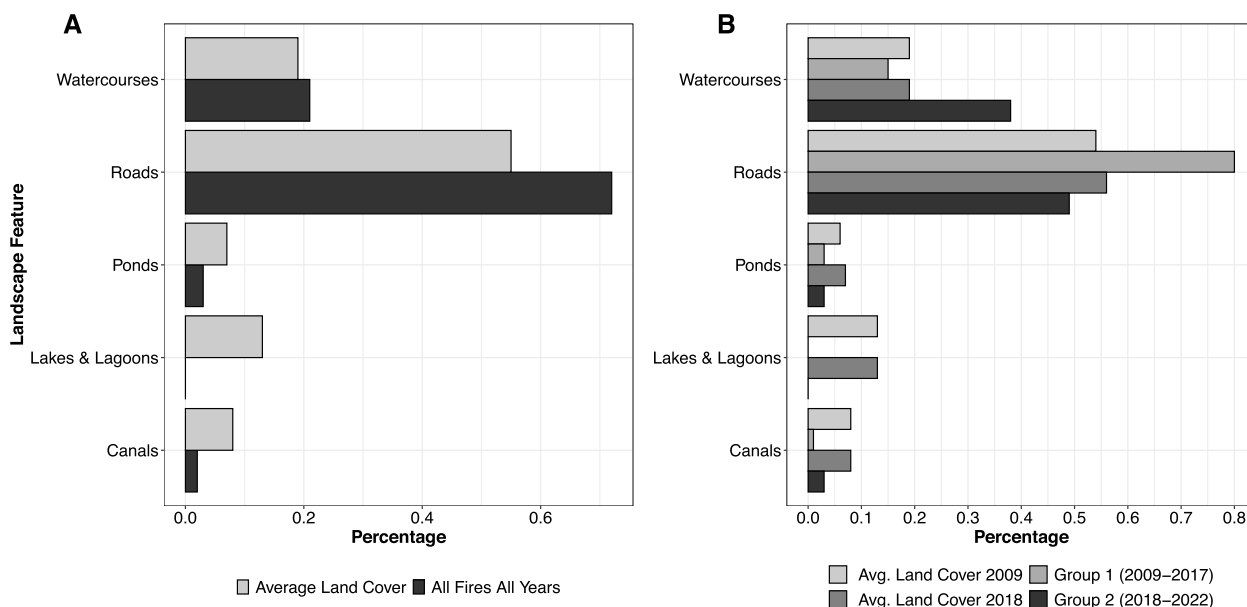
Post-fire land cover transitions (RQ3) were assessed by using both the 2009 and 2018 land cover datasets. Fires that occurred between 2009 and 2017 (Group 1–139 fires) were used in this analysis, by comparing land cover values in these fire polygons, firstly in 2009 and secondly in 2018. The difference between the land cover values in these years indicates the extent of changes in post-fire landscapes.

Finally, we combined the results of RQ1, 2, and 3, along with the place-based knowledge gained from interactions with the fire service and the integration of relevant literature, to evaluate Catalonia’s status as a fire resilient landscape.

## **Results**

### **Influence of landscape features on fire edges**

Overall, roads are one of two landscape features present more often in fire edges (0.72%) than on average (0.55%) within Catalonia (Fig. 5A). Broken down by group (4b),



**Fig. 5** **A** The percentage of landscape features averaged from both groups of wildfires along with the average from both land cover years, indicating the significant landscape features around the fire edges are roads and watercourses. **B** The percentage of pixels classified as each landscape feature in each group of wildfires aligned with their respective land cover year, showing roads are only significant in group 1 and watercourses in group 2 fires

roads are noticeable in older fires (2009–2017, 0.8%) but this effect is not visible in more recent fires (2018–2022, 0.49%). Watercourses are also slightly more present around the fire edge (0.21%) than on average in the landscape (0.19%). When broken down by group (5b), watercourses are present much more often in the recent fires (2018–2022), than older fires. The other landscape features (ponds, lakes and lagoons, and canals) are not present more around the wildfire edge than within the average land cover.

**Land cover-wildfire interactions**

Moving from landscape features to land cover, “cultivated areas” were more common in the fire refugia (49%) and fire edges (33%), when compared to the interior of the fires (25%) and average land cover (29%) (Fig. 6). Conversely, “shrub and grassland” was more prominent in the fire interior (31%), at just over twice the percentage present in the average land cover (14.5%). “Shrub and grassland” was also more common in the fire edges (24%), than on average, but fire refugia values lay close to average (12%). The class “forests and woodlands” was found at the highest levels within the fire interiors (40%) and fire edges (38%), but both were lower than the average land cover percentage (47%), with fire refugia (32%) being lower than all other fire contexts and average land cover.

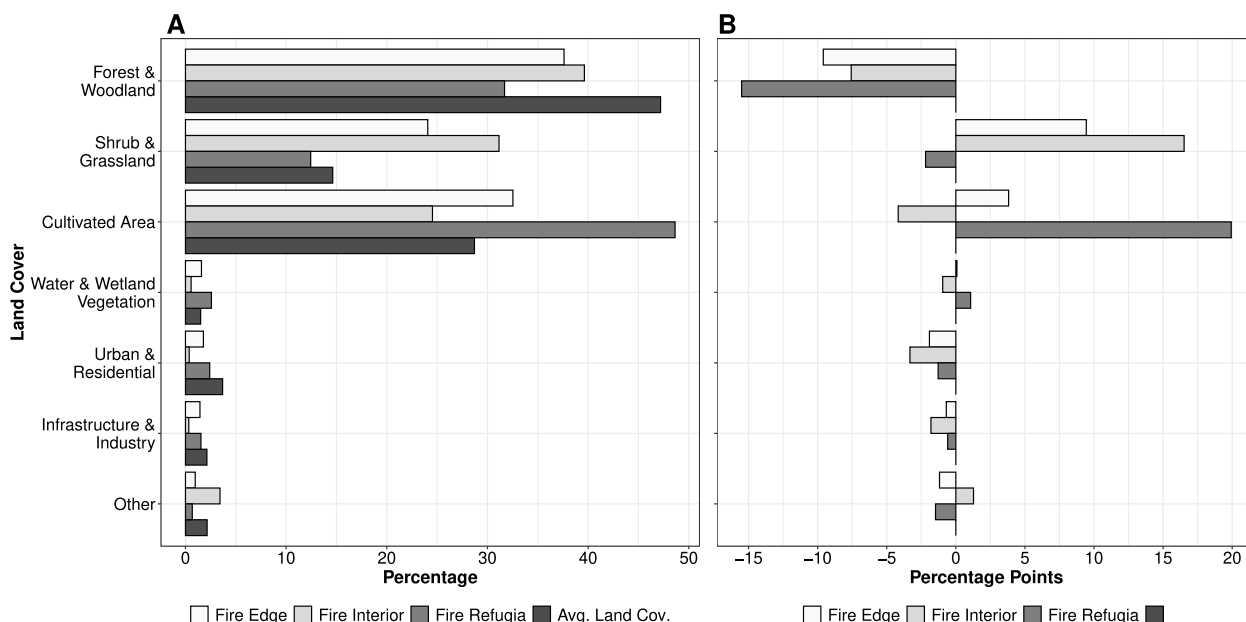
Within the classes “urban and residential,” “water and wetland vegetation,” “infrastructure and industry,” and

“other” (comprising of rocky outcrops and burnt area) the values remained low (< 4%) in all wildfire contexts. However, all aforementioned classes, except for “other,” were proportionally much lower in the fire interior (< 1%) than in the other areas of the fire and within the average land cover.

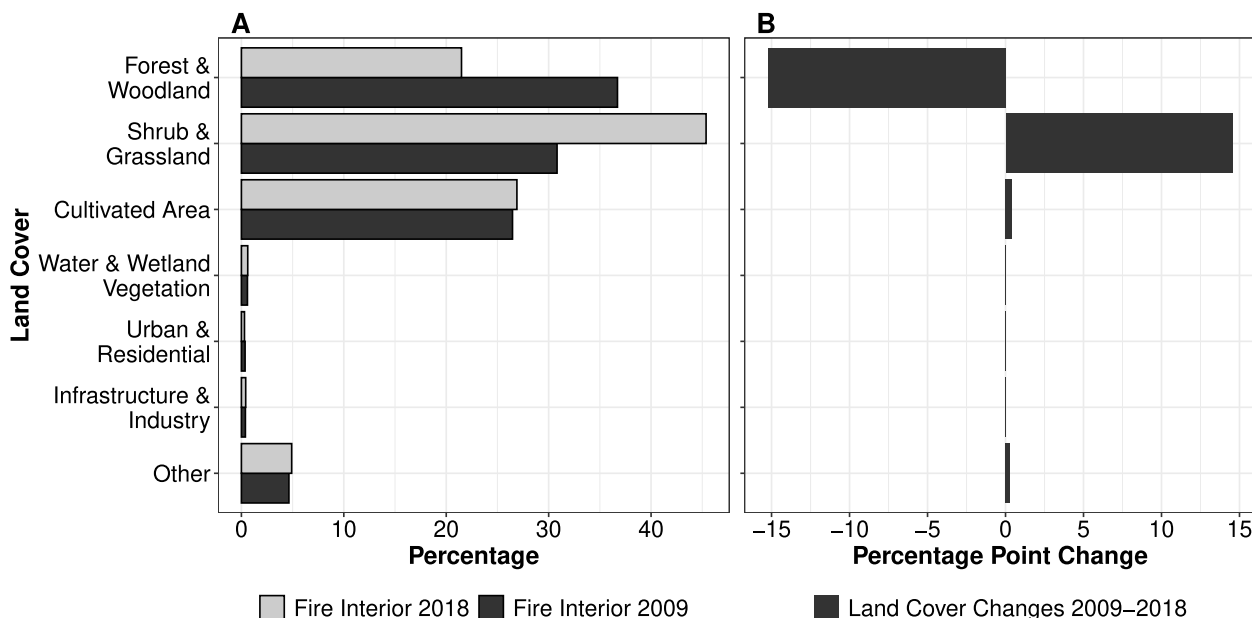
Analysis of post-fire land cover transitions show a sizeable decrease in forest and woodland cover within the burned areas, alongside a large increase in shrub and grassland cover (Fig. 7). Post fire (2018), forest and woodland pixels decreased by 15% when compared to pre-fire values in 2009 (Fig. 7A). Consequently only 22% of pixels in these burned areas were classified as forest and woodland in 2018, much less than the average value (47%). Concurrently, there was a 14.5% increase in shrub and grassland within fire affected areas, when comparing post-fire 2018 values to those pre-fire (2009), increasing the extent of shrub and grassland from 30 to 45% within these burned areas (Fig. 7B). Cultivated areas saw a very small increase of 0.4%, and the class ‘other’ also marginally increased by 0.3%. The three remaining classes experienced no change.

**Place-based knowledge from GRAF (CFRS)**

When working alongside the GRAF members and throughout the preparation of this manuscript, many meaningful discussions were held surrounding past, present and future wildfire events in Catalonia. GRAF fire



**Fig. 6** **A** Extent of different land cover types for each element of the studied wildfires, alongside the average land cover, indicating high values of shrub and forested areas in the fire interior and of cultivated areas in the fire edge and fire refugia. Values are in percentages to allow for proportional comparison. **B** The deviation from average for each type of land cover and element of the wildfire in percentage points



**Fig. 7** **A** Land cover values for the fire interiors in 2009 and 2018, and **B** the percentage point change for each class as a proportion of the landscape

crew members highlighted a continuing struggle with changing fire behavior alongside shifting fuel and meteorological conditions. The lengthening of the wildfire season, with more fires being observed in early spring in addition to traditional summer months, is also a cause for concern. Resources become stretched year-round,

and there is less time for prevention and training activities. GRAF members highlight that more resources alone (e.g., firefighters, aerial attack planes, helicopters) are likely not the answer, instead focusing on the need for more proactive strategies around managing fuel loads and creating more resilient landscapes. Fire will always be in

Catalonia's landscapes, and many ecosystems in this area need fire to survive. From the perspective of GRAF, the concentration should be on ensuring there is effective landscape management to give firefighters a chance to manage the fire in a way which prevents significant losses. Without opportunities such as breaks in highly hazardous landscapes, more suppression resources are unlikely to make an impact on Catalonia's current wildfire problem.

Organizing landscape management on this scale is outside the sole jurisdiction of GRAF and the CFRS. While the fire service performs prescribed burns in strategic locations in low-risk months, these are primarily training exercises for firefighters. The fire service cannot, and should not, be responsible for fuel management across the entirety of Catalonia, particularly due to the high level of private ownership in Catalonia's forested lands. The distinct changes in landscape composition, e.g., increases in unmanaged young forest stands and shrublands alongside decreases in agricultural areas, across Catalonia, is recognized by GRAF to be compounding the challenge. Looking to the future, there are concerns across the fire service about the high fuel build up, the vulnerability of the rural–urban interface and continuing climate change.

## Discussion

In this section, the obtained results are interpreted utilizing place-based knowledge from GRAF, the entity responsible for landscape fire suppression in Catalonia. We interweave this knowledge with our quantitative analysis to explore the relationship between contemporary wildfire events, land cover and fire suppression. We provide explanations for the surprisingly inconsistent presence of roads and other landscape features along the wildfire perimeter. Additionally, through the lens of wildfire suppression strategies, we explore the degree to which different land covers burn: the propensity for shrub, grass and forested lands in fire interiors, and the relative abundance of cultivated land in the fire refugia and fire edges. Finally, we frame our results within the theory of fire resilient landscapes (Newman Thacker et al. 2023), and summarize potential actions for increasing Catalonia's resilience to wildfire events.

### Interactions between landscape features and wildfire edges

Landscape features can be important assets for fire suppression forces. In this study, roads were present more within the buffer zone around wildfire edges than on average within Catalonia (Fig. 5A), supporting previous evidence that roads can influence fire cessation (Narayanaraj and Wimberly 2011; Yocom et al. 2019). Firefighting teams can use roads strategically, to place vehicles and supporting operations (Zhang et al. 2020). When using tactical fire, roads can be used as an anchor

point or a fuel break under the right conditions (Yocom et al. 2017; Thompson et al. 2021). In Catalonia, roads are viewed by firefighters an opportunity, due to their potential to influence fire behavior, but they are not a necessity. Roads can offer safe spaces to work the fire (Thompson et al. 2021), where the fire can lower in intensity and access is clearer, but GRAF will also move to the flanks of the fire through vegetated spaces.

Alongside being strategically relevant when fighting a fire, roads are invaluable for the initial approach to the fire (Zhang et al. 2020). In areas of Catalonia where access points are sparse, the location of a road in proximity to the wildfire increases in importance. Fires which are hard to reach can have more opportunity to spread before suppression forces gain access, as also found by Moreira et al. (2010) in Portugal. Nonetheless, within the more recent fires (2018–2022), roads appeared less in the fire edge buffers than on average for the overall land cover (Fig. 5A). While this result may be because of the increasing accuracy of the perimeter gathering in later years (Fig. 4), the use of the buffers within the methodology was designed to mitigate these disparities. Another factor explaining the inconsistent presence of roads within the more recent fire edges (2018–2022) is that roads are not the predominant determining factor for CFRS and GRAF when carrying out fire suppression. Internal discussions with GRAF members corroborates these findings—roads are an opportunity to work the fire but other land cover types can also offer spaces for suppression. This conclusion indicates the importance of conducting research on a regional level, and the added value of results interpretation with the relevant fire service.

Roads were the most influential landscape feature within fire edges, despite previous research indicating that watercourses are often significantly influential (Brzuszek et al. 2010; Fisher et al. 2022). In our results, watercourses, classified in this research as rivers and streams, are only slightly more prevalent in fire edges compared to average land cover (Fig. 5A). This relationship is only present in more recent fires (Fig. 5B). Previous studies on this topic (Brzuszek et al. 2010; Fisher et al. 2022), were conducted in Florida and Australia (tropical savanna) respectively, where waterbodies are more permanent fixtures. Comparatively, watercourses form a small element of Catalonia's overall land cover (under 0.2%, Fig. 5A). Watercourses are also often diminished in summer months, peak wildfire season, due to lack of precipitation or drought (Momb Blanch et al. 2015; Jorda-Capdevila et al. 2016). The inconsistency of watercourses in the fire perimeter in our results can be explained to some extent by environmental controls and the location of Catalonia within a Mediterranean, seasonally dry, climate. Other water-based landscape features (canals, ponds

and lakes/lagoons) were less abundant in fire perimeters than on average across Catalonia's landscape. The same reasoning of drought effects could apply here, and even more so considering ponds are often small and water levels low within the fire season.

Summarily, the stopping influence of roads and watercourses, when regarding the studied fires, is not consistent over the two time periods studied. Combined with the lack of influence of other landscape features studied (canals, ponds, and lakes/lagoons), results show the overall influence of such features on wildfire cessation in the studied context to be small (Fig. 5A). Consequently, there is a disparity between the results obtained in this research and those in other geographical locations, e.g., the USA (Narayanaraj and Wimberly 2011). This further reiterates the importance of conducting regional level research and the relevance of considering the role of differing fire suppression techniques.

## Land cover controls

### *Cultivated areas*

Cultivated areas showed a clear influence over fire spread in our results. This land cover class had an increased presence within the fire edge and fire refugia, compared with the interior of the fire and the overall average land cover (Fig. 6). These results support previous literature indicating that agricultural areas are less likely to burn than other vegetated land covers (Nunes et al. 2005; Moreira et al. 2009, 2011) and offers evidence that this relationship is also present in Catalonia. The place-based knowledge described in the section "[Land cover-wildfire interactions](#)" is used throughout this following section to help understand this relationship from a fire suppression perspective. GRAF and CFRS view cultivated areas similar to roads: as an area where fire behavior becomes less intense and fire management can be more successful. Cultivated areas also offer the opportunity to tackle fire events with fewer resources. Within GRAF's experiences, fires are less likely to reignite within croplands, negating the need to always check for reignitions. As fires can decrease in intensity within these areas (Aquilué et al. 2020), less personnel are needed to contain the fire. Due to the increased potential for simultaneous wildfire events, the availability of resources has become a critical component of successful wildfire campaigns (Xifré-Salvadó et al. 2020; Oliveres et al. 2025). In the summer of 2022, lightning strikes initiated 22 fires simultaneously over a period of 8 days across Catalonia (Pineda et al. 2024). In this situation, it is imperative to manage each fire with as few resources as possible, to ensure the availability of a crew for further potential fires. While not the sole factor in ensuring the success of each containment strategy, in this example, the fire service's ability to

capitalize on the cultivated areas present contributed to the avoidance of a collapse of the fire service.

Nonetheless, cultivated areas are only useful for fire suppression relative to the fire behavior and fire location, alongside the location of the cultivated area. Not all fires will be able to be contained in these areas, and not all cultivated areas will offer a safe opportunity for containment. For example, a wildfire modeling study by Aquilué et al., (2020) suggests that the benefits of agricultural land in fire management are greatest when they are scattered, rather than aggregated, supporting the idea that their influence is not spatially equal. Despite this, from the given results (Fig. 6), the incorporation of wildfire suppression strategies and referenced literature, they are evidently still a vital asset in the suppression toolbox.

### *Forest and woodland*

Moving from land covers that burn least to those that burn most, the highest percentage of pixels within the fire interior and the fire edge were from the class "forests & woodlands" (Fig. 6). This is as expected, given that forest and woodlands comprise the most present land cover class on average (47%). Furthermore, with the observed landscape changes (land abandonment, rural-urban migration and increasing challenges for rural economies), forests in Catalonia can be a high wildfire risk (Moreira et al. 2011; Lecina-Diaz et al. 2021; Wunder et al. 2021). Ownership of forested lands is highly fragmented and privatized, providing challenges in their management on a significant scale (Gonzalez-Olabarria et al. 2019). This contributes to many of Catalonia's forests being high density, young forested plots with high homogeneity and a low ecological state (Cervera et al. 2019). Our finding that forest and woodland is highly prevalent within the fire interior accentuates that this land cover type is susceptible to wildfire, contributing to fire spread as indicated across previous research (Lloret et al. 2002; Loepfe et al. 2010, 2012).

The fire suppression techniques and prioritization of assets by CFRS and GRAF can be used to explore the high presence of forest and woodland pixels around the fire edge and within the fire interior (Fig. 6). In low to medium intensity fires, firefighters can use forested areas as a strategic area for suppression forces, slowing or stopping the fire, contributing to their prevalence in the fire edge. Under some scenarios, wildfires in Catalonia will slow down as they reach forested areas, depending on the vegetation structures, maturity of the woodland (Kitzberger et al. 2012) and the propensity for crown fire. GRAF will also try to protect forests from the fire over other vegetation types such as shrubland. Forests take significantly longer to regenerate than shrublands (Eugenio et al. 2006; Capitanio

and Carcaillet 2008), and may be eliminated after a fire if seed dispersal and germination fails (Retana et al. 2002; Eugenio et al. 2006). Forests also contribute to Catalonia's biodiversity (Torrás et al. 2012), bioeconomy (Verkerk et al. 2018) and carbon storage (Peñuelas et al. 2021). While forest and woodland pose a high fire risk, they are important to maintain in the landscape for such benefits (biodiversity and bioeconomy). While acknowledging that these benefits exist within such land cover, it is important to note that the mismanagement, or lack of management, in Catalonia's forests are a contributor to recent large wildfire events (Alcasena et al. 2018; Cervera et al. 2019).

Here, the potential limitations of using satellite imagery to examine wildfire events should be noted. As indicated by Gale and Cary (2022), detecting burnt pixels within forested areas has limitations, particularly when the forest is dense and over 3 m in height. Understory fires in such forests can be missed by satellites if the canopy is dense and unburnt. It is possible in this research that the extent of burnt area may be underestimated within the forest and woodland. For example, a fire may have been recorded as having stopped within or at a forest boundary, when it may have continued as a surface fire underneath the tree canopy. Nonetheless, the use of the buffer-based methodology described in the section *GIS analysis of fire edges, interiors and refugia* was designed to reduce the impact of such limitations. In addition, forest and woodland was already the predominant land cover in the fire interiors and edges. Any increase in this land cover type being burned due to undetected understory burns would therefore only strengthen the main finding that forest and woodland predominantly burns in Catalonia.

### **Shrub and grassland**

Shrub and grasslands are present more within fire interiors (31%) when compared proportionally to the overall average land cover in Catalonia (14.5%) (Fig. 6), indicating the propensity of this land cover in influencing fire spread. The extensive presence of shrub and grassland pixels in the fire interior, and to a lesser extent the fire edge, when compared to average land cover, has also found by Moreira et al., (2009) and Oliveira et al., (2014) in Mediterranean landscapes. From GRAF's perspective, the fire service typically views shrub and grasslands the least valuable vegetation, in terms of bioeconomy and biodiversity, and so suppression efforts are rarely concentrated in these areas (Lloret et al. 2002; Moreira et al. 2011). Shrubland can also burn faster than forested areas due to the fuel types' characteristics (Salis et al. 2016). Therefore, they do not offer ideal land cover for suppression forces. Shrub and grassland features much less

in the fire refugia (Fig. 6). This result can be attributed to the reduced stopping power of shrub and grasslands. A fire burning through shrub and grasslands is likely to have fewer barriers to prevent further spread, in comparison to cultivated land (the most prevalent land cover in fire refugia). In cultivated land, horizontal connectivity of fuels may be limited and the presence of suppression forces is more likely, due to GRAF's strategic use of this land cover.

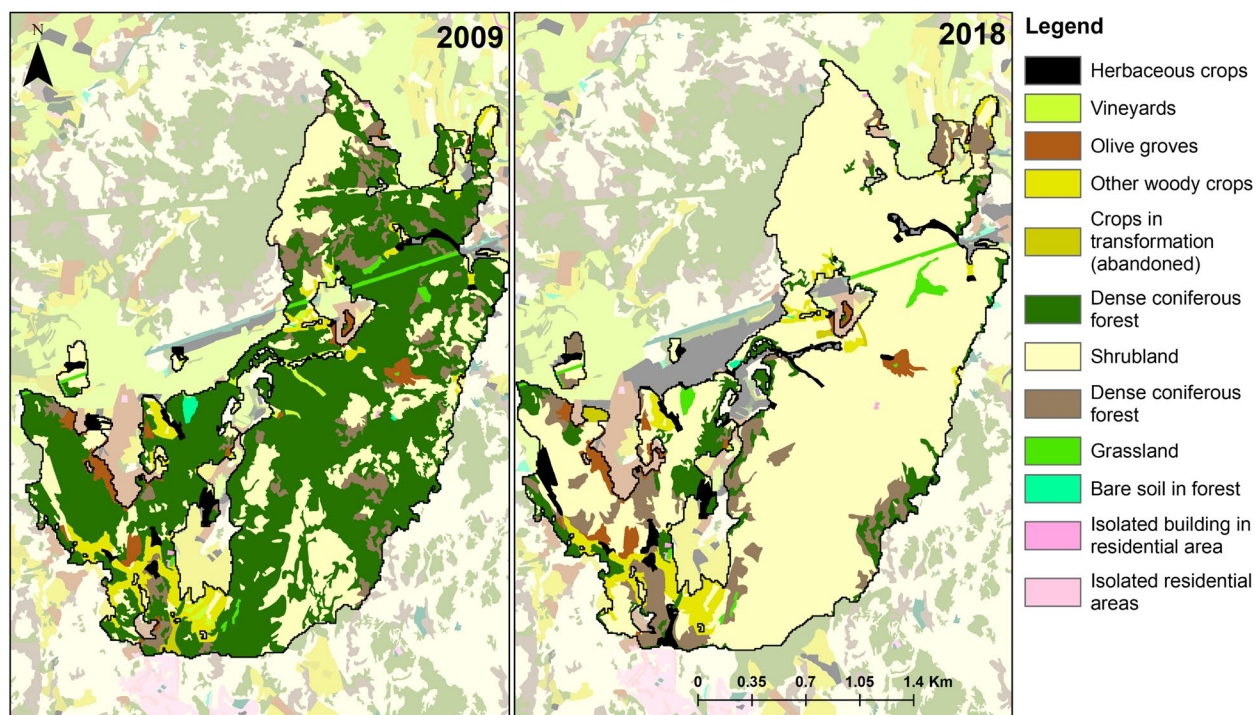
### **Non-vegetated land cover and the influence of fire suppression strategies**

Non-vegetative land classifications feature little in the interior of the fires studied in this research. The land cover classes "urban and residential" and "infrastructure and industry" occur much less within the fire interior, compared to the fire edge and refugia, alongside average land cover. CFRS have a duty to protect infrastructure and assets including residential areas, as second in priority to human life, and higher in priority to the natural environment (Castellnou et al. 2019), priorities that are mirrored in other wildland firefighting forces across the world (Ruby et al. 2023). Therefore, it is predominantly the case that protecting urban or industrial land covers will be a primary concern when a fire occurs nearby. With this aim in mind, it is understandable, and commendable, that these land cover types form a low proportion of fire interiors.

### **Landscapes in transition**

Our results provide evidence for land cover transitions in the wildfire affected areas from 2009–2017 (Fig. 7). An example of this land cover transformation is included in this research, using the 'La Pobla de Montornès' fire in 2016 (Fig. 8). Comparing pre and post-fire land cover maps shows that a distinct reduction in forest and increase in shrubland has occurred in this area.

The main transition (conversion of forest and woodland to shrubland) observed is well supported in previous literature investigating vegetation succession pathways post fire (Retana et al. 2002; De Luis et al. 2006; Eugenio et al. 2006). Our results offer further, contemporary empirical evidence for this transition within Catalonia. After a wildfire, the replacement shrubland is slowly outcompeted by fire resilient tree species such as *Pinus Halepensis*, with time restoring the landscape to its pre-fire composition (Capitanio and Carcaillet 2008). However, the near-term transition to shrubland increases the risk of more frequent wildfires, due to their horizontal continuity and expansive cover (Retana et al. 2002). Shrubland can also act as 'connectors' between forested areas, driving wildfire spread at high intensity (Sá et al. 2022).



**Fig. 8** Land cover in the area of the La Pobla de Montornès' fire (black outline) in 2009 and 2018. The fire occurred in 2016, and a clear reduction in forest with replacement by shrubland can be observed from between the two land cover years

The post-fire transition of forest to shrubland deduced in this research emphasizes the vulnerability of forested landscapes in the immediate years after a fire, such as in Fig. 7, before the trees have begun to mature (Cervera et al. 2019; Francos et al. 2020). Shrubland presence increases wildfire risk in Mediterranean regions (Ganteaume et al. 2021) and can increase the propensity for further fires, shortening fire return intervals. Shortened fire return intervals interrupts the recovery of species, even those classed as “fire resilient” (Díaz-Delgado et al. 2002; Eugenio and Lloret 2004; Cervera et al. 2019). This is of consequence considering Catalonia's changing fire regime, with fires of higher frequency, severity and size occurring, driven by a multitude of factors including climate change (Eugenio et al. 2006; Oliveras et al. 2009; Wunder et al. 2021). Many of the coniferous tree species present in Catalonia (*P. halepensis*, *P. nigra*, and *P. sylvestris*) are resilient up to a point (Eugenio and Lloret 2004; Eugenio et al. 2006). Nonetheless, recurrent wildfire events can cause seed banks to become irrevocably damaged (Eugenio et al. 2006). Shrubland will then become further entrenched, inviting further fire and leading to a vicious cycle whereby Catalonia's forests cannot recover, impacting overall landscape resilience.

The results summarized in this discussion further emphasizes the value in exploring the relationship between land cover and wildfire events through the

lens of fire suppression. Documenting the relationship between the natural landscape and decisions taken by GRAF offered an important dissemination opportunity surrounding the strategic use of land cover variables within fire suppression. This is likely to be particularly useful for countries where fire is an emerging risk, and knowledge of wildfire spread behavior is less established.

#### Catalonia as a fire resilient landscape

In this section, we synthesize our quantitative analysis of wildfire interactions with land cover alongside the place-based knowledge gained from working directly with GRAF. We frame these findings in the context of Catalonia as a fire resilient landscape as outlined in Newman Thacker et al., (2023). Firstly, the predominantly insignificant role of landscape features in stopping fires in Catalonia provides insights into the resilience of Catalonia—particularly its wildland fire suppression force. While this relationship is only one indicator of a well-trained and successful firefighting team, the fire service does not have to rely heavily on the placement of landscape features is advantageous, particularly in situations this reliance could lead to difficult or dangerous outcomes. The presence of a well-trained, adaptable and flexible fighting force is an important aspect of a fire resilient landscape (Newman Thacker et al. 2023). Nonetheless, relying on fire suppression alone has been proven

to be counter-productive in creating resilient landscapes (Castellnou et al. 2019; Kreider et al. 2024). Trained suppression forces are one element of resilient landscapes, which are most effective in conjunction with other environmental and social landscape components (Newman Thacker et al. 2023).

When using these research results to evaluate Catalonia as a fire resilient landscape, it is vital to consider landscape management (Riva et al. 2016; Newman Thacker et al. 2023). In this study, shrub, grass and forested lands are the most prominent vegetation types within wildfire interiors, and cultivated lands are more influential around the fire edge and within fire refugia (Fig. 6). The increase in these land cover types over the past decade is well documented, linked to large-scale land abandonment (Moreira et al. 2011; Cervera et al. 2019). The restoration of cultivated areas in strategic places (Aquilué et al. 2020), alongside mosaic landscapes (Cervera et al. 2019), can bolster the resilience of the landscape to wildfire events. Cultivated areas offer safer suppression spaces, lowering fire intensity and providing resources through land managers and farmers. Various management strategies such as grazing (Domenech & Soy 2013), prescribed burning (Alcasena et al. 2018; Duane et al. 2019) and mechanical thinning (Piqué and Domènech 2018) can be introduced to maintain or increase mosaic landscapes, including within particular vegetation types. For example, these strategies have been utilized to improve the quality of Catalonia's many forested areas (Torrás et al. 2012). Encouraging higher quality forested plots decreases these areas vulnerability to stand replacing fires (González et al. 2007) and reduces the shrubland encroachment indicated in the post fire-transformations (Figs. 6 and 7) (Moreira et al. 2011).

Social systems are important for the success of landscape management, and are inherently linked to these environmental processes (Moritz et al. 2014; Spies et al. 2014; Ager et al. 2015; Uyttewaal et al. 2023). Community engagement is also an integral element of fire resilient landscapes (Newman Thacker et al. 2023). While our analysis does not examine social processes explicitly, land cover interactions with wildfire in the Mediterranean are usually linked to anthropogenic mechanisms as indicated by Moreira et al. (2011). It is not possible to sustain agricultural processes, or widespread landscape management strategies in rural areas, without supporting communities and rural economies (Wunder et al. 2021). A significant issue facing forest management is the high levels of private landholders (Rodríguez-Carreras et al. 2020) who own small, fragmented plots (Otero et al. 2015), which are often then abandoned. The young forest stands which form part of these abandoned land have low value within timber or bioeconomy sectors (Cohen et al. 2011). These

areas are highly flammable (Cervera et al. 2019), contributing to the high levels of forested areas recorded in the interior of the studied fires (Fig. 5). Therefore, investment into rural economies is a strategy that could have significant positive repercussions for landscape wildfire resilience (Wunder et al. 2021).

The exploration outlined in this manuscript surrounding Catalonia as a fire resilient landscape, through the lens of land cover-wildfire interactions, was made possible by open access data of a high spatial and temporal resolution. The methodology is also designed to be reproducible for other regions. Looking further across Europe, currently the application of this methodology is limited by the availability of comparable data sources concerning accurately derived wildfire perimeters, particularly within temperate Europe (Belcher et al. 2021; Stoof et al. 2024). This is particularly pertinent when considering the projected increase in fire danger in such regions, under global climatic changes (Belcher et al. 2021; Galizia et al. 2023; Lambrechts et al. 2024) and the need to increase understanding of wildfire-land cover interactions in emerging risk regions. Addressing the disparity surrounding wildfire data provisions in Europe could thus increase the geographic scope of this methodology and facilitate its application outside of Catalonia.

In summary, this research approach in Catalonia offers novel insights into the relationship between land cover, wildfire events and the strategies of GRAF. We placed these outcomes within the framework of (Newman Thacker et al. 2023) to evaluate fire resilience. Results indicate that several aspects of Catalonia's landscape can be considered resilient—many native species are fire-adapted, and the presence of a proficient firefighting force can positively influence the outcome of wildfire events. When looking to discern how Catalonia's resilience to wildfire could be increased, our results indicate the need for more targeted vegetation management. Over 60% of Catalonia's landscape consisted of forest, shrub and grassland in 2018, but these land covers comprised over 70% of burnt pixels (Fig. 6). Increased fire frequency can decrease the ability of forest and woodlands to recover, and encourage the proliferation of highly flammable shrubland, with negative impacts for biodiversity, bioeconomy and carbon storage. To reduce the likelihood of extreme wildfire events and shortened fire return intervals, there is a need for concentrated management efforts surrounding these land cover types, alongside engaging with local communities about wildfire risk. Combining these actions, alongside the continued work of GRAF and other relevant actors, is likely to have positive implications for the resilience of Catalonia to future wildfire events.

## Conclusions

This study investigates the interactions between land cover, landscape features and recent wildfire events in Catalonia. The results indicate that most of the landscape features analyzed are not present significantly more around the fire edge when compared to average, with the exception of roads and watercourses to a small extent. When expanding the analysis to examine overall land cover around the fire edge, forest and woodland was the most prominent land cover type, followed by cultivated areas. There was also a prominence of forest and woodland within the fire interior, along with shrub and grassland, with both classes combined contributing to over 70% of the burnt pixels. Conversely, fire refugia were most often cultivated land and forest/shrubland land covers are found in refugia less than on average. Thus, we summarize that forest, woodland, and shrub vegetation are most likely to be burnt, while cultivated areas can provide refugia areas and strategic suppression points in the landscape. When looking at transitions in land cover post-fire, our results indicate that there is a short term trend towards the replacement of forest and woodland with shrub and grassland land cover. We identify this trend to be in line with vegetation succession pathways, but emphasize the higher vulnerability of the landscape after this transition has occurred. Finally, we combine these results to examine Catalonia as a wildfire resilient landscape, concluding further land management is needed to enhance resilience in this area, particularly in view of global environmental change.

## Abbreviations

|      |  |
|------|--|
| GIS  | Geographic Information System          |
| GRAF | Support Group of Forest Interventions  |
| CFRS | Catalan Fire and Rescue Service        |
| NDVI | Normalized Difference Vegetation Index |

## Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42408-025-00372-5>.

Supplementary Material 1: Table S1: Showing the distribution of fire perimeters between the two groups. Table S2: The original 41 classes of the land cover maps taken from Institut Cartogràfic i Geològic de Catalunya, and their distillation, resulting in 7 overall classes. Figure S2: Showing A) land cover in 2009 with original 41 classes and B) land cover in 2018 with original 41 classes and C) land cover in 2018 with distilled 7 classes. All maps are shown at the same scale.

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## Authors' contributions

FNT: conceptualization, methodology, investigation, writing, visualization. HM: methodology, writing. MRI: conceptualization, resources, writing. JLM: software, writing. CRS: conceptualization, methodology, writing, funding acquisition. All authors read and approved the final manuscript.

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## Data availability

Data will be made available on publication at Zenodo using the following DOI: <https://doi.org/10.5281/zenodo.15115415>

## 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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