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APLICACIÓN DE HERRAMIENTAS DE TELEDETECCIÓN MULTIESCALA PARA LA CARACTERIZACIÓN ESPACIAL DE INDICADORES Y CONDICIONANTES DEL IMPACTO ECOLÓGICO DE LOS INCENDIOS FORESTALES

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PhD Thesis

APPLICATION OF MULTI-SCALE REMOTE SENSING TOOLS FOR SPATIAL CHARACTERIZATION OF INDICATORS AND DRIVERS OF FIRE-INDUCED ECOLOGICAL IMPACT

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Doctorate program: Functional and Applied Ecology

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Application of multi-scale remote sensing tools for spatial characterization of indicators and drivers of fire-induced ecological impact

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Pictures on the PhD Thesis cover and back cover:

- Cover: Coniferous forest canopies affected by different burn severity categories (David Beltrán Marcos)

- Back cover: NASA Earth Observatory image of Navalacruz wildfire (central Spain, 2021) by Lauren Dauphin, using Landsat 8 OLI data from the U.S. Geological Survey.

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Application of multi-scale remote sensing tools for spatial characterization of indicators and drivers of fire-induced ecological impact

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“Science is never completely right, but it is rarely completely wrong and generally has a better chance of being right than non-scientific theories.”

"La ciencia nunca tiene toda la razón, pero rara vez se equivoca del todo y, por lo general, tiene más posibilidades de acertar que las teorías no científicas".

Bertrand Russell

“No one should believe himself perfect or worry too much about the fact that he is not.”

“Nadie debería creerse perfecto, ni preocuparse demasiado por el hecho de no serlo.”

Bertrand Russell

Dedicated to my mother and Lidia,

For teaching me to resist, and resisting with me.

Dedicado a mi madre y a Lidia,

Por enseñarme a resistir, y resistir conmigo.

TABLE OF CONTENTS

ABSTRACT

In recent decades, anthropogenic activity has caused remarkable changes in the fire regime attributes in the western Mediterranean Basin, mainly due to the loss of traditional land use derived from rural abandonment, climate change and the absence of adequate forest management strategies, leading to a dense and continuous accumulation of fire-prone biomass. The new fire regime, characterized by an increase in the frequency of extensive and severe wildfires, affects important ecosystem functions and services, with unprecedented impacts at socioeconomic level. This fact is particularly relevant in wildland urban interface (WUI) areas, where extreme wildfires represent a serious threat to human life and assets. In this context, spatial characterization of fire-induced impact, commonly referred to as burn severity, is crucial to provide scientific basis to design appropriated forest management strategies that enhance adaptive responses to current fire regimes. Field methods are considered highly trustworthy for assessing the impacts on vegetation and soils in burned landscapes, though they often lack spatial exhaustiveness to evaluate large wildfires. Therefore, remote sensing methods have emerged as reliable tools for monitoring and quantifying burn severity because of their cost-effectiveness and synoptic nature. In this context, the main objective of this PhD Thesis is the development of new multiscale remote sensing techniques aimed to identify spatial indicators of fire-induced ecological impacts and evaluate the drivers of extreme wildfire behavior under different fire regimes along an Iberian climatic gradient, with particular focus in WUIs due to their high socioeconomic vulnerability.

First, we aimed to improve the estimation of burn severity in forest soils, which are critical ecosystem compartments driving ecosystem functions and processes, by linking ecological indicators of burn severity with the spectral signal of very high spatial resolution remote sensing products obtained with unmanned aerial vehicles (UAV) (***Articles I & II***). Soil burn severity was assessed in the field 1-month after a wildfire through a Composite Burn Soil Index (CBSI) and, a set of individual indicators (ash depth, ash cover, fine debris cover, coarse debris cover and unstructured soil depth). Furthermore, indicative soil properties of fire-induced changes were analyzed: mean weight diameter (MWD), soil moisture content (SMC), and soil organic carbon (SOC). Simultaneously, post-fire multispectral images from the Sentinel-2A MSI satellite sensor, and RGB and multispectral images from a UAV survey were collected. We found that UAV multispectral products had a better performance than RGB products for estimating fire impacts on soils, being more related to integrative indices (ie., CBSI) than to individual indicators (***Article I***). Depth and ash cover were the most representative indicators of fire effects on soils. The inclusion of spatially and spectrally enhanced remote sensing data through novel remote sensing techniques, such as the fusion of Sentinel-2 and UAV images, significantly improved the prediction of fire-sensitive soil properties highly related to burn severity, mainly SOC (***Article II***). This approach provides a powerful tool for estimating fire impacts in complex and heterogeneous landscapes affected by mixed severity wildfires, and consequently to identify priority areas where post-fire restoration actions need to be implemented.

Once the potential ecological impact of high severity wildfires has been adequately characterized using new remote sensing techniques, we studied fire regime shifts conducive to extreme fire behavior along an Atlantic-Transition-Mediterranean climatic gradient in the Iberian Peninsula

(***Article III***), characterized by the occurrence of extreme wildfire events in the last few years. For this purpose, we analyzed (i) the variation patterns of temporal (recurrence and time since last fire) and magnitude (burn severity) fire regime attributes over 35-years using historical wildfire scars derived from Landsat satellite imagery collection, and (ii) the link between fire regime and pre-fire vegetation characteristics controlling extreme fire behavior. We selected eight extreme wildfires occurring during the period 2017-2022, in which we characterized both (i) the pre-fire fuel type and structure by means of image classification techniques and radiative transfer models (RTMs), and (ii) the ecological impact through the differenced Normalized Burn Ratio (dNBR) derived from bi-temporal Sentinel-2 MSI images. Fire recurrence showed the same downward trend along the climatic gradient, burn severity trends significantly differed among Atlantic and Mediterranean areas. The observed shifts in fire regime attributes had a remarkable influence in shaping fuel types and build-up patterns in landscapes prone to extreme fire behavior along the climate gradient but following distinct pathways as a function of the environmental context. In Atlantic areas, recurrent wildfires of low to moderate severity may foster forest transitions to shrubland stable states prone to high burn severity feedback in subsequent wildfires. A similar pattern was observed in Mediterranean and Transition shrublands after the recurrence of high burn severity wildfires. Under all climatic conditions, long times since the last high-severity wildfires may enhance fuel build-up in conifer forests and shrublands highly prone to extreme fire behavior.

Finally, we broadened the generated knowledge about the biophysical contexts shaping extreme fire behavior in wildland urban interface areas to identify the scenarios prone to high burn severity in WUI areas due the growing concern about the socio-economic and environmental implications (***Article IV***). For this purpose, we chose fourteen large wildfires occurred between 2016 and 2021 across Spain that encompassed different WUI typologies. Density and distance between buildings criteria was used to differentiate isolated, scattered, dense and very dense WUIs, while several pre-fire fuel characteristics inside WUI areas were estimated through multispectral satellite imagery, following the methodology used in the ***Article III***. Then, the combined effect of pre-fire fuel and building density patterns was used to recognize the WUI scenarios most prone to extreme fire behavior. Isolated, scattered and sparsely clustered buildings enclosed in a dense shrub matrix were the WUI typologies with the highest fire hazard. Additionally, WUIs dominated by sparse trees with a dense and continuous shrubby understory constituted another critical typology prone to severe fire impacts. We highlighted the role of pre-fire fuel management to minimize the risk to human lives and assets, particularly under increasing human pressure in WUI areas.

The results obtained in this PhD Thesis allowed to predict priority scenarios for effective land use planning, wildfire prevention and management strategies, community education, and collaborative efforts in WUI areas, which are essential to address the challenges posed by new-generation wildfires to population in rural areas. We emphasize that the reduction of homogeneous fuel types, particularly shrub fuels around isolated and dispersed WUIs must be a priority intervention line. These actions should focus on breaking the fuel horizontal continuity and encouraging the development of diverse landscape mosaics to foster resistance and resilience to fire. This target can be achieved by supporting sustainable and traditional activities such as extensive livestock grazing or silvicultural actions by work crews, which is essential for population fixation in sociologically relevant areas such as WUIs.

RESUMEN

En las últimas décadas, la actividad antropogénica ha causado cambios notables en los atributos del régimen de incendios en los países de la cuenca del Mediterráneo occidental, debido principalmente a la pérdida de usos tradicionales derivados del abandono rural, el cambio climático y la falta de estrategias de gestión forestal adecuadas, lo que ha llevado a una acumulación de biomasa propensa a incendios. El nuevo régimen de incendios, caracterizado por un aumento en la frecuencia de incendios forestales extensos y severos, afecta a importantes funciones y servicios de los ecosistemas, con impactos sin precedentes a nivel socioeconómico. Este hecho es especialmente relevante en las zonas de interfaz urbano-forestal (WUI), donde los incendios forestales extremos representan una grave amenaza para la vida humana y los bienes. En este contexto, la caracterización espacial del impacto inducido por el fuego, comúnmente como como severidad del fuego, es crucial para proporcionar una base científica que permita diseñar estrategias de gestión forestal adecuadas que mejoren la respuesta adaptativa de los ecosistemas a los regímenes de incendios actuales. Los métodos de campo se consideran muy fiables para evaluar los impactos en la vegetación y el suelo en paisajes quemados, aunque a menudo carecen de la exhaustividad espacial que permita evaluar incendios forestales de gran tamaño. Por ello, los métodos de teledetección han surgido como herramientas fiables el seguimiento y la cuantificación de la severidad a gran escala debido a su rentabilidad y su naturaleza sinóptica. En este contexto, el objetivo principal de esta Tesis Doctoral es el desarrollo de nuevas técnicas de teledetección multiescala dirigidas a identificar indicadores espaciales de los impactos ecológicos inducidos por el fuego y evaluar los impulsores del comportamiento extremo de los incendios forestales bajo diferentes regímenes de fuego a lo largo de un gradiente climático ibérico, con especial atención a las WUIs debido a su alta vulnerabilidad socioeconómica.

En primer lugar, se pretendió mejorar la estimación de la severidad del fuego en los suelos forestales, que son compartimentos críticos del ecosistema que impulsan las funciones y procesos del ecosistema, vinculando indicadores ecológicos de la severidad con la señal espectral de productos de teledetección de muy alta resolución espacial obtenidos con vehículos aéreos no tripulados (UAV) (***Artículos I y II***). La severidad del fuego en el suelo se evaluó en el campo 1 mes después de un incendio forestal a través de un Índice Compuesto de Severidad en el Suelo (CBSI), y de un conjunto de indicadores individuales (profundidad y cobertura de la capa de cenizas, cobertura de restos finos, cobertura de restos gruesos y profundidad de suelo desestructurado). Además, se analizaron propiedades de suelo potencialmente indicadoras de cambios inducidos por el fuego: diámetro medio ponderado (MWD), contenido de humedad del suelo (SMC) y carbono orgánico del suelo (SOC). Simultáneamente, se recolectaron imágenes multiespectrales posteriores al incendio del sensor satelital Sentinel-2A MSI (resolución espacial moderada) e imágenes RGB y multiespectrales procedentes de un vuelo UAV (resolución espacial muy alta). Se ha encontrado que los productos multiespectrales UAV tenían mejor rendimiento para estimar la variación del impacto del fuego en el suelo que los productos RGB, estando más relacionados con índices multi-integrados (es decir, CBSI) que con indicadores individuales (***Artículo I***). La profundidad y la cobertura de cenizas fueron los indicadores más representativos de los efectos del fuego en los suelos. La inclusión de datos de teledetección espacial y espectral

mejorados mediante técnicas novedosas de teledetección, como la fusión de imágenes de Sentinel-2 y UAV, mejoró significativamente la predicción de las propiedades del suelo sensibles al fuego, relacionadas en gran medida con la severidad, principalmente el SOC (***Artículo II***). Este enfoque proporciona una herramienta importante para estimar los impactos del fuego en paisajes complejos y heterogéneos afectados por incendios de severidad mixta, y, en consecuencia, para identificar áreas prioritarias donde se deben implementar acciones de restauración posteriores al incendio.

Una vez que se caracterizó adecuadamente el impacto ecológico potencial de los incendios forestales de alta severidad, se estudió que cambios del régimen de incendios pueden dirigir el comportamiento extremo del fuego, aspecto que se ha evaluado a lo largo de un gradiente climático Atlántico-Transición-Mediterráneo en la Península Ibérica (***Artículo III***), caracterizado por la ocurrencia de eventos extremos de incendios forestales en los últimos años. Con este propósito, se analizaron (i) los patrones de variación de los atributos temporales (recurrencia y tiempo desde el último incendio) y de magnitud (severidad de la quema) del régimen de incendios durante 35 años, utilizando para ello los perímetros históricos de incendios forestales derivados de la colección de imágenes de satélite Landsat, y (ii) la relación entre el régimen de incendios y las características de la vegetación previas al incendio que controlan el comportamiento extremo del fuego. Se seleccionaron ocho incendios extremos que ocurrieron durante el período 2017-2022, en los cuales se caracterizó tanto (i) el tipo y la estructura de los combustibles previos al incendio mediante técnicas de clasificación de imágenes y modelos de transferencia radiativa (RTMs), como (ii) el impacto ecológico a través del índice de Severidad de Diferencia Normalizada (dNBR) derivado de imágenes bitemporales del sátelite Sentinel-2 MSI. La recurrencia de incendios mostró la misma tendencia descendente en el tiempo a lo largo del gradiente climático, pero los patrones temporales de la severidad diferían significativamente entre las áreas Atlánticas y Mediterráneas. Los cambios observados en los atributos del régimen de incendios tuvieron una influencia notable en la formación de tipos de combustibles y en los patrones de acumulación en el paisaje propicios para el comportamiento extremo del fuego, pero siguiendo distintas vías en función del contexto ambiental. En las áreas Atlánticas, los incendios recurrentes de baja a moderada severidad pueden promover transiciones forestales hacia estados estables de matorrales propensos a retroalimentaciones de alta severidad en incendios posteriores. Un patrón similar se observó en los matorrales Mediterráneos y de Transición después de la ocurrencia repetida de incendios de alta severidad. En todas las condiciones climáticas, un largo periodo de tiempo transcurrido desde el último incendio de alta severidad puede favorecer la acumulación de combustibles en bosques de coníferas y matorrales, los cuales son altamente propensos al comportamiento extremo del fuego.

Por último, se ha ampliado el conocimiento científico generado sobre los contextos biológicos que definen el comportamiento extremo del fuego en áreas de interfaz urbano-forestal con el fin de identificar los escenarios propensos a una alta severidad en las áreas de WUI debido a la creciente preocupación sobre las implicaciones socioeconómicas y ambientales (***Artículo IV***). Con este propósito, se eligieron catorce grandes incendios forestales ocurridos entre 2016 y 2021 en toda España que abarcaron diferentes tipologías de áreas de WUI. Utilizando criterios de densidad y distancia entre edificios se diferenciaron áreas de WUI aisladas, dispersas, densas y muy densas, así mismo, se estimaron varias características de combustibles previos al incendio dentro de las áreas de WUI, para lo cual se utilizaron imágenes de satélite multiespectrales, siguiendo la metodología utilizada en el ***Artículo III***. El efecto combinado de los patrones de combustibles previos al incendio y la densidad de edificios se utilizó para identificar los escenarios de WUI más propensos al comportamiento extremo del fuego. Las tipologías de WUI con edificios aislados, dispersos y agrupados de manera dispersa, rodeados de un denso matorral, fueron las que presentaron el mayor riesgo de incendio. Además, las áreas WUI dominadas por árboles dispersos con un sotobosque de matorral denso y continuo constituyeron otra tipología crítica propensa a impactos severos por incendios. Se ha puesto de relieve el papel de la gestión del combustible antes de los incendios para minimizar el riesgo para las vidas humanas y los bienes, en particular bajo la creciente presión humana en las zonas WUI.

Los resultados obtenidos en esta Tesis Doctoral permiten predecir escenarios prioritarios para una planificación efectiva del uso del suelo, estrategias de prevención y gestión de incendios forestales, educación comunitaria y esfuerzos colaborativos en áreas WUI, lo cual es esencial para abordar los desafíos planteados por los incendios forestales de nueva generación a la población en las zonas rurales. Se destaca que la reducción de tipos de combustibles homogéneos, en particular los combustibles de matorral alrededor de áreas de WUI aisladas y dispersas, debe ser una línea de intervención prioritaria. Estas acciones deben centrarse en romper la continuidad horizontal de los combustibles y fomentar el desarrollo de mosaicos paisajísticos diversos para promover la resistencia y la capacidad de recuperación frente al fuego. Esto se puede lograr apoyando actividades sostenibles y tradicionales, como el pastoreo extensivo de ganado o acciones silvícolas, lo cual es esencial para la fijación de la población en áreas sociológicamente relevantes como las áreas WUI.

1

INTRODUCTION

Fire regimes in the Mediterranean Basin

The terrestrial ecosystems of the Mediterranean Basin have been subject to frequent wildfires for millennia (Pausas et al., 2008; Moreira et al., 2023), representing one of the most fire-prone geographic territories worldwide (Keeley et al., 2012). The Mediterranean climate favors the accumulation of highly flammable fuels (e.g., pine woodlands and shrublands), which facilitates the incidence and spread of fires (Moreno et al., 2021). Currently, wildfires are considered one of the major ecological and social disturbances (Pausas and Vallejo, 1999; Johnstone et al., 2016) due to the significant loss of ecosystem services and economic resources (Lee et al., 2015). In this region, about half a million forest hectares are affected by wildfires every year (San-Miguel-Ayanz et al., 2021). They cause significant emissions of greenhouse gases (Migliavacca et al., 2013) and imbalances in the energy budget of the Earth's surface, and thus negatively impact the climate system (Archibald et al., 2018). For example, in southern European countries, wildfires destroyed 645,000 ha annually on average from 2017 to 2022 (San-Miguel-Ayanz et al., 2023), with singular extreme wildfire events affecting large areas (most of them over 10,000 hectares ha), becoming one of the worst fire seasons ever recorded in countries such as Spain (Chas-Amil et al., 2020; Fernández-Guisuraga et al., 2023a), Portugal (Rodrigues et al., 2023), Italy (Malandra et al., 2022), or Greece (Giannaros et al., 2022) (Fig. 1).

Although wildfires under natural fire regimes are an integral part of many Mediterranean ecosystems (Keeley et al., 2012), modulating both (i) vegetation adaptations to regenerate after fire (Calvo et al., 2008) and (ii) landscape diversity patterns in terms of functionality, structure and dynamics (Pausas et al., 2008), unprecedented fire regimes may lead to irreversible socio-ecological consequences in the Mediterranean Basin (Fernandes et al., 2016). During the last 50 years, human activity has caused remarkable changes in fire regime attributes, mainly due to the loss of traditional uses as a consequence of rural land abandonment (Pausas and Fernández-Muñoz, 2012), climate change (González-De Vega et al., 2016; Pausas and Keeley, 2021), and absent or inadequate forest management practices (Stephens et al., 2013; Moreira et al., 2020), driving to a dense and continuous accumulation of fire-prone fuels. Fire regime is a key concept in fire ecology studies, which reflects the temporal, spatial and magnitude variability of fire in a specific ecological system (Fernández-García et al., 2018a; Rundel et al., 2018), often being determinants of its resistance and resilience capacity in the face of wildfire disturbances (Huerta et al., 2022a). Among their temporal attributes, recurrence (number of fires in a given period), fire-free interval (the time since the last fire; TSLF) and fire return interval (mean time elapsed between fires) have played a key role in shaping plant communities (Fernández-García et al., 2020), with an evolution of fire-stimulated responses emerging based on a specific fire history (He et al., 2019). Closely linked to fire intensity, which correspond to the energy released by the fire in the combustion process (Keeley, 2009), burn severity is one of the most important fire regime attributes reflecting the magnitude of fire-induced ecological and socioeconomic impacts (Morgan et al., 2014). In this sense, burn severity is known as the degree of fire-induced ecological change (Key and Benson, 2006; Fernández-García et al., 2018b), and operationally quantified by the change or loss in above- and belowground ecosystem biomass (Keeley, 2009). Fire severity assessments have particular implications for land management and post-fire restoration strategies

(Gonzalez-Olabarria et al., 2019). Recent and anticipated shifts in the fire regime in southern Europe, marked by increased frequency, extent, and burn severity of wildfires (sixth generation wildfires; Resco de Dios, 2020), have the potential to strongly erode several functions and services provided by forest ecosystems (Pausas et al., 2008; Fernandes et al., 2014; Huerta et al., 2022a), resulting in an uncertain scenario of responses to future disturbances (Fernández-García et al., 2018a). Therefore, it is crucial to understand the ecological implication of fire regime shifts in this region to adequately develop fire management policies.

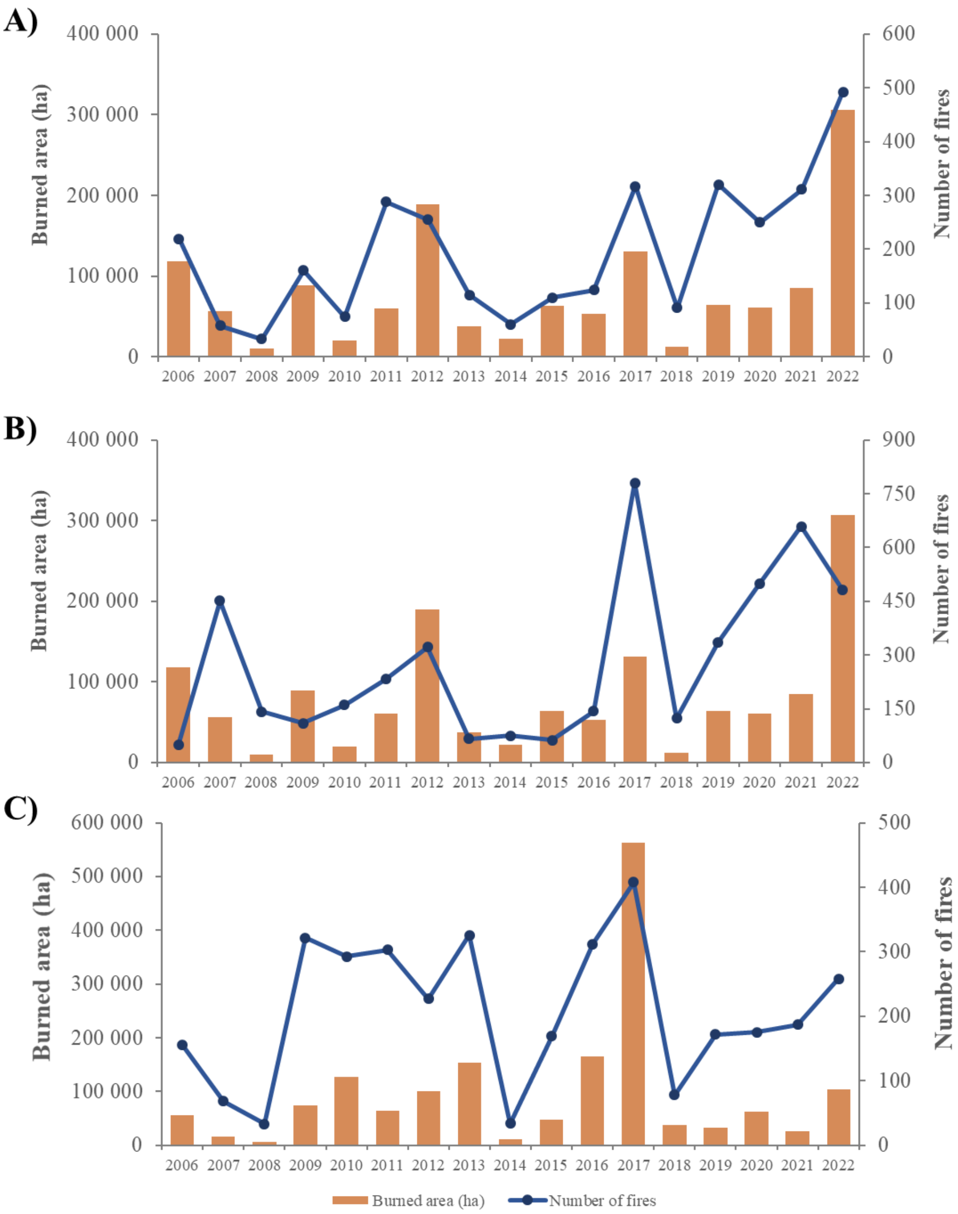

Figure 1. Annual Statistics of the European Forest Fire Information System (EFFIS) using mapped wildfires ≥ 30 ha for (A) Spain, (B) Italy, and (C) Portugal over the period 2006-2022.

The ability of plant communities in Mediterranean Basin to cope with fire has been modulated by evolutionary pathways shaping fire-adaptive traits, such as resprouting from surviving tissues, fire resistant structures (e.g., thick bark), serotiny, or fire-stimulated germination. These traits had been acquired due to ecological memory of past disturbances under natural fire regimes (Pausas, 2008), ensuring adequate post fire vegetation recovery rates. However, the current increase in extreme wildfires may hinder ecosystem resilience to fire through the impact of resprouting response (Moreira et al., 2012), or diminishing the recruitment of obligated seeders due to direct effects (biomass consumption) or indirect effects (nutrient loss and destruction of soil structure) (Vega et al., 2013; Pausas and Keeley, 2021). This is especially aggravated when increase the frequency of extreme wildfire events (Taboada et al., 2018; Fernández-García et al., 2020). For instance, there is evidence that regeneration of many obligated seeder species (e.g., *Pinus* species on the Iberian Peninsula) is strongly impaired by short fire intervals (Calvo et al., 2008; Fernández-Guisuraga et al., 2020). This may promote a high fuel build-up resprouting shrub species (Taboada et al., 2018), with substantial implications on the fire behavior of subsequent wildfires (Gould et al., 2011; Vasques et al., 2023), as well as a decline of fire-sensitive species' diversity (Fernández-García et al., 2020; Kelly et al., 2020). Furthermore, burn severity also strongly affects regeneration strategies and physiological traits in Mediterranean Basin ecosystems (Fernández-García et al., 2020), inducing short and long-term post-fire effects (Key and Benson, 2006; Harris and Taylor, 2017; Quintano et al., 2018) on vegetation and soils, such as plant mortality or soil erosion (Bassett et al., 2017; San-Miguel et al., 2017). Nonetheless, these effects often display a very high spatial variability (mixed-severity wildfires; Fig. 2) (Viedma et al., 2020) within the same wildfire event, strongly linked to environmental conditions (Whitlock et al., 2003; Pausas and Paula, 2012; Fernández-Guisuraga et al., 2020). In this context, developing spatial characterization techniques of fire regime attributes in different climatic contexts is essential to provide forest management advice targeted at improving ecosystem adaptive responses in the current situation of global change (De Santis and Chuvieco, 2007; Chuvieco et al., 2014; González-De Vega et al., 2016; Strand and Bunting, 2023).

Figure 2. Ecosystems of *Pinus sylvestris* L. (Scots pine) with *Cytisus oromediterraneus* Rivas (black broom) understory affected by a mixed severity fire in Navalacruz in 2021 (Ávila; Spain; western Mediterranean Basin)

Soil burn severity monitoring through passive remote sensing techniques

Burn severity provides crucial information on how the fire impacts in the ecosystems both immediately after the fire (initial short-term assessments, IA) (Zavala et al., 2014; Fernández-García et al., 2018b) and over long periods of time (extended long-term assessments, EA) (Key and Benson, 2006; González-De Vega et al., 2016; Fernández-Manso et al., 2020). In this sense, fire-induced ecological changes can be evaluated using two different approaches: field (Morgan et al., 2014; Fernández-García et al., 2018b) and remote sensing (Lentile et al., 2006; De Santis and Chuvieco, 2007; Fernández-Manso et al., 2016a) assessments. In the field data approach, visual indicators such as char height, ash color or depth, litter consumption, vegetation consumption, tree mortality, or remaining branch diameter are used (Key and Benson, 2006; Keeley, 2009). Traditionally, these indicators are combined in integrative field indices using a multi-strata approach, such as the Composite Burn Index (CBI; Key and Benson, 2005) or the Geometrically structured CBI (GeoCBI; De Santis and Chuvieco, 2009). These integrative indices use a semi-quantitative scale ranging from unburned to totally or severely burned to rate individual fire impacts on four vegetation strata (vegetation burn severity) and substrate (soil burn severity). These scores can be used jointly (site burn severity) to provide a comprehensive assessment of fire damage, or individually, in terms of the compartments considered critical for post-fire management (Keeley, 2009). Field methods are highly reliable for assessing fire impacts on vegetation and soils in burned landscapes (Gonzalez-De Vega et al., 2016; Holden et al., 2016) using visual estimations or instrumental techniques (Li et al., 2015; Fernández-García et al., 2018b). However, they require a considerable amount of time and are labor-intensive, particularly for large-scale applications (De Santis and Chuvieco et al., 2007; Veraverbeke et al., 2011). Despite the CBI has frequently been used in studies that only use fieldwork as data source (Amato et al., 2013), its initial purpose was to validate burn severity estimates derived from remotely sensed data (e.g., Quintano et al., 2018; Fernández-Guisuraga et al., 2023a).

Within this context, remote sensing methods have emerged as powerful tools for monitoring and quantifying fire-induced impacts across large burned areas for their cost-effectiveness, accurate links with ground measurements and synoptic nature (Veraverbeke et al., 2012; Yin et al., 2020). The most commonly-used approaches in the literature include (i) mono- and bi-temporal spectral indices computed from passive optical data (Mallinis et al., 2018; Fernández-García et al., 2018b), (ii) spectral unmixing analysis (SMA) to retrieve the fractional cover of post-fire constituents at sub-pixel level (Quintano et al., 2013; Fernández-Manso et al., 2016b), and (iii) radiative transfer models (RTMs) based on the simulation of the reflectance signal of fire impacts through the radiative transfer theory (Verrelst et al., 2019; Fernández-Guisuraga et al., 2023a). Traditionally, optical multispectral sensors aboard satellite platforms have been widely used to quantify changes in vegetation status in fire-affected areas (Garrigues et al., 2002; Veraverbeke et al., 2012), being also used in numerous studies to evaluate post-fire vegetation recovery (Fernández-Guisuraga et al., 2019) and identify areas susceptible to erosion (Jain et al., 2012). Nevertheless, the spatial and spectral resolution of these sensors often presents limitations in explaining the high spatial variability that characterizes heterogeneous burned areas in the context of large wildfire events

(Meng et al., 2018), particularly at the soil level (Kokaly et al., 2007). Sensors with low (e.g., MODIS) to moderate (e.g., Landsat and Sentinel-2) spatial resolution may fail to capture the fine-scale variation of vegetation horizontal structure in heterogeneous landscapes (Miller and Thode, 2007; Harris et al., 2011; Hosseini and Saradjian, 2011). This may limit the ability to accurately monitor wildfire impacts at fine scales (Viana-Soto et al., 2017). Also, optical multispectral sensors may not capture the full range of spectral information needed to discriminate between different burn severity levels (Chu et al., 2016; Roy et al., 2016). Overcoming these limitations requires advancements in sensor technology, such as the integration of higher spatial and spectral resolution data sources, including hyperspectral sensors or very high spatial resolution multispectral imagery (Lewis et al., 2008; Ge et al., 2019).

In this regard, unmanned aerial vehicles (UAVs), commonly known as drones, offer a potential solution to the limitations of optical imagery collected by earth observation satellites in assessing fire impacts on ecosystems. UAVs equipped with high-resolution cameras can capture imagery at a much finer spatial resolution (higher than 1 m) with lower economic costs compared to alternative remote sensing techniques for relatively small-scale area surveys (Aldana-Jague et al., 2016; Fernández-Guisuraga et al., 2018; Pla et al., 2019), allowing a better understanding of fine-scale variations in fire-induced ecological impacts within heterogeneous landscapes (Fernández-Guisuraga et al., 2018; Melville et al., 2019; Pla et al., 2019). Moreover, UAVs can be equipped with multiple sensors, including RGB, multispectral, hyperspectral, thermal infrared, and LiDAR, enabling researchers to study vegetation health, soil status, and other ecological features in-depth (Colomina and Molina, 2014). Despite the considerable potential of UAVs, there are still research challenges regarding the implementation of operative multispectral UAV products in fire assessments due to the common low spectral resolution of the most widely used commercial sensors in comparison with multispectral satellite imagery (Fernández-Guisuraga et al., 2018). Recent methodological advances, such as data fusion of high spectral and high spatial resolution satellite and UAV imagery, respectively, are promising in addressing these challenges (Näsi et al., 2015; Dash et al., 2018; Ge et al., 2019).

Indicators of fire-induced ecological change on forest soils

Severe wildfires may induce important direct (vegetation consumption) and indirect effects on the ecosystems (Gonzalez-De Vega et al., 2016; Fernández-García et al., 2019), such as poor plant regeneration, soil erosion, increased surface runoff, water pollution, or flooding (Pausas et al., 2008; Pereira et al., 2018). Of particular interest are fire-induced shifts in soil mineral and organic layers, including loss of organic matter and nutrients (DeBano et al., 1998; Lentile et al., 2006), as they can drastically alter multiple ecosystem functions and services (Huerta et al., 2022b). For instance, the soil organic matter consumption at extreme temperatures causes loss of soil structure (Mataix-Solera et al., 2011; Marcos et al., 2018; Fernández-García et al., 2019), decreasing the soil capacity to retain water and nutrients, and affecting vegetation recovery as well as ecosystem productivity (Johnstone and Chapin, 2006; Vega et al., 2010). In addition, soil exposure to high temperatures generates impermeable layers on the soil surface, which increase runoff and erosion susceptibility (Zavala et al., 2014; Vieira et al., 2015).

Soil burn severity is influenced by multiple factors, including abiotic variables such as microtopography or soil moisture (Harris and Taylor, 2017), or the burned vegetation type (Fernández-García et al., 2019). In this way, it is very common to find a heterogeneous mosaic of soil burn severity levels within the wildfire (Neary et al., 2005; Sobrino et al., 2019) (Fig. 3). It has been reported that high soil burn severity may heavily impact soil properties in the upper 2-3 cm (Badía et al., 2017), such as aggregate stability, water repellency, pH electrical conductivity, microbial biomass carbon or enzymatic activities (Vega et al., 2013; Mataix-Solera et al., 2011; Muñoz-Rojas et al., 2016; Fernández- García et al., 2019). However, minimal, or even positive effects have also been described at low severity on some soil properties, such as a slight increase in the coarse fraction of soil aggregates due to an increase in soil organic carbon in incomplete combustion of vegetation biomass (Marcos et al., 2009). The development of scientific knowledge of these soil attributes based solely on field data has been useful to understand fire-induced impacts on the ecosystem functioning (Vega et al., 2013; Marcos et al., 2018; Fernández-García et al., 2019). Nevertheless, the implementation of new remote sensing techniques that procure fine-scale spatial information of fire impacts on forest soils is necessary to achieve enough accuracy in large-scale spatial assessments to be useful for post-fire management.

Figure 3. Spatial variation of soil burn severity in broadleaf (left) and coniferous forest (right). White and orange ash patches indicate highly affected areas.

Apart from soil properties, other metrics have been used to identify the magnitude of fire impacts at the soil level (Keeley et al., 2009, Maia et al., 2012). One of the most widespread and clearest methods is based on the observation of certain observable and measurable soil indicators, such as the presence and characteristics of char and ash (Lentile et al., 2006; Hudak et al., 2013), or soil structural alterations visually-assessed (Vega et al., 2013; Fernández and Vega, 2016). Soil burn severity visual indicators can be rated individually (Marcos et al., 2018; Miesel et al., 2018), due to their easy measurement and applicability, or integrated in the CBI classification system (Key and Benson, 2005). While field-based indicators can be valuable tools for assessing fire impacts on soil at local scales, land managers need tools that allow wall-to-wall assessments of fire severity on soils at large spatial scales (Hudak et al., 2007). Despite this, little research has been carried out on the combination of field-based indicators to validate the information gathered by remote sensing data (Rodrigo-Comino et al., 2018; Sobrino et al., 2019).

Estimation of vegetation characteristics driving burn severity by remote sensing data

In the context of changing fire regimes, related to the occurrence of more extreme wildfire events, management strategies tailored to the conservation of forest ecosystems require a thorough understanding of the underlying factors driving burn severity (Moreira et al., 2011; García-Llamas et al., 2019a). During the last years, previous research has evaluated driving mechanisms of burn severity in the Mediterranean Basin, which are controlled by four main factors: topographic effects, weather conditions, fire history patterns, and vegetation characteristics (fuel amount, fuel type, fuel structure and fuel moisture) (Alexander et al., 2006; Collins et al., 2007; Oliveras et al., 2009; Steel et al., 2015; Viedma et al., 2015; Fernández-Guisuraga et al., 2021a). Due to the complex interactions among these variables (Lecina-Diaz et al., 2014; Parks et al., 2018), remote sensing methods are considered the most feasible alternative to model at large scale, and with high reliability, the relationships between environmental drivers and extreme fire behavior in heterogeneous ecosystems (Viedma et al., 2015; García-Llamas et al., 2019a). Among these four drivers, only vegetation characteristics are susceptible to being managed (Prichard et al., 2020), which is crucial to design planning strategies aimed to reduce the surface burned at high burn severity (Picotte et al., 2020; Viedma et al., 2020). In this sense, high fuel load and horizontal fuel continuity of flammable vegetation types may lead to the most severe ecological impacts (Coppoletta et al., 2016; Fernández-Guisuraga et al., 2021a). For example, Iberian Peninsula landscapes dominated by pine forests, such as *Pinus pinaster* Ait. and *Pinus halepensis* Mill., have been reported to be highly susceptible to severe fires due to the homogeneous vegetation and ladder fuels susceptible to crowning (Pausas et al., 2008; Viedma et al., 2015; Fernández-García et al., 2019). On the other hand, heterogeneous landscapes formed by mixed agricultural areas and native forests may preclude wildfire severity (Fernandes, 2013). Therefore, the fine-scale spatial characterization of these fuel driving factors, which may be controlled by fire history, is essential for defining forest management guidelines and policies to reduce wildfire hazard in fire-prone landscapes (Fernandes et al., 2016; García-Llamas et al., 2020).

Remote sensing data sources are less time-consuming for large-scale assessments necessary in the context of extreme wildfire events (Chen et al., 2017; Garcia-Llamas et al., 2019b; Fang et al., 2023). The quantification of pre-fire vegetation amount through satellite data has been traditionally accomplished by empirical approaches based on statistical relationship among field measurements at plot-level and spectral products such as vegetation indices (e.g., Normalized Difference Vegetation index -NDVI-, or Normalized Difference Water index, -NDWI-) (Parks et al., 2018). However, the lack of physical meaning of spectral indices in heterogeneous burned landscapes (Fernández-Guisuraga et al., 2021b; 2023a) lead to a poor generalization ability among different vegetation types (Huang et al., 2021), which introduces uncertainties in the fuel amount estimation process. In this sense, other remote sensing methods such as RTMs have been used to overcome these limitations, obtaining a better fuel characterization (Yebra et al., 2013; Fernández-Guisuraga et al., 2021b). Physical methods applied to satellite imagery, such as RTMs, simulate the interaction of electromagnetic radiation with the Earth's surface and atmosphere, allowing more meaningful and generalizable measurements of certain biophysical variables, such as the fraction of vegetation cover (FCOVER), the leaf area index (LAI), the canopy water content (CWC), or the fraction of absorbed photosynthetically active radiation (FAPAR) (Garrigues et al., 2006; Jia et al., 2016; Fernández-Guisuraga et al., 2021b). Until a few years ago, there were not many examples of the use of RTMs in characterizing pre-fire vegetation structure. Recently, RTMs have been used to estimate forest resilience and vegetation recovery rates in heterogeneous landscapes affected by mixed-severity fires (Fernández-Guisuraga et al., 2021b; 2023a). Despite their generalization capability (Tao et al., 2019), and their non-dependence on field data (Campos-Taberner et al., 2018), RTM products have not been leveraged to directly retrieve biophysical variables related to pre-fire vegetation structure.

Challenges of the new generation wildfires: vulnerability of the wildland-urban interface to high burn severity

The increased risk of sixth-generation fires (i.e., large wildfires of extreme fire behavior) in southern Europe is involving areas of high socio-economic value (Molina-Terrén et al., 2019), such as wildland-urban interfaces (WUI), where humans, goods and ecosystem services are highly vulnerable (Modugno et al., 2016; Badia et al., 2019). WUI areas are geographical zones where human development, such as settlements and constructions, meets or intermix with wildland areas (Bento-Gonçalves and Vieira, 2020), creating a new landscape context formed by conjunction of housing and wildland fuels (Lampin-Maillet et al., 2009). In these areas, susceptibility to severe wildfires has increased due to the depopulation and agricultural land abandonment in rural areas (Alamá-Sabater et al., 2021), and to the urbanization and human pressure in forested areas (Calviño-Cancela et al., 2016; Badia et al., 2019). As a consequence, many buildings are adjacent to areas holding large amounts of fire-prone biomass, where anthropogenic ignitions are frequent (Pausas and Fernández-Muñoz, 2012; Calviño-Cancela et al., 2017), assuming an added concern in the development of policies for preparing, staying, defending or leaving actions under large wildfire events. Under this scenario, extensive WUI areas are expected to be burned at high burn severity because of the connection between large wildfire spread and extreme fire behavior (Tedim et al., 2018) (Fig. 4). Therefore, it is essential to establish a scientific basis for identifying vulnerable situations and planning the most appropriate strategies to reduce land susceptibility to severe fires in WUI areas (Caggiano et al., 2020).

Figure 4. Scattered WUI area affected by moderate-high burn severity in Sierra de la Culebra wildfire occurred in summer 2022.

The assessment of conducive factors to extreme fire behavior has historically been ignored in WUI scientific literature in favor of fire ignition probability (Calviño-Cancela et al., 2017; Molina-Terrén et al., 2019) and fire spread (Vacca et al., 2020; Hysa, 2021). In wildland areas, burn severity has been shown to be controlled by multiple variables (Harris and Taylor, 2017; Viedma et al., 2020), such as those related to fuel characteristics (García-Llamas et al., 2019b; Walker et al., 2020). However, the human interaction degree in the intermix of settlements with wildland areas, with a higher variety of land uses and an increase in the presence of anthropogenic elements (e.g., roads, gardens, or power lines) may produce variations in fire behavior (Nielsen-Pincus et al., 2015). For this reason, the inclusion of building patterns as a covariate in fire behavior modelling in WUI areas may contribute to a better understanding of the vulnerability of human assets (Moreira et al., 2011). Building patterns influence not only fire behavior by means of changes in fuel types and structural characteristics (Safford et al., 2009; Chas-Amil et al., 2013), but also firefighting procedures (Lampin-Maillet, et al., 2009). The terms “isolated WUI”, “scattered WUI”, “dense clustered WUI”, and “very dense clustered WUI” have been used to describe different patterns of WUI development based on the arrangement and density of buildings (Lampim-Maillet et al., 2009) (Fig. 5), which have helped to identify wildfire risk (Lampin-Maillet, et al., 2011; D'Este et al., 2021) and to design mitigation strategies (Sturtevant et al., 2007; 2009). In this way, WUI mapping at different spatial scales (Tonini et al., 2017; Sarricolea et al., 2020), or fire occurrence (Modugno et al., 2016) and vulnerability (Badia et al., 2019) modelling in WUI areas have been traditionally accomplished by using building patterns and vegetation characteristics such as (i) forest density (Caballero et al., 2007; D'Este et al., 2021), (ii) vegetation fragmentation (Lampin-Maillet et al., 2010; Chas-Amil et al., 2013; Sirca et al., 2017), or (iii) land cover change (Lampin-Maillet et al., 2011; Calviño-Cancela et al., 2016). To date, however, no methodologies have been developed for creating complete WUI classification systems that can be used across wide geographic areas to recognize the most vulnerable situations in terms of extreme fire behavior. In this sense, determining the relationship between burn severity, pre-fire fuel type and structure, and building spatial patterns may be essential not only for developing management strategies in WUI areas (Modugno et al., 2016), but also for promoting landscapes and socio-ecological contexts less susceptible and more resilient to high burn severity (Pastor et al., 2020).

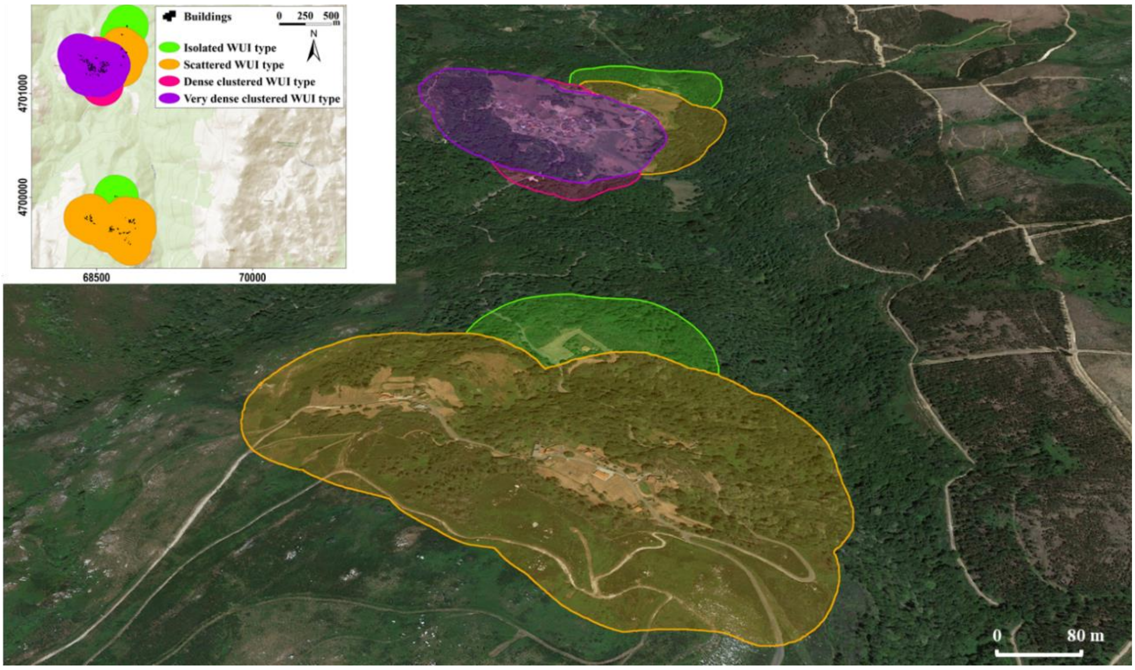

Figure 5. Different WUI types according to building patterns (distance and density between settlements) over a 3D Google Earth map corresponding to Carballeda de Avia wildfire.

Research justification

Drastic changes in the frequency, severity and size of wildfires are expected to increase in the western Mediterranean Basin (González-De Vega et al., 2016) as a consequence of rural land abandonment and climate change (Pausas and Fernández Muñoz, 2012; San-Miguel-Ayanz et al., 2013; Turco et al., 2013, Moreira et al., 2020). Rural abandonment has led to an increase in the amount and continuity of flammable fuels, promoting dense and continuous shrublands and woodlands, and a decline in grasslands and cultivated areas (García-Llamas et al., 2019b). Climate change, mainly expressed as an intensification of prolonged droughts and high-temperature periods, favors fuel dryness and thus high fuel ignition scenarios and extreme fire behavior (Stephens et al., 2013). As a result of these shifting patterns, the risk of large and severe wildfires is rising, especially in areas of particular concern for human life and assets such as the wildland-urban interfaces (WUI) (Stephens et al., 2013.

The current Doctoral Thesis pretends to advance knowledge in the application of multi-scale, passive remote sensing data and techniques to analyze both burn severity variability and its drivers across large burned landscapes in the context of changing fire regimes under different climatic conditions in the western Mediterranean Basin. In this regard, we sought to address the following questions:

- ***Articles I & II:*** (i) What are the most effective ecological indicators to determine at fine spatial scales the impact induced by wildfires on soils of forest ecosystems? (ii) Do multispectral sensors on board UAVs have enough potential to identify these variations?
- ***Article III:*** (iii) What are the most relevant pre-fire fuel characteristics controlling burn severity behavior over different climatic contexts? (iv) Are passive remote sensing techniques valuable in identifying the link between fire regime and pre-fire vegetation characteristics controlling extreme fire behavior? (v) What is the relationship between fire regime shifts and fire behavior in 6th generation wildfires?
- ***Article IV:*** (vi) How do pre-fire fuel characteristics influence fire behavior in highly vulnerable WUI areas? (vii) Can passive remote sensing techniques contribute to fine-scale characterization of WUI typologies prone to high burn severity?

Answers to these questions will allow the promotion of science-based pre-fire management strategies to reduce environmental and socio-economic impacts of large and severe wildfires in fire-prone forest ecosystems of the western Mediterranean Basin. Regarding the ***Articles I & II***, we expect that imagery collected at very high spatial resolution from UAVs will allow for a better characterization of the short-term spatial variability in soil burn severity than satellite imagery. It has been shown that images acquired through on-board satellite sensors may be inappropriate for assessing fire impact on soils due to their coarse spatial resolution (e.g., Fernández-García et al., 2018b). Furthermore, the spectral resolution of commercial multispectral sensors aboard UAVs may not be sufficient to determine fire-sensitive soil biochemical properties (Žížala et al., 2019). Thus, the application of fusion techniques targeted at producing spatially and spectrally enhanced products on UAV and satellite images is expected to provide the best performance.

Regarding fire behavior (***Article III***), we hypothesize that passive remote sensing products with physical basis and low dependence on field data will procure reliable predictive models of burn severity as a function of pre-fire fuel characteristics and landscape configuration along the climatic gradient. However, changes in the dynamics of temporal (fire recurrence and time since last fire) and magnitude (burn severity) fire regime attributes may imply substantial variations in fire behavior due to pre-fire fuel characteristics (e.g., biomass accumulation) control (Pausas and Paula, 2012; Fernández-Guisuraga et al., 2020). In this sense, we anticipate that large fire-free periods and no repeated severe wildfires may promote a significant build-up of flammable fuel types and landscape homogenization, particularly in Mediterranean environments (Moreira et al., 2011), making the landscape more prone to high-severity feedbacks in subsequent wildfires (Fernandes et al., 2016). Nevertheless, we expected that this control would be dependent on the climatic context, as recurrence and fire severity effects are less persistent in humid climates (e.g., Atlantic sites) due to rapid post-fire regeneration (Meng et al., 2018; Fernández-García et al., 2020).

Nonetheless, these feedbacks would not be so clear in WUIs areas (***Article IV***) due to: (i) the coexistence of anthropic elements with different types of fuels, and (ii) differences in fuel accumulation rates and structure with respect to wildland areas (Nielsen-Pincus et al., 2015). As a result, fuel connectedness would determine the occurrence of high severity fires in WUI areas, similar to wildland areas (Collins et al., 2007). Finally, we also expect that burn severity would significantly decrease with building spatial clustering, since fire suppression efforts will become more intensive and fuel load will be lower (Lampin-Maillet et al., 2009; Pastor et al., 2020).

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2

OBJECTIVES

Objectives

The main objective of this PhD Thesis is to develop new multiscale remote sensing tools to characterize spatially the ecological impacts of extreme wildfires on soils, and identify the most relevant pre-fire fuel drivers, as modulated by fire regime, across a climatic gradient in the Iberian Peninsula. We focus especially on wildland-urban-interface (WUI) areas because of their high socioeconomic vulnerability to extreme wildfire events and, we provide scientific-technical basis for decision-making related pre-fire adaptive management.

In particular, the specific objectives are:

- **Specific objective 1.** To identify soil burn severity indicators through spectral products derived from very high spatial resolution multispectral imagery acquired with unmanned aerial vehicle (UAVs). Concretely, we aim:
    - To determine the potential of UAV-derived spectral products to support field assessments of soil burn severity ***(Article I)***.
    - To explore the ability of UAV and satellite multispectral data fusion to predict biophysical properties sensitive to soil burn severity ***(Article II)***.

- **Specific objective 2.** To analyze the link between spatio-temporal variation patterns of fire regime attributes and pre-fire vegetation characteristics, and their joint role in controlling extreme wildfire behavior in landscapes prone to severe wildfires along an Atlantic-Mediterranean climatic gradient using physical-based remote sensing techniques ***(Article III)***. Concretely, we aim:
    - To examine the dynamics of fire regime attributes under different environmental conditions over a 35-year period.
    - To determine which pre-fire vegetation characteristics are the most relevant in controlling fire behavior of subsequent wildfires.
    - To explore how fire regime attributes shapes landscapes prone to high severity wildfires under different climatic contexts.

- **Specific objective 3.** To propose an integrated and generalizable wildland-urban interface (WUI) classification for identifying WUI typologies prone to high burn severity based on building spatial configuration and fuel characteristics ***(Article IV)***. Concretely, we aim:
    - To identify manageable fuel proxies related to extreme burn severity behavior in WUI areas.
    - To classify and characterize WUI typologies prone to extreme fire behavior as a function of pre-fire vegetation drivers and the building density patterns.

- **Specific objective 4.** To generate scientific-based knowledge for pre-fire management in fire-prone ecosystems of the western Mediterranean Basin to reduce high burn severity likelihood of future wildfires in the context of global change, with particular focus on WUI areas ***(General Discussion)***.

Objectives

3

CONCEPTUAL THESIS DIAGRAM

Conceptual Thesis diagram

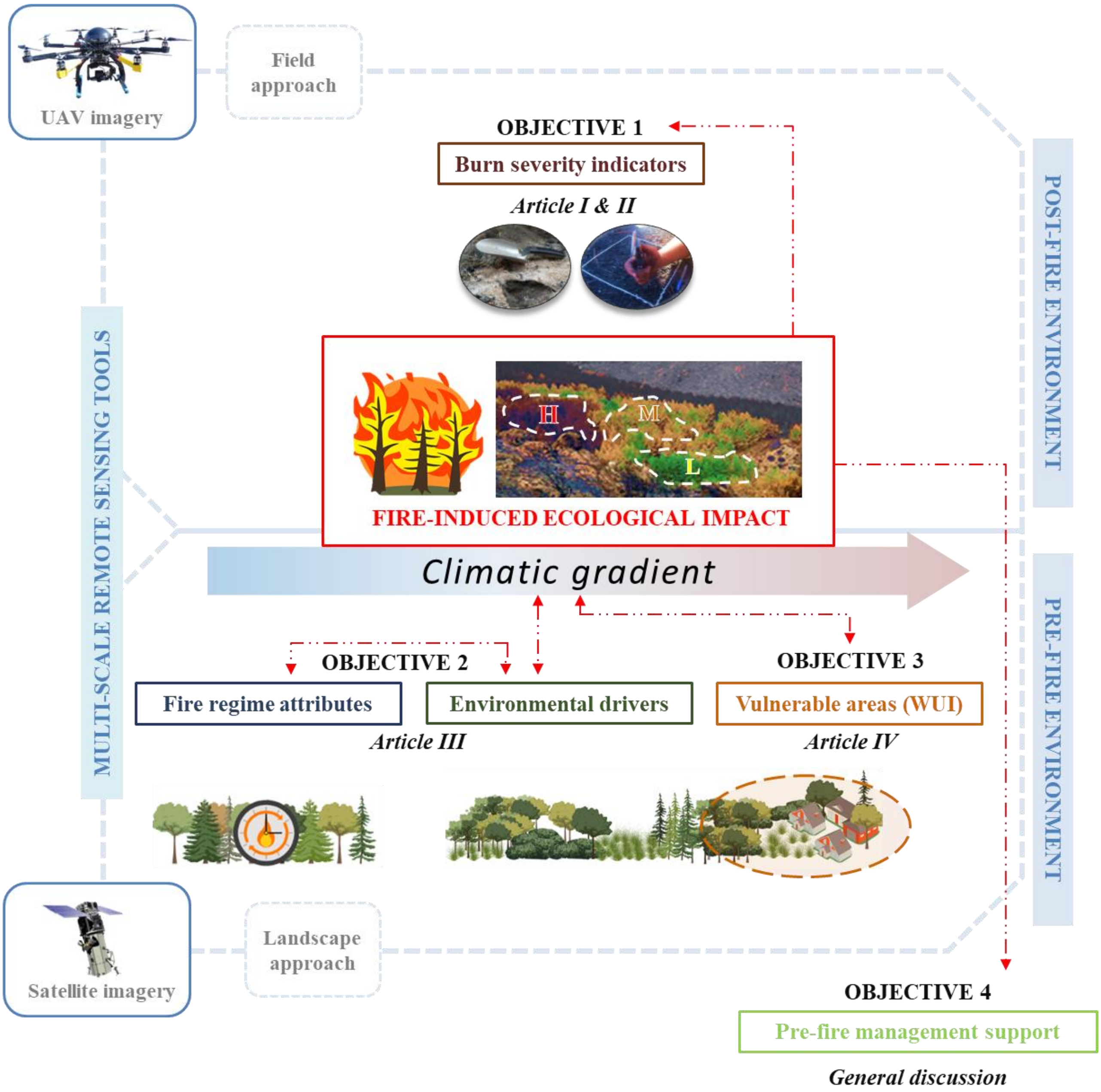

Figure 6. PhD Thesis outline.

Conceptual Thesis diagram

4

STUDY SITES

All wildfire selected as case studies in this PhD Thesis encompass different burn severity scenarios, as well as different topographic, climatic and fuel conditions in the western Mediterranean Basin. The selected 18 wildfires burned 113,989 ha between 2016 and 2022 (Fig. 7). Except for wildfire nº 11 used for Articles I & II, all the wildfires in the Spanish Iberian Peninsula are located along an Atlantic-Transition-Mediterranean climatic gradient and are mainly characterized by: (i) the inclusion of a significant number of urban settlements within their fire perimeter, and (ii) their extensive size and extreme fire behavior, some of them being catalogued as the largest wildfires in the country's history.

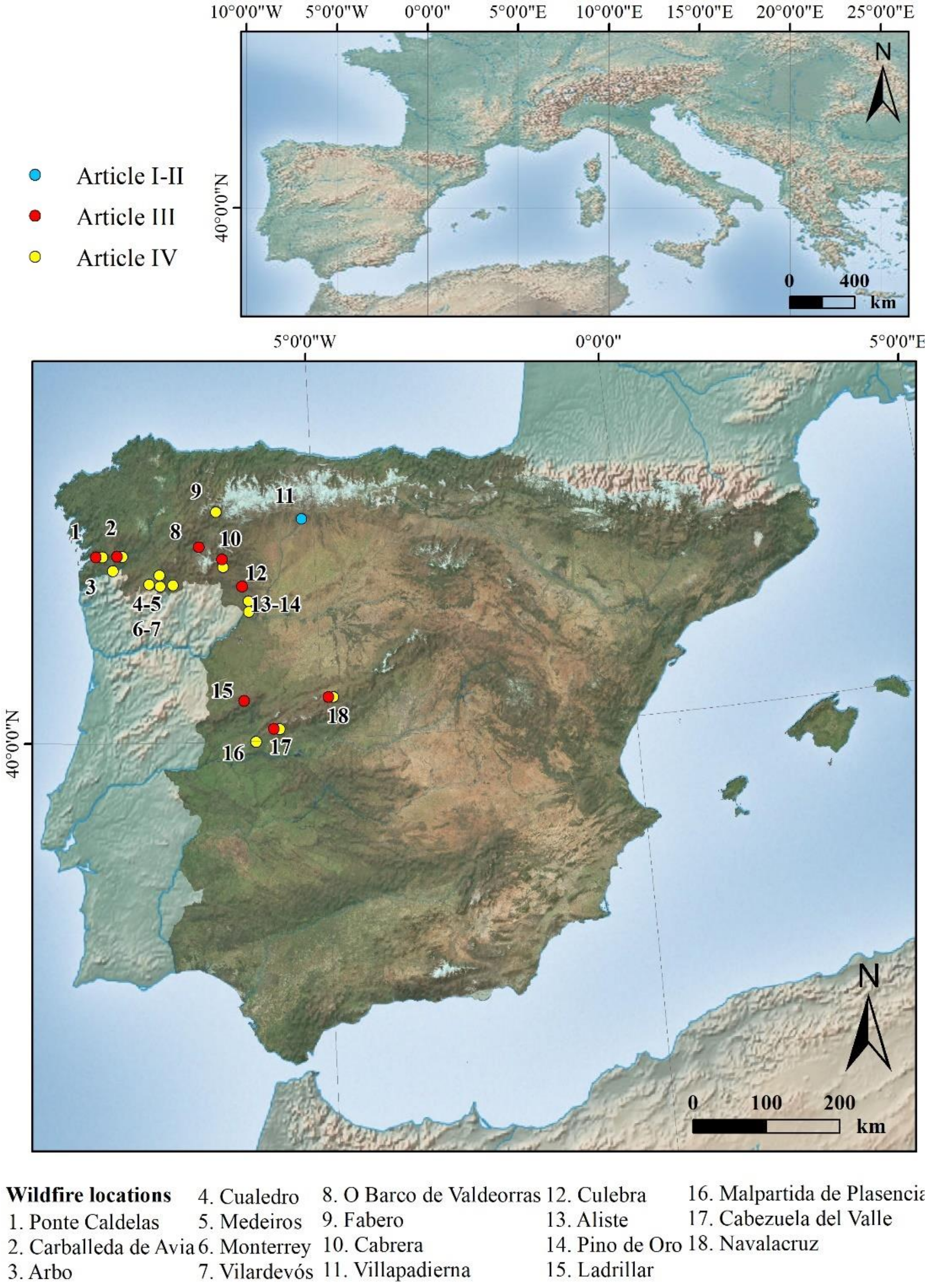

Figure 7. Geographical location of the wildfires included in this PhD Thesis.

In ***Articles I & II*** of the PhD Thesis, the wildfire selected occurred in Villapadierna (Cantabrian Mountain range, León province, NW Spain) on 22 August 2019, and affected 82.47 ha of a complex landscape mosaic. For these studies, a mixed-severity fire was required, where specific field assessments and UAV surveys could be conducted in a small burned area. The dominant burned vegetation types were: (i) extensive mature forest stands of *Quercus pyrenaica* Willd. (35.47 ha) with a dense shrubby understory dominated by heaths, namely *Erica australis* L. and *Erica arborea* L., and H*alimium alyssoides* Lam.; (ii) young forest plantations of *Pinus sylvestris* L. (21.47 ha) and mature forest plantations *Pinus pinaster* (14.45 ha). The fire was mostly a stand-replacing event with a high degree of vegetation consumption, high tree mortality, and residual presence of scorched canopies and living trees. The area affected by the fire has a smooth relief, with elevation ranging between 922-1027 m a.s.l. (ASL), and slopes between 6-27%. Soils are classified as Dystric, Gleyic and Humic Cambisols (ITACYL, 2020), according to the World Reference Base for Soil Resources (WRB) system (Jones et al. 2005). The lithology is dominated by silts, sands, and clays, with conglomerate layers in the lowest areas (IGME, 2020). Climate is Mediterranean with an annual average precipitation of 761 mm, a mean annual temperature of 10.7 °C and 2-3 months of summer drought (Ninyerola et al., 2005).

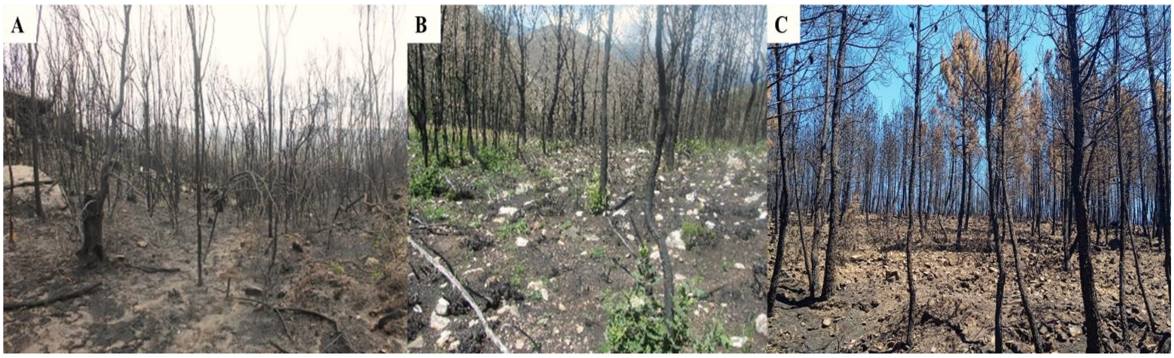

Figure 8. Wildfires of (A) Ponte Caldelas, (B) Cabrera, and (C) Sierra de la Culebra occurred in summer 2017 (A and B) and 2022 (C) in a peninsular climatic gradient.

In the ***Article III***, we selected eight large wildfires along an Atlantic-Transition-Mediterranean climatic gradient occurred between 2017 and 2022 (Fig. 8). In northwestern Spain, we targeted two extreme wildfire events occurred in 2017 in Ponte Caldelas (burned area of 9,440 ha; Pontevedra province, NW Spain) and Carballeda de Avia (burned area of 5,956 ha; Pontevedra province, NW Spain). The rugged topography was covered by plantations of *Pinus pinaster*, *Pinus radiata* D. Don. and *Eucalyptus globulus* Labill., as well as a landscape mosaic made of broadleaf forest mixed with heathlands (*Erica umbellata* Loefl. ex L.), broom (*Cytisus scoparius* L.) and gorse (*Ulex europaeus* L.) shrublands. Moreover, grasslands and cultivated areas near urban settlements were affected. These locations have a typical Atlantic/Oceanic climate with minimal summer drought, 925-1763 mm of annual precipitation on average, and a mean annual temperature of 11-13 °C (Ninyerola et al., 2005). These wildfires were also used in the ***Article IV*** of the PhD Thesis. As representative sites of transition climatic conditions, we selected two large fires that occurred between 2017 and 2022. The first one was the wildfire of Sierra de Cabrera

(León province, NW Spain) that burned 9,940 ha between 21st and 27th August 2017. The area was mainly covered by (i) shrublands dominated by *Erica australis*, *Genista hystrix* Lange., and *Genista florida* L., (ii) tree stands dominated by *Quercus pyrenaica* and *Pinus sylvestris* and, (iii) grasslands on valley bottoms. This wildfire was also selected for the ***Article IV*** of the PhD Thesis. The second one was the wildfire of O Barco de Valdeorras (Ourense province, NW Spain), which burned in 2022 about 12,591 ha dominated by sclerophyllous forests (*Castanea sativa* Mill., *Quercus pyrenaica* and *Quercus ilex* L.), coniferous forests (*Pinus pinaster*, *Pinus radiata* and *Pinus sylvestris*) and shrublands mixed with agricultural lands and grasslands. In both sites, the lithology is siliceous (IGME, 2019). Dominant soils are acidic (ITACYL, 2019), predominantly classified as Cambisols and Leptosols (Jones et al., 2005). The relief in both sites is abrupt, with prominent crests mixed agricultural valleys. These areas are characterized by mean annual precipitation between 600-1500 mm, mean annual temperature between 5-15 °C, and by a summer drought of 2 months, an intermediate period between the Atlantic and Mediterranean climate conditions (Ninyerola et al., 2005). The Mediterranean climatic site encompasses four large fires. The Cabezuela del Valle wildfire (Cáceres province, CW Spain) burned 3,949 ha in August 2020, dominated by broadleaved forests (*Quercus pyrenaica*, and *Castanea sativa*), shrublands (e.g., *Cytisus multiflorus* (L´Hér.) Sweet., *Cistus ladanifer* L., and *Erica* spp.), and grasslands. The Navalacruz wildfire (Ávila province, C Spain), located in the center of Iberian Peninsula, occurred in summer 2021 and burned 22,444 ha of *Pinus sylvestris* and *Quercus ilex* forests, as well as Mediterranean shrublands and grasslands. These wildfires were also used in the ***Article IV*** of the PhD Thesis. In 2022, the wildfires of Ladrillar in the region of Las Hurdes (Cáceres province, CW Spain) and the Sierra de la Culebra (Zamora province, NW Spain) burned 11,927 ha and 25,228 ha, respectively. Both sites are dominated by heathlands (*Erica arborea* and *Erica australis*), and broom (*Genista florida*) shrublands, as well as by *Quercus pyrenaica*, *Quercus ilex*, *Pinus pinaster* and *Pinus sylvestris* forest stands. These study sites show rugged topography, with steep slopes and wide valleys, and have climatic conditions typical of Mediterranean environments, with four months of warm dry summers (Ninyerola et al., 2005).

In the ***Article IV*** of this PhD Thesis, we focus on 14 large wildfires occurred between 2016 and 2021 in the Spanish Iberian Peninsula, mainly characterized by their high proximity to urban settlements. Some of them were already described (Ponte Caldelas, Carballeda de Avia, Sierra de Cabrera, Cabezuela del Valle y Navalacruz) and we will focus here on the new wildfires. In northwestern Spain, under Atlantic environmental conditions, we selected the following wildfires: (i) Arbo (Pontevedra, NW Spain), which burned 2,157 ha in 2016, affecting heathlands and conifer and eucalyptus planatations; (ii) Vilardevós (Ourense, NW Spain) affected 1,292 ha in August 2017, mainly occupied by pine and mixed forests, as well as heathlands and transitional woodlands; (iii) Monterrey (740 ha; Ourense, NW Spain), (iv) Medeiros (1,517 ha; Ourense, NW Spain), and (v) Cualedro (1,353 ha; Ourense, NW Spain) wildfires burned in summer and autumn seasons of 2020 landscape mosaics of heathlands, grasslands, and cultivated areas, seriously affecting WUI areas, resulting in the evacuation of a significant number of municipalities. Under transitional environmental conditions, we focus on the following wildfires: (i) Fabero burned 2,608 ha in 2016 close to populated areas, mostly conifer and deciduous forests, as well as shrublands and crops. Furthermore, in 2017 and 2020, (ii) Pino de Oro and (iii) Aliste (Zamora province, NW Spain) burned 2,858 ha and 1,795 ha of sclerophyllous forests and shrublands mixed with agricultural lands and grasslands, respectively. In the central region of Spain with typical Mediterranean climatic conditions, we selected the wildfire of Malpartida de Plasencia (Cáceres province, CW Spain), which burned in August 2020 about 470 ha of sclerophyllous forests dominated by *Quercus* spp. and woodland-shrubland transition mixed with grasslands.

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5

RESULTS

Article I

Mapping Soil Burn Severity at Very High Spatial Resolution from Unmanned Aerial Vehicles

Article I

Mapping Soil Burn Severity at Very High Spatial Resolution from Unmanned Aerial Vehicles

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ABSTRACT

The evaluation of the effect of burn severity on forest soils is essential to determine the impact of wildfires on a range of key ecological processes, such as nutrient cycling and vegetation recovery. The main objective of this study was to assess the potentiality of different spectral products derived from RGB and multispectral imagery collected by unmanned aerial vehicles (UAVs) at very high spatial resolution for discriminating spatial variations in soil burn severity after a heterogeneous wildfire. In the case study, we chose a mixed-severity fire that occurred in the northwest (NW) of the Iberian Peninsula (Spain) in 2019 that affected 82.74 ha covered by three different types of forests, each dominated by *Pinus pinaster*, *Pinus sylvestris*, and *Quercus pyrenaica*. We evaluated soil burn severity in the field 1 month after the fire using the Composite Burn Soil Index (CBSI), as well as a pool of five individual indicators (ash depth, ash cover, fine debris cover, coarse debris cover, and unstructured soil depth) of easy interpretation. Simultaneously, we operated an unmanned aerial vehicle to obtain RGB and multispectral postfire images, allowing for deriving six spectral indices. Then, we explored the relationship between spectral indices and field soil burn severity metrics by means of univariate proportional odds regression models. These models were used to predict CBSI categories, and classifications were validated through confusion matrices. Results indicated that multispectral indices outperformed RGB indices when assessing soil burn severity, being more strongly related to CBSI than to individual indicators. The Normalized Difference Water Index (NDWI) was the best-performing spectral index for modelling CBSI (R^2cv = 0.69), showing the best ability to predict CBSI categories (overall accuracy = 0.83). Among the individual indicators of soil burn severity, ash depth was the one that achieved the best results, specifically when it was modelled from NDWI (R^2cv = 0.53). This work provides a useful background to design quick and accurate assessments of soil burn severity to be implemented immediately after the fire, which is a key factor to identify priority areas for emergency actions after forest fires.

Keywords*: ash depth; Composite Burn Index; multispectral indices; Normalized Difference Water Index; Parrot SEQUOIA; soil visual indicators; wildfire*

Article II

Relevance of UAV and Sentinel-2 data fusion for estimating topsoil organic carbon after forest fire

Article II

Relevance of UAV and sentinel-2 data fusion for estimating topsoil organic carbon after forest fire

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ABSTRACT

The evaluation at detailed spatial scale of soil status after severe fires may provide useful information on the recovery of burned forest ecosystems. Here, we aimed to assess the potential of combining multispectral imagery at different spectral and spatial resolutions to estimate soil indicators of burn severity. The study was conducted in a burned area located at the northwest of the Iberian Peninsula (Spain). One month after fire, we measured soil burn severity in the field using an adapted protocol of the Composite Burn Index (CBI). Then, we performed soil sampling to analyze three soil properties potentially indicatives of fire-induced changes: mean weight diameter (MWD), soil moisture content (SMC) and soil organic carbon (SOC). Additionally, we collected post-fire imagery from the Sentinel-2A MSI satellite sensor (10 - 20 m of spatial resolution), as well as from a Parrot Sequoia camera on board an unmanned aerial vehicle (UAV; 0.50 m of spatial resolution). A Gram-Schmidt (GS) image sharpening technique was used to increase the spatial resolution of Sentinel-2 bands and to fuse these data with UAV information. The performance of soil parameters as indicators of soil burn severity was determined through a machine learning decision tree, and the relationship between soil indicators and reflectance values (UAV, Sentinel-2 and fused UAV-Sentinel-2 images) was analyzed by means of support vector machine (SVM) regression models. All the considered soil parameters decreased their value with burn severity, but soil moisture content, and, to a lesser extent, soil organic carbon discriminated at best among soil burn severity classes (accuracy= 91.18%; Kappa= 0.82). The performance of reflectance values derived from the fused UAV-Sentinel-2 image to monitor the effects of wildfire on soil characteristics was outstanding, particularly for the case of soil organic carbon content (R^2= 0.52; RPD= 1.47). This study highlights the advantages of combining satellite and UAV images to produce spatially and spectrally enhanced images, which may be relevant for estimating main impacts on soil properties in burned forest areas where emergency actions need to be applied.

Keywords*: soil organic carbon; image fusion; UAV; Sentinel-2; wildfire; soil properties*

HIGHLIGHTS

1. Soil organic carbon is a very effective biophysical parameter to indicate soil burn severity
2. Image sharpening technique showed a notably potential to estimate soil organic carbon accurately
3. UAV products enhance spatial information of satellite imagery
4. Multispectral products fusion provides relevant information of post-fire soil status

Article III

Fire regime attributes shape pre-fire vegetation characteristics controlling extreme fire behavior under different climatic conditions

Article III

Fire regime attributes shape pre-fire vegetation characteristics controlling extreme fire behavior under different climatic conditions

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Article under review in **Science of The Total Environment**

ABSTRACT

Designing effective land management actions addressed to increase ecosystem resilience requires to understand how shifting fire regimes are shaping landscapes under different climatic conditions. In this study, we aim to assess the role of the link between fire regime and pre-fire vegetation biophysical characteristics (type, amount, and structure) in controlling extreme fire behavior along an Atlantic-Transition-Mediterranean climatic gradient. We used remote sensing metrics to estimate fire severity and pre-fire vegetation characteristics in eight study areas recently affected by large and highly severe wildfires under different climatic and ecological conditions. Furthermore, to account for fire regime attributes, we retrieved, for each target wildfire, the perimeter of the past fires occurred between 1985 and 2022 and calculated fire recurrence, time since the last fire and fire severity of the previous wildfire. The effect of fire regime attributes on pre-fire vegetation was examined using generalized linear mixed models. During the study period, fire recurrence decreased significantly along the entire climatic gradient. Fire severity increased under Atlantic conditions and decreased at the Mediterranean end of the gradient, where times since the last fire was the highest. Pre-fire fuel type and amount were identified as primary drivers of fire severity, being both strongly modulated by fire regime depending on the climatic context. In Atlantic sites, more frequent wildfires of low to moderate fire severity drove to fire-prone shrublands accounting for moderate fuel amount, which increases the risk of severe wildfires. Similar trends occurred in Transition and Mediterranean sites but under the previous occurrence of highly severe wildfires. Specifically, long times after highly severe wildfires increased fuel amount in conifer-dominated ecosystems under all climatic contexts, heightening susceptibility to extreme fire behavior. Our findings highlight that adaptative management strategies to mitigate the effects of shifting fire regimes in fire-prone ecosystems should be specific to the climatic and ecological context.

Keywords*: *dNBR, fire history, fire severity, fire recurrence, fuel type, fuel amount,

HIGHLIGHTS

1. Atlantic and Mediterranean sites had different fire histories over the last 35-years
2. Fire regime modulated pre-fire vegetation characteristics driving extreme wildfires
3. Links among fire regime attributes and pre-fire vegetation were climate-dependent
4. Recurrence and severity lead to extreme fire behavior by tree-shrubland transition
5. Long times after severe wildfires drive the highest risk pre-fire situations

Article IV

Wildland-urban interface typologies prone to high severity fires in Spain

Article IV

Wildland-urban interface typologies prone to high severity fires in Spain

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ABSTRACT

Due to complex interactions between climate and land use changes, large forest fires have increased in frequency and severity over the last decades, impacting dramatically on biodiversity and society. In southern European countries affected by demographic challenges, fire risk and danger play special relevance at the wildland-urban interfaces (WUIs), where decision-making and land management have strong socio-ecological implications. WUIs have been historically typified according to both fire occurrence probability and settlement vulnerability, but those classifications lack generality regarding fire regime components. We aim to develop an integrated and comprehensive scheme for identifying the WUI typologies most at risk to fire severity across large territories. We selected fourteen large wildfires (over than 500 ha) occurred in Spain (2016-2021) containing different WUI scenarios. First, based on a building cartography and a multi-temporal series of Sentinel-2 imagery, each WUI was delimited and spatially characterized according to building density and pre-fire fuel characteristics (type, amount, and structure). Afterwards, a decision tree regression model was applied to identify the most relevant pre-fire vegetation parameters driving burn severity. The combined effect of the selected pre-fire vegetation drivers and the building density patterns on fire severity was evaluated using linear mixed models. Finally, the WUI typologies most prone to high burn severity were recognized using Tukey post-hoc tests. Results indicated that building density, land cover class and vegetation cover fraction determined fire severity in areas close to human settlements. Specifically, isolated, scattered and sparsely clustered buildings enclosed in a high-cover shrub matrix were the WUI typologies most susceptible to high-severity fires. These findings contribute to the development of appropriate strategies to minimize the risk of severe fires in WUIs and avoid potential losses of multiple ecosystem services valuable for society.

Keywords; burn severity; large fire; building density; WUI; Sentinel-2; fractional vegetation cover.

HIGHLIGHTS

1. WUIs became a growing concern for forest fire risk and danger in southern Europe
2. Fuel type and load drive the extreme burn severity behaviour in WUIs
3. Fuel continuity has no relevance on classifying WUIs based on high burn severity risk
4. Isolated and scattered buildings highly shrub covered tend to suffer higher severity
5. WUI characterization and adaptative measures could reduce the severe fire threat

6

GENERAL DISCUSSION

Fire behavior has been evolving during the 20th century (Pechony and Shindell, 2010), particularly during the last decades (San-Miguel-Ayanz et al., 2013), leading to increasingly severe wildfires in the context of climate and land use changes in the western Mediterranean Basin (Pausas et al., 2008; Rodrigues et al., 2020; Calheiros et al., 2021). Therefore, the assessment of fire-induced ecological impacts, particularly on forest soils because of their connections with ecosystem functioning and processes rates (Moya et al., 2019; Fernández, 2023), is of utmost importance to provide the scientific basis for adaptive post-fire management strategies aimed at promoting the resilience of wildfire-prone ecosystems (Viedma et al., 2020; Fernández-García et al., 2022). In this context, the pre- and post-fire characterization of forest structures associated with high burn severity likelihood requires the implementation of accurate remote sensing techniques together with field assessments and ecological modelling (Lentile et al., 2006; Matin et al., 2017; Fernández-Guisuraga et al., 2022a). These approaches are particularly relevant when considering critical ecosystem compartments such as forest soils (Mallinis et al., 2016; Torresan et al., 2017), or areas of particular socioeconomic vulnerability such as the WUI (Sirca et al., 2017), where reliable assessments are deemed necessary to provide valuable guidelines for public safety (Safford et al., 2009; Fernandes, 2013). The findings of this PhD Thesis contribute to the development of advanced remote sensing techniques and geospatial approaches (i) to comprehensively assess burn severity in forest soils, including UAV and satellite image fusion techniques, and (ii) to characterize biophysical contexts leading to extreme fire behavior in fire-prone ecosystems of the western Mediterranean Basin, including highly vulnerable areas such as WUIs.

Soil burn severity assessment and characterization of biophysical contexts conducive to extreme fire behavior by using passive remote sensing techniques

Passive remote sensors are highly sensitive to spectral changes caused by wildfires (Mallinis et al., 2018), which are mainly linked to vegetation consumption and char signal (Lentile et al., 2006). These spectral changes not only provide useful feedback on burn severity, but also on post-fire recovery dynamics over time (Meng et al., 2018), which will determine the need for post-fire restoration actions to recover the functions and services provided by the ecosystems (Jain et al., 2012; Fernández and Vega, 2016). The results of this PhD Thesis evidenced that high spatial resolution imagery obtained by UAVs can accurately capture the spectral variability associated to soil burn severity in complex burned landscapes, where different pre-fire vegetation types induced a high spatial heterogeneity of fire-induced ecological effects. In particular, spectral indices such as NDWI or NDVI obtained by a multispectral sensor aboard the UAV platform performed better than indices based exclusively on the RGB domain to assess soil burn severity. These spectral indices have already been reported as adequate for establishing relationships between field measurements of soil burn severity and remotely sensed data derived from Sentinel-2 MSI and Landsat-7 ETM+ satellite imagery (Marcos et al., 2018; Sobrino et al., 2019), including in post-fire assessments conducted in WUI areas (Efthimiou et al., 2020). However, the obtention of wall-to-wall soil burn severity estimates based on specific field measurements, such as visual indicators (either individually or integrated within an integrative index such as the CBSI), is more realistic when using UAV imagery due to the fine-scale spatial variation of post-fire soil constituents at the centimeter scale (Johnstone and Chapin, 2006; Fraser et al., 2017), being this PhD Thesis pioneering to this purpose. In this regard, NDWI better modelled and classified soil burn severity through the CBSI index, which integrates biophysical factors such as fine and coarse debris consumed, ash color or char depth, rather than easily interpreted visual indicators (Vega et al., 2013; Morgan et al., 2014). Among the latter, ash depth and cover were the best variables individually related to UAV-derived products, in line with the findings of previous studies (Smith et al., 2005; Robichaud et al., 2007; Hudak et al., 2013).

Although the results of this PhD Thesis evidenced that products at very high spatial resolution are effective for predicting visual indicators of fire effects on soils, UAV multispectral imagery with limited spectral resolution are not accurate enough to evaluate the fire impact on soil biophysical properties (Soriano-Disla et al., 2017). In this respect, passive optical sensors spanning spectral bands in the SWIR region have been reported to improve the prediction of soil properties (Crucil et al., 2019), even in highly heterogeneous environments (Lewis et al., 2008; Dindaroglu et al., 2021). To solve this shortcoming, this PhD Thesis is pioneer in using image sharpening techniques to fuse post-fire UAV multispectral imagery with Sentinel-2 MSI satellite scenes, overcoming the limited UAV spectral resolution and providing enhanced images at high spatial and spectral resolution. These fused images demonstrated a remarkable potential for predicting soil properties highly related to fire behavior, such as soil organic carbon (SOC). These results are in accordance with the recent findings of Brook et al. (2022), who reported that SOC content can be used as a reliable burn severity indicator. Besides SOC, we observed that soil moisture content (SMC) also exhibited noteworthy variations between low-moderate and high soil burn severity, although its estimation performed poorly in all remotely-sensed datasets used. This could be attributed to SMC temporal variability (even during a single day) in burned areas, as other authors have already reported (Gómez-Plaza et al., 2000; Baroni et al., 2013). The aforementioned circumstance, in conjunction with the delay between the timing of the UAV surveys and Sentinel-2 imagery acquisition, may add a degree of uncertainty in the SMC prediction outcomes. Nevertheless, we evidenced that UAV and Sentinel-2 multispectral image fusion have a remarkable potential to procure wall-to-wall soil burn severity estimates in heterogeneous burned areas, and appear to be a potential alternative to increase estimation accuracy in large-scale assessments of fire-induced damage on other ecosystem compartments, such as the vegetation canopies.

Besides post-fire burn severity assessments, UAV remote sensing data can be implemented to assess the risk of extreme fire behavior in the pre-fire stage (Keerthinathan et al., 2023), i.e., by estimating fuel amount (Carvajal-Ramírez et al., 2019) or classification of flammable vegetation (Carbonell-Rivera et al., 2022). Indeed, high-resolution data offered by UAV acquisitions have been useful in identifying wildfire hazard in highly vulnerable areas such as WUI areas (Fernández-Álvarez et al., 2019; Polinova et al., 2019), where a fine-scale analysis of vegetation types, fuel density, and building locations is essential for accurate risk assessment and mitigation planning (Keerthinathan et al., 2023). Nonetheless, satellite imagery at moderate spatial resolution, such as Sentinel-2 MSI (10-20 m of spatial resolution), are more suitable for vegetation surveys over very large areas (Chuvieco et al., 2020), as it is less time-consuming and more cost-effective than UAV approaches (Keerthinathan et al., 2023). Indeed, the retrieval of vegetation biophysical parameters through physical-based methods applied to satellite imagery may procure a high accuracy and generalization ability (Fernández-Guisuraga et al., 2021a).

This fact is in line with the results of the PhD Thesis, in which the characterization of pre-fire fuel metrics by using physical-based methods applied to multispectral Sentinel-2 MSI data enabled the identification of biophysical contexts conducive to extreme fire behavior under different climatic conditions, particularly in WUI areas. Indeed, the retrieval of biophysical variables such as FCOV or FAPAR through radiative transfer models (RTMs) allowed us to identify fuel amount as the most important proxy for controlling extreme fire behavior both in wildland (García-Llamas et al., 2019; 2020; Viedma et al., 2020; Fernández-García et al., 2022), and in WUI (Fernández-García et al., 2023) areas. These biophysical properties are crucial to characterize the fuel amount in pre- and post-fire environmental assessments in a wide variety shrubland and forest ecosystems (Chu et al., 2016; Verrelst et al., 2019; Fernández-Guisuraga et al., 2021a), providing realistic simulated spectra that are highly correlated with field measurements (Walker et al., 2020; Fernández-Guisuraga et al., 2023a). Moreover, we evidenced that burn severity was not only controlled by the variability of pre-fire vegetation amount, but also by the climate context and dominant ecosystem type, which was successfully identified by pixel classification techniques (Fernández-Guisuraga et al., 2021b Basheer et al., 2022). In contrast, textural features or patch metrics characterizing the horizontal spatial arrangement of the different fuel types were not particularly relevant in the prediction of high burn severity in wildland and WUI areas, probably because these metrics are more related to the biopsychical conditions conducive to fire spread than to burn severity (Fernandes et al., 2016). Nevertheless, FCOV homogeneity improved the prediction of burn severity exclusively in highly clustered WUIs, where vegetation structural characteristics are likely to be affected by human activity (Nielsen-Pincus et al., 2015). Regarding climatic contexts, the accuracy of remote sensing proxies related to pre-fire vegetation characteristics in predicting fire behavior was stronger under Transition and Mediterranean climatic conditions as compared to Atlantic areas. This may be partially explained by the significance of fire weather variables in most humid and productive regions (weather-limited fire regimes), as other authors have previously reported (Fernández-Alonso et al., 2017; Arellano-Pérez et al., 2018). Nonetheless, in this PhD Thesis we have only considered manageable fuel-related variables derived from satellite imagery, and essential to design pre-fire planning actions aimed at mitigating extreme fire behavior in wildland and WUI areas (Fernández-García et al., 2022; 2023). In this sense, we identified dense conifer stands and intermediate-high fuel amounts in shrublands as the vegetation types most prone to severe wildfires in Transition-Mediterranean and Atlantic areas, respectively. Specifically, the remote sensing techniques used in this PhD Thesis could establish a comprehensive and generalizable classification of susceptibility to extreme fire behavior in WUI areas, where typologies associated to low building densities and high fractional cover of shrubland vegetation type were more prone to severe wildfires. The implications of these finding will be discussed further in the next section.

Time series of historical satellite imagery from Landsat missions (TM, ETM +, and OLI sensors) was also essential to characterize fire regimes in the study sites, and, subsequently, how fire regime attributes have shaped landscapes prone to high fire severity along the climate gradient. Specifically, monthly visual analysis of Landsat images from 1985 to 2022 using false color composites (RGB 541 bands for TM and ETM+ sensors, and 652 for the OLI sensor) allowed an accurate mapping of wildfire scars (Fernández-García et al., 2018; 2020) and computing temporal attributes of the fire regime (i.e., fire recurrence and time since last fire; TSLF). Additionally, recent geospatial tools such as Google Earth Engine (GEE; Gorelick et al., 2017) facilitated the estimation of the variation in fire-induced ecological impacts over the time series, observing a different behavior as a function of the climatic context. In this sense, we observed an upward trend in burn severity in Atlantic areas, as opposed to that found under Transition or Mediterranean environmental conditions. This may be associated to the ecological context of Atlantic areas, which generally show high fuel build-up rates of fast-recovering resprouting species after short fire-free intervals (Pausas and Keeley, 2014; Fernández-García et al., 2020), together with the increase in extreme fire weather conditions in weather-limited areas (Cardil et al., 2015; Calheiros et al., 2021).

Scientific-based support for pre-fire management in non-WUI and WUI areas

Extreme wildfire events, whose frequency is increasing higher than expected as a consequence of global change (Dupuy et al., 2020; Rodrigues et al., 2020), may impair the provision of ecosystem services such as soil conservation, carbon storage or biodiversity (Huerta et al., 2022). In this regard, national and international organizations (e.g., Camia et al., 2017) encourage the investment, development, and implementation of proactive decision support tools for the minimization of drastic ecological consequences promoted by severe wildfires. Nonetheless, strategic wildfires policies are still only partially addressed, which implies the need for a common action framework (Pastor et al., 2020). In this sense, the mapping of soil burn severity by different remote sensing techniques evidenced in this PhD Thesis provides a useful background to design quick and accurate post-fire assessments, which is especially relevant for estimating areas where emergency actions should be focused. Thus, in patches of high soil burn severity would be advisable to avoid both soil tillage and intensive grazing (Moreira et al., 2011; Fernández and Vega, 2016), as well as to promote straw mulching treatment (Huerta et al., 2022) and the establishment of anti-erosion log barriers that can increase water retention and the incorporation of available nutrients into the severely damaged soils (Robichaud et al., 2007; Moody et al., 2013). Moreover, the scientific knowledge generated in this PhD Thesis could also aim to assist land managers in optimizing fire-smart forestry practices that seek to reduce hazardous fuel accumulations and modify the fuel structure, thus increasing forest resistance and resilience to future extreme wildfire events (Fernandes,2013; García-Llamas et al., 2020).

The evidenced decrease in this PhD Thesis of fire recurrence over the last 35-years in all climatic contexts, probably associated with wildfire suppression policies (Ruffault and Mouillot, 2015), may be an important determinant of gradual fuel build-up and thus of large and severe wildfire occurrence (Duane et al., 2021). We identified dense shrublands and conifer stands to be the vegetation types most prone to extreme fire behavior wildfires. Consequently, pre-fire management actions should be targeted at reducing the fuel amount in these vegetation types (Moreira et al., 2011; Fernández-García et al., 2022). For this purpose, land managers may use wall-to-wall assessments with physical basis conducted in the PhD Thesis, with low dependence on field data (Fernández-Guisuraga et al., 2021a), to prioritize intervention areas. In this sense, the management of dense and flammable shrublands must be a priority to avoid the perpetuation of high-severity patches prone to recurrent fire feedbacks (van Wagtendonk et al., 2012), as this may foster transitions to shrubland stable states prone to high fire severity in subsequent wildfires. For this purpose, prescribed burning treatments and frequent mechanical clearing activities have been found to be highly effective in generating uneven-aged shrubland patches for mitigating fire behavior by enhancing landscape heterogeneity while reducing fuel load (Valkó et al., 2014). Specifically, these strategies should focus on mature and dense shrubland stands located for intermediate site productivity in Atlantic areas, and to a lesser extent under Transitional or Mediterranean conditions, since were situations highly prone to severe wildfires (Fernández-Alonso et al., 2017; García-Llamas et al., 2019; Fernández-Guisuraga et al., 2021b). Concerning the coniferous stands, pine forests with high fuel continuity were the most prone vegetation type to extreme fire behavior under Transition and Mediterranean environmental conditions, which may be related to the presence of dense, ladder fuels in the understory of unmanaged stands with high crowning potential (Fernandes and Rigolot, 2007; Kane et al., 2015; García-Llamas et al., 2020; Fernández-Guisuraga et al., 2021a, 2023b). High post-fire seedling recruitment after severe wildfires in these regions, together with long fire-free periods, may be responsible for the accumulation of flammable fuels that are likely to undergo high severity feedbacks in subsequent wildfires. Therefore, the implementation of different silvicultural practices such as (i) pruning and removal of low and dead branches to raise the base height of the canopy and avoid ladder fuels (Fernández-Guisuraga et al., 2021b), (ii) breaking vertical continuity by reducing fuel accumulation in the understory (Fernandes, 2013), and (iii) thinning the stand combined with low to moderate intensity prescribed fires to create open patches and reduce the canopy horizontal continuity (Moreira et al., 2011; García-Llamas et al., 2020; Viedma et al., 2020), must be priority actions. Furthermore, the prevention of extreme wildfires may be also facilitated through the establishment of heterogeneous landscape mosaics, with distinct vegetation types and tree cover densities (Fernandes, 2013). A landscape characterized by resilient vegetation mosaics effectively maintained in areas with long fire-free periods, would not only serve as an effective measure to reduce wildfire hazard, but also enhance the potential of ecosystem services’ provision (Moghli et al., 2022). In this sense, the promotion of fuel-type conversion under reforestation policies after wildfires with less flammable vegetation types (Dimitrakopoulos and Papaioannou, 2001) may provide an opportunity to promote fuel-limited woodlands with strong post-fire resilience and resistance to fire (Fernandes, 2013). Additionally, recovery of traditional land uses such as extensive livestock farming would allow for better landscape management by avoiding large continuities of shrub fuels prone to high severity (García-Llamas et al., 2019: 2020; Viedma et al., 2020). Moreover, these actuations are a priority in areas with high rural abandonment, where landscape fragmentation may impair large fire spread and intensity (Azevedo et al., 2011).

The identification in this PhD Thesis of priority scenarios for effective land use planning, wildfire prevention and management strategies, community education, and collaborative efforts in WUI areas are essential to address the challenges posed by new-generation wildfires to population in rural areas (Chas-Amil et al., 2013; Modugno et al., 2016; Samara et al., 2018; Pastor et al., 2020). Besides the management strategies abovementioned for wildland areas, we emphasize that the reduction of homogeneous fuel types, particularly shrub fuels around isolated and dispersed WUIs must be a priority intervention line. These actions should focus on breaking the fuel horizontal continuity and encouraging the development of diverse landscape mosaics to foster resistance and resilience to fire (Fernandes, 2013). This can be achieved by supporting sustainable and traditional activities such as extensive livestock grazing or silvicultural actions by work crews, which is essential for population fixation in sociologically relevant areas such as WUIs.

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7

CONCLUSIONS

Burn severity indicators in forest soils

1) Multispectral products, such as the NDWI index, are well suited to characterize spatial variation on soil burn severity at fine scales when derived from very high spatial resolution imagery obtained with UAV technology. These multispectral products are more correlated with integrated field measurements, such as the composite multi-parameter soil burn severity index (CBSI), than with individual indicators. Nonetheless, ash depth and ash cover are the visual indicators that reflect most accurately fire-induced ecological impact on forest soil.
2) Soil organic carbon and soil moisture content are effective biophysical parameters to indicate soil burn severity in heterogeneous burned areas but cannot be predicted with exclusively UAV-derived data. However, the fusion of multispectral satellite and UAV data through image sharpening techniques shows remarkable potential to provide accurate soil status information after mixed-severity wildfires.

Link between fire regime attributes and pre-fire vegetation characteristics that drive bun severity in extreme wildfires

3) Satellite time-series data at high spatial resolution reveal a decreasing trend in fire recurrence along the Atlantic-Transition-Mediterranean climatic gradient, as well as an increase in burn severity under Atlantic conditions. Fire regime attributes strongly modulate pre-fire vegetation characteristics that shape landscapes prone to high fire severity, being the underlying mechanisms climate-dependent.
4) Pre-fire fuel type and amount are the primary drivers of burn severity across the climatic gradient. Extreme fire behaviour is controlled by the presence of dense and closed coniferous stands, under Mediterranean and Transitional conditions, and by intermediate-high shrub amount, under Atlantic conditions, where very dense live biomass suffer flammability limitations caused by high moisture loads under mesic environments.
5) In all climatic conditions, long times after high-severity wildfire disturbances enhance fuel build-up of conifer-type fuels, and, thus, proneness to subsequent severe fire behavior. In Atlantic sites, high fire recurrence, even at low to moderate fire severity, induces transitions to shrubland stable ecosystem states with intermediate fuel amount and perpetuates fire-prone vegetation types. The same behavior is evidenced in shrublands of Transition and Mediterranean sites after high fire severity wildfires.

Vulnerability of wildland-urban interfaces to high severity fires

6) In WUI areas, the most at-risk typologies, in terms of suffering an extreme fire behavior, rely largely on fuel type and amount, as well as on the configuration of building aggregations. Horizontal fuel structure has been particularly useful in explaining fire risk, in terms of ignition density and proportion of area burned, but does not show great relevance for understanding spatial variations in burn severity.

7) Low building density enclosed into a homogeneous and dense pre-fire shrubland matrix defines the WUI typology most prone to high burn severity. In addition, interface areas dominated by forest fuel with low vegetation cover values, which often have a dense and continuous understory of small shrubs, is another key typology prone to extreme fire behavior.

Science-based implications for pre-fire management decision-making

8) General actions aimed at reducing the risk of extreme wildfires should involve, under all climatic conditions, a reduction of fuel density in coniferous stands through thinning, pruning or clearing techniques, mainly after long fire-free periods. In Atlantic areas and, to a lesser extent, in Transitional or Mediterranean sites, it is also advisable to thin mature shrub accumulation and create uneven-aged vegetation patches by combining clearing with prescribed burning. These actions should create breaks in ladder fuel continuity and increase landscape heterogeneity, which helps to reduce the probability of crown fires and mitigate extreme fire behaviour.
9) In WUI areas, the priority line of intervention is the increase of landscape heterogeneity, mainly in isolated and dispersed WUIs enclosed in high-cover shrub matrices. Supporting sustainable and traditional agroforestry and pastoral activities in rural areas is key, not only for population fixation, but also for enabling landscape management that hinders large and severe wildfires.

8

CONCLUSIONES

Indicadores de severidad en suelos forestales

1) Los productos multiespectrales, como el índice NDWI, son muy adecuados para caracterizar la variación espacial de la severidad del suelo a escala fina cuando se obtienen a partir de imágenes de muy alta resolución espacial obtenidas con tecnología UAV. Estos productos multiespectrales están más correlacionados con las mediciones de campo integradas, como el índice compuesto multiparamétrico de severidad del fuego en el suelo (CBSI), que con indicadores individuales. No obstante, la profundidad y la cobertura de ceniza son los indicadores visuales que reflejan con mayor precisión el impacto ecológico inducido por el fuego en el suelo forestal.
2) El carbono orgánico del suelo y el contenido de humedad del suelo son parámetros biofísicos eficaces para indicar la severidad del suelo en áreas quemadas heterogéneas, pero no pueden predecirse exclusivamente con datos obtenidos mediante UAV. Sin embargo, la fusión de datos multiespectrales de satélite y de UAV mediante técnicas “pansharpening” muestra un potencial notable para proporcionar información precisa sobre el estado del suelo tras incendios forestales de severidad mixta.

Relación entre los atributos del régimen de incendios y las características de la vegetación previas al incendio que determinan la severidad de los incendios forestales extremos

3) Los datos de series temporales de satélites de alta resolución espacial revelan una tendencia decreciente en la recurrencia de incendios a lo largo del gradiente climático Atlántico-Transición-Mediterráneo, así como un aumento en la severidad en condiciones Atlánticas. Los atributos del régimen de incendios modulan fuertemente las características de la vegetación previas al incendio que dan forma a los paisajes propensos a una alta severidad del fuego, siendo los mecanismos subyacentes dependientes del clima.
4) El tipo y la cantidad de combustible previo al incendio son los principales factores determinantes de la severidad en todo el gradiente climático. El comportamiento extremo del fuego está controlado por la presencia de masas densas y cerradas de coníferas, en condiciones Mediterráneas y de Transición, y por la cantidad intermedia-alta de arbustos, en condiciones Atlánticas, donde la biomasa viva muy densa sufre limitaciones de inflamabilidad causadas por las altas cargas de humedad en ambientes mésicos.
5) En todas las condiciones climáticas, los largos periodos de tiempo que transcurren tras los incendios forestales de alta severidad aumentan la acumulación de combustibles de tipo coníferas y, por tanto, la propensión a incendios severos posteriores. En las zonas Atlánticas, la alta recurrencia de incendios, incluso de baja a moderada severidad, induce transiciones a estados estables del ecosistema de matorral con una cantidad intermedia de combustible, perpetuando los tipos de vegetación propensos al fuego. El mismo comportamiento se evidencia en matorrales de sitios de Transición y Mediterráneos tras incendios forestales de alta severidad.

Vulnerabilidad de las interfaces urbano-forestal ante incendios de alta severidad

6) En las zonas WUI, las tipologías de mayor riesgo, en términos de sufrir un comportamiento extremo del fuego, dependen en gran medida del tipo y la cantidad de combustible, así como de la configuración de las agrupaciones de edificios. La estructura horizontal del combustible ha sido particularmente útil para explicar el riesgo de incendio, en términos de densidad de ignición y proporción de superficie quemada, pero no muestra gran relevancia para comprender las variaciones espaciales en la severidad del fuego.
7) La baja densidad de construcción encerrada en una matriz de matorral homogénea y densa previa al incendio define la tipología WUI más propensa a incendios de alta severidad. Además, las zonas de interfaz dominadas por el combustible forestal con valores bajos de cubierta vegetal, que a menudo tienen un sotobosque denso y continuo de pequeños arbustos, es otra tipología clave propensa a un comportamiento extremo del fuego.

Implicaciones de base científica en la gestión pre-incendio

8) Las acciones generales destinadas a reducir el riesgo de incendios forestales extremos deberían implicar, en todas las condiciones climáticas, una reducción de la densidad del combustible en las masas de coníferas mediante técnicas de aclareo, poda o desbroce, principalmente tras largos periodos sin incendios. En las zonas Atlánticas y, en menor medida, en los lugares de Transición o Mediterráneos, también es aconsejable aclarar la acumulación de arbustos maduros y crear manchas de vegetación de edad desigual combinando la limpieza con la quema prescrita. Estas acciones deberían crear rupturas en la continuidad del combustible de escalera y aumentar la heterogeneidad del paisaje, lo que ayuda a reducir la probabilidad de incendios de copa y a mitigar el comportamiento extremo del fuego.
9) En las zonas WUI, la línea prioritaria de intervención es el aumento de la heterogeneidad del paisaje, principalmente en WUI aisladas y dispersas encerradas en matrices arbustivas de alta cobertura. El apoyo a las actividades agroforestales y pastorales sostenibles y tradicionales en las zonas rurales es clave, no sólo para la fijación de población, sino también para posibilitar una gestión del paisaje que dificulte los incendios forestales grandes y muy severos.

9. AGRADECIMIENTOS

9

AGRADECIMIENTOS

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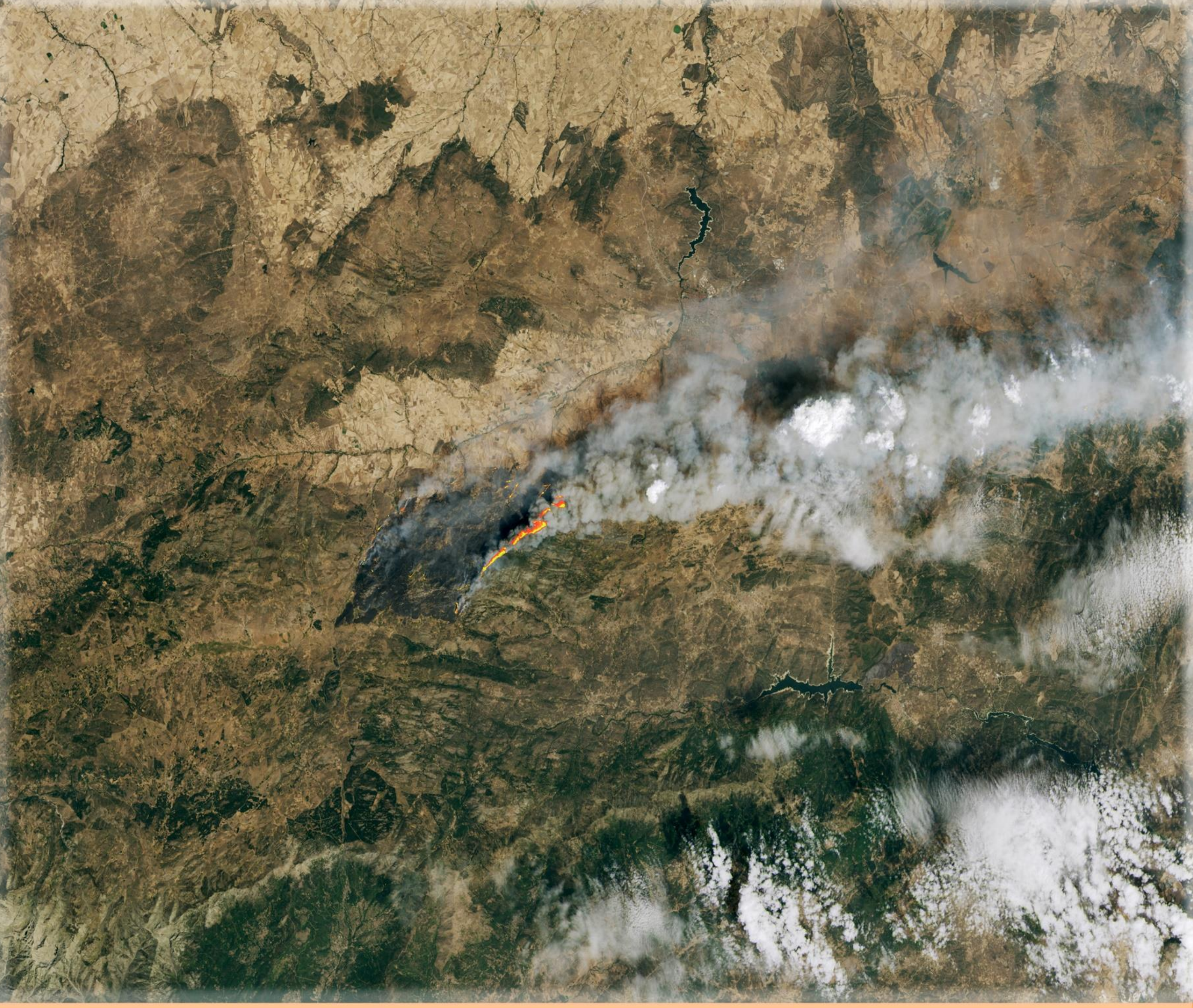

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