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Monitoring ecological impacts of large wildfires through novel multiscale remote sensing techniques

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Monitoring ecological impacts of large wildfires through novel multiscale remote sensing techniques

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Tesis Doctoral

Evaluación del impacto ecológico de grandes incendios forestales mediante nuevas técnicas de teledetección multiescala

Estudiante de Doctorado

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para optar al grado de doctor por la Universidad de León

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"In all human affairs there are efforts, and there are results, and the strength of the effort is the measure of the result"

"En todos los asuntos humanos hay esfuerzos, y hay resultados, y la fortaleza del esfuerzo es la medida del resultado"

James Allen

Dedicated to my children, Alma and Yahel

Dedicado a mis hijos, Alma y Yahel

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ABSTRACT

In recent decades, land use changes, anthropogenic climate warming and a lack of appropriate forest policies aimed at enhancing global change adaptation of terrestrial vegetation in the long term, have resulted in abrupt shifts in the fire regime of Mediterranean Basin ecosystems, promoting the development of fire-prone forest stands with increasing fuel load and continuity. In this context, the assessment of wildfire impacts in the composition, structure and functioning of forest ecosystems in the Mediterranean Basin, and how they recover towards its pre-fire state, is critical for endorsing adaptive management strategies that promote ecosystem resilience in the global change context. Field work methods are highly reliable for this purpose, but they are labor-intensive and time-consuming for large scale application. Hence, the synoptic nature of remote sensing earth observations offers nowadays an efficient way to achieve this goal. The main objective of the PhD Thesis was to evaluate the potential of novel multiscale remote sensing techniques (RST) for monitoring ecological impacts of large wildfires in fire prone landscapes of the western Mediterranean Basin, under different fire regime scenarios.

First, we have assessed fire regime effects of large wildfires on the vegetation structure and ecological interactions of heterogeneous burned landscapes across the western Mediterranean Basin through multispectral remote sensing data at different spatial resolutions (***Article I, II and III***). In the ***Article I***, we found that texture metrics computed from WorldView-2 satellite imagery at high spatial resolution accurately captured in empirical models the fine scale of variation of vegetation structure in pine ecosystems dominated by *Pinus pinaster* Ait. This approach enabled, under different fire recurrence and severity scenarios, separate modeling of vegetation structure variables both at the level of the tree population (density and cover) and the understory community (cover, height and richness). However, the generalization of the modeled relationships with empirical models to other ecosystems in distinct geographical or climatic contexts must be assessed through transferability analyses. Physical methods based on the hybrid inversion of radiative transfer models (RTMs) were used in the ***Article II*** as a novel RST to retrieve fractional vegetation cover (FVC) from high spatial resolution WorldView-3 satellite imagery, as an indicator of fire effects on the horizontal structure of the vegetation in a complex burned landscape encompassing a wide range of shrub and forest ecosystems. Satellite imagery at moderate spatial resolution (Sentinel-2) were used as benchmark in the RTM approach. The accuracy of the FVC estimates retrieved from high spatial resolution imagery was markedly high, considering the great spatial heterogeneity of the landscape and the low reliance of this RST on field data. However, the use of moderate spatial resolution satellite data induced noticeable FVC under and overestimation errors. Transferability analyses are not required with the RTM approach, but separate modeling of vegetation structural parameters at several compartments in the ecosystem was restricted. Thus, empirical models and hybrid inversion of RTMs feature limitations and strengths that can be complementary for monitoring fire effects on the vegetation structure of fire-prone landscapes. Unmanned aerial vehicle (UAV) data were used in the ***Article III*** for quantifying intra-specific competitive interactions in the pine saplings population of burned ecosystems dominated by *Pinus pinaster* and *Pinus halepensis* Mill., as well as inter-specific competition exerted by the understory shrub species according to their regenerative traits (seeders *vs* resprouters) as a response to the fire disturbance regime. The fusion of multispectral and height information at very high spatial resolution derived from a UAV photogrammetry workflow featured a high accuracy in plant species mapping and enabled to characterize reliably vegetation cover and height at individual plant species level. This approach revealed that intra-specific competition in pine saplings population was not a relevant interaction at short-term after the wildfire, whereas the growth of pine saplings was non-linearly impacted by inter-specific competition with shrub species. Seeder shrub species exerted more intense competition effects in open post-disturbance habitats against densely vegetated areas, where resprouter species featured competitive advantages. Despite the opportunities of UAV platforms for measuring ecological processes at fine spatial scales, several challenges were encountered in the acquisition and processing of large volumes of UAV data at very high spatial resolution (***Article IV***). The correction of radiometric anomalies in the imagery collected by a novel UAV camera was an unaffordable task when dealing with large imagery datasets, and the computational demand of the photogrammetry workflow was very high. Nevertheless, these challenges did not affect the capability of the UAV imagery to provide scale-appropriate data both to capture ground spatial variability in fire prone landscapes and ecological processes at plant species level.

The attainment of transferable ecological models for supporting anticipatory predictions instead of explanatory models is crucial to enhance the efficiency of post-fire management actions, which are broadly context dependent. The effects of the fire regime and the environmental conditions on the transferability of empirical vegetation structure models were assessed both between burned landscapes within a climatic gradient (***Article V***) and between fire recurrence scenarios within burned areas (***Article VI***). The distribution and abundance of seeder and resprouter species as a response to the fire

disturbance regime and environmental conditions had a significant impact on model transferability performance. Empirical models exhibited the highest transferability between burned areas with a more similar vegetation community composition and, therefore, with comparable spectral profiles arising from the species assemblage according to their regenerative traits. Also, the use of fine-grained remote sensing data improved transferability of the modeled empirical relationships.

The post-fire recovery trajectories and resilience of fire-prone ecosystems as a function of the fire regime were studied through generalizable remote sensing techniques with physical basis (pixel unmixing models and RTM) applied to multispectral satellite imagery at several spatial resolutions (***Article VII and Article VIII***). Pixel unmixing models based on multiple endmember spectral mixture analysis (MESMA) accurately retrieved FVC as a resilience indicator in a *Pinus pinaster* forest. Vegetation cover estimated by MESMA from high spatial resolution satellite imagery (WorldView-2) only slightly outperformed the estimation from moderate spatial resolution satellite imagery (Landsat). Remarkably, the hybrid inversion of RTM was a more reliable alternative for quantifying ecosystem resilience in extensive landscapes than pixel unmixing models, since the RTM parametrization is not ecosystem-specific and does not require to account for spatiotemporal changes in biophysical conditions of different land cover types. However, RTM approach should be based on remote sensing data at high spatial resolution to capture subpixel level arrangement of vegetation legacies. Ecosystems dominated by resprouter species such as heathlands of *Erica australis* L., affected by recurrent wildfires, featured a higher resilience to fire than facultative or obligate seeders-dominated ecosystems such as gorse (*Genista hystrix* Lange) and broom (*Genista florida* L.) shrublands, or *Pinus sylvestris* L. forests. In general, burn severity hindered ecosystem resilience, being this effect was more pronounced in ecosystems dominated by facultative or obligate seeders than in those dominated by resprouter species.

Finally, remote sensing data as a proxy of three-dimensional vegetation canopy structure were used to anticipate the fire impact on fire-prone landscapes and quantify changes in carbon sink service as a function of ecosystem impact. A novel data fusion technique of airborne light detection and ranging (LiDAR) and broadband land surface albedo (bLSA) enabled in the ***Article IX*** an accurate quantification of vegetation structure drivers of high burn severity, such as the base height, vertical complexity, volume or cover of the canopy. We found that the importance of these drivers was strongly ecosystem-specific in complex landscapes but, in general, canopy fuel continuity and the accumulation of surface fuels promoted an extreme fire behavior in pine forests and shrublands. The impact of burn severity and environmental conditions on aboveground

carbon stock recovery in shrubland ecosystems was assessed in the ***Article X***. Airborne LiDAR data allowed to scale reliable and accurate aboveground carbon stocks, as well as to identify changes in their spatial patterns as a function of burn severity. In the most productive environments (Atlantic shrublands), carbon stock recovery was higher compared to the less productive sites (Mediterranean shrublands). The effect of burn severity on carbon stock recovery was negligible in productive environments because of the significant increases in net primary productivity in the early post-fire periods, opposite patterns being observed in less productive shrublands.

Altogether, the different RST developed in this PhD Thesis could assist forest managers to implement pre-fire smart forest policies aimed at reducing the fuel load and modifying the fuel arrangement, particularly in the most prone ecosystems to high burn severity. The results of this dissertation also provide the scientific knowledge and the operational needs at short-term in the less resilient ecosystems to identify areas where restoration actions are necessary for assisting vegetation recovery and controlling harmful environmental processes in the context of global change.

ABSTRACT IN SPANISH (RESUMEN)

En las últimas décadas, los cambios en el uso del suelo, el cambio climático antropogénico y la ausencia de políticas forestales enfocadas a mejorar la adaptación a largo plazo de la vegetación terrestre al cambio global, han provocado cambios abruptos en el régimen de incendios de los ecosistemas de la Cuenca Mediterránea. Como consecuencia, se ha promovido el desarrollo de masas forestales propensas a los incendios, con una carga y continuidad del combustible cada vez mayores. En este contexto, la evaluación del impacto de los incendios forestales en la composición, estructura y funcionamiento de los ecosistemas forestales de la Cuenca Mediterránea, y la dinámica de regeneración hacia su estado anterior al incendio, es fundamental para respaldar estrategias de gestión adaptativa que promuevan la resiliencia de los ecosistemas en el contexto del cambio global. Los métodos basados en trabajo de campo son altamente fiables para este propósito, pero son cuantiosos en términos de mano de obra y tiempo para su aplicación a gran escala. Por lo tanto, la naturaleza sinóptica de las observaciones terrestres mediante teledetección ofrece hoy en día una forma eficiente de lograr este propósito. El objetivo principal de la Tesis Doctoral fue evaluar a diversas escalas el potencial de técnicas de teledetección novedosas para monitorizar el estado de los ecosistemas y los impactos ecológicos de los grandes incendios forestales en los paisajes propensos al fuego de la Cuenca Mediterránea occidental, bajo diferentes escenarios de régimen de incendios.

En primer lugar, se evaluaron los efectos del régimen de fuego de grandes incendios forestales sobre la estructura de la vegetación y las interacciones ecológicas en paisajes quemados heterogéneos de la Cuenca Mediterránea occidental, mediante datos de teledetección multiespectrales de diferente resolución espacial (***Artículo I, II y III***). En el ***Artículo I*** se determinó que las métricas de textura calculadas a partir de imágenes de satélite WorldView-2, con alta resolución espacial, capturaron con precisión en modelos empíricos la variación a fina escala de la estructura de la vegetación en ecosistemas de pinar dominados por *Pinus pinaster* Ait. Este enfoque permitió, bajo diferentes escenarios de recurrencia y severidad de incendios, modelizar por separado las variables de la estructura de la vegetación tanto a nivel de la población arbórea (densidad y cobertura) como de la comunidad del sotobosque (cobertura, altura y riqueza). Sin embargo, la extrapolación de las relaciones modelizadas a ecosistemas en diferentes contextos geográficos o climáticos debe ser evaluada mediante análisis de transferibilidad de los modelos empíricos. Métodos físicos basados en la inversión híbrida de modelos de

transferencia radiativa (RTM) se utilizaron en el ***Artículo II*** como una novedosa técnica de teledetección en la obtención de la fracción de cubierta vegetal (FVC) a partir de imágenes de satélite de alta resolución espacial (WorldView-3), a fin de ser utilizada como indicador de los efectos del fuego sobre la estructura horizontal de la vegetación en un paisaje quemado complejo que engloba una amplia gama de ecosistemas arbustivos y forestales. Imágenes del satélite Sentinel-2, de resolución espacial moderada, se utilizaron a modo de comparativa en el enfoque RTM. La precisión de las estimaciones de la FVC obtenidas a partir de imágenes de alta resolución espacial fue notablemente alta teniendo en cuenta la gran heterogeneidad espacial del paisaje y la escasa dependencia de datos de campo de esta técnica de teledetección. Sin embargo, la utilización de datos de satélite de resolución espacial moderada indujo notables errores de subestimación y sobreestimación de la FVC. Cabe destacar que el enfoque RTM no requiere realizar análisis de transferibilidad de las estimaciones a otros contextos, pero presenta la desventaja de que no es posible modelizar por separado los parámetros estructurales de la vegetación en varios compartimentos del ecosistema. Así pues, los modelos empíricos y la inversión híbrida de RTM presentan limitaciones y fortalezas que pueden ser complementarias para el seguimiento de los efectos de los incendios en la estructura de la vegetación de los paisajes propensos al fuego.

Las interacciones competitivas intraespecíficas post-incendio en la población de plántulas de *Pinus pinaster* y *Pinus halepensis* Mill., así como la competencia interespecífica ejercida por las especies de matorral en función de su estrategia regenerativa (germinadoras y rebrotadoras) como respuesta al régimen de incendios, se identificaron a partir de datos de vehículos aéreos no tripulados (UAV) en el ***Artículo III***. La fusión de información multiespectral y de altura de la vegetación a muy alta resolución espacial, derivada de un flujo de trabajo de fotogrametría UAV, presentó una alta precisión para cartografiar la distribución de las especies y permitió caracterizar de forma fiable tanto su cobertura como su altura. Este enfoque reveló que la competencia intraespecífica en la población de plántulas de pino no fue una interacción relevante a corto plazo después del incendio, mientras que el crecimiento de las plántulas se vio afectado de forma no lineal por la competencia interespecífica del matorral. Las especies de matorral germinadoras ejercieron efectos competitivos más intensos en hábitats post-incendio más abiertos frente a zonas de vegetación más densa, donde las especies rebrotadoras presentan ventajas competitivas.

A pesar de las oportunidades que ofrecen las plataformas UAV para monitorizar la estructura de la vegetación y los procesos ecológicos a fina escala, se encontraron varios retos en la adquisición y el procesamiento de grandes volúmenes de datos UAV a muy alta resolución espacial (***Artículo IV***). La corrección de las anomalías radiométricas en las imágenes adquiridas por una cámara no evaluada previamente en la literatura fue una tarea inasequible al tratarse de un gran conjunto de datos. Por otra parte, la demanda computacional del flujo de trabajo de fotogrametría fue muy alta. No obstante, estos retos no afectaron a la capacidad de las imágenes UAV para proporcionar datos con una escala adecuada, tanto para capturar la variabilidad espacial del terreno en paisajes propensos al fuego, como las interacciones ecológicas a nivel de especie.

La consecución de modelos ecológicos transferibles, que permitan obtener predicciones anticipatorias en lugar de modelos explicativos, es crucial para mejorar la eficiencia de las acciones de gestión post-incendio, las cuales son ampliamente dependientes del contexto. En este sentido, los efectos del régimen de incendios y de las condiciones ambientales sobre la transferibilidad de los modelos empíricos de estructura de la vegetación se evaluaron tanto entre paisajes quemados dentro de un gradiente climático (***Artículo V***) como entre escenarios de recurrencia de incendios dentro de paisajes quemados (***Artículo VI***). La distribución y abundancia de las especies germinadoras y rebrotadoras como respuesta al régimen de incendios y a las condiciones ambientales tuvieron un impacto significativo en la capacidad de transferibilidad de las relaciones predictivas. Los modelos empíricos de estructura de la vegetación mostraron una mayor transferibilidad entre áreas quemadas con una composición de la comunidad vegetal más similar y, por tanto, con características espectrales comparables. Además, el uso de datos de teledetección de alta resolución espacial mejoró la transferibilidad de las relaciones empíricas modelizadas.

Las trayectorias de recuperación post-incendio y la resiliencia de los ecosistemas propensos al fuego en función del régimen de incendios se estudiaron mediante técnicas de teledetección generalizables con base física (modelos de mezclas espectrales y RTM), aplicadas a imágenes de satélite multiespectrales a varias resoluciones espaciales (***Artículo VII y Artículo VIII***). Los modelos de mezclas espectrales de múltiples miembros finales (MESMA) estimaron con precisión la FVC como indicador de resiliencia en un bosque de *Pinus pinaster*. La FVC estimada por MESMA a partir de imágenes de satélite de alta resolución espacial (WorldView-2) sólo superó ligeramente la precisión en la estimación a partir de imágenes de satélite de resolución espacial moderada (Landsat). De forma notable, la inversión híbrida de RTM fue una alternativa más factible que los modelos de mezclas espectrales para cuantificar la resiliencia de los ecosistemas en paisajes extensos, ya que la parametrización del RTM no es contexto-dependiente y no requiere tener en cuenta los cambios espaciotemporales en las condiciones biofísicas de los diferentes tipos de cobertura del suelo. Sin embargo, el

enfoque RTM debe basarse en datos de teledetección de alta resolución espacial para capturar la disposición de los legados de la vegetación a nivel subpíxel. Los ecosistemas dominados por especies rebrotadoras, como los brezales de *Erica australis* L., afectados por incendios recurrentes, presentaban una mayor resiliencia al fuego que los ecosistemas dominados por especies germinadoras facultativas u obligadas, como los matorrales de aulaga (*Genista hystrix* Lange) y piorno (*Genista florida* L.), o los bosques de *Pinus sylvestris* L. En general, la severidad del fuego disminuyó la resiliencia del ecosistema, siendo este efecto más pronunciado en los ecosistemas dominados por germinadoras facultativas u obligadas que en los dominados por especies rebrotadoras.
Por último, se utilizaron datos de teledetección como indicadores de la estructura tridimensional del dosel de la vegetación para predecir el impacto del fuego en el ecosistema y cuantificar los cambios en el servicio ecosistémico de sumidero de carbono de la vegetación en función de dicho impacto. Una nueva técnica de fusión de datos láser (LiDAR) y de albedo de la superficie terrestre de banda ancha (bLSA) permitió en el ***Artículo IX*** una cuantificación precisa de las variables de estructura de la vegetación que determinan la severidad del fuego, como la altura de la base, complejidad vertical, volumen o cobertura del dosel. La importancia de estos determinantes de la severidad fue específica para cada ecosistema en paisajes complejos, pero, en general, la continuidad del combustible del dosel y la acumulación de combustible de superficie favorecieron un comportamiento extremo del fuego en bosques de pinos y ecosistemas de matorral. En el ***Artículo X*** se evaluó el impacto de la severidad del fuego y de las condiciones ambientales en la regeneración de las reservas de carbono en ecosistemas de matorral. Los datos LiDAR permitieron escalar, de forma fiable y precisa, las reservas de carbono, así como identificar los cambios en sus patrones espaciales en función de la severidad del fuego. En los entornos más productivos (matorrales Atlánticos), la recuperación de las reservas de carbono fue mayor en comparación con los entornos menos productivos (matorrales Mediterráneos). El efecto de la severidad del fuego sobre la regeneración de las reservas de carbono fue reducido en ambientes productivos debido a al significativo incremento en la productividad primaria neta en los periodos inmediatamente post-incendio, observándose patrones opuestos en los ecosistemas de matorral menos productivos.

En conjunto, las técnicas de teledetección desarrolladas en esta Tesis Doctoral podrían ayudar a los gestores forestales a implementar políticas pre-incendio eficientes, dirigidas a reducir la carga de combustible y a modificar la disposición del mismo, particularmente en los ecosistemas más propensos a alta severidad del fuego. Los resultados de esta Tesis Doctoral también proporcionan el conocimiento científico y las

necesidades operativas a corto plazo para identificar, en los ecosistemas menos resilientes, las áreas en las que son necesarias acciones de restauración para promover la regeneración de la vegetación y controlar procesos ambientales perjudiciales en el contexto del cambio global.

1. GENERAL INTRODUCTION

1.1. Wildfire concerns in the Mediterranean Basin

Wildfires are major ecological disturbances across most terrestrial ecosystems around the globe (De Santis and Chuvieco, 2007; Bennett et al., 2016; Collins et al., 2018), causing significant impacts on their biological composition, structure and functioning (Calvo et al., 2008; Lozano et al., 2008) and, therefore, on the ecosystem capacity to provide services and goods for society (Lee et al., 2015; Robinne et al., 2020). The fire-induced shifts in ecosystem structure and composition further influence ecosystem biogeochemical cycles (Lasslop et al., 2019) and land surface energy budgets at local, regional and continental scales over a long time period after fire (Liu et al., 2005; Archibald et al., 2018), leading to a forcing on the regional to global climate (Ward et al., 2012; Archibald et al., 2018).

In the Mediterranean Basin, terrestrial ecosystems feature a great capacity to recover their structural characteristics to an equivalent pre-disturbance state under historical fire disturbance regimes (Keeley et al., 2011, Seidl et al., 2014, Johnstone et al., 2016). However, during the last century, abrupt shifts in Mediterranean ecosystems' fire regime (Pausas and Keeley, 2014) have occurred due to land use changes associated to rural abandonment (Pausas, 2004; Sagra et al., 2019), anthropogenic climate warming (González-De Vega et al., 2016) and lack of adequate forest management practices for enhancing long-term adaptation to global change (Vilà-Cabrera et al., 2018), promoting the development of dense fire-prone stands with a high fuel continuity (Figure 1). The shifts in the fire regime in the Mediterranean Basin include an increase in the fire recurrence and severity of large wildfires (Pausas and Fernández-Muñoz, 2012, González-De Vega et al., 2016, Chergui et al., 2018, Sagra et al., 2019), resulting in altered biological legacies (i.e. biological structures that persist past disturbances; Franklin et al., 2000) that might hinder feedbacks that promote ecosystem resilience (Seidl et al., 2014, Johnstone et al., 2016, Turetsky et al., 2017, Taboada et al., 2018). This pattern is expected to remain or even to aggravate owing to the predictions on the effects of global change in the terrestrial ecosystems of the Mediterranean Basin (IPCC, 2014).

Figure 1. Dense open shrubland (left) and *Pinus pinaster* Ait. (right) ecosystems with high fuel loads in the western Mediterranean Basin.

Large and recurrent wildfires may lead to harsh post-fire environmental conditions, such as partial or total removal of vegetation cover and aboveground biomass (Díaz-Delgado et al., 2002) and soil degradation (Espelta et al., 2008), as well as to changes in plant community structure and composition (Pausas et al., 2008; Taboada et al., 2017) due to induced variation in plant species fitness (Keeley et al., 2011). In this sense, plant-regenerative traits are key in plant species fitness and, therefore, in ecosystem resilience against recurrent fire disturbances (Lloret et al., 2005). In the Mediterranean Basin, post-fire vegetation recovery relies on two plant-regenerative traits (Paula et al., 2009; Moreira et al., 2012; Pausas and Keeley, 2014): (i) resprouting from above-ground or below-ground surviving tissues; and (ii) seedling recruitment from canopy or soil banks. In general, the community species assemblage presents both regeneration mechanisms (Calvo et al., 2008), although the proportion is affected by fire recurrence (Lloret et al., 2005; Espelta et al., 2008). Several studies evidenced that obligate seeders could be hindered by short fire-free periods that do not allow to accumulate a canopy or soil seed bank viable for persistence (Pausas, 2001; Pausas and Keeley, 2014; Knox and Morrison, 2005; Taboada et al., 2017). Under these circumstances, resprouter species are promoted because repeated wildfires barely affect their post-fire survival (Bonfil et al. 2004; Espelta et al., 2008; Taboada et al., 2018).

Burn severity, quantified by the change in aboveground and belowground organic matter (Keeley, 2009), is one of the most critical factors that shape ecosystem recovery trajectories in the early stages of succession (Bastos et al., 2011) and influence long-term ecological effects of wildfires in the Mediterranean Basin (Harris and Taylor, 2017). High burn severity increases vegetation mortality (Fernández-García et al., 2018) and impact ecosystem recovery trajectories (Pausas and Keeley, 2014). Extremely severe fires might restrict the resprouting response by the destruction of the belowground resprouting tissues regardless of the level of stored carbohydrates and nutrients (Moreira et al., 2012). Although obligate seeder shrubs feature heat-stimulated germination (Baskin and Baskin, 2014), the soil seed bank could be also hindered by severe fires (Pausas et al., 2003; Calvo et al., 2008), noticeably influencing short-term vegetation recovery trends (Meigs et al., 2009). High burn severity also involves significant impacts to the soil of fire-prone ecosystems, such as loss of organic matter (Vega et al., 2013) and structure deterioration (Varela et al., 2015), among others, promoting these impacts substantial post-fire erosion processes (Shakesby, 2011; Fernández-García et al., 2018). Additionally, fire regime shifts in the Mediterranean Basin also involves an increasing landscape heterogeneity leading to the occurrence of mixed-severity wildfires (Figure 2) with a high spatial variability on the degree of biomass consumption within a single fire event (Viedma et al., 2020), which could entail unpredictable shifts in ecosystem processes such as biogeochemical cycling (Meigs et al., 2009).

Figure 2. Mixed-severity wildfire effects in *Pinus pinaster* (left) and *Quercus pyrenaica* Willd. (right) ecosystems.

In this context, the assessment of wildfire impacts in the composition and structure of vegetation communities and how ecosystems in the Mediterranean Basin evolve towards its pre-fire function, in the short or medium term after fire, should be conducted considering the spatial variation of fire regime parameters. This evaluation is essential for quantifying wildfire effects on ecosystem carbon pools and fluxes (Meigs et al., 2009), predicting climate impacts associated to changes in the ecosystem carbon cycling (Fusco et al., 2019), as well as for endorsing adaptive management strategies that promote ecosystem resilience in the global change context (De Santis and Chuvieco, 2009, Veraverbeke et al., 2012a; Miesel et al., 2018).

1.2. Monitoring post-fire vegetation structure and dynamics through passive remote sensing techniques

Field work methods are highly reliable for evaluating the vegetation condition in burned landscapes (Merlin et al., 2015, González-De Vega et al., 2016), and provide the most accurate measures through visual estimations or instrumental methods (Li et al., 2015). However, these approaches are labor-intensive and time-consuming, especially for large scale application (Zhang et al., 2013). Hence, the synoptic nature of remote sensing earth observations offers nowadays an efficient way to achieve this goal (Veraverbeke et al., 2012a), together with accurate ground measures for remote sensing data validation (Zhou and Robson, 2001). Remote sensing techniques (RST) are recognized as indispensable tools to monitor vegetation patterns after fire, particularly across large areas (Lozano et al., 2012, Veraverbeke et al., 2012a, Fernández-Manso et al., 2016). However, the application of RST is still a challenge in the case of wildfires with high variability in fire regime parameters (Schoennagel et al., 2008, Chu et al., 2016) which result in a high ground spatial heterogeneity due to local differences in post-fire regeneration patterns, accumulation of non-photosynthetic material and bare soil (Meng et al., 2018).

Conventionally, multispectral imagery acquired by passive satellite optical sensors at low spatial resolution (e.g. Moderate Resolution Imaging Spectroradiometer -MODIS-, SPOT-VEGETATION) (Fraser and Li, 2002; Van Leeuwen, 2008; Caccamo et al., 2015) and at moderate spatial resolution (e.g. CHRIS/Proba, Landsat) (Solans-Vila and Barbosa, 2006; Veraverbeke et al., 2012a; Chu et al., 2016) have been used to monitor post-fire environments. Nevertheless, the spatial resolution of these sensors is commonly larger than the fine scale of variation of the vegetation horizontal structure in heterogeneous landscapes (Xiao and Moody, 2005; Garrigues et al., 2008, Li et al., 2015; Meng et al., 2018). Moreover, field validation in these landscapes requires information on the scale of individual plant elements, this approach being problematic with coarse imagery (Gutman and Ignalov, 1998). In this regard, the increased availability of high spatial resolution imagery, acquired by satellite missions such as Deimos-2 or WorldView-2/3, provides a valuable opportunity for monitoring post-fire vegetation communities in heterogeneous environments (Viedma et al., 2012; Chu et al., 2016; McKenna et al., 2018; Meng et al., 2018; Talucci et al., 2020) to account for: (i) the fine-grained arrangement in small patches of living vegetation legacies (Walker et al., 2019);

(ii) vegetation mortality at individual species level (Lentile et al., 2006); and (iii) post-fire vegetation dynamics (Van Leeuwen, 2008). Nevertheless, very high spatial resolution satellite imagery has received little attention for this purpose, especially in the fire ecology field, and is normally used to validate coarse resolution data or in image classification schemes (Melville et al., 2019).

In recent years, unmanned aerial vehicles (UAVs) also represent a suitable alternative for measuring ecological processes from the acquisition of very high spatial resolution data on-demand (Anderson and Gaston, 2013). Besides being able to produce orthomosaics of the region of interest through RGB or multispectral orthorectified images collected by on-board UAV sensors, height data can be also derived from UAV imagery by a Structure-from-Motion (SfM) photogrammetry workflow (Deng et al., 2018), which is of particular relevance in the monitoring of post-fire environments. However, the operational and processing challenges faced in the acquisition and management of large volumes of very high spatial resolution UAV data in extensive burned areas remains unanswered. In addition, technological limitations of lightweight novel multispectral cameras to be installed underneath UAV platforms must be addressed.

The analysis of post-fire vegetation structure through RST has been traditionally accomplished using empirical models based on the building of statistical relationships between local field data and remote sensing products such as vegetation indices (VIs) (e.g. normalized difference vegetation index -NDVI-, soil-adjusted vegetation indices -SAVIs- or Enhanced Vegetation Index -EVI-) computed from multispectral satellite imagery (e.g. Diaz-Delgado et al., 2003; Lozano et al., 2010, Veraverbeke et al., 2012a) or reflectance values directly used as predictors of vegetation structure (Pleniou and Koutsias, 2013). Additionally, some authors propose the use of satellite imagery texture analysis as a proxy of vegetation horizontal and vertical structure, allowing for quantifying the spatial variability of the feature of interest within a defined area (e.g. Eckert, 2012; Viedma et al., 2012; Wood et al., 2012; Gu et al., 2013; Pu and Cheng, 2015). Empirical models have been also extensively used in remote sensing research related to post-fire forest dynamics and ecosystem resilience monitoring (e.g. Viedma et al., 1997; Clemente et al., 2009; Ireland and Petropoulos, 2015). The results of these models, applied to both post-fire vegetation structure and forest dynamic assessment, are site-specific because the approach is highly dependent on local measurements (Jiapaer et al., 2011) and not generalizable to other sites without a sound transferability analysis (Chu et al., 2016) given their lack of physical basis. In fact, canopy reflectance is not only governed by the vegetation greenness locally estimated by VIs or texture products, but also by leaf angle distribution (Buchhorn et al., 2013) pigment composition and content (Xiao and Moody, 2008; Veraverbeke et al., 2012a), as well as with the cover of different plant functional types (Buchhorn et al., 2013, Thenkabail et al., 2011). Hence, the performance of empirical models locally calibrated is expected to vary across burned areas with different environmental conditions (Tao et al., 2013; Fernández-García et al., 2018), or even within the same burned area where different fire regime scenarios and community species assemblage coexist according to species regenerative traits (Bond et al., 2005).

The transferability of site-specific and non-generalizable remote sensing models to other geographic/climatic contexts can be assessed by determining whether a model calibrated under a given set of conditions (i.e. reference system) can successfully provide accurate predictions under different conditions (i.e. target system) (Sequeira et al., 2018). Nevertheless, model transferability between burned sites remains challenging because it may be hindered by different constraints such as study design, species traits, model type and/or input data (Yates et al., 2018; Werkowska et al., 2017; Jiménez-Alfaro et al., 2018; Sequeira et al., 2018). Particularly relevant are: (a) sampling bias in the reference system (Barnes et al., 2014; Tsalyuk et al., 2017); (b) non-appropriate model algorithm and model overfitting (Wenger et al., 2011; Sequeira et al., 2018); (c) non-stationarity of the ecological relationships (Osborne et al., 2007; Whittingham et al., 2007); or (d) non-analogous conditions in the target system (Thuiller et al., 2004). The evaluation of model transferability must deal with these constraints to provide a reliable and generalizable tool for supporting resource management (Yates et al., 2018; Sequeira et al., 2018).

In contrast to empirical models, RST with physical basis, such as pixel unmixing models and radiative transfer models (RTMs), do not experience transferability issues if they are properly calibrated. Particularly, pixel unmixing models (e.g. spectral mixture analysis -SMA- and multiple endmember spectral mixture analysis -MESMA-) have been commonly used to monitor vegetation structure and post-fire recovery dynamics using coarse satellite imagery (e.g. Veraverbeke et al., 2012b; Chu et al., 2016, Fernandez-Manso et al., 2016). Pixel unmixing models rely on the assumption that the image pixel consists of several ground components that contribute a part to the surface reflectance captured by the remote sensor (Zhang et al., 2013; Li et al., 2015), being the pixel vegetation fraction the ground component proportion that corresponds to vegetation cover (Wang et al., 2017). In fact, ground cover abundance is directly retrieved from remote sensing data, without the need of an initial calibration based on field data (Veraverbeke et al., 2012b). This approach has a direct physical sense, and its accuracy depends, to a large extent, on the precise delineation of representative spectral features (i.e. endmembers) of each post-fire ground component (Melville et al., 2019). Pixel unmixing models have not been applied to unmix multispectral satellite imagery at high spatial resolution, despite the potential of this approach in the ecological assessment of burned areas with heterogeneous ground cover. Conversely, these models have been frequently used in the literature to derive homogeneous endmembers from high spatial resolution data to unmix coarse imagery (Melville et al., 2019). Likewise, physical methods based on the inversion of RTMs have also received little attention for monitoring post-fire landscapes, particularly using satellite reflectance data at high spatial resolution. RTMs simulate the physical relationships between vegetation canopy reflectance and certain biophysical variables (e.g. leaf area index -LAI-, fractional vegetation cover -FVC- or leaf chlorophyll content -LCC-, among others) (Jia et al., 2016), and their inversion using observed optical satellite reflectance data can be exploited to directly retrieve the biophysical variable of interest to be used as a measure of vegetation structure or a vegetation dynamics indicator.

Significantly, physical relationships of pixel unmixing models and RTMs are not site or ecosystem-specific, and, therefore, they are widely applicable over areas with heterogeneous ground cover because of their generalization ability (Tao et al., 2019). In contrast to empirical models' approach, field data are only needed for retrieval validation purposes (Campos-Taberner et al., 2018). To minimize the reliance on field data is very relevant, since site-specific field data might not be available for scientists and land managers with the required quality and representativeness in extensive burned areas at short or medium-term after fire (Atzberger et al., 2015).

1.3. Estimation of ecosystem impact through active remote sensing techniques and active-passive data fusion

Remote sensing earth observations also offer nowadays the most feasible alternative for land managers to model at large scale, in a spatially explicit manner, the relationships between the three-dimensional pre-fire forest structure and the ecosystem impact of the wildfire with high reliability (Viedma et al., 2015), as well as to relate this impact to the loss of ecosystem service provision such as carbon storage (Zhu et al., 2010; Csillik et al., 2019). For these applications, passive remote sensing data are constrained in specific ecosystems, such as multi-layered forests, where the reflectance signal captured by optical sensors is mostly determined by the structural properties of the top of the canopy (Healey et al., 2020). In such cases, the estimation of variables related to ecosystem three-dimensional structure will be limited to secondary correlations with canopy traits, such as shadowing or moisture content (Avitabile et al., 2012; Vogeler and Cohen, 2016;

Healey et al., 2020), avoiding the precise quantification of burn severity drivers or aboveground carbon stocks in the complete vegetation vertical profile.

Recently, active remote sensing data, such as those provided by airborne Light Detection and Ranging (LiDAR) sensors, have been used to establish relationships between pre-fire forest structure and burn severity behavior with high reliability (e.g. Montealegre et al., 2014; Kane et al., 2015; Fernandez-Manso et al., 2019). Given the limited availability of commercial airborne multispectral LiDAR sensors (Morsy et al., 2017), remote sensing data derived from passive sensors, such as VIs computed from multispectral satellite imagery, have been successfully used in combination with single-wavelength LiDAR data to estimate the contribution of pre-fire fuel load to burn severity (García-Llamas et al., 2019; Viedma et al., 2020). In this sense, the implementation of novel remote sensing data fusion techniques that maximize the potential and the strengths of active and passive remote sensing observations is considered critical for improving the predictive performance of pre-fire fuel structure models in complex landscapes. The identification of fuel drivers of severe fire impact as a function of ecosystem type by using specific fuel structure metrics rather than coarse-scale maps of vegetation type is equally essential for the operative implementation of these techniques (Viedma et al., 2020). Several studies have also evaluated the role of burn severity on the aboveground carbon stock recovery in forest ecosystems through airborne LiDAR data (e.g. Garcia et al., 2017; Bayer, 2019). This approach entails a significant improvement in terms of cost and effort when applied over extensive burned areas, over conventional methods in which aboveground carbon density (ACD; tn C ha^{-1}) is estimated using exclusively field data at plot level and allometric models (Chave et al., 2005). LiDAR data offer nowadays a feasible alternative for regionally scaling ACD in forest stands when coupled with a limited number of field calibration plots (Zhu et al., 2010; Csillik et al., 2019) and create spatially explicit estimates (Fusco et al., 2019). Despite the available knowledge on this topic in forest stands, little research has been conducted in shrubland ecosystems dominated by low and sparse vegetation, where the application of LiDAR data to estimate vegetation structural parameters and scale reliable carbon stocks remains challenging (Estornell et al., 2011; Bond, 2011; Mitchell et al., 2011; Greaves et al., 2016).

1.4. Justification, innovative aspects and management implications

Nowadays, a vast amount of data is available on wildfires at local, regional and global scales. However, one major challenge is ensuring that environmental policies and decision-making practices related with wildfire behavior and ecosystem responses to fire are based on scientific findings and novel developments (Rego et al., 2018). This is particularly relevant in the context of global change in the Mediterranean Basin, where rural depopulation, land-use changes and more frequent climatic extreme conditions (Pausas and Keeley, 2014; González-De Vega et al., 2016; Chergui et al., 2018), has led to an increase in fuel load and fire proneness of the landscapes (Pausas et al., 2008). This has created complex scenarios for policy-makers, which demand reliable and cost-efficient methodologies to support management decisions and minimize environmental and socio-economic impacts of large wildfires in fire-prone ecosystems (Mansourian et al., 2005).

This PhD Thesis contributes to filling research gaps about the implementation of innovative techniques based on active and passive remote sensing data at different spatial and spectral resolutions for understanding the impact of large wildfires on the: (i) vegetation structure and ecological interactions; (ii) ecosystem resilience; and (iii) ecosystem service provisioning.

The attainment of spatially explicit outputs reflecting post-fire vegetation structure and ecological interactions have broad implications for designing realistic management policies in fire-prone ecosystems by enabling the identification of priority areas prone to harmful post-fire environmental processes or to severe loss of ecosystem services supplies (Taboada et al., 2017; Calama et al., 2019; Mitsopoulos et al., 2019). In this sense, novel RST are applied in the ***Article I, II and III*** for modeling fire effects, considering the fire regime, both on vegetation structure at several ecological organization levels and on intra and inter-specific competitive interactions in heterogeneous burned landscapes. The technological limitations of lightweight novel multispectral cameras and the technical challenges encountered in the acquisition, for the first time in remote sensing research, of large volumes of UAV data at very high spatial resolution to measure ecological processes in extensive burned areas, are addressed in the ***Article IV***.

Despite the transferability of empirical models aimed at estimating post-fire forest structure is a subject of particular interest in fire ecology (Yates et al., 2018) to support resource management with reliable, generalizable and robust tools (Sequeira et al., 2018), this aspect has not been investigated in the related literature. This dissertation addresses this research gap by evaluating the transferability of locally calibrated vegetation structure models, both between burned sites within a climatic gradient (***Article V***) and fire recurrence scenarios within fire-prone ecosystems (***Article VI***), providing new insights about the influence of environmental factors, community structure and composition and remote sensing techniques on the generalization ability of the models. The development of transferable empirical models could reduce the cost of field data acquisition within extensive burn surfaces in the context of post-fire decision-making

(Latif et al., 2016; Roach et al., 2017) and support management decisions when large data deficiencies exist in some portions of the area being surveyed (Clark et al., 2001).

Resilience concepts have not been widely applied in forest management (Reyer et al., 2015) due to a lack of spatially explicit and generalizable methods to implement them (Nikinmaa et al., 2020). This dissertation novelty introduces the use of high spatial resolution satellite imagery to quantitatively estimate, as a function of the fire regime, post-fire recovery trajectories and ecosystem resilience of fire-prone ecosystems through different pixel unmixing models (***Article VII***) and, also for the first time, physical based models based on the inversion of RTMs are proposed as a tool to assess fire disturbance impact and ecosystem resilience (***Article VIII***). These tools allow scientists and land managers to reliably assess ecosystem resilience due to their ability to generalize results (He et al., 2020) and their non-reliance on field data and transferability analyses (Vila and Barbosa, 2010). Additionally, the analysis of how the fire regime influences the resilience of different fire-prone ecosystems is a priority to improve management actions (Newton and Cantarello, 2015, González-De Vega et al., 2016) and determine the threshold of fire regime parameters that may exceed ecosystem resilience (Andrade et al., 2020).

Spatially explicit predictive models of ecosystem impact measured as burn severity could assist forest managers in decision-making processes to be applied in fire-prone landscapes with two essential aims: (i) to identify priority areas for implementing pre-fire forest management strategies (Mitsopoulos et al., 2019); (ii) to decide the most suitable actions based on the relative importance of the drivers contributing to high burn severity (Lecina-Diaz et al., 2014). This is particularly relevant in heterogeneous landscapes, since the location, design and implementation of fuel treatments in these areas will be widely ecosystem-specific (Lee et al., 2009; Stephens et al., 2013). In this sense, this PhD Thesis proposes in the ***Article IX*** a novel remote sensing fusion technique based on LiDAR and albedo data that maximizes the potential of passive and active RST to improve the predictive capacity of ecosystem impact in complex landscapes integrated by distinct ecosystems with high variability in terms of vegetation structure and environmental characteristics. Finally, the research gap in the evaluation of carbon recovery of aboveground live pools in shrubland ecosystems as a function of ecosystem impact through RST is covered in the ***Article X*** of the PhD Thesis. This scientific knowledge will be essential to assess the need for mitigation strategies and support adequate management decisions in burned areas at large spatial scales, focused on stabilizing aboveground carbon stocks in these ecosystems (Hurteau and Brooks, 2011), since shrublands constitute significant carbon pools in the Mediterranean Basin and are particularly prone to wildfire occurrence (Conti et al., 2013; Vallejo and Alloza, 2019).

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2. OBJECTIVES

The main objective of the PhD Thesis is to evaluate the potential of novel methodological approaches based on multiscale remote sensing data for analyzing the ecological impacts of large wildfires on vegetation patterns and dynamics, considering the fire regime, in fire prone landscapes of the western Mediterranean Basin located along an Atlantic-Mediterranean environmental gradient. The applicability of these multiscale techniques for supporting management decisions and environmental policies is also evaluated.
The conceptual diagram of the PhD Thesis is shown in Figure 3.

The specific objectives of the dissertation are as follows:

Specific objective 1. To model the effects of the fire regime on the vegetation structure and the ecological interactions between plant species in complex and heterogeneous burned landscapes using multispectral imagery at several spatial resolutions. Specifically, we aim:
- To assess post-fire vegetation structure at several ecological organization levels by means of empirical and physical approaches using satellite imagery at high and moderate spatial resolution (***Article I*** and ***Article II***).
- To evaluate intra and inter-specific competitive interactions on pine saplings in burned landscapes under different environmental conditions using UAV-borne data at very high spatial resolution (***Article III***).
- To address the challenges encountered in the acquisition of large volumes of UAV-borne data in extensive burned areas (***Article IV***).
- To assess the effects of the fire regime and the environmental conditions on the transferability of empirical vegetation structure models (***Article V*** and ***Article VI***).

Specific objective 2. To estimate the impact of the fire regime on the resilience of fire-prone ecosystems through generalizable remote sensing techniques with physical basis applied to multispectral satellite imagery at several spatial resolutions (***Article VII*** and ***Article VIII***).

Specific objective 3. To anticipate fire impact on fire-prone landscapes and quantify changes in carbon sink service based on ecosystem impact from remote sensing data as a proxy of three-dimensional vegetation canopy structure. Specifically, we aim:

- To improve the predictive capacity of burn severity behavior in complex landscapes through active and passive remote sensing data fusion techniques (***Article IX***).
- To evaluate aboveground carbon stock recovery in shrubland ecosystems as a function of burn severity and environmental conditions by means of active remote sensing data (***Article X***).

Specific objective 4. To provide scientific-based evidence for supporting adaptive management policies that promote ecosystem resilience in fire-prone ecosystems (***General Discussion***).

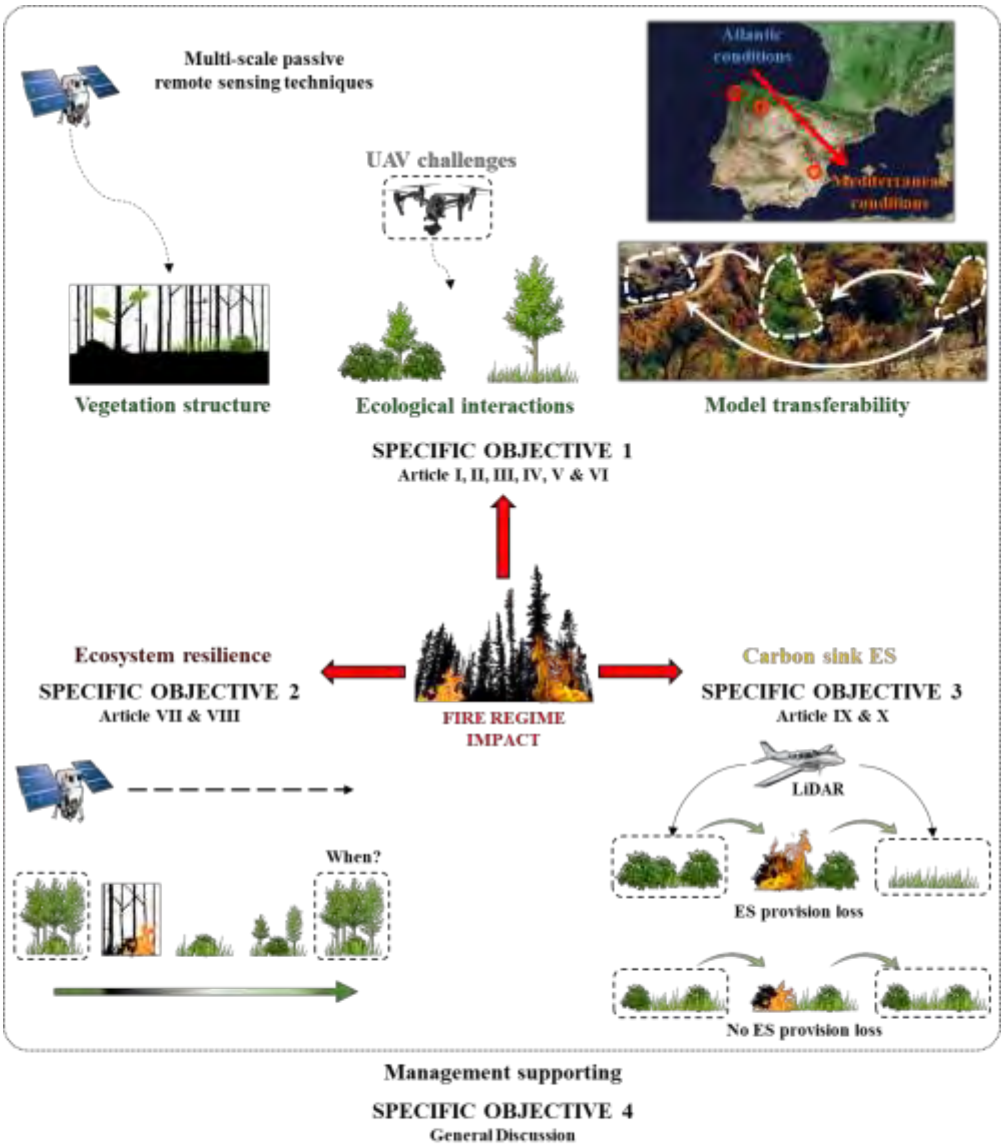

Figure 3. Conceptual diagram of the PhD Thesis.

3. STUDY SITES

The four sites selected as case study are located along an Atlantic-Transition-Mediterranean climatic gradient on a west-east axis of the Iberian Peninsula, encompassed in the western Mediterranean Basin (Figure 4). The sites burned between 2012 and 2017.

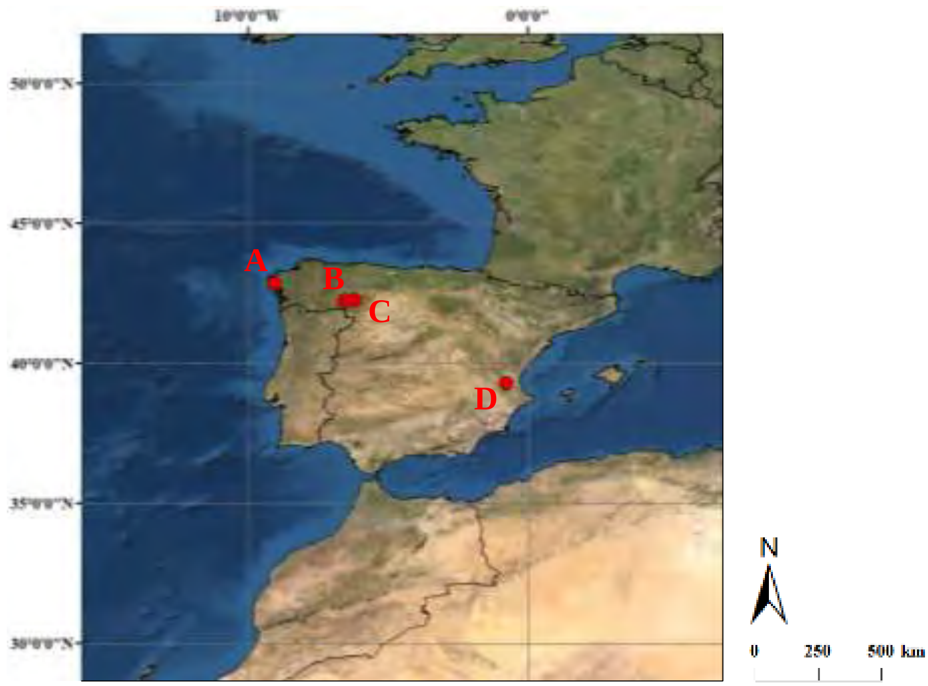

Figure 4. Location of Monte Pindo (A), Sierra de Cabrera (B), Sierra del Teleno (C) and Cortes de Pallás (D) study sites in the Iberian Peninsula.

Monte Pindo site (province of A Coruña, Spain) is located within the perimeter of a wildfire that burned 2,523ha in September 2013 in the northwestern Iberian Peninsula. The vegetation affected by the wildfire consists of *Pinus pinaster* and *Eucalyptus globulus* Labill. stands, as well as extensive shrubland formations dominated by *Cytisus scoparius* (L.) Link, *Erica australis* L., *Rubus* L. sp. and *Ulex europaeus* L. The site has an abrupt relief because of the contrast between the prominent granitic relief and the coastal plain. Soils are acidic and mostly classified as Umbrisols (Jones et al., 2005; Panagos et al., 2012). The altitude ranges between 0 and 628m above sea level (ASL). The climate of the site is Atlantic, with mean annual temperature and precipitation for a 50-year period of 13ºC and 1655mm, respectively, with absence of summer drought (Ninyerola et al., 2005).

Sierra de Cabrera site (province of León, Spain) lies within the perimeter of a wildfire that burned 9,940ha of shrubland and forest ecosystems in August 2017 in the north-northwestern Iberian Peninsula. Shrublands were mainly dominated by *Genista hystrix*

Lange, *Genista florida* L. and *Erica australis*. For their part, tree stands were dominated by *Quercus pyrenaica* Willd. and *Pinus sylvestris* L. The site has a rough and heterogeneous topography and the altitude ranges between 836 and 1938m ASL. Soils are acidic and predominantly classified as Lithic Leptosol (Jones et al., 2005; Panagos et al., 2012). The site is located at the transition of Atlantic and Mediterranean climate regions, with mean annual temperature and precipitation of 9°C and 850mm, respectively, registering less than two months of summer drought (Ninyerola et al., 2005).

The wildfire of Sierra del Teleno site (province of León, Spain) was declared in the north-northwestern Iberian Peninsula in August 2012. The wildfire affected 11,602ha predominantly covered by *Pinus pinaster* and *Quercus pyrenaica* stands. The understory and open shrubland formations were dominated by *Erica australis*, *Halimium lasianthum* subsp. *alyssoides* (Lam.) Greuter and *Pterospartum tridentatum* (L.) Willk. The site has a heterogeneous relief made up of wide valleys, prominent crests and sedimentary plains, and it ranges at an altitude between 836 and 1499m ASL. The soils are predominantly acidic and classified as Haplic Umbrisol and Dystric Regosol (Jones et al., 2005; Panagos et al., 2012). The climate of the region corresponds to an Atlantic-Mediterranean transition area, with mean annual temperature of 10ºC and mean annual precipitation of 640mm, featuring less than two months of summer drought (Ninyerola et al., 2005).

Cortes de Pallás site (province of Valencia, Spain) lies within the perimeter of a wildfire that occurred in June 2012 and burned 29,752ha in the eastern Iberian Peninsula. The pre-fire landscape was characterized by *Pinus halepensis* Mill. stands, as well as a large extension of shrubland formations dominated mainly by *Cistus* L. sp., *Quercus coccifera* L., *Rosmarinus officinalis* L. and *Ulex parviflorus* Pourr. The relief of the site is heterogeneous, with wide valleys and prominent crests, with steeper slopes than the Sierra del Teleno site. The altitude of the site ranges between 114 and 995m ASL. Soils are basic and classified as Haplic Calcisol and Lithic Leptosol (Jones et al., 2005; Panagos et al., 2012). The climate of the site is Mediterranean, with mean annual temperature and precipitation of 16ºC and 582mm, respectively. The site registers three months of summer drought (Ninyerola et al., 2005).

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4. RESULTS


LIDAR
RESILIENT
COMMUNITY
MEASURE
DECISION
GROUND
SATELLITE
FOREST
LOSS
FUEL
SPECIFIC
FUNCTION
SUCH
PAUSAS
RELATE
EFFECT
HEIGHT
EMPIRICAL
SHRUBLAND
SPECTRAL
IMPROVE
SEVERITY
FIRE
CONTINUE
SAPLING
COVER
CANOPY
REMOTE
DATA
PHD
LEVEL
ARTICLE
BOTH
UNDER
ECOSYSTEM
PINUS
VI
MULTISPECTRAL
SPATIAL
CHANGE
GARCIA
RESPROUTER
LANDSCAPE
INCREASE
IMPACT
PRONE
IMAGERY
TRANSFER
FEATURE
HIGH

Article I

MODELING PINUS PINASTER FOREST STRUCTURE AFTER A LARGE WILDFIRE USING REMOTE SENSING DATA AT HIGH SPATIAL RESOLUTION

José Manuel Fernández-Guisuraga, Susana Suárez-Seoane, Leonor Calvo

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Journal impact factor: 3.170

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Indexation database: Journal Citation Reports (JCR)

ABSTRACT

In the Mediterranean Basin, wildland fires are major drivers of forest ecosystem dynamics. In the current context of global change, these fires are becoming more severe and recurrent because of climatic conditions, land use changes and invasive species. In areas affected by mega-fires (burned area > 10,000 ha), the patterns of regeneration may be heterogeneous due to local variations in fire regime, community composition and environmental features. The goal of this study was to analyze the post-fire structure of both *Pinus pinaster* Aiton. seedlings population and understory community in a Mediterranean fire-prone ecosystem at short-term by means of high spatial resolution satellite imagery within the perimeter of a full stand replacing mega-fire that burned around 12,000 ha of a *Pinus pinaster* forest in NW Spain. We established 234 field plots of 2m x2m to cover four recurrence-severity scenarios. In each plot, we sampled 15 vegetation structural variables at both pine seedlings population and understory community levels. From the WorldView-2 satellite imagery, we obtained three sets of spectral variables (reflectance, spectral indices and image textures) that were used as predictors of vegetation recovery in generalized linear models. At population level, the number and cover of pine seedlings were successfully modeled with spectral indices and textural information (normalized root mean square error of 16% and 17%, respectively). At understory community level, woody species cover was correlated with first order textures (normalized root mean square error of 9%). Other understory structure variables (height and richness of woody species, percentage of bare soil, necromass and leaves) were predicted with an error lower than 20%. The predictive capacity of the models was similar for all recurrence-severity scenarios. Our results highlight the usefulness of spectral indices and textural data at high spatial resolution in the analysis of post-fire recovery in large and heterogeneous burnt areas. Given the accuracy and predictive capacity of the models obtained in this study, high spatial resolution satellite imagery together with field data provide useful information in post-fire decision making in fire prone ecosystems.

Article II

HYBRID INVERSION OF RADIATIVE TRANSFER MODELS BASED ON HIGH SPATIAL RESOLUTION SATELLITE REFLECTANCE DATA IMPROVES FRACTIONAL VEGETATION COVER RETRIEVAL IN HETEROGENEOUS ECOLOGICAL SYSTEMS AFTER FIRE

José Manuel Fernández-Guisuraga, Jochem Verrelst, Leonor Calvo, Susana Suárez-Seoane

Article published in **Remote Sensing of Environment** 255 (2021), 112304

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Indexation database: Journal Citation Reports (JCR)

ABSTRACT

In forest landscapes affected by fire, the estimation of fractional vegetation cover (FVC) from remote sensing data using radiative transfer models (RTMs) enables to evaluate the ecological impact of such disturbance across plant communities at different spatio-temporal scales. Even though, when landscapes are highly heterogeneous, the fine-scale ground spatial variation might not be properly captured if FVC products are provided at moderate or coarse spatial scales, as typical of most of operational Earth observing satellite missions. The objective of this study was to evaluate the potential of a RTM inversion approach for estimating FVC from satellite reflectance data at high spatial resolution as compared to the standard use of coarser imagery. The study was conducted both at landscape and plant community levels within the perimeter of a megafire that occurred in western Mediterranean Basin. We developed a hybrid retrieval scheme based on PROSAIL-D RTM simulations to create a training dataset of top-of-canopy spectral reflectance and the corresponding FVC for the dominant plant communities. The machine learning algorithm Gaussian Processes Regression (GPR) was learned on the training dataset to model the relationship between canopy reflectance and FVC. The GPR model was then applied to retrieve FVC from WorldView-3 (spatial resolution of 2m) and Sentinel-2 (spatial resolution of 20m) surface reflectance bands. A set of 75 plots of 2x2m and 45 plots of 20x20m was distributed under a stratified schema across the focal plant communities within the fire perimeter to validate FVC satellite derived retrieval. At landscape scale, the accuracy of the FVC retrieval was substantially higher from WorldView-3 ($R^2 = 0.83$; RMSE = 7.92%) than from Sentinel-2 ($R^2 = 0.73$; RMSE = 11.89%). At community level, FVC retrieval was more accurate for oak forests than for heathlands and broomlands. The retrieval from WorldView-3 minimized the over- and underestimation effects at low and high field sampled vegetation cover, respectively. These findings emphasize the effectiveness of high spatial resolution satellite reflectance data to capture FVC ground spatial variability in heterogeneous burned areas using a hybrid RTM retrieval method.

Article III

MONITORING POST-FIRE NEIGHBORHOOD COMPETITION EFFECTS ON PINE SAPLINGS UNDER DIFFERENT ENVIRONMENTAL CONDITIONS BY MEANS OF UAV STRUCTURE-FROM-MOTION PHOTOGRAMMETRY

José Manuel Fernández-Guisuraga, Leonor Calvo, Susana Suárez-Seoane

Under review in **Journal of Environmental Management**

ABSTRACT

In burned landscapes, the recruitment success of the tree dominant species mainly depends on plant competition mechanisms operating at fine spatial scale, that may hinder resource availability during the former years after the disturbance. Data acquisition at very high spatial resolution from unmanned aerial vehicles (UAV) have promoted new opportunities for understanding context-dependent competition processes in post-fire environments. Here, we explored the potentiality of UAV-borne data for assessing intra and inter-specific competition in pine saplings across three burned landscapes located along a climatic/productivity gradient in the Iberian Peninsula. Geographic object-based image analysis (GEOBIA), including multiresolution segmentation and support vector machine classification, was used to map pine saplings and understory shrubs at species level. Input data were, on the one hand, multispectral (11.31 cm·pixel^{-1}) and structure-from-motion (SfM) canopy height model (CHM) data fusion, hereafter MS-CHM, and, on the other, RGB (3.29 cm·pixel^{-1}) and CHM data fusion, hereafter RGB-CHM. A Random Forest (RF) regression algorithm was used to evaluate the effects of neighborhood competition on the relative growth in height of 50 pine saplings randomly sampled across the MS-CHM classified map. Circular plots of 3m radius were set from the centroid of each target pine sapling to measure percentage cover, mean height of all individuals in the plot and mean height of individuals contacting the target sapling. Competing shrub species were differentiated according to their fire-adaptive traits (i.e. seeders *vs* resprouters). Object-based image classification applied on MS-CHM yielded higher overall accuracy for the three sites (83.67%±3.06%) than RGB-CHM (74.33%±3.21%). Intra-specific competitive effects were not detected, whereas increasing cover and height of shrub neighbors had a significant non-linear impact on the growth on pine saplings across the study sites. The strongest competitive effects of seeder shrubs occurred in open areas with low vegetation cover and fuel continuity, following a gap-dependent model. The non-linear relationships evidenced in this study between the structure of neighboring shrubs and the growth of pine saplings have profound implications for considering possible competing thresholds in post-fire decision-making processes. These results endorse the use of UAV multispectral and SfM photogrammetry for measure accurately the effect of competition in heterogeneous burned landscapes.

Article IV

USING UNMANNED AERIAL VEHICLES IN POSTFIRE VEGETATION SURVEY CAMPAIGNS THROUGH LARGE AND HETEROGENEOUS AREAS: OPPORTUNITIES AND CHALLENGES

José Manuel Fernández-Guisuraga, Enoc Sanz-Ablanedo, Susana Suárez-Seoane, Leonor Calvo

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Indexation database: Journal Citation Reports (JCR)

ABSTRACT

This study evaluated the opportunities and challenges of using drones to obtain multispectral orthomosaics at very high spatial resolution that could be useful for monitoring large and heterogeneous burned areas. We conducted a survey using an octocopter equipped with a Parrot SEQUOIA multispectral camera in a 3000ha framework located within the perimeter of a megafire in Spain. We assessed the quality of both the camera raw imagery and the multispectral orthomosaic obtained, as well as the required processing capability. Additionally, we compared the spatial information provided by the drone orthomosaic at very high spatial resolution with another image provided by the WorldView-2 satellite at high spatial resolution. Parrot SEQUOIA raw imagery presented some anomalies, such as horizontal banding noise and non-homogeneous radiometry. Camera locations showed a lack of synchrony of the single frequency GPS receiver. The georeferencing process based on ground control points achieved an error lower than 30cm in X-Y and lower than 55cm in Z. The drone orthomosaic provided more information in terms of spatial variability in heterogeneous burned areas in comparison with the WorldView-2 satellite imagery. The drone orthomosaic could constitute a viable alternative for the evaluation of post-fire vegetation regeneration in large and heterogeneous burned areas.

Article V

EFFICIENCY OF REMOTE SENSING TOOLS FOR POST-FIRE MANAGEMENT ALONG A CLIMATIC GRADIENT

José Manuel Fernández-Guisuraga, Leonor Calvo, Víctor Fernández-García, Elena Marcos-Porras, Ángela Taboada, Susana Suárez-Seoane

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Journal ranking: 5 of 68 (**D1**) in **Forestry**

Indexation database: Journal Citation Reports (JCR)

ABSTRACT

Forest managers require reliable tools to evaluate post-fire recovery across different geographic/climatic contexts and define management actions at the landscape scale, which might be highly resource-consuming in terms of data collection. In this sense, remote sensing techniques allow for gathering environmental data over large areas with low collection effort. We aim to assess the applicability of remote sensing tools in post-fire management within and across three mega-fires that occurred in pine fire-prone ecosystems located along an Atlantic-Transition-Mediterranean climatic gradient. Four years after the wildfires, we established 120 2m x 2m plots in each mega-fire site, where we evaluated: (i) density of pine seedlings, (ii) percentage of woody species cover and (iii) percentage of dead plant material cover. These variables were modeled following a Bayesian Model Averaging approach on the basis of spectral indices and texture features derived from WorldView-2 satellite imagery at 2m of spatial resolution. We assessed model interpolation and transferability within each mega-fire, as well as model extrapolation between mega-fires along the climatic gradient. Texture features were the predictors that contributed most in all cases. The woody species cover model had the best performance regarding spatial interpolation and transferability within the three study sites, with predictive errors lower than 25% for the two approaches. Model extrapolation between the Transition and Mediterranean sites had low levels of error (from 6% to 19%) for the three field variables, because the landscape in these areas is similar in structure and function and, therefore, in spectral characteristics. However, model extrapolation from the Atlantic site achieved the weakest results (error higher than 30%), due to the large ecological differences between this particular site and the others. This study demonstrates the potential of fine-grained satellite imagery for land managers to conduct post-fire recovery studies with a high degree of generality across different geographic/climatic contexts.

Article VI

TRANSFERABILITY OF VEGETATION RECOVERY MODELS BASED ON REMOTE SENSING ACROSS DIFFERENT FIRE REGIMES

José Manuel Fernández-Guisuraga, Susana Suárez-Seoane, Leonor Calvo

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DOI: https://doi.org/10.1111/avsc.12500

Journal impact factor: 3.252

Journal ranking: 8 of 67 (**Q1**) in **Forestry**

Indexation database: Journal Citation Reports (JCR)

ABSTRACT

AIM: To evaluate the transferability between fire recurrence scenarios of post-fire vegetation cover models calibrated with satellite imagery data at different spatial resolutions within two Mediterranean pine forest sites affected by large wildfires in 2012.

LOCATION: Northwest and East of the Iberian Peninsula.

METHODS: In each study site, we defined three fire recurrence scenarios for a reference period of 35 years. We used image texture derived from the surface reflectance channels of WorldView-2 and Sentinel-2 (2m x 2m and 20m x 20m of spatial resolution, respectively) as predictors of post-fire vegetation cover in Random Forest regression analysis. Vegetation cover percentage was sampled in two sets of field plots with a size roughly equivalent to the spatial resolution of the imagery. The plots were distributed following a stratified design according to fire recurrence scenarios. Model transferability was assessed within each study site by applying the vegetation cover model developed for a given fire recurrence scenario to predict vegetation cover in other scenarios, iteratively.

RESULTS: For both wildfires, the highest model transferability between fire recurrence scenarios was achieved for those holding the most similar vegetation community composition regarding the balance of species abundance according to their plant regenerative traits (RMSE around or lower than 15%). Model transferability performance was highly improved by fine-grained remote sensing data.

CONCLUSIONS: Fire recurrence is a major driver of community structure and composition so the framework proposed in this study would allow land managers to reduce efforts in the context of post-fire decision-making to assess vegetation recovery within large burned landscapes with fire regime variability.

Article VII

COMPARISON OF PIXEL UNMIXING MODELS IN THE EVALUATION OF POST-FIRE FOREST RESILIENCE BASED ON TEMPORAL SERIES OF SATELLITE IMAGERY AT MODERATE AND HIGH SPATIAL RESOLUTION

José Manuel Fernández-Guisuraga, Leonor Calvo, Susana Suárez-Seoane

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Indexation database: Journal Citation Reports (JCR)

ABSTRACT

In Mediterranean fire-prone ecosystems, shifts in fire regime as a consequence of global change could modify the resilience of vegetation communities. In this paper, we aim to compare the efficiency of high and moderate spatial resolution satellite imagery in the evaluation of resilience in a fire-prone landscape under different fire regime categories using two pixel unmixing techniques. A time series of Landsat (ETM+ and OLI; spatial resolution of 30m) and WorldView-2 (spatial resolution of 2m) imagery collected between 2011 (pre-fire conditions) and 2016 were used to estimate the temporal variation of fractional vegetation cover (FVC) as a quantitative measure of forest resilience. For this time series, FVC was computed under four fire-regime categories of recurrence and severity using two approaches: dimidiate pixel model and multiple endmember spectral mixture analysis (MESMA). The dimidiate pixel model was computed using NDVI as spectral response for the case of Landsat imagery and NDVI and red-edge NDVI (RENDVI) for WorldView-2. MESMA was applied to unmix WorldView-2 and Landsat imagery into four fraction images: photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV), soil and shade. The PV shade normalized fraction corresponds to the FVC. In summer of 2016 we established 85 30m x 30m field plots and 360 2m x 2m field plots to measure the percentage of total vegetation cover in order to validate the FVC estimates made from remote sensing data. The FVC time series showed the same general pattern with both spatial scales and modeling approaches, high fire recurrence categories registering the highest resilience. The accuracy of the dimidiate pixel model was significantly higher for WorldView-2 based estimates (RMSE: 5-10%) than for Landsat (RMSE: 10-15%). The dimidiate pixel model computed from NDVI for both Landsat and WorldView-2 underestimated FVC at high field-sampled vegetation cover, while MESMA estimations were accurate for the entire range of vegetation cover for both satellites. The fraction of photosynthetic vegetation calculated using WorldView-2 had a higher performance (RMSE: 4-6%) than that quantified from Landsat (RMSE: 6-8%). The linear relationships assumed for validation purposes were statistically significant for both sensors and modeling approaches. Our study demonstrates the highest performance of high spatial resolution satellite imagery and MESMA models in the quantitative estimation of FVC as a measure of post-fire resilience.

Article VIII

RADIATIVE TRANSFER MODELING TO MEASURE FIRE IMPACT AND FOREST ENGINEERING RESILIENCE AT SHORT-TERM

José Manuel Fernández-Guisuraga, Susana Suárez-Seoane, Leonor Calvo

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DOI: https://doi.org/10.1016/j.isprsjprs.2021.04.002

Journal impact factor: 8.979

Journal ranking: 2 of 32 (**D1**) in **Remote Sensing**

Indexation database: Journal Citation Reports (JCR)

ABSTRACT

Forest managers demand reliable and cost-efficient methodologies to implement forest resilience concepts in post-fire decision-making at different spatio-temporal scales. In this paper, we developed a generalizable remote sensing-based tool to measure disturbance impact and engineering resilience at short-term in forest ecosystems affected by wildland fires. The case study was a mixed-severity wildfire that burned several shrubland (dominated by gorse, broom and heath) and tree forest (dominated by oak and pine) ecosystems. Specifically, we retrieved fractional vegetation cover (FVC) over a time-series of pre and post-fire Deimos-2 imagery (spatial resolution of 4m) from a radiative transfer model (RTM) hybrid inversion approach (Gaussian processes regression algorithm learned from a simulation dataset generated using the PROSAIL-D model). Pre and post-fire FVC retrieval was validated with field data stratified by dominant ecosystem. High accuracy (> 90%) and low error (< 7%) were achieved in the retrieval over the time-series, despite the influence of background signal of soil and burned legacies. A random point sampling stratified by ecosystem and burn severity was used to extract validated FVC values for the time-series. A two-way repeated measures ANOVA was performed to evaluate the effect of burn severity along the time-series on FVC for each ecosystem. One-way repeated measures ANOVA and Tukey's pairwise comparison test were applied to determine the earliest point in the time-series for which the FVC does not differ significantly from the pre-fire FVC. In tree forest ecosystems, the fire impact on FVC was stronger at high burn severity, being similar the impact on shrub ecosystems at medium and high burn severity. Engineering resilience was conditioned both by burn severity and species regenerative strategies. In ecosystems dominated by facultative or obligate seeders, pre-fire FVC was reached later across the time-series, compared to resprouter-dominated ecosystems. The RTM hybrid inversion tool has proved its reliability for assessing disturbance impact and ecosystem engineering resilience at short-term in heterogeneous fire-prone landscapes affected by mixed severity wildfires.

Article IX

VEGETATION STRUCTURE PARAMETERS DETERMINE HIGH BURN SEVERITY LIKELIHOOD IN DIFFERENT ECOSYSTEM TYPES: A CASE STUDY IN A BURNED MEDITERRANEAN LANDSCAPE

José Manuel Fernández-Guisuraga, Susana Suárez-Seoane, Paula García-Llamas, Leonor Calvo

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Journal impact factor: 6.789

Journal ranking: 34 of 274 (**Q1**) in **Environmental Sciences**

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ABSTRACT

The design and implementation of pre-fire management strategies in heterogeneous landscapes requires the identification of the ecological conditions contributing to the most adverse effects of wildfires. This study evaluates which features of pre-fire vegetation structure, estimated through broadband land surface albedo and Light Detection and Ranging (LiDAR) data fusion, promote high wildfire damage across several fire-prone ecosystems dominated by either shrub (gorse, heath and broom) or tree species (Pyrenean oak and Scots pine). Topography features were also considered since they can assist in the identification of priority areas where vegetation structure needs to be managed. The case study was conducted within the scar of a mixed-severity wildfire that occurred in the Western Mediterranean Basin. Burn severity was estimated using the differenced Normalized Burn Ratio index computed from Sentinel-2 multispectral instrument (MSI) Level 2A at 10m of spatial resolution and validated in the field using the Composite Burn Index (CBI). Ordinal regression models were implemented to evaluate high burn severity outcome based on three groups of predictors: topography, pre-fire broadband land surface albedo computed from Sentinel-2 and pre-fire LiDAR metrics. Models were validated both by 10-fold cross-validation and external validation. High burn severity was largely ecosystem-dependent. In oak and pine forest ecosystems, severe damage was promoted by a high canopy volume (model accuracy = 79%) and a low canopy base height (accuracy = 82%), respectively. Land surface albedo, which is directly related to aboveground biomass and vegetation cover, outperformed LiDAR metrics to predict high burn severity in ecosystems with sparse vegetation. This is the case of gorse and broom shrub ecosystems (accuracy of 80% and 77%, respectively). The effect of topography was overwhelmed by that of the vegetation structure portion of the fire triangle behavior, except for heathlands, in which warm and steep slopes played a key role in high burn severity outcome together with horizontal and vertical fuel continuity (accuracy = 71%). The findings of this study support the fusion of LiDAR and satellite albedo data to assist forest managers in the development of ecosystem-specific management actions aimed at reducing wildfire damage and promote ecosystem resilience.

Article X

SHORT-TERM RECOVERY OF THE ABOVEGROUND CARBON STOCK IN IBERIAN SHRUBLANDS AT THE EXTREMES OF AN ENVIRONMENTAL GRADIENT AND AS A FUNCTION OF BURN SEVERITY

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ABSTRACT

Shrubland ecosystems store large amounts of carbon sequestered from the atmosphere and contribute significantly to regulate the global carbon cycle. Despite wildfire impact on this capacity, the degree to which burn severity influences the recovery of aboveground carbon density (ACD) of live pools in shrublands remains unclear. An area-based approach with multitemporal LiDAR data was used to evaluate ACD recovery three years after fire in shrubland ecosystems as a function of burn severity immediately after fire across an environmental and productivity gradient in the western Mediterranean Basin. Two large mixed-severity wildfires were assessed: an Atlantic site, dominated by resprouter shrubs and located at the most productive extreme of the gradient, and a Mediterranean site, dominated by obligate seeders and located at the less productive extreme. Initial assessment of burn severity was performed using the differenced Normalized Burn Ratio index computed from Landsat imagery. Thresholds for low and high burn severity categories were established using the Composite Burn Index (CBI). LiDAR canopy metrics were calibrated with field measurements of mean shrub height and cover at plot level in post-fire situation. Pre-fire and post-fire ACD estimates, and their ratio to calculate carbon stock recovery (ACD_r), were computed from the predictions of LiDAR grid metrics at landscape level using shrubland allometric relationships for the dominant vegetation formations. A two-way ANOVA was used to evaluate the effect of burn severity, productivity and their interactions on ACD_r. Overall, ACD_r decreased both with high burn severity and low productivity, although the burn severity impact was not homogeneous within the gradient. In the Atlantic site, ACD_r was similar under low and high burn severity, whereas it decreased with burn severity in the Mediterranean site. These results suggest that carbon cycling models at regional scale could be systematically biased by not accounting for both fire regime and species composition of shrublands under different environmental conditions.

5. GENERAL DISCUSSION AND MANAGEMENT SUPPORTING

5.1. Modeling the effects of large wildfires on post-fire vegetation structure through passive remote sensing techniques

The quantitative characterization of post-fire vegetation structure in burned landscapes through RST is a suitable approach to assess fire effects at large spatial scales and identify the post-fire recovery dynamics of vegetation communities (Zhang et al., 2013; Chu et al., 2016; Yang et al., 2017). The findings of the present PhD Thesis evidenced that multispectral imagery at high spatial resolution acquired by WorldView-2 and WorldView-3 satellites properly captured vegetation structure variability in fire-prone burned landscapes of the Mediterranean Basin, which exhibit a high ground spatial heterogeneity arising from the fine-grained arrangement of vegetation legacies, accumulation of non-photosynthetic material and bare soil exposed to the remote sensors (Fang et al., 2019; Walker et al., 2019). In these landscapes, the use of multispectral imagery at lower spatial resolution induced noticeable under and overestimation errors of vegetation structure variables since a single coarse pixel contains spectra from different ground features (Stefanov and Netzband, 2005; Xiao and Moody, 2005), producing average values of a broader area than the ground scale of variation (Kimm et al., 2020).

In particular, texture features have been evidenced in this dissertation as a reliable proxy of post-fire vegetation structure in empirical modeling approaches. In areas of high spatial heterogeneity, texture analysis optimizes the spatial information characterization, since it accounts for both the pixel reflectance values and the spatial variation of these values between adjacent pixels (Gu et al., 2013). In this sense, image texture is more sensitive to variations in vegetation structural parameters, such as leaf area index, canopy cover, height and density or vertical and horizontal heterogeneity (Sarker and Nichol, 2011; Wood et al., 2012) than other satellite products, such as raw reflectance data or spectral indices (Sarker and Nichol, 2011; Eckert, 2012). Accordingly, image texture novelty enabled a separate modeling of key post-fire vegetation structure variables in a fire-prone pine ecosystem both at the level of the dominant tree species population (i.e., density and cover of pine seedlings) and the understory community (i.e., cover, maximum height and richness of woody species, necromass cover and percentage of bare soil) under different fire recurrence and severity scenarios with a high reliability, which has clear implications for land management in landscapes affected by large wildfires (Leone and Lovreglio, 2004; Shakesby, 2011; Gonzalez et al., 2013; Joyce et al., 2019). Only in areas affected by high burn severity and recurrent wildfires, where the density of seedlings was very low and they were situated under a dense shrub canopy, neither spectral information nor textures could explain the population structural variables due to the small contribution of the seedlings to the overall reflectance of the plots (Viedma et al., 2012). The sensitivity of the red-edge region of the electromagnetic spectrum to shifts in vegetation biophysical parameters, such as chlorophyll content or biomass density (Xie et al., 2018), as well as its efficiency in discriminating the vegetation spectral signal from background features (Schumacher et al., 2016), may explain the high contribution of texture metrics computed from red-edge region in the post-fire vegetation structure modeling.

This PhD Thesis is also pioneer in the use of high spatial resolution satellite imagery to retrieve FVC by means of physical methods based on the hybrid inversion of RTMs through machine learning regression algorithms (MLRA), achieving reliable results both at landscape and plant community levels. FVC is a crucial biophysical property to characterize vegetation structure in post-fire environmental assessments (Chu et al., 2016). Remarkably, FVC can be retrieved by the RTM approach from remote sensing scenes acquired over other burned landscapes with similar environmental characteristics (Darvishzadeh et al., 2008), requiring only some field measurements to validate the MLRA (Liang et al., 2015) since the RTM was parametrized without site-specific prior information that is not usually available at short or medium-term after fire. The use of site-specific prior information for leaf and canopy RTM parametrization may provide more realistic simulated spectra and alleviate the ill-posed nature of the model inversion (Yebra and Chuvieco, 2009; Verger et al., 2011; Jurdao et al., 2013). However, considerable accurate FVC estimations can still be achieved using a generic training simulation dataset as demonstrated in this dissertation. In fact, the prediction error of the FVC retrieval from high spatial resolution imagery at landscape level, encompassing a wide range of shrub and forest communities, was well below the accepted accuracy threshold of 10% for biophysical variable retrieval (Drusch et al., 2012; Verrelst et al., 2016). The error in the post-fire vegetation cover estimation using empirical models was similar but dealing only with a single plant community (i.e. much lower spatial heterogeneity) and at the expense of extensive field data gathering to calibrate the models. However, as mentioned earlier in this section, empirical models allowed to estimate separately key structural parameters of both the dominant tree species and the understory, this approach being restricted in the hybrid RTM retrieval approach. Both

RST therefore feature particular strengths that can be complementary for supporting context-specific post-fire management decisions.

5.2. Effects of large wildfires on ecological interactions measured from UAV-borne data

Multispectral and RGB cameras on-board UAV platforms provide a myriad of opportunities for developing innovative RST, but the technological limitations of these novel cameras require a thorough assessment of their implications for measuring ecological processes (Kelcey and Lucieer, 2012). This PhD Thesis evidenced that the raw imagery acquired by the Parrot Sequoia multispectral sensor presented some undesired radiometric anomalies not previously reported in the literature because of the camera novelty. In other commercial sensors, corrections for radiometric anomalies have been proposed to be applied to each image individually following some photogrammetric steps (Ortega-Terol et al., 2017). However, these corrections became an unaffordable task in this dissertation when dealing with large imagery datasets, in the line with the findings of Laliberte et al. (2011).

Radiometric anomalies and processing challenges because of the computational demand of the large SfM photogrammetry workflow did not affect the capability of the UAV imagery to provide scale-appropriate data to capture ground spatial variability in burned *Pinus pinaster* and *Pinus halepensis* forests and identify the fire effects on ecological competitive interactions at plant species level. In burned landscapes, these interactions are governed by fine-scale spatial patterns at the centimeter scale, and vegetation mapping of fine-grained mosaics of heterogeneous species composition remains challenging (Prošek and Šímová, 2019). In this context, the fusion of spectral and height information derived from UAV-borne data was evidenced for the first time as a sound alternative for mapping post-fire species distribution and structure through geographic object-based image analysis (GEOBIA). Vegetation structure parameters of *Pinus pinaster* and *Pinus halepensis* saplings and shrub species extracted from the post-fire classified species map and a canopy height model (CHM) revealed that intra-specific competition in pine saplings population was not a relevant interaction four years after the wildfire. It has been demonstrated that severe density-dependent effects can be expected on the survival of pine seedlings during the first and second years after fire (Ne'eman et al., 1995; De las Heras et al., 2002; Calvo et al., 2008; Taboada et al., 2017). Thus, the absence of intra-specific competitive effects four years after fire may be associated with the preceding decline of pine sapling density and, also, with the acquisition of a better mineral nutrition capacity after the first years of sapling growth

(Ne'eman et al., 1992). Nevertheless, the growth of pine saplings was impacted in a non-linear manner by inter-specific competitive effects of neighboring shrub species, the stronger the effect as the cover and height of such species increased. Belowground competition of pine saplings for water and nutrients is considered one of the main mechanisms of interaction with neighboring vegetation because of root interference (De las Heras et al., 2002; Sardans et al., 2004; Calvo et al., 2008; Rodríguez-García et al., 2011). These interactions will be more intense with increasing space occupation (related to cover) and plant development (related to mean height) of shrub individuals in the sapling neighborhood, as evidenced in this dissertation. In addition, *Pinus pinaster* and *Pinus halepensis* saplings feature strongly light-dependent growth patterns (Zavala et al., 2011), so asymmetric competition for light is also a frequent interaction in pine sapling neighborhoods (Calvo et al., 2008), particularly when the saplings are well-developed and have greater access to soil resources (Rodríguez-García et al., 2011). Indeed, this dissertation evidenced that light limitation because of neighbor shade had a major negative impact on pine sapling growth. Following a gap-dependent model (Keeley and Zedler, 1978; Keeley et al., 2016), higher intensities of seeder species competition were promoted in open post-disturbance habitats against densely vegetated areas, where resprouter species feature competitive advantages as they are assumed to be better competitors than seeders (Taboada et al., 2017).

5.3. Effects of large wildfires and environmental conditions on the transferability of vegetation structure models

Post-fire management decisions are largely context-dependent (Taboada et al., 2017) because post-fire vegetation recovery depends on pre-fire vegetation community composition, fire regime and climatic factors of each specific site across large spatial scales (Puig-Gironès et al., 2017). The search for RST that may facilitate decision-making and reduce field data gathering efforts has been one of the most important aspects in recent years (Wulder et al., 2005, Mohammadi et al., 2011, Meng et al., 2016), since most of management decisions require accurate data at short-term to be applied (Schmidt et al., 2018). For that reason, RST should allow the transfer of predictive relations from the information obtained in different geographical or climatic contexts (Foody et al., 2003, Cutler et al., 2012).

The results of this PhD Thesis evidenced that species regenerative traits had a significant impact on model transferability performance because these traits reflect the species' response to the disturbance regime and, together with the environmental conditions, their distribution and abundance (Syphard and Franklin, 2010; Street et al., 2015; Regos et al., 2019). A specific species assemblage features a characteristic spectral profile arising from the phenology and physiological characteristics of the species (Ustin and Gamon, 2010), as well as from the structural layering and multiple scattering between different species (Verrelst et al., 2009). Hence, empirical models for exhibited the highest transferability between burned areas with a more similar vegetation community structure and composition and spectral response. Under this circumstance, the stationary vegetation responses enabled the modeled relationships between plant community composition and remote-sensing data to be kept relatively constant, therefore obtaining a good performance of the model transferability approach (Maguire et al., 2016; Osborne and Suárez-Seoane, 2002; Sequeira et al., 2018). In less favorable transferability schemes, the performance was still acceptable, probably because the spectral response dissimilarity between the reference and target systems (non-analogous conditions) arising from vegetation non-stationary responses was not high enough to produce truncation in the model calibration (Yates et al., 2018; Regos et al., 2019). The results of this dissertation also demonstrated that the use of fine-grained remote sensing data is advisable because it captures better the variability of the ground cover patterns, allowing better transferability of the modeled relationships between sites. Likewise, modeled relationships must be transferred to the target area using remote-sensing data acquired during the same phenological stage of the vegetation in which the relationships were calibrated in the reference area (Wehlage et al., 2016), preferably within the peak of green biomass to minimize the effect of non-photosynthetic vegetation to the modeled relationships (Jansen et al., 2018).

5.4. Effects of large wildfires on ecosystem resilience

Knowledge of post-fire vegetation trajectories considering the fire regime is key for understanding the resilience of communities to present and future disturbances (Yang et al., 2017). Although remote sensing-based studies to assess post-fire forest dynamics have traditionally been based on empirical models (e.g. Viedma et al., 1997; Clemente et al., 2009; Yi et al., 2013; Ireland and Petropoulos, 2015), the lack of physical basis of this approach requires the validation of the resilience indicator estimates through field measurements across the entire pre and post-fire time-series of interest (i.e. several transferability analyses), involving high field survey efforts (Vila and Barbosa, 2010). In this sense, the results of this PhD Thesis demonstrated the potentiality of physically based RST (i.e. pixel unmixing models and RTMs) to measure post-fire resilience of several ecosystems at short-term considering the variability in the fire regime, while minimizing the reliance on field data.

Pixel unmixing models based on multiple endmember spectral mixture analysis (MESMA), a novel RST applied in this dissertation to high spatial resolution satellite imagery, have been successfully used to retrieve FVC as a resilience indicator in fire-prone ecosystems, with errors lower than the accuracy threshold of 10%. The reliability of this model is related with the physical meaning of the photosynthetic vegetation (PV) fraction image extracted as a proxy of FVC and the spectral representability of the selected endmembers through the Iterative Endmember Selection (IES) technique (Quintano et al., 2013; Tane et al., 2018). Moreover, in the MESMA model, all available reflectance bands are used to unmix the satellite imagery, instead of using two bands as most common spectral indices do (Fernandez-Manso et al., 2016), and the background influence of non-vegetation components is minimized (Xiao and Moody, 2005). In addition, MESMA unmixing better captured the ground spectra variability of heterogeneous burned areas than other spectral unmixing methods that use a limited number of endmembers (Xiao and Moody, 2005), such as the dimidiate pixel model used as benchmark in this dissertation. Remarkably, the overall accuracy of the MESMA modeled fraction of PV from high spatial resolution satellite imagery (RMSE between 4-6%) only slightly outperformed MESMA model accuracy from moderate spatial resolution satellite imagery (RMSE between 6-8%). In fact, MESMA approach allows several endmember spectra to characterize each pixel constituting feature regardless of its spatial resolution (Quintano et al., 2017) accounting for all the variability of the ground feature (Veraverbeke et al., 2012). However, high spatial resolution satellite imagery enabled a delineation of more spectrally pure endmembers, leading to a slight increase in the accuracy of the unmixing approach (Melville et al., 2019). It should be assessed whether the increase in MESMA model accuracy when using remote sensing data at high spatial resolution compensates for the higher economic costs of the imagery. Nevertheless, it should be emphasized that the collection of an extensive spectral library to account for endmember variability caused by spatiotemporal changes in biophysical conditions of the different land cover types (Roberts et al., 1998; Somers et al., 2009), may be unaffordable in burned landscapes with much larger extensions than the considered in this dissertation.

These limitations are overcome by an RTM approach, novelty used in this dissertation to assess ecosystem resilience, but contrary to pixel unmixing models, the evaluation of resilience to fire using RTM approaches should be based on remote sensing data at high spatial resolution, as previously evidenced in this dissertation. Otherwise, the fine-grained arrangement of vegetation legacies would not be captured at subpixel level in heterogeneous landscapes and the ecosystem resilience would be underestimated

(Walker et al., 2019). The errors in FVC retrieval as a resilience indicator through hybrid inversion of RTM were also below the 10% threshold, particularly in post-fire immediate situation (five days' post-fire), with sparse photosynthetic material and abundant burned vegetation legacies exposed to the satellite sensor. The representative characterization of soil and non-photosynthetic material background signal extracted from high spatial resolution satellite imagery in the training dataset of simulated canopy reflectance improved the MLRA inversion to retrieve FVC (Verrelst et al., 2007). Also, the leaf RTM version chosen in this study (PROSPECT-D) simulates leaf reflectance and transmittance considering brown pigments and anthocyanins (Féret et al., 2017). Therefore, this leaf model provided an added value in resilience studies at short-term, since these pigments are important constituents of leaves in post-fire environments under plant stress conditions (Gould, 2004).

Remarkably, the results obtained both by MESMA and RTM hybrid inversion approaches agreed with those achieved in previous studies based exclusively on in-situ field surveys, which proves the potential of the proposed RST for assessing ecosystem resilience at short-term across large spatial scales. In this PhD Thesis, faster recovery times were identified for ecosystems dominated by resprouter species, associated with high fire recurrence situations, in comparison with facultative or obligate seeders-dominated ecosystems. Surviving tissues of resprouter species allow for a quick recovery of plant aboveground biomass (Pausas and Keeley, 2014) and recolonization of the space occupied before the fire (Calvo et al., 2003; Vivian and Cary, 2012). This behavior confers to resprouters higher resilience than facultative or obligate seeders (Valdecantos et al., 2009; Chergui et al., 2018). The findings of Storey et al. (2016) and Kibler et al. (2019) in chamise chaparral shrublands in California, are also in agreement with the results of the present dissertation regarding the recovery rates of resprouters and facultative or obligate seeders. Likewise, burn severity hindered resilience to fire, thus affecting both resprouting and seeding capacity (Vallejo et al., 2012). This effect was more pronounced in ecosystems dominated by facultative or obligate seeders, where pre-fire FVC was reached later across the time-series compared to resprouter-dominated ecosystems, as the burn severity increased. In this sense, several research evidenced similar trait-dependent recovery patterns related to burn severity in forest and shrubland Mediterranean ecosystems (Díaz-Delgado et al., 2003; Heath et al., 2016).

5.5. Impact of large wildfires on ecosystem services

Data fusion of airborne LiDAR with low pulse density and broadband Land Surface Albedo (bLSA), novelty proposed in this PhD Thesis, enabled an accurate quantification of vegetation biophysical variables and three-dimensional canopy structure as drivers of high burn severity across different types of ecosystems. This data fusion technique maximized the well-known strengths of active remote sensing data for characterizing the vertical vegetation profile in forest ecosystems (e.g. Hall et al., 2005; Latifi et al., 2010; Bottalico et al., 2017; Joyce et al., 2019) and passive bLSA data for describing top of canopy traits in patchily vegetated areas with high canopy closure (Tian et al., 2014; Healey et al., 2020). This complimentary information revealed in this dissertation that the importance of vegetation structure drivers of burn severity was strongly ecosystem-specific in complex landscapes.

Canopies with high aerial fuel continuity promoted an extreme fire behavior in oak stands dominated by *Quercus pyrenaica* as evidenced by the high contribution of the LiDAR canopy volume metric in the modeling approach. By contrast, the stratified canopy architecture of pine stands dominated by *Pinus sylvestris* enabled high burn severity to be better predicted by the vertical distribution of the fuel load (Mitsopoulos and Dimitrakopoulos, 2007; Perchemlides et al.,2008; Fernández-Alonso et al., 2017) through the 25th percentile LiDAR metric, directly related to crown base height (Kelly et al., 2018). In *Pinus sylvestris* stands, enhanced vertical connectivity with the understory, serving as ladder fuel with high susceptibility to crowning (García-Llamas et al., 2020), was strongly associated with an increased probability of high burn severity. For the case of heathland ecosystems dominated by *Erica australis*, mature stands with high three-dimensional fuel continuity, measured by rumple LiDAR index, were prone to high burn severity. Indeed, mature heath stands tend to accumulate fine dead fuel in the lowest stratum as a consequence of lower light availability (Quintano et al., 2019), which is associated with an increased likelihood of extreme fire behavior (Baeza et al., 2006). In contrast, horizontal fuel continuity measured by bLSA metrics drove by itself burn severity in gorse and broom shrublands, dominated by *Genista hystrix* and *Genista florida*, respectively, which are characterized by a sparsely vegetation cover. Indeed, strong relationships between vegetation cover and bLSA metrics, novelty used in burn severity assessment, are expected in patchy vegetated areas due to the larger spectral changes associated to variations in vegetation cover as compared to more densely vegetated areas (Tian et al., 2014). In light of these results, the proposed LiDAR and bLSA data fusion approach could assist forest managers to implement fire-smart forest strategies aimed at reducing the risk of severe fire events and enhancing ecosystem resilience with high reliability (Corona et al., 2015).

Despite the nature and spatial variation of fuels is the only burn severity control that can be handled through adaptive management strategies in fire prone ecosystems (Sánchez-Pinillos et al., 2021), fire weather variables are key drivers of fire severity and may shift the evidenced effects (Dillon et al., 2011; Viedma et al., 2015; Estes et al., 2017). However, many weather predictors operate at macro-scale (Costa et al., 2011) and, therefore, they do not match the spatial scale of this dissertation analyses. Besides, weather data are not usually available at the high spatial resolution required for studies at ecosystem level (Fang et al., 2018).

The inherent challenges in the deployment of LiDAR data in shrubland ecosystems with low point cloud density (e.g. Estornell et al., 2011a; Mitchell et al., 2011; Greaves et al., 2016) did not undermine the potential of this RST for estimating biophysical characteristics of shrubland vegetation to scale reliable aboveground carbon stocks and identifying changes in their spatial patterns as a function of burn severity for the first time in these ecosystems. The use of a plot-stand approach translates the cloud density to a reasonable number of points per plot for computing shrubland metrics assuming a stable height distribution (Estornell et al., 2012; Hudak et al., 2012), as evidenced by previous studies in complex Mediterranean ecosystems (Domingo et al., 2018).

The slight underestimation of shrub canopy structure variables using a LiDAR area-based approach, widely reported in the literature (e.g. Su and Bork, 2007; Glenn et al., 2011; Mitchell et al., 2011; Li et al., 2015), may affect the scaling of aboveground carbon density recovery (ACD_r) as a function of burn severity. However, this error was systematically distributed across the selected case study sites and burn severity scenarios, and, therefore, did not undermine the main observed trends. In this sense, the present dissertation revealed that short-term ACD_r in shrubland ecosystems is strongly conditioned by both burn severity and ecosystem productivity of the sites. The conditions of the most productive site will be translated into dramatic increases of NPP in the early post-fire periods (Clarke et al., 2005; Pausas and Keeley, 2014), which is consistent with the higher overall shrub ACD_r compared to the less productive site. In addition, shrubs with post-fire resprouting regeneration strategy are favored as resource availability increases (Pausas and Keeley, 2014; Keeley et al., 2016) and several authors evidenced that, to a certain extent, resprouter shrubs are less vulnerable to burn severity than post-fire obligate seeders (Díaz-Delgado et al., 2003; Heath et al., 2016). Despite the lack of research about the burn severity influence on ACD_r in shrublands, several studies assessed wildfire effects on the carbon pools of understory shrub communities, among other compartments, in forest ecosystems. Meigs et al. (2009) and North and Hurteau (2011) found a strong post-fire shrub response in the understory of mixed-conifer forests in North America, reaching or exceeding pre-fire NPP levels four or five years after the fire regardless of burn severity. However, under harsh post-fire physical environments in fire-prone open shrublands (Taboada et al., 2017), with marginal microclimate amelioration and usually less soil nutrient availability compared to forest ecosystems (Caon et al., 2014; Huerta et al., 2020), the influence of burn severity and ecosystem productivity interaction on aboveground carbon pools has turned out to be remarkable. This implies that the effects of fire disturbance in carbon cycling models and environmental policies at regional scales could be systematically biased if the related analyses are not focused on all landscape components (Meigs et al., 2009), including open shrublands prone to mixed-severity wildfires.

Management implications in fire-prone ecosystems

There is growing concern for decision makers, forest stakeholders and citizens in general about the ecological and socio-economic impacts of wildfires in the Mediterranean Basin (Moreira et al., 2011; Raftoyannis et al., 2014), particularly under climate and land use/land cover changes (Fernandes, 2009; González-De Vega et al., 2016), which is expected to aggravate in the following decades (Moriondo et al., 2006; Verburg et al., 2010). These factors have promoted landscapes of high combustibility through the availability and continuity of dry fuel loads (Sluiter and de Jong, 2007; Moreira et al., 2011). In this context, pre-fire management in the Mediterranean Basin have traditionally relied upon fuel break isolation policies, which are conductive to fuel accumulation processes and contribute to more severe wildfires (Piñol et al., 2007; Fernandes, 2013). Instead, adaptive management policies based on area-wide fuel treatments aimed at reducing the fuel load and continuity at the forest stand level (Moreira et al., 2011) are required for minimizing the impact of wildfires, thus promoting ecosystem resilience (Reinhardt et al., 2008). These policies should be applied according to advances in scientific knowledge to maximize their effectiveness while minimizing undesired effects (Corona et al., 2015). The RST proposed in this PhD Thesis could assist forest managers to implement fire-smart forest strategies based on these principles. The results of the present dissertation provided evidence on the need of reducing the fuel load and modifying the fuel arrangement, particularly in the most prone ecosystems to high burn severity.

Disruption of vertical fuel continuity should be a priority in ecosystems dominated by *Pinus* species with stratified canopy architectures for reducing the risk of active crown fire initiation (Agee et al., 2000). Hence, one of the most effective measures to minimize the probability of severe fires in these ecosystems is associated with the increase of the canopy base height by pruning (Scott et al., 2007; Corona et al., 2015) and low thinning (Agee and Skinner, 2005; Crecente-Campo et al., 2009). Low thinning reduces the density of ladder fuels and break fuel continuity (García-Llamas et al., 2020). Alternatively, stand thinning could improve, in some conifer species, the self-pruning mechanism of dead branches at the canopy base due (Mäkinen and Colin, 1999). The proposed RST for identifying stands where it is necessary to break up fuel vertical continuity could be generalizable to other Mediterranean conifer forests of Europe and North America where base height and continuity of the forest canopy play a key role in active crown fire incidence (Agee and Skinner, 2005; Safford et al., 2012; García-Llamas et al., 2020). Likewise, low stand thinning, together with low to moderate intensity prescribed fires, could be suitable treatments in young broadleaf tree stands for reducing the canopy horizontal continuity and the accumulation of surface fuels (Brose et al., 2013). This strategy will preserve the oak trees in the stand with the largest diameter, which are the most fire-resistant because of the thicker bark and tall crown (Agee and Skinner, 2005; Fernandes et al., 2010; Corona et al., 2015). In general, thinning treatments in conifer and broadleaf ecosystems should maintain enough canopy closure to limit understory fuel development (Viedma et al., 2020). In heath ecosystems dominated by *Erica australis*, as in other Mediterranean ecosystems such as chaparral and gorse shrublands, prescribed fire could be one of the most effective pre-fire management actions to reduce fuel load (Ascoli and Bovio, 2010; Fernandes, 2015) and increase landscape heterogeneity by creating stand age mosaics (Keeley, 2002). Based on the results of this dissertation, the development of a diverse heathland structure is essential for reducing the risk of stand replacing fires (Harper et al., 2018). Prescribed fire might be also a target action on the breakdown of fuel horizontal continuity in gorse and broom ecosystems with a high canopy cover (Fernandes, 2015; Lasanta et al., 2018). The implementation of these recommendations should be a priority in shrublands of less productive environments, dominated by seeder species according to the resource-productivity model (Clarke et al., 2005; Keeley et al., 2016), in order to minimize the burn severity impact on their carbon sink capacity as evidenced by the results of this dissertation.

This PhD Thesis also revealed through novel RST that improved resilience to fire can be achieved through the promotion of shrub and tree resprouter stands, in line with Vallejo and Alloza (1998). Real fuel type conversion to less flammable and more resilient vegetation types is mostly limited to landowners' decisions in wildland-urban interfaces, whereas wildland areas mostly rely on natural succession process to promote diverse species composition and mature stages (Moreira et al., 2011). However, reforestation policies after stand-replacing wildfires provides an opportunity to promote fuel-limited forests and woodlands dominated by resprouter species with strong post-fire responses (Stephens et al., 2010; Fernandes, 2013). The proposed RST may also provide at short-term the operational needs in the less resilient ecosystems to identify areas where restoration is necessary for assisting vegetation recovery and controlling soil erosion processes.

The post-fire spatially explicit modeling approach proposed in this PhD Thesis was able to identify priority areas with low vegetation recovery (Storey et al., 2016), in terms of the dominant tree species and the understory, where post-fire management actions should be focused. In this regard, burned areas dominated by obligate seeder shrub species under low fire recurrence situations were characterized by a low vegetation cover at short-term after fire. In these areas, it would be advisable to avoid intensive grazing (Fernández-García, 2019) and the implementation of mulch treatments or log barriers to mitigate runoff and erosion rates (Robichaud et al., 2008; de las Heras et al., 2012; Robichaud et al., 2013). *Pinus pinaster* seedling/sapling density was insufficient under high fire recurrence scenarios to guarantee the natural population recovery (Rodríguez-García et al., 2011), and, consequently, intervention through planting or sowing is advisable to facilitate the persistence of the pine forest (Fernández-García, 2019). By contrast, thinning of the regeneration stand would be appropriate in burned areas characterized by longer fire-free periods, where empirical models identified desirable to excessive densities (Rodríguez-García et al., 2011; de las Heras et al., 2012).

The non-linear relationships evidenced in this dissertation between the structure of neighboring shrubs and the growth of pine seedlings/saplings have profound implications for considering possible competing thresholds in post-fire decision-making processes. For instance, woody understory species cover higher than 30% and a height that allows to overtop saplings, was found to severely impact the saplings' growth, which is in line with the findings evidenced by McDonald and Fiddler (2011) in Ponderosa pine plantations in California. Under this situation, moderate mechanical treatments such as cutting can be effective in controlling woody competitors for ensuring the regeneration of the dominant tree species (Balandier et al., 2006).

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6. GENERAL CONCLUSIONS

6.1. Modeling the effects of large wildfires on post-fire vegetation structure

1. Multispectral remote sensing data at high spatial resolution capture the fine-grained arrangement of vegetation legacies and non-photosynthetic material in heterogeneous burned landscapes.
2. Texture features are more sensitive in empirical models to fine-scale variation of vegetation horizontal and vertical structure than spectral indices, enabling a separate modeling of post-fire vegetation structure both at the level of the tree regeneration stands and the understory community.
3. Physical methods based on the inversion of RTMs can deal with greater spatial heterogeneity and are less reliant on field data than empirical models, but at the expense of not being able to model separately the dominant tree species and the understory structure.

6.2. Identification of wildfire effects on ecological interactions

4. The fusion of spectral and height information derived from UAV- SfM workflows is appropriate for mapping post-fire vegetation at species level through geographic object-based image analysis and quantifying ecological competitive interactions.
5. Intra-specific competition in *Pinus pinaster* and *Pinus halepensis* saplings population, monitored through classified species maps and canopy height models, is not a relevant interaction at the medium-term after the wildfire, whereas the growth of *Pinus pinaster* and *Pinus halepensis* saplings is non-linearly impacted by space occupation and plant development of shrub species in the sapling neighborhood.

6.3. Impact of the fire regime and environmental conditions on the transferability of vegetation structure models

6. Plant regenerative traits as a response to the disturbance regime and the environmental conditions of the landscape influence the post-fire species distribution and abundance.
7. Empirical models of wildfire effects on vegetation structure exhibited the highest transferability between burned areas with a more similar vegetation community composition regarding the species regenerative traits and, therefore, with comparable spectral profiles.

8. The use of fine-grained remote sensing data is advisable to improve transferability of the modeled relationships between burned areas as it better captures the variability in land cover and minimizes the spectral response dissimilarity between the reference and target systems.

6.4. Monitorization of post-fire recovery trajectories and ecosystem resilience

9. The use of physical models to account for the variability in biophysical conditions of the different land cover types represents a sound alternative to quantify ecosystem resilience in large landscapes.

10. Ecosystems dominated by resprouter species, associated with high fire recurrence situations, featured a higher resilience to fire than facultative or obligate seeders-dominated ecosystems. Burn severity hindered vegetation recovery, being this effect was more pronounced in ecosystems dominated by facultative or obligate seeders than in those dominated by resprouter species.

6.5. Impact of large wildfires on ecosystem services

11. Data fusion of airborne LiDAR with low pulse density and bLSA enables an accurate quantification of vegetation biophysical variables and three-dimensional canopy structure as drivers of high burn severity, which turns out to be strongly ecosystem-specific.

12. LiDAR data deployment in shrubland ecosystems allows to scale reliable aboveground carbon stocks and identifying changes in their spatial patterns as a function of burn severity. In the most productive environments, the effect of burn severity on carbon stock recovery is negligible because of the significant increases in net primary productivity in the early post-fire periods.

6.6. Management implications

13. The disruption of fuel vertical continuity in conifer ecosystems with stratified canopy architectures is of critical importance to minimize the risk of active crown fire, whereas the reduction of the canopy horizontal continuity and the accumulation of surface fuels should be a priority in young broadleaf tree stands.

14. The development of a diverse shrubland structure through prescribed fire is essential for reducing the risk of severe wildfire damage. This treatment should be a priority in shrublands of less productive environments to minimize the burn severity impact on their carbon sink capacity.

6. GENERAL CONCLUSIONS IN SPANISH (CONCLUSIONES GENERALES)

6.1. Modelización de los efectos de los grandes incendios forestales en la estructura de la vegetación post-incendio

1. Los datos de teledetección multiespectral de alta resolución espacial capturan la disposición a fina escala de los legados de vegetación y no fotosintéticos en paisajes quemados heterogéneos.
2. Las métricas de textura en los modelos empíricos son más sensibles a la variación a escala fina de la estructura horizontal y vertical de la vegetación que los índices espectrales, lo que permite una modelización separada de la estructura de la vegetación post-incendio tanto a nivel de la población arbórea dominante como de la comunidad del sotobosque.
3. Los métodos físicos basados en la inversión de RTM pueden afrontar una mayor heterogeneidad espacial y son menos dependientes de los datos de campo que los modelos empíricos, pero a costa de no poder modelizar por separado la estructura de la especie arbórea dominante y del sotobosque.

6.2. Identificación de los efectos de los incendios forestales sobre las interacciones ecológicas

4. La fusión de información espectral y altura, derivada de los flujos de trabajo UAV-SfM, es apropiada para cartografiar la vegetación post-incendio a nivel de especie mediante el análisis de imágenes basado en objetos y cuantificar las interacciones ecológicas de competencia.
5. La competencia intraespecífica en la población de plántulas de *Pinus pinaster* y *Pinus halepensis*, monitorizada a través de mapas de clasificación de especies y modelos de altura, no es una interacción relevante a medio plazo tras el incendio, mientras que el crecimiento de las plántulas se ve afectado de forma no lineal por la ocupación y el desarrollo de especies arbustivas.

6.3. Impacto del régimen de incendios y de las condiciones ambientales en la transferibilidad de los modelos de estructura de la vegetación

6. Las estrategias regenerativas de la vegetación como respuesta al régimen de perturbaciones y las condiciones ambientales del paisaje influyen en la distribución y abundancia de las especies tras el incendio.

7. Los modelos empíricos de estructura de la vegetación mostraron una mayor transferibilidad entre áreas quemadas con una composición de la comunidad vegetal más similar en cuanto a las estrategias regenerativas de las especies y, por tanto, con perfiles espectrales comparables.
8. El uso de datos de teledetección de alta resolución espacial es aconsejable para mejorar la transferibilidad de las relaciones modelizadas entre áreas quemadas, ya que capturan mejor la variabilidad de la cubierta del terreno y minimizan la disimilitud de la respuesta espectral entre los sistemas de referencia y diana.

6.4. Monitorización de las trayectorias de recuperación post-incendio y resiliencia de los ecosistemas

9. El uso de modelos físicos para considerar la variabilidad de las condiciones biofísicas de los diferentes tipos de cubierta del terreno representa una alternativa fiable para cuantificar la resiliencia de los ecosistemas en paisajes extensos.
10. Los ecosistemas dominados por especies rebrotadoras, asociados a situaciones de alta recurrencia de incendios, presentaron una mayor resiliencia al fuego que los ecosistemas dominados por germinadoras facultativas u obligadas. La severidad del fuego dificultó la recuperación de la vegetación, siendo este efecto más pronunciado en los ecosistemas dominados por germinadoras facultativas u obligadas que en los dominados por especies rebrotadoras.

6.5. Impacto de los grandes incendios forestales en los servicios ecosistémicos

11. La fusión de datos de LiDAR con baja densidad de puntos y bLSA permite una cuantificación precisa de las variables biofísicas de la vegetación y de la estructura tridimensional del dosel como determinantes de alta severidad del fuego, los cuales resultan ser altamente específicos de cada ecosistema.
12. El despliegue de datos LiDAR en ecosistemas de matorral permite escalar de forma fiable las reservas de carbono de la vegetación e identificar los cambios en sus patrones espaciales en función de la severidad del fuego. En los ambientes más productivos, el efecto de la severidad del fuego sobre la recuperación de las reservas de carbono es mínimo debido a los significativos incrementos en la productividad primaria neta en los primeros periodos post-incendio.

6.6. Implicaciones en gestión

13. La disrupción de la continuidad vertical del combustible en ecosistemas de coníferas con arquitecturas de dosel estratificadas es de vital importancia para minimizar el riesgo

de incendio de copa activo, mientras que la reducción de la continuidad horizontal del dosel y la acumulación de combustibles de superficie debería ser una prioridad en los rodales jóvenes de frondosas.

14. El desarrollo de una estructura de matorral diversa, mediante quemas prescritas, es esencial para reducir el riesgo de sufrir severidades altas. Este tratamiento debería ser prioritario en ecosistemas de matorral en entornos menos productivos, con el fin de minimizar el impacto de la severidad del fuego en su función como sumidero de carbono.