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Optimizing prescribed fire allocation for managing fire risk in central Catalonia

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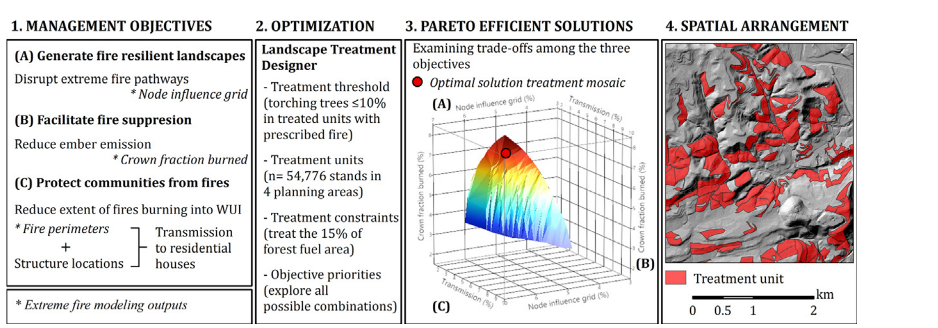
HIGHLIGHTS

- Prescribed fire treatment optimization for reducing wildfire risk is challenging.
- We designed a multi-objective treatment mosaic for a fire-prone Mediterranean area.
- We used an optimization program to explore trade-offs among competing objectives.
- Results can be used to evaluate ongoing projects and improve long-term efficiency.
- Spatial optimization can guide investments on large landscape management projects.

GRAPHICAL ABSTRACT



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ABSTRACT

We used spatial optimization to allocate and prioritize prescribed fire treatments in the fire-prone Bages County, central Catalonia (northeastern Spain). The goal of this study was to identify suitable strategic locations on forest lands for fuel treatments in order to: 1) disrupt major fire movements, 2) reduce ember emissions, and 3) reduce the likelihood of large fires burning into residential communities. We first modeled fire spread, hazard and exposure metrics under historical extreme fire weather conditions, including node influence grid for surface fire pathways, crown fraction burned and fire transmission to residential structures. Then, we performed an optimization analysis on individual planning areas to identify production possibility frontiers for addressing fire exposure and explore alternative prescribed fire treatment configurations. The results revealed strong trade-offs among different fire exposure metrics, showed treatment mosaics that optimize the allocation of prescribed fire, and identified specific opportunities to achieve multiple objectives. Our methods can contribute to improving the efficiency of prescribed fire treatment investments and wildfire management programs aimed at creating fire resilient ecosystems, facilitating safe and efficient fire suppression, and safeguarding rural communities from catastrophic wildfires. The analysis framework can be used to optimally allocate prescribed fire in other fire-prone areas within the Mediterranean region and elsewhere.

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1. Introduction

Uncharacteristic large fire events in the Mediterranean basin during the last decades suggest a rapid evolution of a fuel-limited anthropogenic fire regime to a weather-driven post-industrial regime (Fernandes et al., 2016; Pausas and Fernández-Muñoz, 2012; Seijo and Gray, 2012). Increasing fuel connectivity and buildup are the main contributing factors to large fires, and result from fire suppression policies, rural exodus, lack of management, and extensive afforestation (Bovio et al., 2017; Curt et al., 2016; Poyatos et al., 2003). Mediterranean areas represent one of the most important fire activity hotspots worldwide (Moritz et al., 2014), and in southern European Union (EU) countries (Portugal, Spain, France, Italy and Greece) 48,640 fires burned 447,807 ha annually on average between 1980 and 2015 (San-Miguel-Ayanz et al., 2016). Relatively few large fires (<10%) associated with extreme fire weather conditions accounted for the bulk of burned area (>80%). These mega fires often occur in multiple-fire episodes, overwhelm suppression capabilities, emit spot-fires capable of breaching fuel breaks (>100 m), spread for long distances (>10 km) and impact many communities located in the wildland urban interface (Alcasena et al., 2016b; Castellnou and Miralles, 2009; San-Miguel-Ayanz et al., 2013). Furthermore stand replacing high severity events threaten remaining old growth forests and increase future fire hazard by promoting dense regeneration from serotinous conifer species ($>10^4$ tree saplings ha^{-1}), resprouting shrublands, and coppice stands (Pausas et al., 2008). Traditional wildfire management strategies based solely on fire suppression and ignition prevention programs have proven to be ineffective (Keane et al., 2008; Piñol et al., 2007), and managing fuels on fire-prone landscapes represents the most promising strategy capable of reversing the escalation of mega fire events and restoring fire resilient ecosystems (Hessburg et al., 2016; Reinhardt et al., 2008).

Prescribed fire is a widely used fuel treatment technique on large landscapes due to its low cost and high efficiency in reducing surface fuels, removing ladder fuels and increasing crown base height (Agee and Skinner, 2005; Casals et al., 2016; Fule, 2002). Fighting fire with fire represents an important paradigm shift after decades of suppression policy, and the positive effects in terms of fire risk reduction, especially in fire adapted ecosystems, have now been widely demonstrated (Arkle et al., 2012; Fernandes, 2015; North et al., 2012; Prichard and Kennedy, 2014; Vaillant et al., 2009). Despite existing administrative and legal constraints, operational limitations and lack of social acceptance, the use of prescribed fire by landscape managers to treat fuels is gaining importance in fire-prone southern European countries (Ascoli and Bovio, 2013; Molina-Terrén et al., 2016). In addition, prescribed fire can be used to restore habitats, maintain forest canopy openings, facilitate natural regeneration, clear logging debris, control pest and disease, and improve pastures in mountain areas (San Emeterio et al., 2016). In fact, until the mid-1950s in many southern EU countries fire was used systematically in rural areas for pasture and edge clearing, and agricultural waste elimination (Lázaro, 2010). However, conditions in some forest stands are not suitable for prescribed fire treatment due to the potential for fire escape, smoke impacts, negative effects on the topsoil and undesired effects on certain vegetation structures or species compositions and tree growth (Armas-Herrera et al., 2016; Valkó et al., 2014; Valor et al., 2015). For instance, mechanical treatments such as thinning and mastication or entire tree harvesting are required in high fuel load conditions or dense forest ecosystems with ladder fuels to reduce canopy bulk density and mitigate hazard prior to using fire to reduce fuels. Thus prescribed fire programs, especially on large, highly fragmented, and complex land tenure landscapes (i.e., $>10^5$ ha) require accurate stand-level information to properly plan fuel treatments.

Planning fuel treatments to reduce large fire spread is a complex problem and must consider how to efficiently treat landscapes in terms of spatial configuration and density of treatments. In addition, legislation regulating management in protected areas, as well as land ownership constraints, complicates treatment allocation. Treatment strategies must consider multiple objectives, causing the spatial configuration of fuel treatments to substantially differ from case to case (Ager et al., 2013; Oliveira et al., 2016; Schmidt et al., 2008; Stevens et al., 2016; Thompson et al., 2017). For instance, while treatments designed to reduce wildfire likelihood may be prioritized in areas likely to maximize reduction in spread rate (Finney, 2007), treatments designed to mitigate structure ignition in residential communities would prioritize treating hazardous fuels surrounding valued assets (Calkin et al., 2014; Cohen, 2000; Elia et al., 2014). In the former case, a fire modeling approach is required to model fire spread, and the latter will depend on the valued asset location and surrounding vegetation. Despite the high interest in developing multi-objective treatment prioritization guidelines to efficiently allocate investments, few studies have provided transferable results that could be used by landscape managers (Salis et al., 2016b; Scott et al., 2016). Previous studies assessed wildfire risk or exposure to highly valued resources and typically did not include assessment of alternative treatment designs and their effect on wildfire (Alcasena et al., 2016b; Argañaraz et al., 2017; Mitsopoulos et al., 2015; Salis et al., 2013; Thompson et al., 2015), but see also Collins et al. (2013) and Moghaddas et al. (2010). For instance, there has been little study of how fuel management activities including mechanical treatments in concert with prescribed fire can meet the divergent objectives of restoring fire adapted ecosystems versus protecting developed areas from wildfire impacts. Specifically, how does focusing on one fuel management objective result in trade-offs in others, and where are these opportunities to achieve multiple fire management objectives? Recent studies have explored these questions using production possibility frontiers (PPFs) to show trade-offs associated with a fixed amount of investment in fuel management (Ager et al., 2016b; Vogler et al., 2015). These analyses used PPFs to graphically represent Pareto efficient optimal resource allocations for competing objectives associated with a fuel treatment program (e.g. habitat restoration vs. wildfire risk mitigation). These PPFs can be used to identify the opportunity cost of a manager's decision to support one particular objective at the expense of the other.

In this study we experimented with new methods for allocating prescribed fire treatments on a large fire-prone landscape ($>10^5$ ha) in central Catalonia (northeastern Spain). Recent catastrophic fires in the study area have motivated managers and policymakers to re-examine fire policies including the development of a comprehensive and strategic fuel treatment program (Castellnou and Miralles, 2009; Costa et al., 2011). To help inform these policy discussions we conducted a case study that combined fire simulation and trade-off analyses to evaluate the compatibility of three prescribed fire management objectives that focused treatments to improve: 1) forest resiliency to fire, 2) effectiveness of fire suppression, and 3) protection of rural communities. We used optimization methods to examine both trade-offs among the objectives and priorities for sample planning areas. We discuss application of the methods to evaluate current and proposed fuel management programs as part of strategic policy development as well as field application by local fire managers.

2. Material and methods

2.1. Study area

The 0.13 million ha study area encompasses Bages County in central Catalonia (northeastern Spain) (Fig. 1A). Major communication corridors transverse the study area from north to south and east to west, apart from the secondary roads which present a radial distribution connecting the capital city of Manresa in the core of the study area with secondary urban centers. The orography ranges in elevation from 150 m in the central valley to >1,250 m in the highest mountains. The climate is predominantly Mediterranean with an average annual precipitation of 500–900 mm, with <15 mm falling in the driest month of July when the mean maximum temperatures exceed 30 °C. Conifer forests are dominated by Aleppo pine (*Pinus halepensis* Mill., 22% of the