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Optimizing prescribed fire allocation for managing fire risk in central Catalonia



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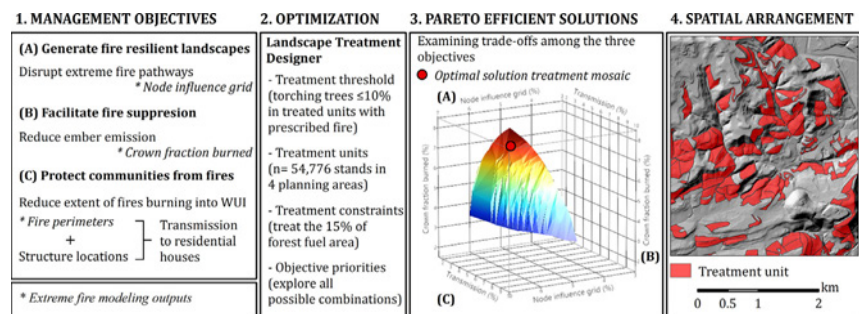
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HIGHLIGHTS

- 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-Ayán 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-Ayán 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 (>10⁴ 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., >10⁵ 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 (>10⁵ 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

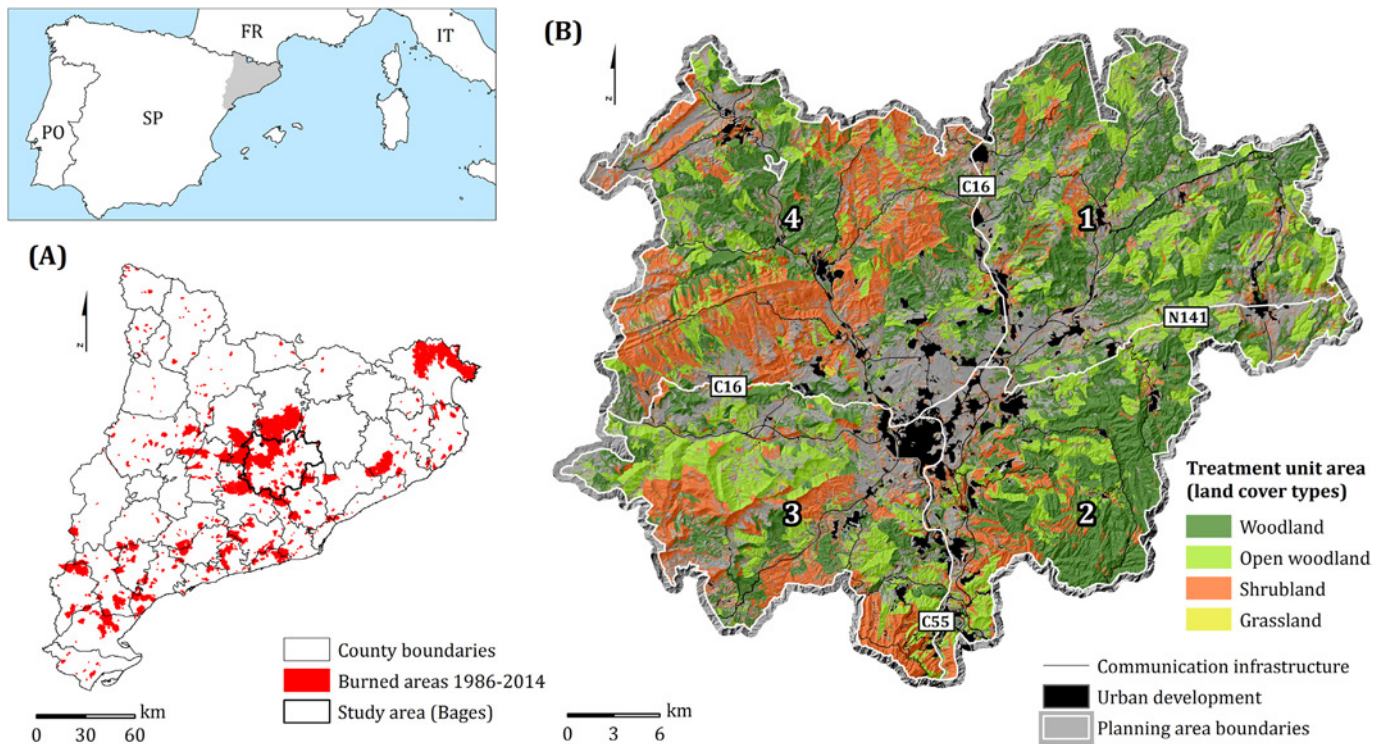


Fig. 1. (A) Location of the study area (Bages County, central Catalonia, northeastern Spain) and recent wildfire perimeters (interior.gencat.cat) and (B) planning area boundaries and treatment area by land cover type (agricultura.gencat.cat). Gray areas in (B) are areas ineligible for treatment.

study area) on south facing slopes and the lowest elevations, with black pine at the higher elevations (*P. nigra* Arn. subsp. *salzmannii*, 14%). Mediterranean pastures and low shrublands dominated by thyme (*Thymus vulgaris* L.), rosemary (*Rosmarinus officinalis* L.), cushion-heads (*Genista scorpius* L.) and kermes oak (*Quercus coccifera* L.) which have colonized abandoned agricultural lands, occupy a substantial portion of the landscape (14%). Overall, Mediterranean oaks (*Q. faginea* Lam, *Q. pubescens* Willd. and *Q. ilex* L.) have a limited presence as pure stands (<10%). Dryland cereal crops cover most valley bottoms (23%) and surround main city centers and urban development areas (8%). On average, about 1,000 ha (i.e., 0.77% of the study area) are burned annually by wildfires (period 1986 to 2015), mostly from human caused ignitions, and historical large fire episodes of 1986, 1994 and 1998 accounted for 86% of the cumulative burned area (MAAyMA, 2015). During the last 30 years large fire events (>100 ha) burned 22% of the study area (Fig. 1A), and here vigorously sprouting oaks and high density Aleppo pine forests replaced the dominant black pine stands (Retana et al., 2002; Rodrigo et al., 2004). Moreover, recent heavy snow and strong wind episodes (e.g., 2006 year) substantially increased coarse fuel loads on unmanaged forests with falling trees and broken branches, and wildfire events in the future will potentially show even greater wildfire hazard.

2.2. Residential housing at risk

The capital city of Manresa is located in the center of the study area and accounts for about 42% of the population (74,752 inhabitants). Nonetheless, several hundred dispersed rural houses and farms are spread across a rural urban interface characterized by very low housing density (i.e., <6.18 houses km²) and high wildfire hazard. Only arable lands remain cultivated and residential structures closely intermingle with forest fuels in most cases. In addition, their often precarious maintenance increases fire susceptibility and makes structures vulnerable to

ignite from showering embers, despite the fire resistant materials used on rural construction. In order to accurately identify all these individual structures, we used the structure polygon centroids from the BTN25 (IGN, 2016) to generate a point file with residential house locations. The 1:25000 scale BTN25 official geodatabase is a widely used spatial information resource for landscape and urban planning at the municipality level. In all, we identified 23,633 individual residential houses across the study area, excluding industrial structures, silos and agricultural machinery storage.

2.3. Planning areas and treatment units

We divided the study area into four planning areas (i.e., project scale blocks) considering major communication infrastructure (north to south C16 and C55 roads, and east to west C25 and N141 roads, Fig. 1B). The planning areas ranged in size from 25,140 to 43,470 ha (average = 32,480 ha). Treatment units (i.e., minimum management area for treatment implementation) were derived from the forest land SIGPAC2016 polygons (agricultura.gencat.cat). These polygons are used as reference in EU rural development and agricultural subsidy monitoring, and accurately delineate at a 1:5000 scale major land cover types (i.e., agricultural, grasslands, shrublands, open woodlands, forested, water bodies, urban areas and rocky outcrops) according to land ownership boundaries (Fig. 1B). We excluded agricultural and unburnable cover types, and then largest land cover units where further divided into polygons with a maximum area of 6 ha to homogenize the spatial resolution and better capture spatial gradients in treatment objective metrics across the landscape. We used forest tracks and natural breaks such as ravines, water divides and slope changes to split the large land cover units into smaller polygons. In total, we obtained 54,773 treatment polygons based on land cover with an average size of 1.67 ha.

2.4. Fire modeling

We used FlamMap for fire spread and behavior modeling (Finney, 2006). FlamMap has been widely used for landscape scale wildlife exposure and risk assessment in studies worldwide, including southern EU Mediterranean countries (Alcasena et al., 2016a; Elia et al., 2014; Jahdi et al., 2016; Mallinis et al., 2016). The landscape input data were constructed with topography, surface fuel and canopy metric grids (Ager et al., 2011). Using hourly weather records from a long series automatic weather station within the study area we characterized the most frequent wildfire season wind scenario (speed and direction), and derived the fuel moisture content (Bradshaw and McCormick, 2000). Fire modeling was conducted at 40 m resolution considering extreme weather conditions (97th percentile) to obtain node influence grid (NIG), crown fraction burned (CFB) and individual fire perimeters (Alcasena et al., in press).

2.5. Wildfire management objectives

We explored three management objectives in this study: 1) increasing the resiliency of sub-Mediterranean forest ecosystems, 2) facilitating fire suppression, and 3) protecting wildland urban interface rural communities from catastrophic events. Currently these objectives

represent the major concerns for fire managers and Civil Protection in Catalonia (Costa et al., 2011). Different spatially explicit metrics were assigned to each objective in order to later facilitate the spatial optimization analysis.

2.5.1. Promote fire resilient forest ecosystems

Currently most forests in the study area are high density or with ladder fuel structures, where stand replacing high severity events threaten forest ecosystems. Endemic sub-Mediterranean old growth black pine stands in the study area (i.e., Castelltallat mountain range) are protected Natura 2000 European Union (EU) sites (Council Directive 92/43/ECC of 21 May 1992) vulnerable to large and intense fire events. Treating forest fuels can reduce large catastrophic fire potential and burn probability on fire-prone landscapes, in addition to mitigating hazard on treated stands and reducing expected tree mortality (Ager et al., 2007). Accordingly, heading fire pathways on large landscapes represent strategic areas to locate fuel treatments, while the minimum treatment area and intensity in reducing fuels also represent very important factors to efficiently design prescribed fire projects (Finney, 2007). We used the node influence grid fire modeling output (NIG; Fig. 2A; Finney, 2006) as the reference metric to optimize fuel treatment efforts to increase resiliency in forest ecosystems. Overall the treatment units with highest values will be prioritized, while units with lowest values and limited

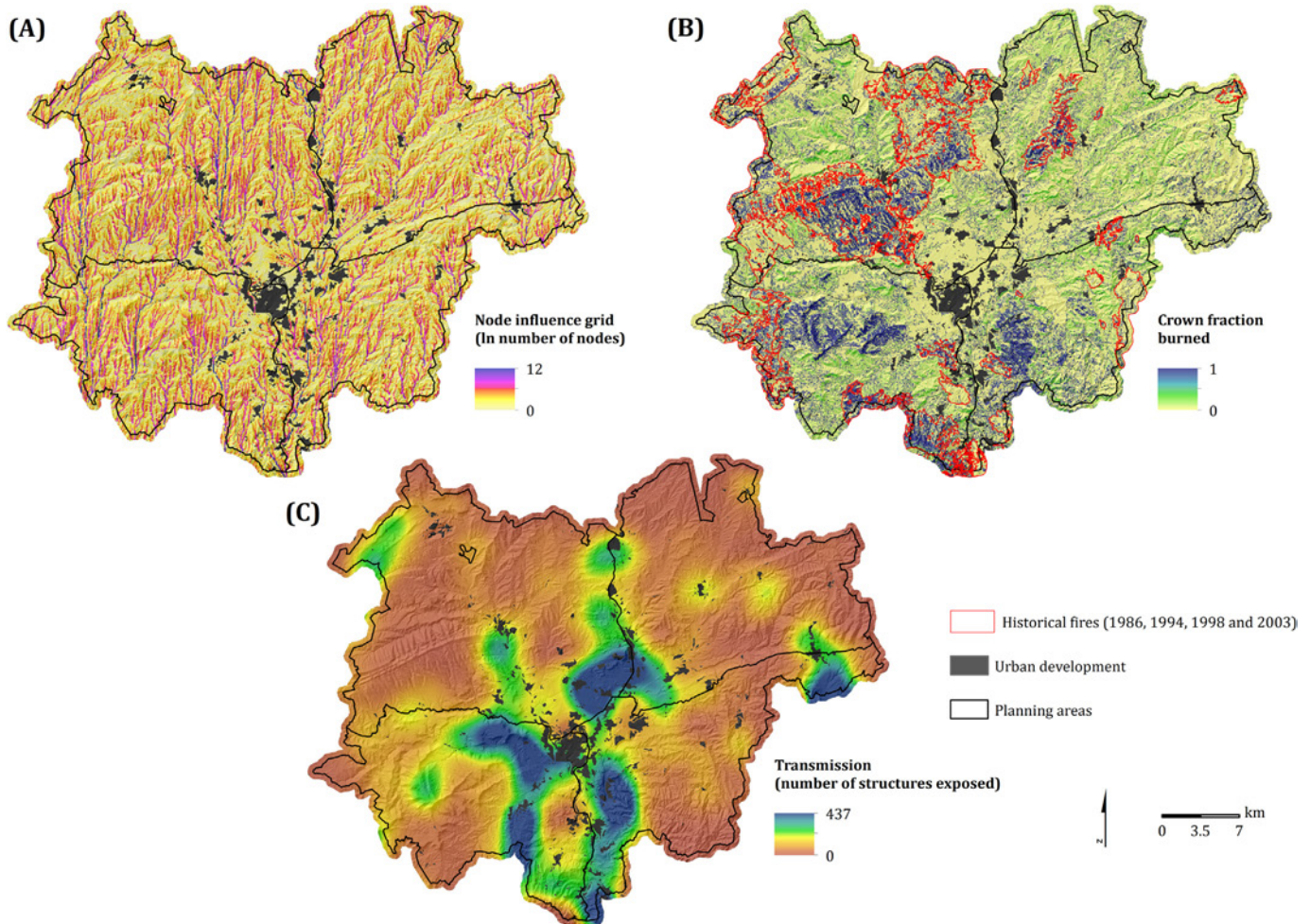


Fig. 2. Fire modeling outputs and exposure metrics corresponding to node influence grid (A), crown fraction burned (B) and wildfire transmission to residential structures (C) used to prioritize prescribed fire treatments in central Catalonia, northeastern Spain. We considered extreme fire weather conditions (97th percentile) for fire modeling with FlamMap (Finney, 2006). See Alcasena et al., in press for further details on modeling outputs and exposure metrics.

influence on major fire propagation will be excluded for treatment allocation. Since the study area is subjected to severe fires and reducing fuels on the entire landscape is impossible, treating areas with high NIG is the most efficient way to reduce large fire spread and therefore increase landscape resiliency to fire.

2.5.2. Facilitate fire suppression

Ember emission represents one of the main factors overwhelming fire suppression capabilities on Mediterranean areas. Despite existing high fragmentation on landscapes with mosaics of cultivated lands and dense communication networks, spot-fires during plume-driven fires easily surpass surface fire strategic containment barriers. In fact, long spotting distances as much as 2 km have been recorded on historical large fire events in Catalonia (Costa et al., 2011). Reducing ember emission will substantially increase firefighter safety and efficiency during fire suppression, reducing entrapment possibilities and increasing fire-front containing success probability via backfires or black-line anchoring implementation from existing linear fuel discontinuities. We used the crown fraction burned (CFB; Fig. 2B) output to target likely ember emitting forest stands. Moreover, treating stands with highest CFB values (i.e., highest crown fire severity) will also increase future fire resistance on treated stands. We prioritize treatments on stands presenting highest average values and intermittent to continuous crown fire types.

2.5.3. Safeguard rural communities from large catastrophic fires

Protecting residential communities from catastrophic fires is the main priority for most civil protection agencies and wildfire managers, since long distance spreading fires can burn into multiple rural communities and affect multiple residential houses. Previous studies demonstrated how landscape fuel treatments can mitigate large fire arrival to residential areas, and in this study we used fire transmission to residential houses to target treatment units where ignited fires affect a high number of structures (Ager et al., 2016a; Ager et al., 2010). We define fire transmission (TR) as the number of structures exposed from fires ignited in a given location during typical blow-up events in the study area. For that purpose, we intersected fire modeling large fire perimeter outputs ($n = 6816$ fires > 100 ha) with residential house centroid locations ($n = 23,633$ structures) to assess fire transmission (Alcasena et al., 2017a). The number of exposed structures was assigned to fire ignition locations, and we used exponential kriging geostatistical methods (radius = 3000 m) to create a 40 m resolution smooth raster surface (Fig. 2C) in order to populate all treatment units with average values.

2.6. Spatial optimization analysis

In order to facilitate the treatment unit identification in the later optimization analysis, we used modeling metrics and exposure results to prioritize treatment allocation according to the different wildfire management objectives. We first populated the treatment unit polygons with average values, and then the percentage contribution with respect to the total of all treatment units (*pct*) was calculated to standardize reporting across all objectives, and assess the attainment degree of all treated units on a given project. We define the objective attainment as the percentage value contribution of a treatment unit or stand on achieving a given objective by implementing a fuel treatment on it, assuming a fulfillment degree proportional to the value on the treated unit with respect to the total in the planning area or study project. In other words, we quantified on every treatment unit the percentage value with respect to the cumulative values of all units (e.g., treating a unit with a value equal to 1 where the total value of all treatment units equals 1000 will have a *pct* = 0.1% for a given objective).

Then, we used the Landscape Treatment Designer (LTD) to optimize prescribed fire fuel treatment allocations in the study area (Ager et al., 2013). LTD has been used in forest restoration studies to analyze trade-offs among competing objectives and rank treatment priorities

on planning areas for large western US landscapes (Ager et al., 2016b; Vogler et al., 2015). The program identifies the treatment units which maximize attainment levels for multiple objectives considering managers' priorities or weights for different objectives, limited resources for treatments (e.g., budgetary restrictions), implementation constraints (e.g., forest stands susceptible to high severity prescribed fire) and legislation (e.g., excluding protected areas). The optimization equation is the following:

$$\text{Max} \sum_{j=1}^k \left(Z_j \times \sum (W_i \times N_{ij}) \right) \quad (1)$$

subject to:

$$\sum_{j=1}^k (Z_j \times A_j) \leq C \quad (2)$$

where C is a global constraint on investment level per planning area (e.g., budgetary funds for treatments or treated equivalent area), Z is a vector of binary variables indicating whether the j -th stand is treated (i.e., $Z = 1$ treated and $Z = 0$ untreated), N_{ij} is the contribution (i.e., *pct* percent contribution to the total) to objective i in stand j if treated, and A is the treated area of the j -th treated stand. Since landscape managers can present different priorities, the maximization equation can integrate a W_i weighting coefficient to promote the i -th objective versus another.

In this study we assumed constant cost per treated ha with prescribed fire within the study area, and therefore polygon area represented the C constraint value for individual treatment units. We considered a 15% treatment area (13,684 ha) on forest lands, since lower treatment intensities have little or no influence on limiting large fire spread (Finney, 2007; Salis et al., 2016b). We are considering the use of prescribed fire as the treatment technique to reduce fuels, but not all forests in the study area are eligible for treatment due to dense ladder fuels on unmanaged timber-stage forests or very dense pole-stage post-fire regenerated stands (i.e., 1986, 1994, 1998 and 2003 fire cohorts). Fire caused mortality of trees requires crown consumption or substantial damage to cambium or roots, and we excluded forest stands with a crown fraction burned higher than 0.10 (i.e., $> 10\%$ of torching trees on the overstory) for prescribed fire burn window conditions (Alcasena et al., in press). In order to accurately identify forested units we used LiDAR derived 20 m resolution canopy height data (ICGC, 2005) to discriminate between low vegetation and tree covered units considering a 3 m height break, and explore the alternative fuel treatment possibilities and potential revenue from stands excluded for prescribed fire treatments (see Appendix 1). In order to explore local managers' potential priorities or choices in the assignation of priorities for the treatment objectives (i.e., trade-offs between objectives), we ranged objective weights (W) from 0 to 5 in all integer combinations. First, for every weighting combination we obtained a solution with the respective attainment values for the three objectives. Planning area level production possibility frontier (PPF) three dimensional graphs were then generated from the representation of all the weighting scheme combination results using a separate axis (X , Y and Z) per objective.

3. Results

3.1. Fire modeling and exposure metrics

The node influence grid (NIG) showed a dominant wind oriented stripe-type spatial gradient, where the highest values were located over south-north oriented major fire pathways in line with the southern wind direction used for fire modeling (Fig. 2A). The average NIG within the study area was 3, and varied from a low of 0 to a high of 12. Treatment unit average NIG values presented similar ranges and distribution

in all the planning areas (Fig. 3A). Although fire pathways were in most cases able to adjust spreading trajectories to valley bottom herbaceous fuels, the fires occasionally spread faster through forest fuels on steep slopes when the orientation of the valley bottom was perpendicular to dominant wind direction. While fuel discontinuities such as unburnable areas in urban development in the central part of the study area locally modified the fire trajectories, the fastest spreading pathways were located in shrublands where fire trajectories were generally straight (Fig. 1B). Nonetheless, average values on the treatment

units classified by land cover type showed very similar distributions (Fig. 4).

Crown fraction burned (CFB) showed very interesting spatial patterns across the study area (Fig. 2B). Large portions of the landscape in the central part of planning area 4 presented continuous crown fire (> 0.9) on the areas burned during 1994 and 1998 wildfire events. On the other hand, the patches burned on more recent wildfires (i.e., 2003, perimeters on the eastern and southeastern portion of planning area 2) indicated the forest has yet to recover and did not present any crown fire activity. On the eastern side and northeastern parts of the study area, the dominant intermittent crown fire level varied between 0.2 and 0.6, and the highest values were usually located on south facing slope mountain edges perpendicular to the dominant winds. In general, treatment unit average CFB values were slightly lower for planning areas 1 and 4 (Fig. 3B). The comparison of treatment unit average CFB values between extreme weather and prescribed fire conditions (Appendix 1) on areas burned within past fire events, indicated that young regenerating forests are especially prone to active crown fires (Fig. 5). While CFB was especially high for extreme fire weather within wildfires burned in 1998, differences between extreme fire weather and prescribed fire conditions within wildfires burned in 2003 were not marked. Currently most forest stands within 1998 wildfire perimeters presented CFB values above the prescribed fire treatment threshold and were therefore excluded from the treatment optimization analysis.

Fire transmission (TR) to residential houses (i.e., structures exposed to wildfire) located within the study area showed clustered patterns that were generally related to structure location, wind direction and fire size (Fig. 2C). Overall, the highest values (> 350 residential structures) were concentrated in the central and southern portions of the study area, the location of the largest urban areas. In many cases, these areas corresponded to dryland cereal crop agricultural lands excluded as potential treatment units for the optimization analysis (Fig. 1B). Areas with the lowest TR were located in the northern and southwestern rough terrain forest lands, where rural communities are especially small in comparison with the larger cities in the central part. Treatment unit average TR value distributions varied between the planning areas and the bulk of values were higher on planning area number 3 (Fig. 3C). Overall, the largest TR values for individual fires surpassed 1000 structures but these did not necessarily correspond to the largest fires, and we did not find a very clear positive correlation between fire size and the number of residential houses exposed to wildfire (Fig. 6A to D). In

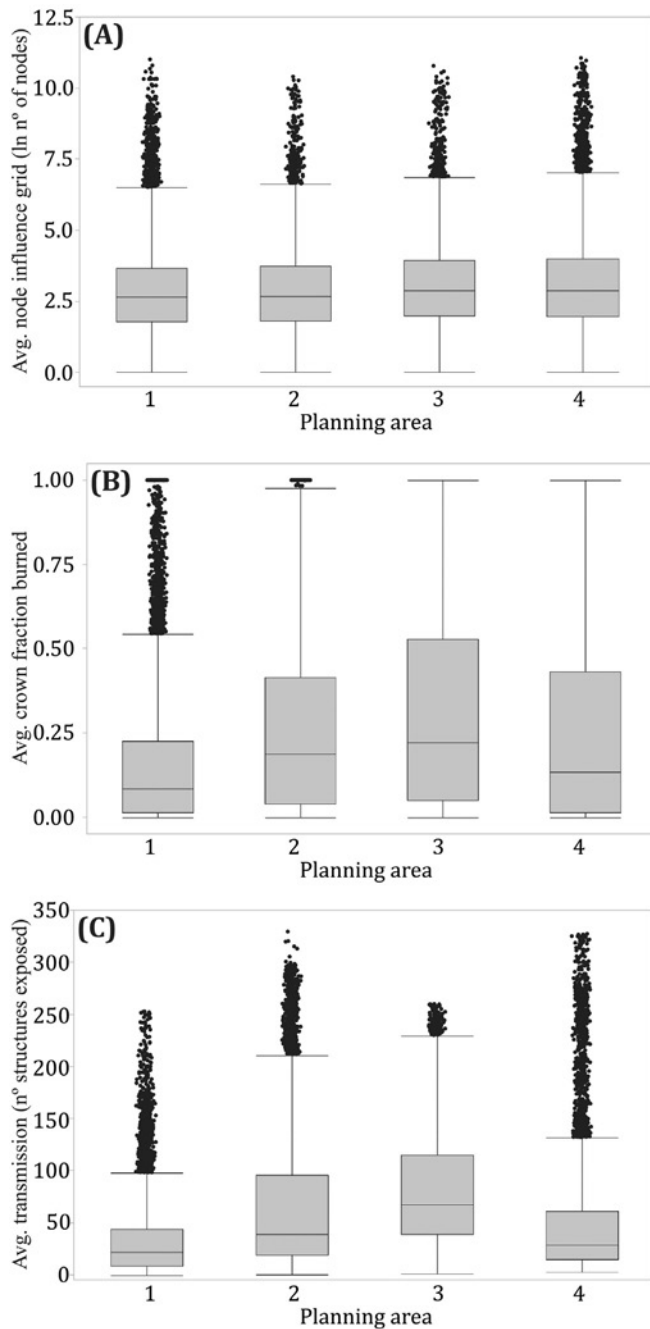


Fig. 3. Box-plots of fire modeling outputs and exposure metrics for treatment units within the four planning areas in the Bages County (central Catalonia, northeastern Spain). The boxes indicate the 1st/3rd quartiles, the whiskers indicate 10th/90th percentiles, the black line within the box is the median, and the dots indicate values below 10th percentile or above the 90th percentile. See methods for details on modeling outputs and exposure metrics.

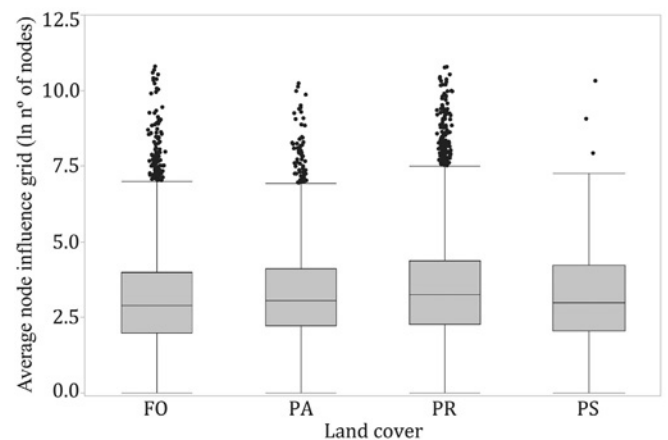


Fig. 4. Average node influence grid values for different land use-land cover types within Bages County (central Catalonia, northeastern Spain). Land cover data are from SIGPAC2016 (agricultura.gencat.cat). The boxes indicate the 1st/3rd quartiles, the whiskers indicate 10th/90th percentiles, the black line within the box is the median, and the dots indicate values below 10th percentile or above the 90th percentile. Abbreviations: FO: woodland, PA: open woodland, PR: shrublands, and PS: grasslands.

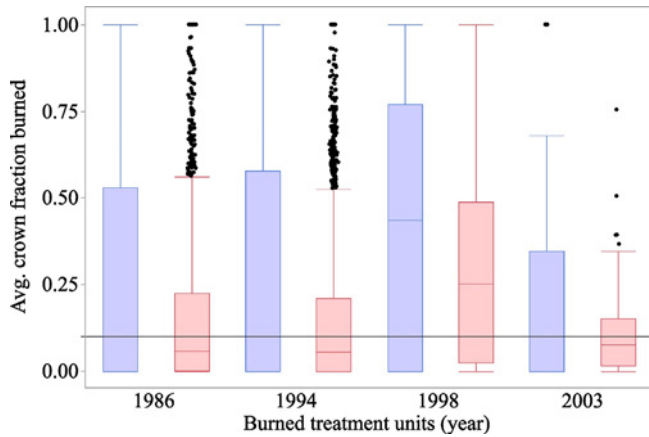


Fig. 5. Crown fraction burned (CFB) fire modeling results box-plots for treatment units located on previously burned areas (1986, 1994, 1998 and 2003) in Bages County (central Catalonia, northeastern Spain). The blue color corresponds to extreme fire weather modeling results (Fig. 2B) and the red refers to prescribed fire treatment weather conditions (Alcasena et al., in press). The boxes indicate the 1st/3rd quartiles, the whiskers indicate 10th/90th percentiles, the black line within the box is the median, and the dots indicate values below 10th percentile or above the 90th percentile. The horizontal line (CFB = 0.1) indicates where forest stands experience >10% of trees torching when implementing prescribed fires and thus were excluded from the treatment optimization analysis.

fact, the largest fires (>12,000 ha) presented TR values below 500 structures (Fig. 6D), and the highest rates corresponded to fires <10,000 ha ignited in planning area 3 (Fig. 6C) with >8 structures ha⁻¹, although it is important to note the capital city of Manresa is located in planning area 3 (and contains 30% of the residential structures in the study area).

3.2. Production possibility frontiers

Attainment values with respect to the total within the entire study when each objective is optimized independently ranged between 19% and 33% (Fig. 7). Treatments located to prioritize the highest NIG units achieved the lowest value, and variation among the four planning areas was <3%. On the other hand, CFB and TR attainment values showed substantial variation, especially between planning areas 1 and 4. The highest planning area level attainment values corresponded to TR reaching very close to 10% in planning areas 2 and 4. The amount of attainment achieved per unit of treated area ranged from a low of 0.0010% ha⁻¹ in planning area number 1 for CFB to a high of 0.0034% ha⁻¹ in planning area 2 for TR.

We calculated production possibility frontiers (PPFs) for each of the four planning areas to explore the trade-offs among the different objectives and how they varied across the study area (Fig. 8). For every planning area, we graphically represented a PPF surface as a three dimensional projection to show the maximum possible attainment level for treatments constrained to 15% of the treatable landscape. Therefore, the surface represents the optimal scenarios where resources

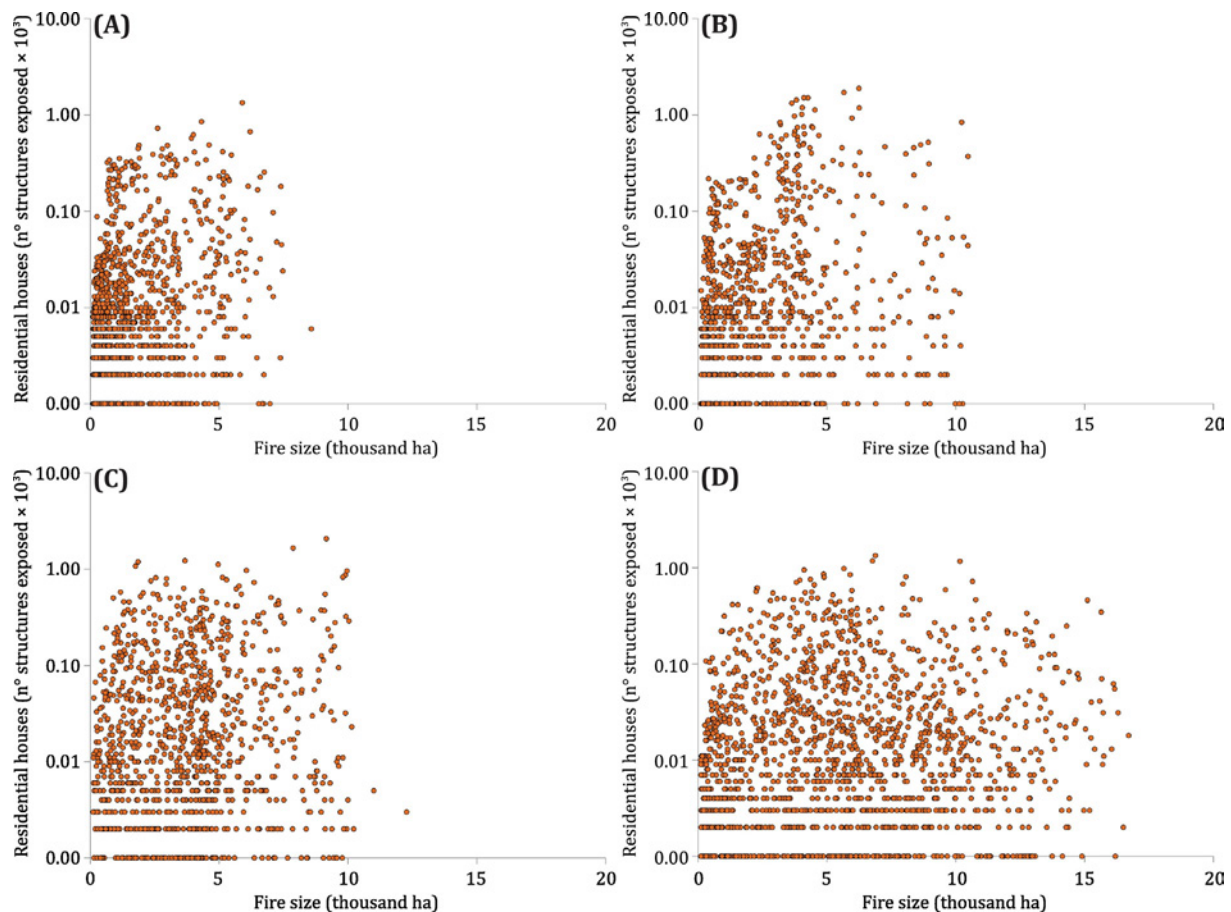


Fig. 6. Fire transmission from randomly simulated large fires (>100 ha) within Bages County (central Catalonia, northeastern Spain) ($n = 6816$). Planning areas 1 to 4 (Fig. 1), correspond respectively to the A to D scatterplots. We considered extreme fire weather conditions and 8 h fire spread duration to replicate historical catastrophic blow-up event patterns (e.g., Bages fire on 4th July 1994) with FlamMap (Finney, 2006). Note that planning area 3 (panel C) contains the capital city Manresa and 30% of the residential structures.

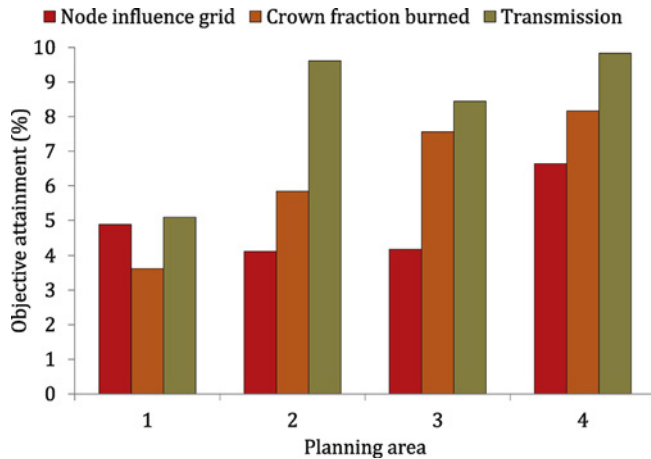


Fig. 7. Planning area attainment values on treated units in Bages County (central Catalonia, northeastern Spain) for each of the three metrics used to assess prescribed fire management objectives for the four planning areas, when each of the metrics is optimized independently. These correspond to optimization results from treating 15% of the burnable landscape within the study area, excluding forest stands where prescribed fire could cause undesired effects on the overstory. Node influence grid, crown fraction burned and transmission results (Fig. 2) were used to conduct the optimization analysis with the Landscape Treatment Designer (Ager et al., 2016b). See methods for more details on the fire model outputs and exposure metrics.

are invested most efficiently. PPF surfaces were concave to the origin and increasing attainment for a single objective was only possible by diverting resources (i.e., treated area) from another. Trade-offs presented an increasing opportunity cost when moving along a PPF surface from the maximum value of a one objective to increasing attainment of a second objective. Sharp trade-offs indicated high co-location possibilities, such as CFB with respect to TR in planning areas 2, 3, and 4 (Fig. 8B, C, D). On the other hand, TR with respect to NIG and CFB represented situations with the lowest joint-production among the objectives on treated units (Fig. 8C). Paradoxically, planning area 1 showed the highest trade-off between NIG and TR, but the lowest co-location between CFB and TR (Fig. 8A). The planning areas with concave PPF curves more distant to the origin (planning area 4; Fig. 8D) represented the highest joint-production potential, and thus the highest priority while implementing fuel treatment projects.

3.3. Treatment allocation spatial priorities

We generated the optimal multi-objective prescribed fire treatment allocation map (Fig. 9A) for the same priority setting in the three wildfire management objectives (i.e., same weights for all objectives in optimization, $W = 1, 1, 1$). These areas represent treatment units where all three of the metrics are optimized but may represent trade-offs between two particular metrics since obtaining the highest value for all the three objectives in one place was not possible. In the case of the three objectives having the same priority (local managers' choice), fuel treatments could be located in an optimal spatial design to promote fire resilient forest ecosystems, facilitate fire suppression and protect rural communities from large fires. This treatment unit selection mosaic is the solution where the joint production of all three metrics has the highest potential. Results revealed a fine grain, complex mosaic across the study area (Fig. 9A).

We also generated a combined map from independently optimized results to explore trade-off implications (i.e., managers' choice on the objective priority) in treatment unit selection for prescribed fire treatments (Fig. 9B). In other words, we overlaid the optimal mosaics for the different metrics to show treatment unit level

potential spatial co-location and how treatment unit selection would change depending on the objective prioritized. As expected, TR results tended to cluster around the main populated areas where we find the highest number of residential structures. Despite most CFB units concentrated on 1998 burned areas in planning area number 4, overall the NIG and CFB showed a more complex widespread pattern across the landscape, especially for NIG. On the overlaid mosaic (Fig. 9B), the treatment units selected where the three metrics overlapped accounted for 2581 ha, and two of the three metrics overlapped in other 7774 ha.

4. Discussion

Rural Mediterranean landscapes have evolved since the mid-20th century from highly fragmented mosaics of small agricultural parcels interspersed with heavily grazed pastures and intensively managed forests, to relatively homogeneous dense vegetation with high fuel loadings (Moreira et al., 2011; Pausas and Fernández-Muñoz, 2012). Fuels fragmentation in the earlier conditions limited the spread of both agro-pastoral and lightning-caused fires, whereas under current conditions, fires spread unimpeded until contained by suppression forces. Relying on fire suppression as a primary strategy is increasingly being questioned in the Mediterranean region and elsewhere (Calkin et al., 2014; Thompson et al., 2017) as fire regularly overwhelms suppression activities and results in large scale human and ecological impacts (Cardil et al., 2017; San-Miguel-Ayanz et al., 2013; Xanthopoulos et al., 2009). Clearly, longer-term strategies to counter wildfire impacts must consider fuels management as a synergistic strategy to reduce fire spread and facilitate containment, particularly in the context of future climate change (Batllori et al., 2013; Bedia et al., 2014; Lozano et al., 2016; Turco et al., 2014). However, integrating the use of prescribed fire and other fuel management activities into current wildfire management on large landscapes poses many challenges for landscape managers. Competing landscape management objectives that may or may not be compatible with prescribed fire creates a complex spatial trade-off problem for managers that seek to identify optimal arrangements within economic and other constraints (Ager et al., 2017b).

In our study, we generated a wide range of potential treatment designs for a 0.13 million ha fire-prone area in central Catalonia, where prescribed fire treatments can potentially be used to re-create fuel mosaics that increase fire resiliency, facilitate fire suppression, and mitigate fire transmission into residential communities. Using large treatment units (>25 ha) average attainment values in the optimization can mask high differences within the polygons, and we used small and homogeneous grain treatment units (≤ 6 ha) to accurately capture existing sharp spatial gradients in objective metrics (Fig. 2B) and increased allocative efficiency. Our approach can be easily adapted to other fire-prone Mediterranean areas or elsewhere considering a range of treatment priorities, objectives or potential environmental constraints for fuel treatment implementation. Accordingly, we should point out that land ownership (i.e., private, public owned by municipalities and public owned by the regional government) is an important factor conditioning fuel treatment allocation not considered in this study but requiring special attention in project implementation. Nonetheless, we generated prescribed fire scenarios that could be fine-tuned by wildfire managers to consider local conditions (topography, safety planning, escape risk, smoke concerns close to residential areas) to develop appropriate treatment allocations. Prior to treatments, selected units could be easily aggregated into larger blocks according to available material and human resources.

Our use of production functions makes it possible to explore a wide range of efficiency analyses in the development of prescribed fire plans. For instance, increasing investment levels will shift PPFs (i.e., current maximum possible attainment level) outwards, and potentially change the shape of the trade-offs as well as the overall efficiency. Although we

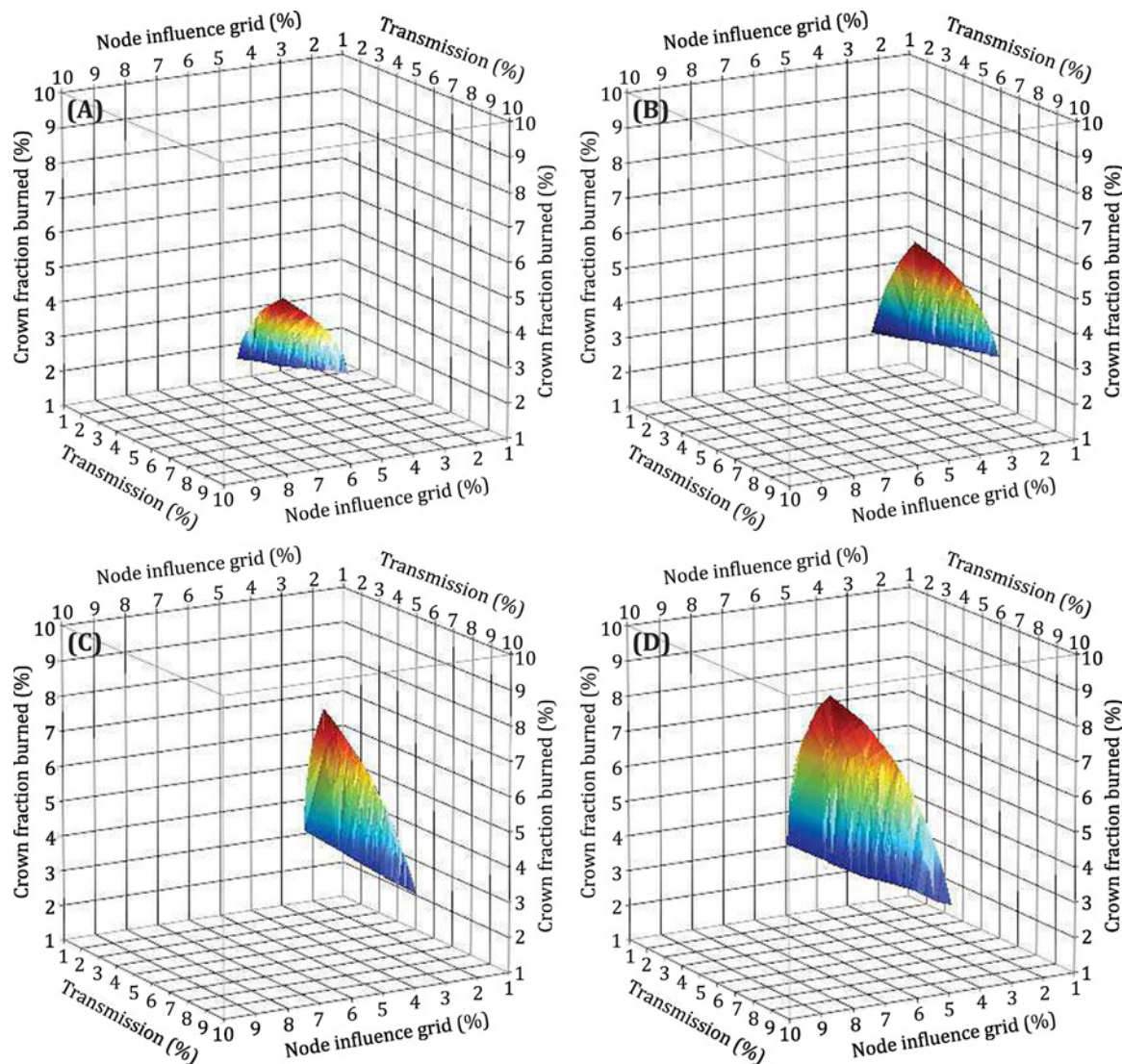


Fig. 8. Production possibility frontiers (PPF) of the three metrics used to assess prescribed fire management objectives for each of the planning areas. Planning areas 1 to 4 (Fig. 1) correspond respectively to panels A to D. The projected surface indicates the maximal-mix attainment within the study area on treated areas for the three metrics. Optimization results were obtained with the Landscape Treatment Designer (Ager et al., 2016a, 2016b) considering all integer weight combinations from 0 to 5 between the three metrics. Every point on the PPF has a corresponding treatment mosaic solution in the study area, where the optimization program identifies the individual treatment units for prescribed fire treatment location. The landscape was divided into 54,773 treatment units and we treated 15% of the burnable area. The convex PPF with respect to the origin indicates sharp trade-offs (e.g., high opportunity cost) when one particular goal is emphasized and the potential for efficient joint production. By contrast, a linear PPF indicates constant opportunity cost over all levels of production.

did not consider revenues on treated areas, we explored to what extent selling the timber stocks on excluded treatment units could increase available area for prescribed treatments. We found that a mere 1% has commercial value (from the 25,000 excluded ha), and revenues would only facilitate economic resources for treating another 0.5% in pre-commercial forest stands (see Appendix 1). Most of the excluded low pole-stage pre-commercial forests (17,258 ha) would require expensive mechanical treatments consisting of a systematic corridor opening with mastication treatments, plus manual lower for canopy pruning in tree covered strips in between (Navascués et al., 2003). At this point, managers have two main options for these areas: utilizing existing subsidies to cover most of the treatment cost, or wait until the first commercial thinning at high pole-stage in 10–15 years despite the risk of an eventual crown fire. Indeed, the annual forest work subsidy call (co-founded with EU agroforestry and rural development 2014–2020 program) contemplates covering $\geq 75\%$ of the total economic cost for risk mitigation thinning and mastication treatments on forest lands within natural sites of special interest ascribed to the certification system and presenting a management plan (e.g., Castelltallat mountain range natural site;

Fig. 9). With regard to the second management option, rather than the marginal economic benefit from first commercial thinning (preferably as a heavy low-level thinning with entire tree extraction for biomass), changing stand structure into a low hazard forest to enable fire re-introduction in a few years should represent the main objective. Best conformation dominant trees (diameter at breast height > 20 cm) must remain after treatments and ladder fuels need to be eliminated from the understory to significantly mitigate wildfire hazard at strategic management points (SMP) (Madrigal et al., 2016; Ordóñez et al., 2005). All in all, target stands in SMPs should have a low tree density ($150\text{--}200$ trees ha^{-1}), single storied structure with a high canopy base (> 5.5 m) and low fuel loads in the understory to withstand the most extreme events (Fernandes et al., 2015; Fulé et al., 2008).

Recent studies conducted in other fire-prone areas tested various optimization models to prioritize prescribed fire. Overall, these studies provide a number of methodological frameworks to solve the many challenges facing wildfire managers tasked with reducing wildfire risk. These challenges include identifying treatment spatial arrangement, treatment timing in long-term forest planning, suitability

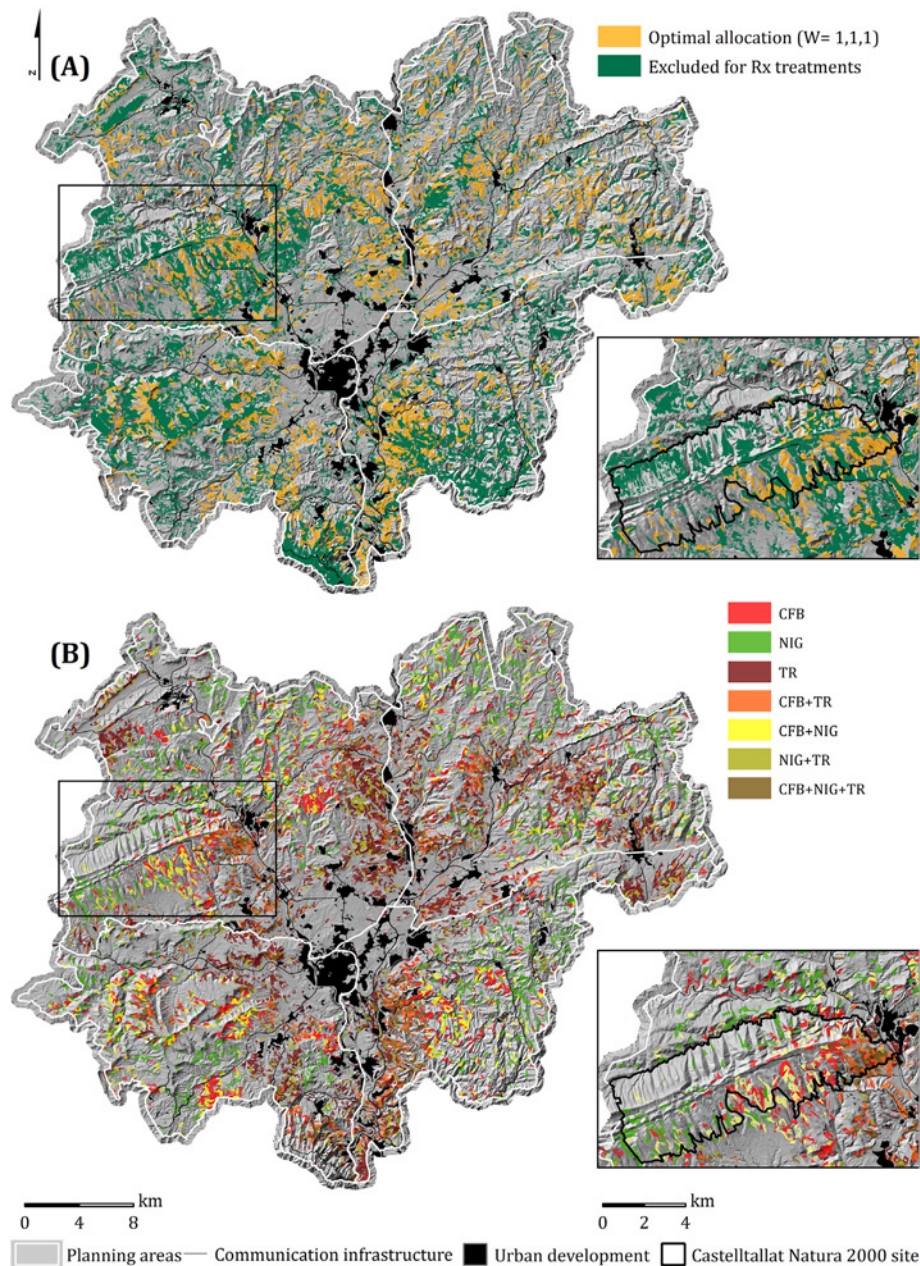


Fig. 9. (A) Optimal prescribed fire treatment locations in Bages County (central Catalonia, northeastern Spain) considering the same weights for all three metrics used to assess prescribed fire management objectives ($W = 1, 1, 1$). Implementing prescribed fire on densely regenerated young forest stands (e.g., *Pinus halepensis* cohorts with $>10^3$ trees ha^{-1} on 1998 Bages fire burned areas) could cause negative effects on the overstory (average crown fraction burned >0.1 or torching $>10\%$), therefore these stands were excluded from the analysis. (B) We overlaid the treatment mosaic results when each metric was optimized independently (see attainments in Fig. 7) to explore areas where optimal solutions for a single metric overlap. The close up view corresponds to the Castelltallat mountain range Natura 2000 site of special interest and Sùria rural community. Abbreviations: CFB = crown fraction burned; TR = transmission; NIG = node influence grid; Rx = prescribed fire.

and combination with other treatments (thinning or mastication), and treatment integration into multi-functional forest management programs (González-Olabarria and Pukkala, 2011; Minas et al., 2014; Rachmawati et al., 2016; Vogler et al., 2015). In the current work we developed a multi-objective optimization approach to define optimal strategies and prioritize areas for implementing prescribed fire activities as part of larger fuel management programs. Previous optimization studies explored how treatment mosaics could be optimized to most efficiently disrupt large fire spread, and mitigate risk to communities (Chung et al., 2013; Rachmawati et al., 2015; Scott et al., 2016; Wei and Yehan, 2014; Wu et al., 2013). By contrast we explored how multiple fire management objectives can be achieved specifically with

prescribed fire by identifying production possibilities (Fig. 9B). The methods are relatively simple compared to many other optimization models, thus facilitating wider implementation in a range of fire prone systems (Ager et al., 2017a). Large backlogs of prescribed fire treatments exist in many land management agencies, particularly in the western US, and tools to prioritize particular burn units to most efficiently achieve landscape resiliency objectives will become increasingly in demand. For instance, prioritizing prescribed fire to achieve desired landscape connectivity (Matsypura et al., 2017) could be performed with the methods we describe here.

In Catalonia, firefighters together with the Forest Service have been managing fuels since 1999, although on a limited basis, and the results

from this study could be used to evaluate ongoing fuel treatment programs and provide insights into new project designs. For the former purpose, PPFs (Fig. 8) can facilitate multi-objective complex-solution project efficiency evaluation as informed by wildfire simulation and optimization. Nonetheless, quantitatively assessing the effectiveness for a specific solution (e.g., treatment mosaic on Fig. 9A) would require subsequent fire modeling considering the same fire weather conditions and treated landscape (Finney, 2007; Salis et al., 2016b). Our treatment plans (Fig. 9) could also be compared with existing management plans and historical wildfires to identify particular landscape features that could contribute to the design and refine the location of SMP for fuel treatments in Catalonia (Costa et al., 2011). For instance, recurrent long-distance spreading fire events burning under particular weather conditions provide interesting baseline information to characterize the most frequent synoptic scenarios associated with catastrophic events (Duane et al., 2015; Pereira et al., 2005; Rasilla et al., 2010), and the fire behavior that led to them (Duane et al., 2016; Salis et al., 2016a).

The development and persistence of vegetation and fuel mosaics on Mediterranean landscapes is influenced by a number of natural and anthropocentric disturbance factors that all must be integrated into strategic fuels planning. Fires can create fuel discontinuities and perpetuate grasslands or open woodlands that can limit the growth and severity of future fires. Post-fire afforestation activities can negate these benefits and perpetuate large continuous areas of hazardous fuels. At a minimum, commercial forestry activities need to consider fuel breaks to fragment the dense multi-storied forested landscapes that develop after afforestation activities. Livestock production can also facilitate fuels fragmentation and retard encroachment by highly flammable shrub vegetation (Elias and Tischew, 2016; Mena et al., 2016). Disturbances that create patches benefit game and protected species that prefer edge and open-habitats (De Cáceres et al., 2013). On the other hand, unburned patches play a key role in the regeneration ecology of low intensity fire-adapted non-serotinous conifer species (e.g., black pine *Pinus nigra*), obligate seeders that require mature stands to regenerate into openings created from severe fires (Martín-Alcón and Coll, 2016; Ordóñez et al., 2006). For instance, remaining old growth endemic black pine habitats after the 1994 and 1998 large fire episodes (e.g., stand-replacing fires burned 50% of Castelltallat mountain range endemic black pine habitat protected site; Fig. 9) are currently a conservation priority, where paradoxically restoring a low intensity cultural fire regime could help protect relict stands (Fulé et al., 2008). The combined effect of all of these factors must be integrated with fuel management plans such that landscape fuel mosaics that support low intensity fire can be created and maintained within economic and ecological constraints. The methods and tools described here can facilitate this process by providing the means to explore and identify spatial patterns of fuel management activities that promote the development of these landscape conditions.

5. Conclusions

Uncharacteristic fires during the last several decades are evidence of an ongoing transition towards an extreme weather-driven fire regime in Mediterranean landscapes. Increasing fuel loads and continuity represent the main factor responsible for these catastrophic events that overwhelm fire suppression capabilities as fires spread across unmanaged forest ecosystems and burn into developed areas. Managing forest fuels with prescribed fire has been demonstrated to be an efficient strategy to fragment fuels and reduce fire spread rates and severity. However, large scale strategic analyses to examine operational aspects of implementing prescribed fire are rare. We demonstrated an optimization framework to design strategically located treatment unit configurations that efficiently disrupt major fire movements, and reduce the potential of fires burning into developed areas. Reversing the current wildfire trends in

Mediterranean areas and building fire resilient landscapes that sustain landscape production will require integrated strategies that consider the myriad land uses and disturbance processes that shape fuel mosaics and resulting fire behavior.

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Appendix A. Alternative fuel treatment possibilities on torching stands excluded for prescribed fire treatments

We explored the possibility of implementing alternative treatments and obtaining revenue from silvicultural treatments on treatment units excluded from prescribed fire implementation due to high torching probability values ($CFB > 0.1$ treatment threshold). We first estimated timber stocking in terms of basal area ($m^2 ha^{-1}$) for the different treatment units using a LiDAR 20 m resolution grid available for Catalonia (icgc.cat). Then, we classified the forest stands considering the slope of the terrain (percentage) and the average dominant height (m). We considered three slope classes ($<30\%$, $30\text{--}60\%$, $>60\%$) in order to account for the potential limitations for tree harvesting and the implementation of fuel mastication treatments (Visser and Stampfer, 2015). Likewise, we considered three dominant tree height classes (h_0 ; <7.5 m, $7.5\text{--}10.5$ m, >10.5 m) according to existing guidelines for intermediate site index, even-aged Aleppo pine stand management for increasing fire resistance and commercial timber production (Beltrán et al., 2011). Finally, we cross-tabulated slope and dominant height classes to estimate timber extractions, considering post-thinning basal areas of 19 and $20 m^2 ha^{-1}$ for high pole-stage ($h_0 = 7.5\text{--}10.5$ m) and timber stage ($h_0 > 10.5$) stands respectively.

Important portions of the landscape were excluded for prescribed fire implementation to prevent negative impacts on the overstory (Fig. 9A). In total, excluded treatment units ($n > 15,000$) accounted for the 19% of the forest land within the study area (about 25,000 ha). In order to address harvesting mechanization possibilities, characterize type of thinning products and quantify extracted timber amounts, we cross-classified these forest stands for management meaningful dominant height and slope intervals that allowed the characterization into nine major combinations (Fig. 1A). Low pole-stage stands ($h_0 < 7.5$ m) account for the bulk of excluded units (17,257 ha), here treatments do not have any commercial interest, and manual pre-commercial thinning plus mastication treatments are only feasible on the lowest slope class areas ($<30\%$; 9534 ha) and would represent a substantial economic outlay ($>1500 € ha^{-1}$). High pole-stage stands ($h_0 = 7.5\text{--}10.5$ m) cover significant portions of the landscape (2682 ha) and might represent some interest for biomass and paper pulp in low slope ($<30\%$) and overstock stands (basal area $> 19 m^2 ha^{-1}$). Specifically, around $3300 m^3$ would be extracted from thinning treatments on these areas, with an approximate market value of $1\text{--}3 € m^{-3}$ (biomass and or paper pulp destination). In addition, it should be noted that $2532 m^3$ correspond to thinning products from only 155 ha where extractions are $>10 m^3 ha^{-1}$ basal area. The timber stage forest stands have the highest commercial interest ($>15 € m^{-3}$), even in the intermediate slope areas, but only occupy 84 ha in total. Here, extractions from all stands ($<60\%$ slope) would vary depending on the thinning weight from the low of 1669 (for a $20 m^2 ha^{-1}$ basal area on stand after low thinning) to $5951 m^3$ (for $10 m^2 ha^{-1}$ basal area on stand after a dissemination cut). Cliffs and steep slopes areas ($>60\%$; 465 ha) were excluded for thinning treatments.

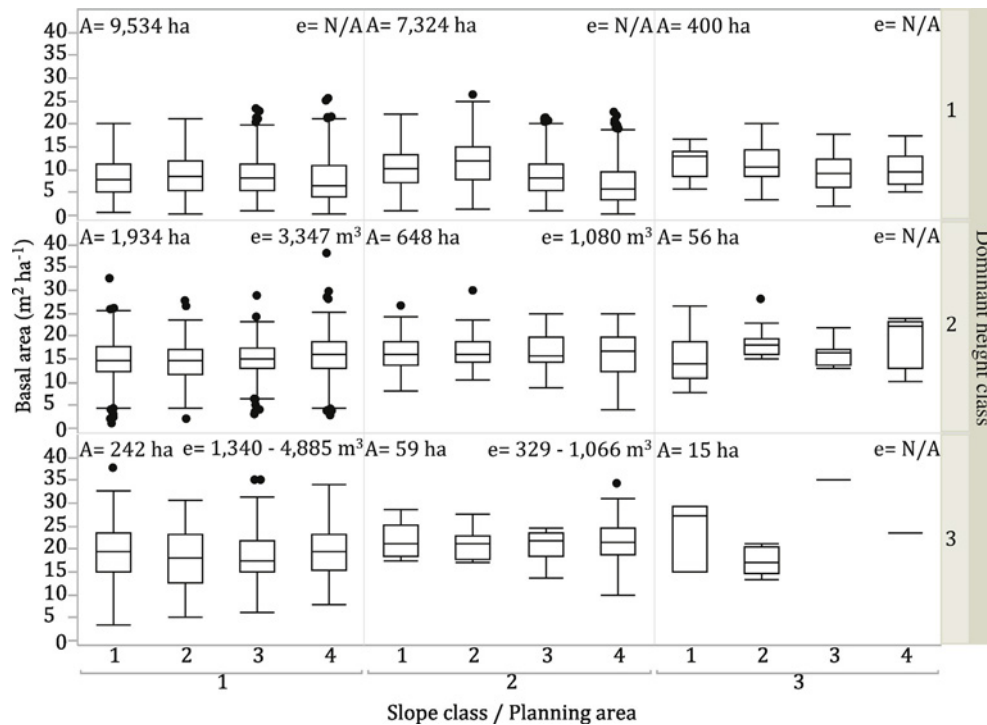


Fig. 1. Timber stocking on treatment units excluded for prescribed fire implementation (Fig. 7A). We explored thinning possibilities on these treatment units ($n = 15,168$) to identify areas where potential revenue from extractions (i.e., biomass, paper pulp and packaging timber) could partially or totally cover the cost required for stand preparation for complementary treatments (i.e., low-pruning, thinning and mastication or entire tree extraction). High resolution (20 m) LiDAR derived basal area ($\text{m}^2 \text{ha}^{-1}$) and stand height (m) grids were used to characterize forest stands (icgcat). We considered three slope classes ($1 \leq 30\%$, $2 = 30\text{--}60\%$; $3 \geq 60\%$) (Visser and Stampfer, 2015) and dominant height classes ($1 \leq 7.5 \text{ m}$, $2 = 7.5\text{--}10.5 \text{ m}$; $3 \geq 10.5 \text{ m}$) (Beltrán et al., 2011) to account for main technological factors on timber harvesting and facilitate the estimation of the type of materials and quantities obtained in thinning. The numbers in the boxes indicate the area (A; top-left) and extractions from thinning (e; top-right) within the study area, for the treatment units within all planning areas corresponding to the respective slope and height cross-classification.

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