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Temporal optimisation of fuel treatment design in blue gum (*Eucalyptus globulus)* plantations

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Abstract

Aim of study: This study was conducted to support fire and forest management planning in eucalypt plantations based on economic, ecological and fire prevention criteria, with a focus on strategic prioritisation of fuel treatments over time. The central objective was to strategically locate fuel treatments to minimise losses from wildfire while meeting budget constraints and demands for wood supply for the pulp industry and conserving carbon.

Area of study: The study area was located in Serra do Socorro (Torres Vedras, Portugal, covering ~1449 ha) of predominantly *Eucalyptus globulus* Labill forests managed for pulpwood by The Navigator Company.

Material and methods: At each of four temporal stages (2015-2018-2021-2024) we simulated: (1) surface and canopy fuels, timber volume (m^3 ha^{-1}) and carbon storage (Mg ha^{-1}); (2) fire behaviour characteristics, i.e. rate of spread (m min^{-1}), and flame length (m), with FlamMap fire modelling software; (3) optimal treatment locations as determined by the Landscape Treatment Designer (LTD).

Main results: The higher pressure of fire behaviour in the earlier stages of the study period triggered most of the spatial fuel treatments within eucalypt plantations in a juvenile stage. At later stages fuel treatments also included shrublands areas. The results were consistent with observations and simulation results that show high fire hazard in juvenile eucalypt stands.

Research highlights: Forest management planning in commercial eucalypt plantations can potentially accomplish multiple objectives such as augmenting profits and sustaining ecological assets while reducing wildfire risk at landscape scale. However, limitations of simulation models including FlamMap and LTD are important to recognise in studies of long term wildfire management strategies.

Keywords: Eucalypt plantations; fire hazard; FlamMap; fuel treatment optimisation; Landscape Treatment Designer; wildfire risk management.

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Introduction

Portugal is covered by 3.2 million hectares of forest, representing 34.5% of the total mainland area, and ranking eighth in Europe as highest country with forestlands (ICNF, 2013). Portuguese plantations are dominated by eucalypt (*Eucalyptus globulus* Labill) encompassing 812 thousand hectares (26% of the whole forested area), and constitute the main forest cover type in continental Portugal (ICNF, 2013). Eucalypt plantations are an important economic resource and support a large and significant pulp and paper industry, one of the key businesses in Portugal (Soares *et al.,* 2007). The culture of eucalypt has many other potential benefits including carbon sequestration (Botequim *et al.*, 2013). However, commercial eucalypt plantations are inherently flammable due to the nature and accumulation of their litter and bark fuels with high levels of biomass, and thus prone to intense wildfires (Fernandes, 2009).

Portugal has the highest incidence of wildfires events in the Mediterranean basin (Pereira *et al.*, 2014). Eucalypt plantations accounted for 35.9% of all Portuguese forest burned during 1996 - 2012 (Mateus &

Fernandes, 2014). These wildfires pose a significant impact on revenues and costs associated with eucalypt management scheduling (Ferreira *et al.*, 2012). However, appropriate management activities can reduce fuel loadings and alter forest structure to change wildfire occurency and reduce wildfire losses (Botequim *et al.,* 2013; Marques *et al.,* 2011). In particular, fuel reduction methods for modifying fire behaviour have become a central management issue and are actively practiced by fire and forest managers in eucalypt stands to reduce wildfire risk (Botequim *et al.*, 2013; Fernandes, 2015).

Wildfire simulation methods provide a framework to quantitatively measure performance of the fuel treatments (Ager *et al.*, 2010), and evaluate the effects of the fuel treatment planning on fire behaviour before and after the fuel treatment design. Large recent wildfires have led to an increased interest in decision support tools to mitigate wildfire risk. These include growth and yield modeling, wildfire behaviour models and optimisation approaches to assist managers in planning and evaluating management decisions to support hazard-reduction fuel practices (Ager *et al.*, 2012; Bradstock *et al.*, 2012; Vogler *et al.*, 2015).

Landscape-scale fuel treatments decrease fire intensity and fire growth rate, hence resulting in smaller and less severe fires (Fernandes, 2015). Fuel reduction treatments (e.g. thinning and prescribed burning) have long been identified as key to decrease fire size and fire severity (Agee & Skinner, 2005), and are a vital part of forest management. However, with limited resources, it is necessary to prioritise where, when, and how fuel treatments should be applied across the landscape. Finney *et al.* (2006) addressed how fuel treatments placed in random and optimal spatial patterns affect fires behaviour. They found that strategic allocation of fuel treatments reduced the predicted growth rates of simulated fires under unfavorable weather conditions more effectively than random placement. Indeed, fire risk and wildfire damage can be reduced by removing or reducing fuels in strategic locations.

Where should the forest manager spatially invest in prevention? Which stands should be assumed for fire prevention treatment management? This study was conducted to monitor trends in wildfire hazard through strategic fuel treatment locations into a spatial-temporal analysis (2015-2018-2021-2024). The main interest was set at reducing the impact of wildfire as determined by fire hazard thresholds (rate of spread, m min^{-1}), and flame length (m) while considering wood supply (m^3 ha^{-1}) for the pulp industry and demands of carbon values (Mg ha^{-1}) with an annual budget constraint (or area treated as surrogate) for the prevention activities in Serra do Socorro. The current framework was designed taking into account several decision support tools used in the United States for wildfire risk management (e.g. FlamMap – Finney, 2006 and Landscape Treatment Designer, LTD - Ager *et al.,* 2012). We used these tools in a three-tiered approach in Serra do Socorro (Centre Portugal). This research resulted in: (i) improved understanding of the relative role of biometric variables (e.g. forest fuel load and stand structure) in fire behaviour characteristics, with the challenge of incorporating such knowledge into fire-management planning; and (ii) information to help policy makers define a scientific approach to spatially and temporally prioritise fuel management interventions for minimising fire impacts, thus protecting eucalypt areas from burning without ecological and commercial timber values losses.

Material and Methods

The study area

The study area is located in Serra do Socorro (Torres Vedras, central Portugal) and covers ~1449 hectares (Fig. 1). Serra do Socorro is the steepest landscape in the municipality of Torres Vedras (Gabinete Técnico Florestal, Torres Vedras, 2015-2019). Topography is dominated by uplands and lowlands ranging from 51 meters to a maximum of 389 meters elevation, with an average value of 168 meters.

The area is characterised by a strong Atlantic wind influence and consequently, throughout the whole year, atmospheric humidity remains high which is especially noticeable in summer when compared with other regions in Portugal (more than 70% relative humidity). In terms of temperature, the maximum (26 °C) is reached during August. Precipitation values, in the fire season (especifically during July and August), do not reach 7 mm as average value per month (values are given for the historical period 1961-1990) (Gabinete Técnico Florestal, Torres Vedras, 2015-2019).

The main forest land cover type is eucalypt plantations (175 ha) surrounded by small agriculture, shrublands and uncultivated land. These plantations are managed by The Navigator Company, the leading paper company in Europe. The site presents the following land use classes: non burnable areas (5.9%), blue gum plantations (12%), extensive agricultural lands and pasture lands (56.7 %), shrublands (24%), pine stands (0.24%).

The municipality of Torres Vedras is considered under a low intensity fire regime with a long fire season. Fire history in Torres Vedras is defined by a significant number of events, mainly in summer season (maximun in October) and small size (less than 1

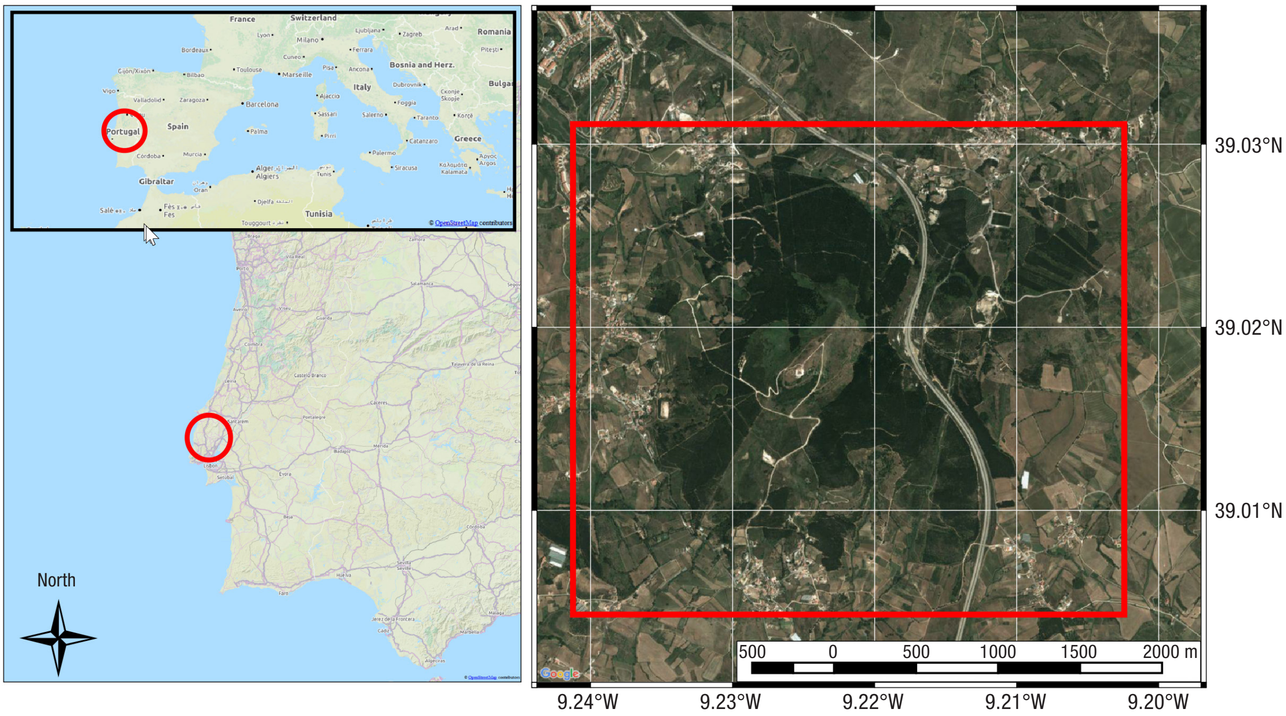

Figure 1. Location of the study area.

hectare) (Gabinete Técnico Florestal, Torres Vedras, 2015-2019). Those autumn and winter fires mainly affect shrublands and farming areas (Marques *et al.*, 2014). Social and demographical factors also play a determining role in Serra do Socorro fire regime, given the strong links between population and agricultural activities and the common use of fire irrespective of season (Raínha & Fernandes, 2002).

Methods

Changes in fuels, carbon, timber volume and fire behaviour, were explored in response to fuel treatments over time for the present (2015, t=0) and three future periods (2018-2021-2024, t=1, t=2, t=3, respectively). A three-tiered strategy was applied as follows.

1. *Dynamic fuel trends*

Field inventory records (year 2013) and data from the growth simulation model (Globulus Model 3, Tomé *et al.*, 2006) were considered for analyses at 3-year intervals in order to conduct the fire behaviour simulation and obtain timber volume and total biomass over time - converted to carbon storage value multiplying by a factor of 0.5 - Kyoto protocol.

A set of 18 customised fuel models developed for Portugal by Fernandes *et al.* (2009), and Cruz (2005) for the case of eucalypt slash were assigned to obtain the surface fuel map of the study area (2015, t=0). Urban areas and structures, water streams, irrigated agricultural lands, roads and forest roads were classified as non-burnable (fuel model 99); short grass (fuel model 232) was assumed for greenhouses, golf facilities, isolated homes, vineyards, agro-forestry systems, fruit orchards, olive groves and natural pastures; in high grass fuel type (fuel model 231) were included non-irrigated agricultural lands and others natural pastures. Besides that, two more classes were introduced to define a region with riparian vegetation (fuel model 221) and small patches with pine forest of *Pinus pinaster* Ait. and *Pinus pinea* L. (227 and 213). The percentage of canopy cover data (84%,60%,44%,22%) assigned to each stand in the current landscape came from previous analysis of the National Forest Inventory blue gum plots (Oliveira *et al.*, 2016) associated with field visits, expert local knowledge and further supported by visual interpretation of georeferenced digital photography.

Dynamic fuel projections (surface fuel types change over time assess changes over time due to planting operations, harvesting, and vegetation regrowth) were defined by fuel model descriptions in field visits and fuel load characterisation based on the dominant vegetation, structures and fuel loads (Identification fuel model key and forest fuel model guideline for Portugal, Fernandes *et al.*, 2009), and expert knowledge provided by The Navigator Company forest protection department.

Canopy characteristics followed equations in Cruz & Viegas (1998) and Soares & Tomé (2001) for canopy bulk density (CBD, kg m^{-3}) and canopy base height (CBH, m) based on the previously calculated biometric data. Canopy cover (CC) percentage was estimated over time based on local experience and inputs from fire managers. A mean CC value was assigned to the plot and classified into intervals (i.e. increased to the next canopy cover percentage category every period until the final cut at 12 years old).

2. *Spatial fire behaviour simulations and fire metrics*

FlamMap5 (Finney, 2006) was used to explore fire behaviour characteristics and fire spread and intensity under constant wind speed and fuel moisture contents. We analysed FlamMap outputs for flame length (FL, m), fireline intensity (FLI, kW m^{-1}), rate of spread (ROS, m min^{-1}). The equations for these parameters are described in Ager *et al.* (2011).

FlamMap uses a gridded input file containing information on fuel and topography. The latter information consisted of elevation (meters), aspect (degrees) and slope (degrees) extracted from a digital elevation model (DEM) at 30 m resolution. Fuel-related data themes consisted of calibrated fuel models (Fernandes *et al.*, 2009), canopy closure, stand height, canopy bulk density and canopy base height derived from inventory records, as well as estimated by growth simulation models and canopy equations. FlamMap simulations were performed for each time period based on temporal projections in surface and canopy fuels as described above.

Wind speed, direction and fuel moisture for the FlamMap simulations were derived from local weather data. Data records from the Dois Portos weather station (ca. 7 km from the study area) were used to calculate fuel moisture for high fire risk season (May-October) for twelve years observation (2001-2012). For fuel moisture, a value of 7% was used for the 1-hour fuels corresponding to air temperature of 20-35 ºC and a relative humidity of 23-35%. These values represented 97th percentile weather during fire season. Values for the 10 and 100-hour dead fuel size classes were computed adding 1% and 3% to the 1-hour dead fuel size, respectively. For live fuel moisture content, we assumed 85-95% for shrubs and canopy fuelbeds, respectively. The simulaton was carried out according 10-m open values for wind speed of 32 km h^{-1} aligned with predominant winds from Northwest, azimuth direction of 320 degrees, generating the maximum fire potential at any given cell.

3. *Optimal treatment locations*

For modeling optimal fuel treatment locations we used the Landscape Treatment Designer (LTD) (Ager *et al.*, 2012, Ager *et al.*, 2013, Vogler *et al.*, 2015). LTD prioritised fuel treatments bases on fire behaviour characteristics, highly valuable resources and economic constraints. LTD creates a sequence of spatially defined project areas that maximises the objectives with the provided constraints and treatment thresholds. The specific variables modeled were fire hazard (FL, ROS), timber volume (m^{3} ha^{-1}), total biomass as carbon storage (Mg ha^{-1}). The treatment thresholds were based on fire potentials conditions and fuel treatments were triggered when a stand exceeded a ROS of 10 meters per minute and a FL of 1.5 meters. Fire behaviour above these thresholds generally exceed firefighting capabilities. Priority stands for treatment were defined by timber volume and total biomass as carbon storage (Mg ha^{-1}). The treatments were constrained to a percentage of the total area of the landscape, 70 ha with a buffer of 10 ha extra "slack variable", as a surrogate for the seasonal budget available for this area (i.e fuel treatment allowance level intensity about 4% for the whole landscape and 40% of the area within eucalypt plantations).

LTD can create both aggregated and non-aggregated project areas. LTD creates a map of treatment priority resulting in a sequence of project areas and respective priorities (ranking in priority planning, e.g. the project labelled "1" represents the highest priority planning area).

Results and discussion

Assessing fire patterns over time

We focused on changes in two fire metrics, flame length (FL) and rate of spread (ROS) patterns over time in response to treatments. The maximum FL was observed at the earlier time periods and decreased thereafter. The maximum FL was observed in year 2018 (t2) presumably due to eucalypt stand structure in young plantations where most trees are between three and five years old. The highest ROS was observed for young eucalypt plantations and in the adjoining shrublands. We observed decreasing ROS with increasing stand age.

Optimising fuel treatment locations at landscape level

LTD creates both aggregated (Fig. 2) and dispersed treatment schedules (Fig. 3), each representing a different spatial treatment scenario. It might be assumed that large land owners such as The Navigator Company would focus on aggregate fuel treatments while forest owners might prefer non-aggregated treatments.

The higher fire risk levels of the periods t_0 and t_1 (Fig. 2a, 2b; 3a ,3b) resulted in the allocation of most of the fuel treatments within plantations in a juvenile stage. This is consistent with the previous fire behaviour outputs by FlamMap in terms of FL and ROS, which were largest in the young eucalypt stands. In t_2 and t_3 (Fig. 2c, 2d; 3c, 3d) fuel treatments were allocated by LTD to both, within eucalypt plantations and outside plantations, in shrublands areas. Young eucalypt plantations often have high density, crowns are low and closer to the ground and have shrubs understory and thus generate a continuous fuel layer and lead to higher fire hazard (Botequim *et al.,* 2013).

The decreasing trend in the number of treatment projects over time was consequence of the forest fire hazard status through time (e.g. the strategic placement of project areas over time in Fig 3a,3b presented projects 1, 2, 3 and 4 while in Fig. 3c, 3d presented only projects 1 and 2). The number of resulting projects decrease as fire metric values decrease over time (t2, t3) and do not surpass the defined thresholds thus do not trigger fuel treatments operations.

The output from fire simulation and strategic allocation of fuel treatment projects from LTD were consistent with experiences from local managment and current silviculture practices performed by the The Navigator Company to manage wildfire risk.

The LTD program selected areas for treatments based on fire hazard and fire risk. In Portugal, a typical eucalypt full rotation may include up to 2 or 3 coppice cuts, each cut being followed by a stool thinning that may leave an average number of shoots per stool ranging from 1 to 2. Harvest ages typically range from 10 to 12 (Soares & Tomé, 2001). Prescriptions further include several shrub cleanings over a rotation (i.e., 1 to 3 fuel treatments per cycle - Duncker *et al.*, 2012).

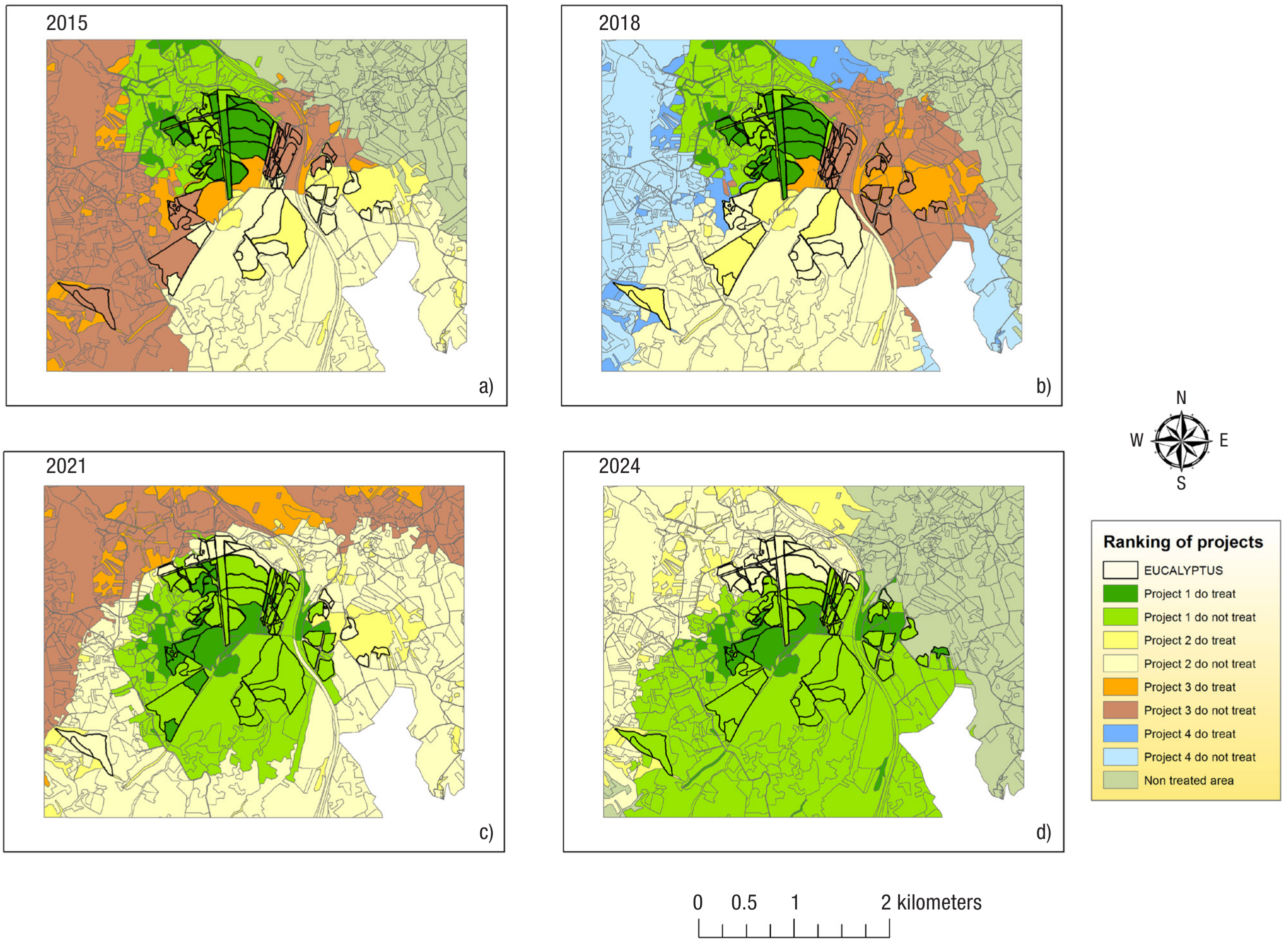

Figure 2. Ranking of projects (aggregate option) to prioritise the entire study area into a sequence of project areas. The project labelled with numbers from 1 to 4 represent respectively the highest to lowest priority planning area for the given objective. Areas labelled as “do treat” were selected for treatment based on the expected flame length and rate of spread exceeding the threshold; the other areas are within the project areas but were not selected for treatment.

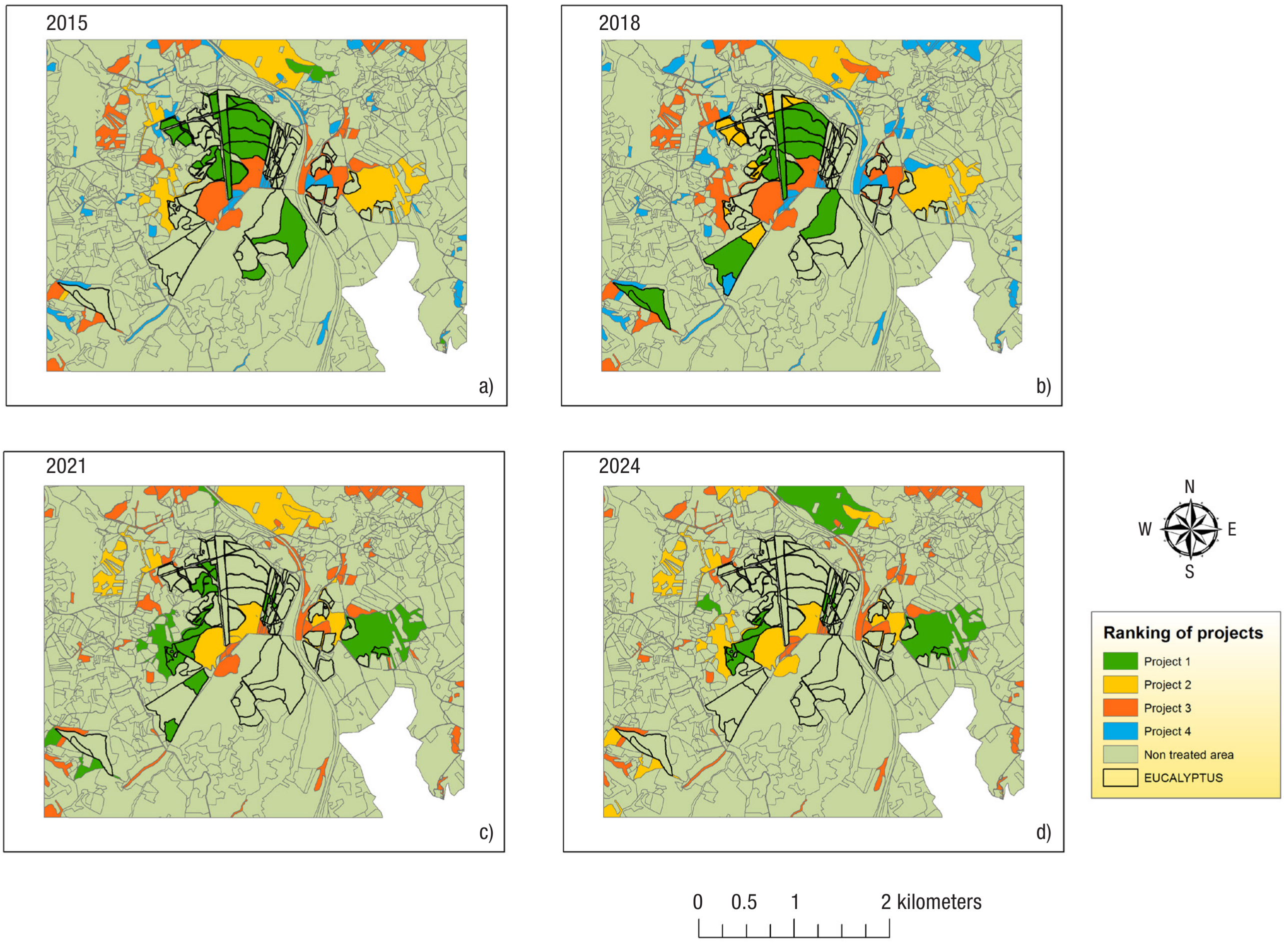

Figure 3. Ranking of projects (non-aggregate option) to prioritise the entire study area into a sequence of project areas. The project labelled with numbers from 1 to 4 represent respectively the highest to lowest priority planning area for the given objective.

The specific fuel treatments, including slash removal and prescribed burning would be carried out in these areas according to local conditions to modify fuel structure and fuel load changes. In our study area, prescribed burning as fuel management is the treatment preferred for the removal of accumulated fuel loads in blue gum plantations (i.e., after stool selection) (Pinto *et al.*, 2013). Other punctual operations depending on the stand status might include mechanical treatments used separately or in concert with prescribed fire to reduce fuel loads and alter fuel structure and thus minimise fire impacts (Fernandes *et al.*, 2011). Nevertheless, several studies suggest that the final size of individual fires can be impacted by landscape treatment rates as low as 5% (e.g. Cochrane *et al.*, 2012).

Contribution to fire-management strategies

The methods we used can potentially have wider application to explore fuel and fire management options in eucalypt plantations. By coupling FlamMap and LTD to examine temporal changes in plantations we were able to add a temporal analyses to the strategic implementation of fuel management. This temporal aspect was made possible by pre-existing research that led to the development of growth and yield model, canopy equations and fuel models descriptions.

Given the fire risk and cost of performing forest and shrublands fuel treatments across large areas, effective allocation of resources is critical. It is very challenging to strategically select fuel treatment locations on space and time with heterogeneous landscape i.e., topography, fuel models, and highly valuables resources susceptible to potential fire damages (Wei & Long, 2014). In this sense, we demonstrated a new approach for prioritising forest management through time in eucalypt stands in Serra do Socorro.

The framework of our method joined models of forest stand dynamics with optimisation models to provide a new decision support system for locating areas for fuel treatments. The study demonstrates new ways to develop efficient risk mitigation practices focusing on spatial-time-investment fuel treatment strategies in fire-prone landscape. The simulation methods also provide a way to communicate wildfire risk to the diverse array of landowners and other stakeholders in Serra do Socorro and adjacent areas in Central Portugal. Thus the methodology can be implemented as part of operational-planning decision-making and helps efficient forest management when answering spatial-temporal question such as where and when fuel treatments are required under the desired objectives.

The literature provides little guidance for determining the required fire behaviour knowledge (e.g. the use of crown fire models developed for conifers and the spotting potential of eucalypts) for an effective protection of eucalypt plantations (Fernandes *et al.*, 2011). Indeed, the limitations of simulation models has been suggested by several authors (Alexander & Cruz, 2013; Cruz & Alexander, 2010). A large number of observations obtained from carrying out experimental simulations studies (e.g. FlamMap5) showed that, in many cases, they are instrumental to predict fire behaviour characteristics and can quantitatively replicate large wildfire events, in terms of predicted burned area (Finney *et al.*, 2011), and size and shape of perimeters (Ager *et al.*, 2014a; Salis *et al.*, 2014). Wildfire simulations should be regarded as general indicators of wildfire exposure and fuel management planning for prioritising fire protection efforts (Salis *et al.*, 2013). We attempted to minmise errors with the application of FlamMap by using calibrated fuel models for the study area (Fernandes *et al.*, 2009). We acknowledge that even if the strategic location of fuel treatments projects are in line with local manager experiences and silviculture practices, uncertainties in the the fuel model and weather data input (i.e., wind conditions) contribute to variability in our modeled outputs (Oliveira *et al.*, 2016).

In future work we will conduct sensitivity analyses to test a wide range of scenarios that vary in terms of intensity of area treated (hectares). We also suggest that future studies include social and demographic factors since these play a role in Serra do Socorro fire regime as evidenced by the strong links between population and agricultural activities and the common use of fire irrespective of season (Raínha & Fernandes, 2002). Coupling mitigation efforts for both social and biophysical risk factors in terms of human ignitions and fuel management is likely the most efficient mitigation strategy for wildfire risk management in fire prone eucalypt plantations in Portugal. Moreover, a better understanding of wildfire risk transmission between eucalypt plantations and surrounding communities (Ager *et al.*, 2014b; Haas *et al.*, 2015; Oliveira *et al.*, 2016) will facilitate the development of strategic fuel treatment plans aimed at reducing future wildfire impacts.

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