Assessing the effect of a fuel break network to reduce burnt area and wildfire risk transmission

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Abstract. Wildfires pose complex challenges to policymakers and fire agencies. Fuel break networks and area-wide fuel treatments are risk-management options to reduce losses from large fires. Two fuel management scenarios covering 3% of the fire-prone Algarve region of Portugal and differing in the intensity of treatment in 120-m wide fuel breaks were examined and compared with the no-treatment option. We used the minimum travel time algorithm to simulate the growth of 150 000 fires under the weather conditions historically associated with large fires. Fuel break passive effects on burn probability, area burned, fire size distribution and fire transmission among 20 municipalities were analysed. Treatments decreased large-fire incidence and reduced overall burnt area up to 17% and burn probability between 4% and 31%, depending on fire size class and treatment option. Risk transmission among municipalities varied with community. Although fire distribution shifted and large events were less frequent, mean treatment leverage was very low (1 : 26), revealing a very high cost–benefit ratio and the need for engaging forest owners to act in complementary area-wide fuel treatments. The study assessed the effectiveness of a mitigating solution in a complex socioecological system, contributing to a better-informed wildland fire risk governance process among stakeholders.

Additional keywords: Portugal, risk governance, risk management, wildfire exposure.

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Introduction

The need for more advanced approaches to mitigating wildfire risk is becoming important as large and destructive wildfires in the fire-prone regions of the world continue to overwhelm fire suppression efforts. Fuel reduction treatments, e.g. thinning and prescribed burning, have long been identified as key to decreasing fire size and fire severity (Agee and Skinner 2005). Fuel treatments can hinder large-fire development and facilitate suppression if implemented on a sufficiently large spatial scale, as demonstrated by case studies in Australia, the USA and elsewhere (e.g. Boer *et al.* 2009). However, most evidence suggests that a large percentage of the landscape (e.g. 20–30%) needs to be effectively treated to substantially alter fire incidence (e.g. Finney *et al.* 2007; Price 2012), which is generally difficult to achieve owing to limited resources and opportunities. Nevertheless, other studies suggest that the final size of individual fires can be impacted by landscape treatment rates as low as 5% (Cochrane *et al.* 2012). Fire behaviour stochasticity and

the uncertainty in quantifying the complexity of fuel treatment–wildfire interactions in real time contribute to disparate findings.

Fuel isolation through linear fuel break networks is an alternative to landscape-wide fuel treatments in Europe (Rigolot 2002; Varela *et al.* 2014) and elsewhere (Amiro *et al.* 2001; Syphard *et al.* 2011). Here, the fuel break function is to enhance the effectiveness and safety of fire control operations (Omi 1996; Weatherspoon and Skinner 1996; Agee *et al.* 2000). Fuel breaks create a linear area where fuels are sufficiently modified to decrease potential fire intensity and rate of spread to a level where suppression resources succeed in containing the fire. Additionally, fuel breaks can be used to anchor indirect control using backfires. Deterministic fire growth modelling to test different fuel management scenarios, including fuel break networks (FBNs), was first used by van Wagtendonk (1996). More recently, simulation modelling has been extensively applied to study fuel breaks and explore optimal treatment

arrangements and levels of treatment (Finney 2001; Loehle 2004; Finney *et al.* 2007; Wei *et al.* 2008; Moghaddas *et al.* 2010; Bradstock *et al.* 2012). Quantitative risk-based approaches to analyse the effects of simulated fuel treatments have also been developed, enabling probabilistic characterisation of fuel treatment impacts on fire-susceptible values (Ager *et al.* 2007*a*, 2010*a*, 2010*b*). Other studies include empirical observations, where for instance Syphard *et al.* (2011) analysed 641 fires in southern California and found that fuel breaks played an important role in 44% of the cases studied in terms of facilitating suppression activities, depending on weather, access and maintenance. However, as FBNs can slow fires but seldom are expected to stop them, fires generally burned through or crossed over them in the absence of active firefighting.

In southern Europe, fuel breaks (6–40 m wide) were implemented in coastal pine forests in the late 19th century and expanded throughout the 20th century as afforestation progressed and defensible infrastructure was needed to hinder fire growth. These fuel breaks were designed to define forest management units and delimit forest plantation from shrub or farmed land, and were strategically placed on ridgetops or critical locations where backfires could be anchored. In Portugal, Barros *et al.* (2012) using 31 years of mapped fires found preferential fire orientations at both local and regional scales, highlighting the need to integrate local information about fire spread patterns to design landscape FBNs. After the catastrophic 2003–05 fire seasons, the Portuguese Forest service coupled their existing experience with contemporary fuel management practices (Agee *et al.* 2000; Rigolot 2002; Agee and Skinner 2005) to put in place a nationwide set of coherent 'regional fire protection networks', which included an FBN, strategic fuel treatment mosaics and forest road and fire water reservoir networks, among others Conselho Nacional de Reflorestação – Algarve (CNR-A 2005). Owing to insufficient funding and limited private landowner engagement, ~10 years later, only 18% of the planned FBN has been implemented (R. Almeida, Instituto da Conservação da Natureza e Florestas, pers. comm.). In the aftermath of recent large wildfire events, Viegas *et al.* (2012) concluded that if the planned FBNs had been built, they might have played a relevant role in reducing wildfire size and losses of assets and lives. However, neither empirical nor modelled quantitative evidence exists regarding FBN effectiveness in southern Europe fire-prone landscapes, and thus its costs and benefits cannot be evaluated or compared among competing policy alternatives. The ongoing public debate about the fire-mitigating role of the FBN would be better informed if its effects were objectively quantified. In particular, it is important to understand FBN benefits when compared with alternatives that might offer better economic, social and ecological trade-offs.

In the present paper, we used simulation modelling to address the potential effectiveness of FBNs on a fire-prone area of southern Portugal. The fuels and fire regimes in the study area are characteristic of many other Mediterranean landscapes. We build on previous work on fire transmission and network analysis methods (Ager *et al.* 2014*a*, 2016; Haas *et al.* 2015) to examine the effect of FBNs in wildfire and the wildfire transmission between municipalities. Specifically, we ask (1) what is the effect of FBNs in terms of affecting expected burned area and burn probability, and (2) can FBNs substantially alter fire transmission among neighbouring municipalities, and thus potentially demonstrate the value of collective and collaborative planning to implement the large-scale FBNs envisioned by policymakers?

Methods

Study area

The study area covered 5878 km^2 in southern Portugal (Fig. 1), comprising the Algarve region (Faro district) and the southern portion of the Alentejo region (Beja district), and encompassed 20 municipalities. Its geography (Fig. 2) is characterised by flat coastal areas and rugged mountain terrain that reaches elevations of 900 m in the west and 600 m in the centre and east. Climate is Mediterranean, with mild and wet winters and warm and dry summers; annual rainfall in the western area can reach 1200 mm. According to Corine land-cover data (European Environment Agency 2012) (Fig. 2*b*), urban and agricultural areas occupy 19 804 and 193 550 ha respectively, and together account for 36% of the area. Urban areas are located mostly along the coast and agriculture is located in valleys and around small inland villages. Forest and shrubland occupy 246 804 and 127 619 ha respectively, representing 64% of the study area. The region has experienced rural exodus from the interior mountains and fast coastal urbanisation since the 1960s (Vaz *et al.* 2012). Since then, afforestation with *Eucalyptus globulus* Labill (bluegum) and *Pinus pinaster* Aiton (maritime pine) has expanded in the western Algarve, resulting in continuous forest stands that dominate the landscape along with *Cistus ladanifer* L. (common gum cistus) shrubland. In the central and eastern parts of the study area, under drier climate and at lower elevation, afforestation projects used *Pinus pinea* L. (stone pine) and *Quercus suber* L. (cork oak), and the traditional agro-forestry mosaic has been encroached upon by *C. ladanifer*. In the valleys, tree orchards and horticulture are being replaced with maquis of *Olea europaea* L. (olive), *Pistacia lentiscus* L. (mastic tree) and *Quercus ilex* L subsp. *rotundifolia* (Lam.) (holm oak).

The historical fire perimeter atlas (Oliveira *et al.* 2012) updated with burned area maps from 2006 to 2012 (ICNF 2013) shows that 201 000 ha burned in the region from 1975 to 2012, ~45% of the available burnable area, corresponding to a mean annual fire incidence of 1.2% (Fig. 1). The proportion of burned area accounted for by large fires (>1000 ha) increased over the time period for which official records exist. Fires >1000 ha did not occur between 1975 and 1981, but 30 years later accounted for 92% of the burned area, including fires >20 000 ha that spread through more than two municipalities (Tedim *et al.* 2015). The regional drivers behind the fire regime suggest that rural exodus, agriculture abandonment, afforestation and fire exclusion policies were responsible for the observed change (Grove and Rackham 2003; CNR-A 2005). After the 2003 and 2004 fire seasons, efforts were undertaken to deal with the problem and a regional fire plan was approved in 2009, including the proposed FBN (Fig. 1). According to the regional reforestation commission report (CNR-A 2005), this FBN design was established after extensive fieldwork carried out by multidisciplinary teams of firefighter officers, forest
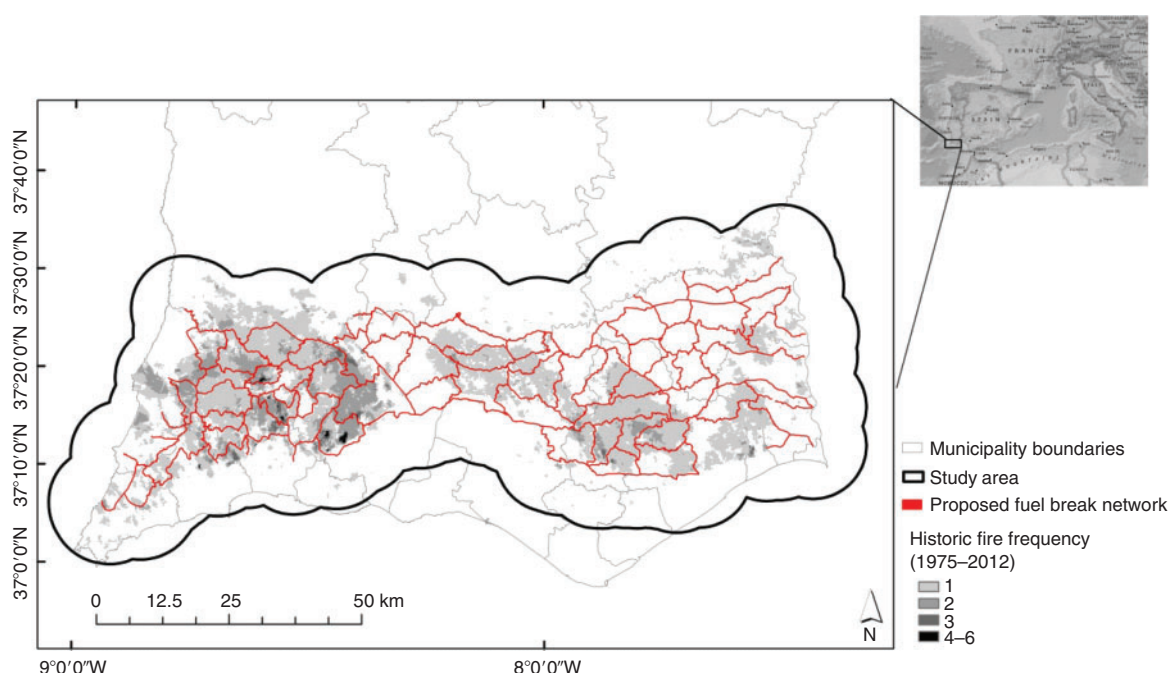
Fig. 1.   Location of the study area in south-west Portugal and the 20 municipalities' boundaries included in the study area, with a 10-km buffer from the fuel break segments.

managers, and civil protection and regional forest authority personnel. Several possibilities were explored and discussed through meetings, before the final layout approval. Without an analytical method or formal process to establish the FBN, as described in CNR-A (2005), the rationale behind the FBN-layout draft design was based on historical fire patterns, local experience, and the existence of fire control anchor opportunities such as roads, rivers, irrigated valleys or mountain ridges, as they facilitate FBN implementation and coincided with municipalities boundaries. To minimise edge effects and let all possible fires ignite and burn into the FBN, the study area in the present paper included a 10-km buffer outside the FBN, as no fires have started farther away in the past (1975–2012).

Wildfire simulation models and data

To analyse the effects of the proposed FBNs on fire incidence, we used the minimum travel time algorithm (MTT) (Finney 2002) incorporated in *Randig*, a command line version of *FlamMap5*, a mechanistic landscape fine-scale fire spread model (Finney 2006). Fire growth is modelled with Huygens' principle and the perimeter is solved using MTT given fuels, weather and terrain (Finney 1998). This algorithm considers all possible travel routes of fire in the landscape through a vector representation of fire spread using pixel characteristics. An average spread rate for the pixel is used, corrected for the elliptical dimension of fire spread relative to the heading direction. For each simulated ignition, the algorithm seeks slope, aspect, elevation, fuel model and canopy cover data for each grid cell in a raster file. Ignitions are randomly sampled on the landscape, based on a defined probability grid. The other

inputs are non-spatial and include dead and live fuel moisture contents and combinations of wind speed and wind direction with their corresponding probabilities of occurrence. The algorithm also requires specification of a burn period – the duration of the fire-spread simulation. The model calculates a flame length and a spread rate for each cell. We modelled major spread events, which typically account for most of the area burned. Thus, we held fuel moisture and weather conditions constant over the course of each simulated fire, as in previous studies (Ager *et al.* 2014*a*). The simulation system (MTT) has been extensively used to predict fire spread and growth in heterogeneous landscapes in the USA (Stratton 2004; Ager *et al.* 2010*b*; Parisien *et al.* 2011), in Europe (Loureiro *et al.* 2006; Duguy *et al.* 2007; Salis *et al.* 2013), and elsewhere (Wu *et al.* 2013).

We obtained aspect (degrees), slope (degrees) and elevation (m) information from a digital terrain model derived from ASTER imagery (NASA Land Processes Distributed Active Archive Center (LP DAAC) 2001). Land-cover maps by vegetation type were derived as in Rosa *et al.* (2011) from Corine 2006 (European Environment Agency 2012) land-use classification. We assigned a custom fuel model to each cover type from the set developed for Portugal (Cruz and Fernandes 2008; Fernandes *et al.* 2009) plus the model for eucalypt slash of Cruz (2005). The canopy cover assigned to each fuel model was derived from an analysis of the National Forest Inventory plots (Fernandes 2009). Urban areas, greenhouses, irrigated agriculture, horticulture, orchards, roads and structures were classified as non-burnable (fuel model 99), and short grass (fuel model 232) was assumed for vineyards, non-irrigated agriculture, annual crops, agro-forestry systems, fruit orchards, olive groves and natural pastures. The Corine land-cover level-3
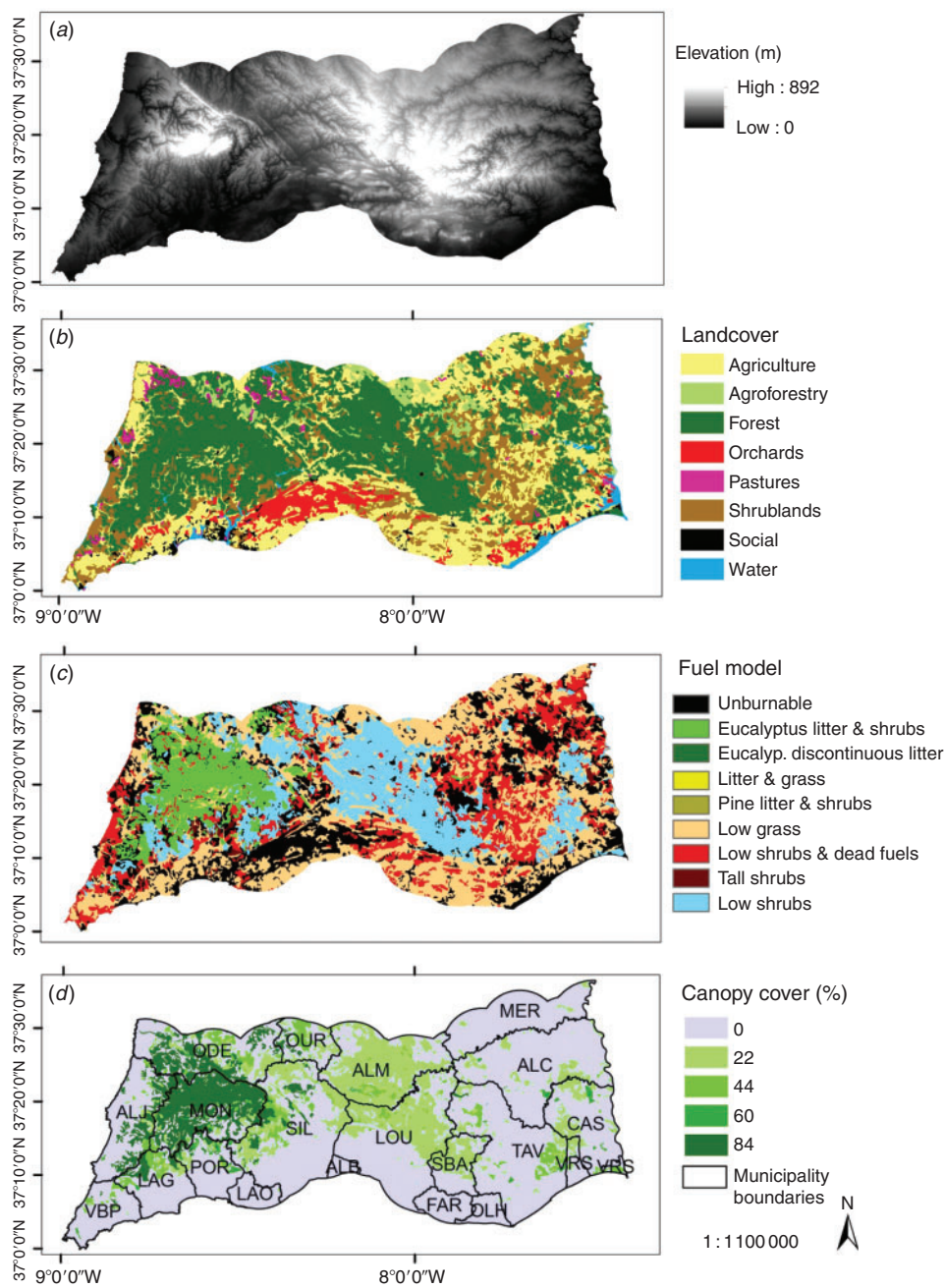
Fig. 2. Maps of elevation (*a*); land cover (*b*); fuel model (*c*); and canopy cover superimposed on municipalities (*d*) for the study area. The study area includes the municipalities of Albufeira (ALB), Alcoutim (ALC), Aljezur (ALJ), Almodôvar (ALM), Castro Marim (CAS), Faro (FAR), Lagoa (LAO), Lagos (LAG), Loulé (LOU), Mértola (MER), Monchique (MON), Odemira (ODE), Olhão (OLH), Ourique (OUR), Portimão (POR), São Brás de Aportel (SBA), Silves (SIL), Tavira (TAV), Vila do Bispo (VBP) and Vila Real de Santo António (VRS).

nomenclature and associated land-cover type, fuel model and canopy cover for the study area are listed in Tables S1 and S2 in the online supplementary material.

Fire modelling used spatially explicit input data (Fig. 2) at a 30-m pixel scale (slope, aspect and elevation) resampled to 120-m spatial resolution to reduce simulation time, to be consistent with the fuel break width and to accommodate the

90-m spatial resolution of Corine land-cover maps from which fuel model and canopy cover were derived. Weather scenarios (wind speed and direction) and their associated probabilities (Table 1) were based on the meteorological conditions associated with most burned area in the past. Based on the work of Pereira *et al.* (2005), who determined that 10% of summer days account for 80% of burned area in Portugal, we identified the
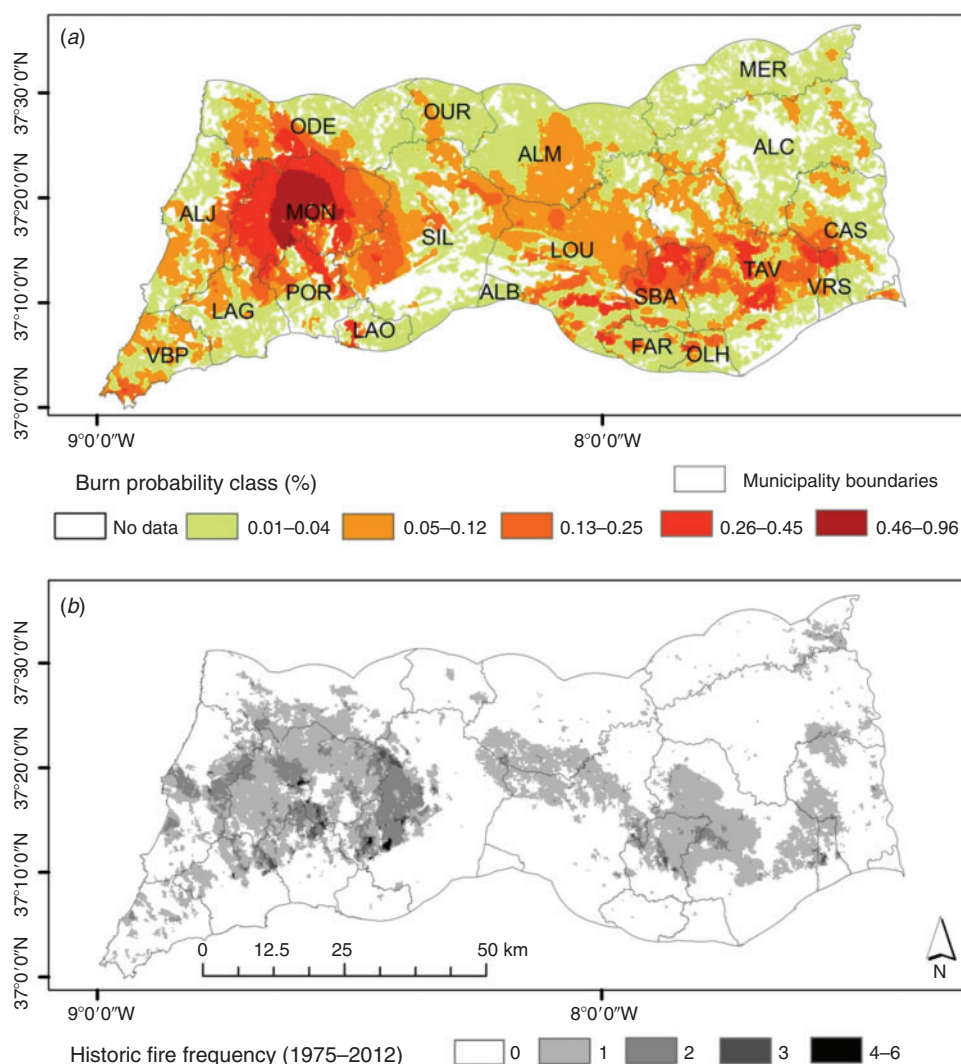
Burn probability class (%)

Municipality boundaries

| No data | 0.01–0.04 | 0.05–0.12 | 0.13–0.25 | 0.26–0.45 | 0.46–0.96 |

Historic fire frequency (1975–2012)   0   1   2   3   4–6

Fig. 3. Burnt probability class map (*a*) for non-treated landscape (NT); and (*b*) historic fire frequency (1975–2012). First figure includes municipalities of Albufeira (ALB), Alcoutim (ALC), Aljezur (ALJ), Almodôvar (ALM), Castro Marim (CAS), Faro (FAR), Lagoa (LAO), Lagos (LAG), Loulé (LOU), Mértola (MER), Monchique (MON), Odemira (ODE), Olhão (OLH), Ourique (OUR), Portimão (POR), São Brás de Alportel (SBA), Silves (SIL), Tavira (TAV), Vila do Bispo (VBP) and Vila Real de Santo António (VRS).

top 10% burned-area days, in the study area, between 1980 and 2005 (Pereira *et al.* 2005). Using daily meteorological fields of the ECMWF (European Centre for Medium-Range Weather Forecasts) provided by the University of Lisbon (DaCamara *et al.* 2014; Amraoui *et al.* 2015), we extracted wind speed and direction at noon for those days over a latitude–longitude 5-km regional grid. Combinations associated with probabilities ≤0.01 were excluded. Fuel moisture content was assumed at 6, 7 and 8% respectively for 1-, 10- and 100-h dead fuel size classes, based on air temperature and relative humidity for the above-mentioned set of fire days, and at 85% for live fuels (Fernandes 2009). Ignitions were spatially allocated to burnable land (Tables S1 and S2), located according to a sampling probability grid based on a fire-ignition logistic regression model (Catry *et al.* 2009); the model has an accuracy of 80% at the national scale and uses population density, human accessibility, land cover and elevation

as input variables. As most ignitions are anthropogenic, 85% occur within 2 km of urban areas or roads Catry *et al.* (2009). For spotting, and in the absence of empirical evidence, we assumed the default software probability of 10%. Each ignition was allowed to burn actively for a period of 24 h using a 120-m spatial resolution for the fire spread calculations, after which fire growth ceased. This burn period was based on trial runs and was set to allow a balanced representation of historical fire size distribution including very large fires. Moreover, similar visual analysis to that presented by Parks *et al.* (2011), suggested that a 24-h burn period resulted in accumulated fire perimeters resembling historical fire records (Fig. 3). The comparison between historical and simulated treatments regarding the proportion of burned area by fire class size was also reasonable except for fires >10 000 ha (Fig. 4*b*), which may occur even under more severe fire weather or have longer durations than simulated here.

Wind speed (km h^{-1})	Azimuth (degrees)	Probability
12	45	0.073
28	45	0.021
12	90	0.094
28	90	0.031
12	135	0.125
28	135	0.104
44	135	0.021
12	180	0.052
12	315	0.063
28	315	0.021
12	360	0.146
28	360	0.250
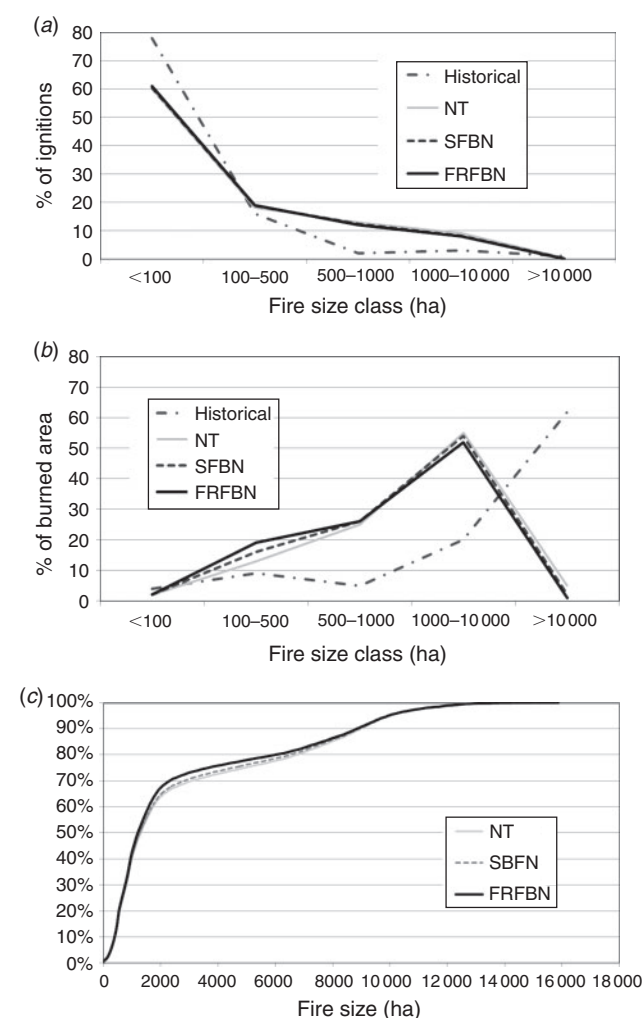
Fig. 4.   Effects of different fuel treatments in distributions of ignition (*a*); burned area (*b*); and cumulative burned area (*c*). NT, non-treated landscape; SBFN, shaded fuel break; FRFBN, full reduction fuel break network.

Fuel treatment scenarios

We simulated a non-treatment scenario (NT) and two fuel treatment scenarios using an FBN layout (ICNF 2013) that consisted of a 120-m-wide linear infrastructure covering 17 964 ha (3% of the study area). The two treatment scenarios were:

(1) Full Removal Fuel Break Network (FRFBN), resulting in a non-burnable area after all vegetation within the 120-m wide strip is removed, leaving bare soil or rocks (fuel model 99).
(2) Shaded Fuel Break Network (SFBN), where vegetation is partially removed from the 120-m-wide strip, leaving canopy cover at 22% and an understorey typified by fuel models 224 (discontinuous litter), 226 (litter and grass) or 232 (short grass).

A map of treatments is presented in Fig. S1.

We simulated 150 000 ignitions for each scenario to ensure that each pixel burnt on average 30 times in the NT scenario, providing a robust sample for estimating burn probabilities as described below. The same simulation parameters (number of ignitions, burn period, ignition probability grid, meteorological scenarios and fuel moistures) were used to simulate fire behaviour and growth in the three treatment scenarios.

Analysis

Simulation outputs included a fire list containing the ignition location and size of each fire and a burn probability (BP) grid representing the burn likelihood of a pixel given a random ignition. To study fire transmission between municipalities, we followed Ager *et al.* (2014*a*) and intersected the fire perimeter and the ignition point with the municipality map, and then calculated burned area per municipality in relation to the municipality of the ignition point. All intersects were done using *ArcGIS* and the Geospatial Modelling Environment (Spatial Ecology LLC 2009).

Network analysis was used to visualise and characterise fire transmission and the change resulting from treatments. In network analyses, as we wanted to highlight the effect of the treatments to each municipality, nodes corresponded to municipalities and linkages represented burned area transmission between municipalities. Transmission from *i* to *j* occurs when a fire starting in municipality *i* burns a certain amount of area in municipality *j*. Transmitted fire area from *i* to *j* (TF_{ij}) is calculated as:

$$TF_{ij} = AB_{ij}/N_i \tag{1}$$

where AB_{ij} is the area burned in municipality *j* from fires started in municipality *i* and N_i is the number of ignitions in municipality *i*. The total area burned in each municipality from fires ignited within the municipality measures non-transmitted (or self-burning) fire (NonTF). The expected average burned area from fires that start in a municipality *i* and escape to its neighbour *j* is measured by outgoing transmitted fire (TF-Out), and the burned area of fires coming from neighbour municipalities *j* and burning in municipality *i* is measured by incoming transmitted fire (TF-In). Transmission among municipalities

Table 2. Differences in burn probability (BP) between treatments

Values represent percentage differences in pixel-level burn probability between the shaded fuel break network (SFBN) and full-removal fuel break network (FRFBN) treatments and the non-treated reference situation (NT) for each non-treatment BP class

		Burn probability class				
		0.01–0.04	0.05–0.12	0.13–0.25	0.26–0.45	0.46–0.96
SFBN-NT	Difference	−0.0006	−0.0052	−0.0138	−0.0268	−0.0625
	decrease (%)	4.1	6.4	7.5	8.2	10.7
FRFBN-NT	Difference	−0.001	−0.0095	−0.0284	−0.0644	−0.181
	decrease (%)	6.7	11.7	15.4	19.8	30.9

can be represented for each of the alternative landscape networks where nodes are arranged according to their geographic positions, and directional links correspond to the amount of TF. Networks for TF change between landscape treatments can also be created, highlighting the relative benefits of building the FBN for each municipality. We compared networks generated for the non-treated landscape with the network produced in the two FBN configurations and examined the benefits in terms of non-transmitted burned area (NonTF) and the expected burned area that each municipality imports (TF-In) and exports (TF-Out) to its neighbours. All network representations were done with *Visone* (Borgatti *et al.* 2002; Brandes and Wagner 2004).

Results

Effect of FBN on burn probability, fire size and burned area

Results showed that treating 3% of the study area to establish a regional FBN would reduce the average BP between 4 and 11% for the SFBN treatment scenario, and between 7 and 31% for the FRFBN scenario (Table 2). The spatial distribution of BP classes (Fig. 5) revealed that around Monchique and Tavira municipalities (central western area), a smaller area was in higher BP classes in the FRFBN scenario (Fig. 5c) compared with the SFBN scenario (Fig. 5b). Treatments decreased the number of pixels with higher BP and increased the number of pixels with lower BP. A pixel-scale map of each scenario is presented in Fig. S2.

For fires escaping initial attack and spreading for 24 h, implementation of the FBN would reduce mean fire size by 17 and 8% for the FRFBN and SFBN respectively, compared with the NT landscape. NT fire size was 377 ± 1002 ha (mean $\pm$ standard deviation), with a coefficient of variation (CV) of 297%, and was reduced to 312 ± 765 ha (CV 245%) and to 348 ± 899 ha (CV 257%) in the FRFBN and SFBN scenarios respectively. The FRFBN was more effective in decreasing mean fire size and its variation. Results by fire size class (Table S3) showed that the change in fire size statistics brought about by the treatments was very small. Both treatments increased total burnt area for fires <500 ha and reduced it in the other size classes, especially in the >10 000 ha class, with a 92 and 58% reduction for FRFBN and SFBN respectively. As ignitions patterns and density were constant for all treatments, the overall reduction of expected burned area (17% for FRFNB and 8% for SFBN) was essentially due to a shift in fire size class distribution, with the treatments increasing the number of fires <500 ha and decreasing the number of fires >500 ha (Fig. 4b and 4c).

This can be due to the size of potential burn units or compartments, i.e. the area in between fuel breaks may be too large, reinforcing the small effect that, on average, the FBN had in reducing the overall burnt area.

Reduction in fire size was not equally distributed among the 20 municipalities in the study area. Comparing the mean fire size of the FRFBN landscape with the NT scenario, municipalities of Portimão, Monchique and Castro Marim (Fig. 6) exhibited a higher proportional reduction in fire size compared with the study area average (17%). The standard deviation decreased for the majority of the municipalities, except in Lagoa, Faro and Albufeira, where the expected average fire size increased slightly in the treatment scenarios. Although those municipalities were the only ones without FBN within their boundaries, their burnable area fraction is very small, and is mostly fragmented and located in gently undulating terrain. Negative difference values may have resulted from the randomness of the ignition and wind patterns, which produce a wider fire distribution with a slightly higher average. Because the average values are small, a small difference has a large effect on the proportion. Maximum fire size also decreased for the majority of municipalities, except for Mértola, Loulé, Lagoa, Faro, Vila Real de Santo António and Castro Marin where little change in fire size was documented.

Can FBN substantially alter fire risk transmission among municipalities?

For the non-treated landscape and all 20 municipalities, the transmission network diagram showed two major subnetworks within the study area: the western region centred in Monchique, and the eastern region around Tavira. Although the FBNs did not change the fire transmission diagram pattern, as shown by comparing the three diagrams in Fig. 7, it changed the magnitude of transmitted burned area. The networks diagrams in Fig. 7 illustrate the average area of fire being transmitted in the non-treated scenario (Fig. 7a) and a net benefit for the two treatment options in comparison with the non-treated landscape (Fig. 7b and 7c). We present the quantitative effects for all municipalities in detail in Tables S4, S5 and S6, and illustrate the rationale for two municipalities as an example. In the NT scenario, fires starting in Odemira are expected to burn on average 369 ha in Monchique, whereas 161 ha (less than half) burn in Odemira from fires starting in Monchique. For the FRFBN scenario, the expected burned area is 120 ha from fires starting in Odemira and spreading to Monchique. Area burned by fires starting in Monchique and spreading to Odemira is reduced by 41 ha on average. Under the SFBN scenario, fires starting in Odemira are
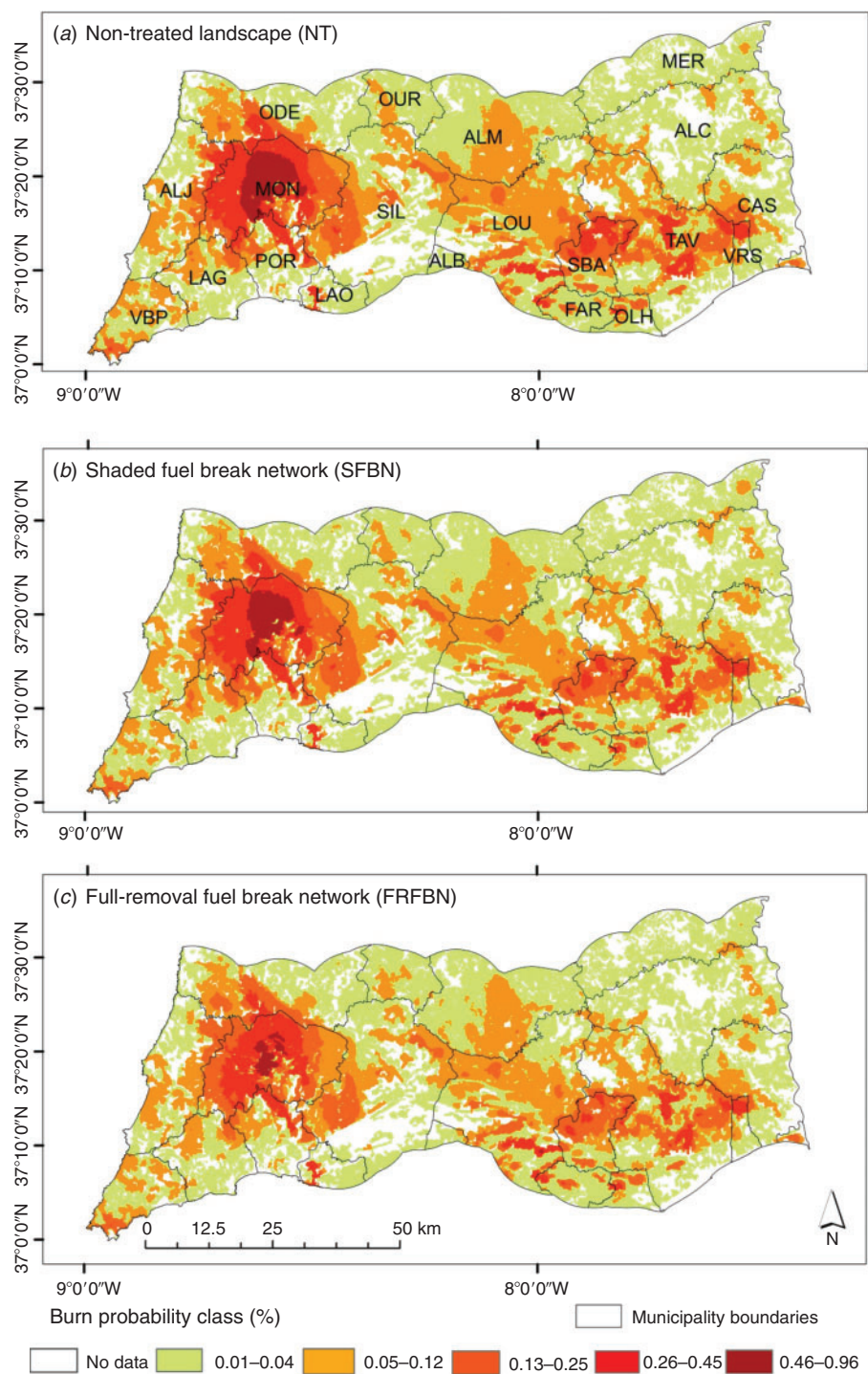
Fig. 5. Burn probability class map for (*a*) non-treated reference (NT); (*b*) shaded fuel break network (SFBN); and (*c*) full removal fuel break network (FRFBN) treatments. First figure includes municipalities of Albufeira (ALB), Alcoutim (ALC), Aljezur (ALJ), Almodôvar (ALM), Castro Marim (CAS), Faro (FAR), Lagoa (LAO), Lagos (LAG), Loulé (LOU), Mértola (MER), Monchique (MON), Odemira (ODE), Olhão (OLH), Ourique (OUR), Portimão (POR), São Brás de Alportel (SBA), Silves (SIL), Tavira (TAV), Vila do Bispo (VBP) and Vila Real de Santo António (VRS).
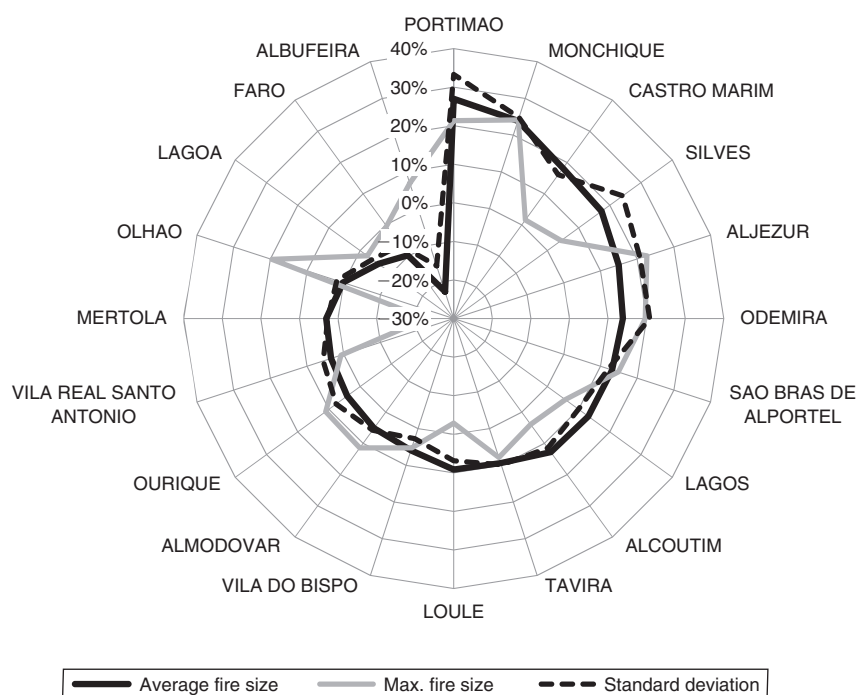
Fig. 6. Difference expressed in percentage in average, maximum and standard deviation of fire size between the full removal fuel break network and the non-treated landscape in each of 20 municipalities.

expected to burn 85 ha less in Monchique, while transmission from the latter to the former is reduced by 17 ha.

The proportion of area burned by fires that started in each municipality that were not transmitted to neighbours (NonTF) was 83% on average. The FBNs had a minor effect in changing NonTF except for Odemira, Aljezur, Portimão and Silves, where NonTF area burned in FRFBN increased from 6% up to 10% in comparison with the NT landscape (Fig. 8a). The FRFBN result was to increase the proportion of area burned within the communities, blocking fire spread to the adjacent communities. Again, the burnable area within FBN boundaries may be too large and fuel breaks may be too far apart, undermining the FBN potential to reduce burned area and alter fire transmission among municipalities. For the communities of Albufeira, Alcoutim, Faro and Castro Marim, the SFBN reduced the proportion of Non-TF burned area slightly, which may be related to the small proportion of burnable area and the grass-dominated fuel mosaic.

The net change in TF-Out and TF-In (Fig. 8b and 8c) from the FBN represents the potential benefit in terms of fire exposure to and from each of the 20 municipalities. For communities where incoming fire (TF-In) exceeded exported fire (TF-Out), the construction and maintenance of the FRFBN would be primarily to decrease fires coming in from adjacent municipalities and secondarily to reduce fire exposure to other communities. Thus, Monchique, Aljezur, Silves and Tavira municipalities all had relatively high values for TF-In, whereas Odemira, Portimão and Ourique had relatively high TF-Out values. Hence, the FBN effect from a risk transmission standpoint varied among the communities in terms of the expected benefits. We found that six of the municipalities accounted for 87% of the total TF-Out,

namely Monchique, Odemira, Aljezur, Portimão, Silves and Tavira. The FBN segments associated with these municipalities accounted for 52% of the total length of the regional FBN.

Discussion

Results suggest that full implementation of the regional FBN (3% of the study area) reduces the overall average fire size up to 17%, and decreases conditional BP up to 31%. Higher reductions are observed in the more intense treatments (FRFBN) when compared with the shaded fuel break scenario. These results are not surprising given the differences in fire potential between the two fuel treatment options. The general findings are similar to other studies (Ager *et al.* 2007b; Syphard *et al.* 2011; Bradstock *et al.* 2012; Price 2012) where treating a small proportion of the subject area resulted in minimal reduction in exposure, risk, and expected burned area. If the FRFBN is fully implemented, simulation results indicate an overall reduction in area burned up to 17%, corresponding to a decrease of 0.016 to 0.039 ha of burned area per hectare treated, considering the average and maximum number of observed events per year respectively. This leverage effect was calculated after examining the historical rural fire database from which we assessed that on average 4.3 events lasting over 24 h occurred annually, with a peak of 14 fires in 2003 and 2005. These leverage values are one to two orders of magnitude lower than observed where prescribed burning is used as an area-wide treatment (Price 2012). Conversely, our results are optimistic when compared with those of Finney (2002) and Ager *et al.* (2010b), where cumulative treatment rates of 20% were required to obtain similar reductions in BP and fire size.
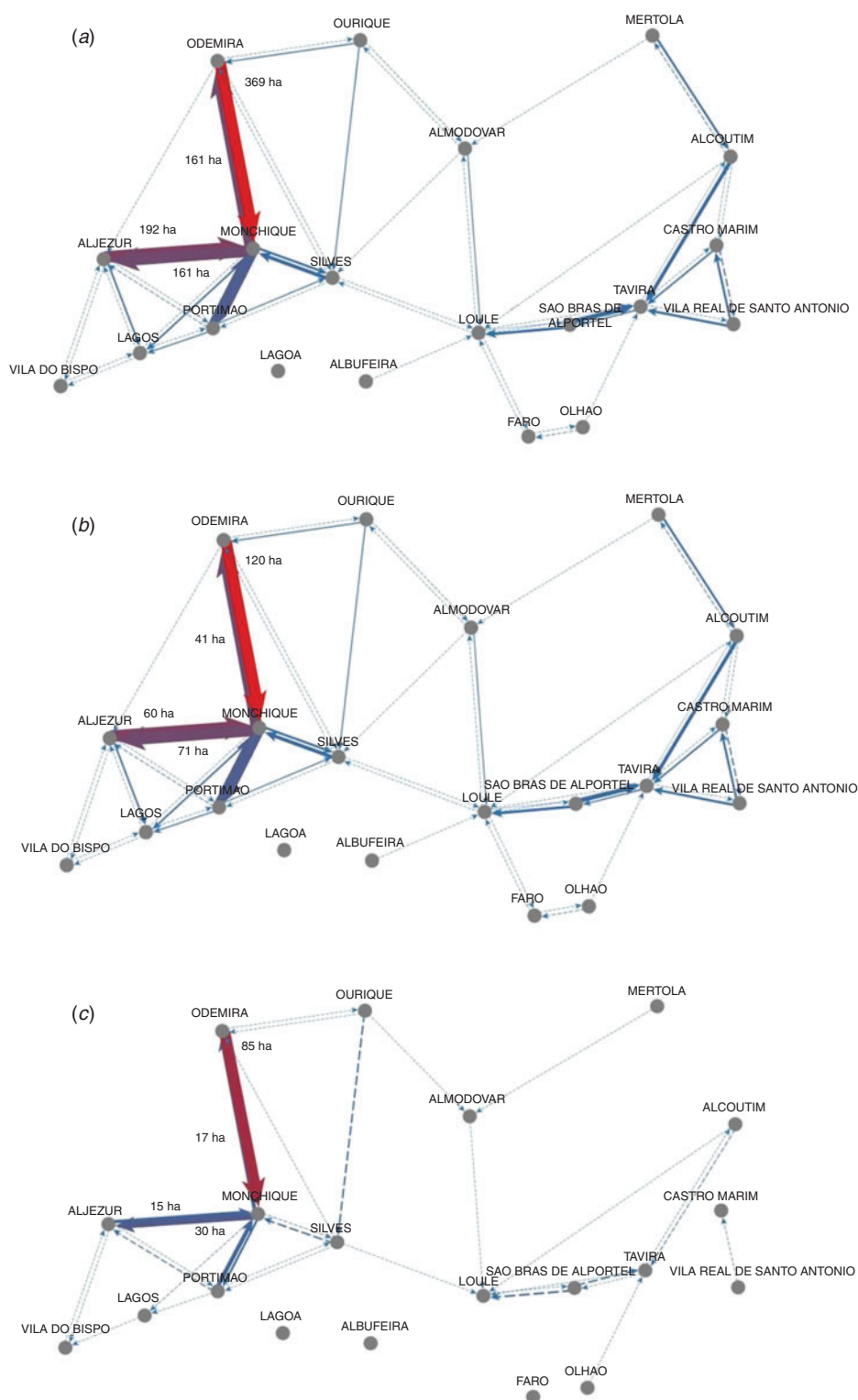
Fig. 7. Fire transmission network diagrams of the study area showing linkages of the 20 municipalities. For three municipalities, (*a*) presents absolute values of expected burnt area being transmitted in the non-treated (NT); (*b*) and (*c*) present net benefit expected in burnt area when comparing the full removal fuel break network (FRFBN) and the shaded fuel break network (SFBN) with the non-treated scenario respectively. Arrow width illustrates the reduction in burned area (ha) transmitted from ignition origin to destination (arrow direction). Transmitted burned area increases from light blue to dark red. Linkages below 10 ha are represented by dotted lines.
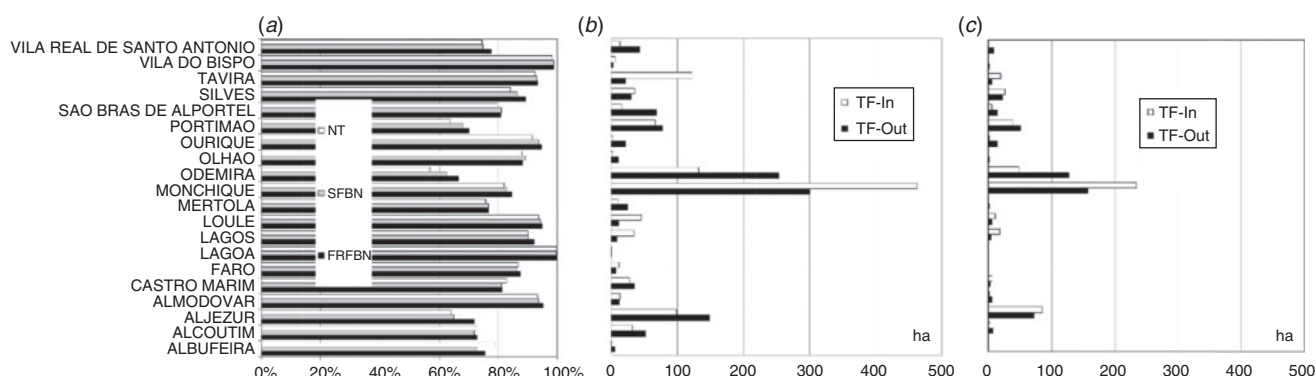
Fig. 8. (*a*) Percentage of non-transmitted burnt area (self-burning) in non-treated landscape (NT), shaded fuel break network (SFBN), and full-removal fuel break network (FRFBN)) for each municipality; (*b*) incoming transmitted fire (TF-In) and outgoing transmitted fire (TF-Out) expressed in burnt area for each municipality in non-treated landscape; and (*c*) net change in incoming transmitted fire (TF-In) and outgoing transmitted fire (TF-Out) for each municipality between the simulated FRFBN and the non-treated reference landscape. TF-In represents the total burned area transmitted from neighbouring municipalities and TF-Out represents the total burned area transmitted to neighbouring municipalities. All values expressed in hectares (ha).

The expected effect of a fuel break is not to halt fire spread but to make firefighting operations more effective (Weatherspoon and Skinner 1996). This synergistic effect was not modelled, because current fire suppression practices in Portugal disregard fire perimeter control and are focussed on civil protection (Beighley and Quesinberry 2004). Moreover, it is difficult to coordinate suppression activities with linear fuel management infrastructure in large fires (Keeley 2002; Rigolot 2002; Finney *et al.* 2003). Fuel breaks, vs landscape-scale treatments, minimise area treated, and it has been suggested for Portugal (Fernandes *et al.* 2012) that an FBN strategy is more cost-effective than a fuel age mosaic established by area-wide treatments. However, fuel mosaics reduce fire severity across the landscape, in contrast with an FBN strategy, which our results also highlight: the decrease in fire incidence was due to a shift in the distribution of fires by size class towards fires <500 ha, but overall burnt area was reduced only by 17%. This can be due to excessively large compartments within the fuel breaks, as they were designed to minimise the chance of large fires (CNR-A 2005). Landscape-scale fuel treatments decrease fire intensity and fire growth rate, hence resulting in smaller and less severe fires than those occurring in untreated landscapes under the same conditions and with the same duration (Fernandes 2015).

We found that reduction in fire exposure in the presence of an FBN as defined by modelled burned area is more relevant where fires are more frequent (Monchique and Tavira). Risk transmission among municipalities differs in the two subregions of the study area. We found that up to 50% of the FBN is located in six municipalities (mostly located in the western region and in the central east) and ignitions in these segments are responsible for 80% of the area burned being transmitted, very similarly to the non-treated landscape. This suggests that fire transmission in the region is determined by site-specific variables such as land cover, fuel composition, topography and ignition patterns, and the tested FBN layout had a minor effect in changing the transmission pattern. The burnt area received and transmitted by each municipality (Fig. 8) quantifies liability in respect to neighbouring communities. This information can facilitate mitigation planning and risk-sharing agreements, and potentially mobilise stakeholders to sponsor landscape-scale mitigation

or other designs. The graphical representation of potential wildfire risk transmission among communities (Fig. 7) and the balance between importers and exporters (Fig. 8) of fire as derived from simulation experiments can also facilitate more accurate risk perception where fires have not occurred in the recent past (e.g. in Odemira and Monchique communities). The arrangement of community ties relative to fire-prone environments in concert with spatial ignition patterns will have a strong influence on wildfire transmission. Reducing network ties among communities needs to be explored by examining the arrangement of fuels and their spread potential, and historical ignition patterns and their relationship to land-management activities.

Further in-depth work should look at the effects of reducing ignition density and extending fire simulation duration and examine alternative fuel treatment layouts that reduce the size of compartments within fuel breaks either based on ridgelines (linear FBNs as in the present study) or in strategically placed area-wide treatment units. Further work could also consider finding the optimal treatment effort necessary to assure specific burned area reduction, or explore the simulation results to produce fire event statistics such as quantifying how often fires crossed all or certain FBNs and identify critical crossing locations. To improve the quality of the results and reduce their uncertainty for planning use, sensitivity analysis could clarify how different individual parameters used as fire simulation input contributed to variation in model predictions. Considering the institutional effort put into the fuel isolation strategy, further studies should document and analyse the outcome of fire–FBN encounters, as in Syphard *et al.* (2011).

The methodology framework can assist fire management agencies in prioritising the construction and maintenance of more effective FBN segments, thus rationalising budget allocation. In the present case study, if totally built, costs could reach €15 million in a 10-year investment time frame, or €856 ha^{-1} considering a 3% interest rate, €750 ha^{-1} for construction and €150 ha^{-1} for maintenance every 5 years. The very low leverage values we found suggest that to avoid 1 ha burned, 61 ha (on average) or 26 ha (for the year with the highest burned area on record) would have to be treated. Considering the highly unfavourable cost–benefit ratio, it is

critical that fire suppression operations take advantage of the FBN to reduce area burned beyond its passive effect. Results also indicate that half of the planned FBN could mitigate 87% of the transmitted risk, hence suggesting that the overall cost can be halved.

Limitations

The use of simulation modelling is an important tool to address policy questions pertaining to fuel management policy at the scale at which fuel management projects are implemented. Modelled outputs can provide important insights into the interactions between wildfire spread and spatial patterns of fuel treatments at landscape scales. Although historical fire records can provide broad trends in wildfire activity (Ager *et al.* 2014*b*), and site-specific observations on modifications in fire behaviour (Prichard and Kennedy 2012), they are grossly inadequate to study the effect of different fuel management strategies (area treated, treatment dimensions, orientation, treatment type) on quantitative wildfire risk, even in severely fire-prone regions like Portugal. Moreover, the inherent uncertainty in future wildfire events demands probabilistic risk-based approaches to wildfire management (Miller and Ager 2013). Although several studies have shown that the MTT family (*FSim*, *FSPro*, *Flammap5*, *Randig*) of simulation models can quantitatively replicate large wildfire events, in terms of predicting area burned (Finney *et al.* 2011) and size and shape of perimeters (Ager *et al.* 2014*b*; Salis *et al.* 2014), the simulation models have many well-known limitations, including: (i) simulated fire behaviour does not account for fire–atmosphere interactions and therefore is likely to underestimate crown fire activity and spread rates (Cruz and Alexander 2010); (ii) meteorological information used as input was derived from synoptic weather models adjusted to reflect major topographic features in the landscape, but likely underestimates wind speed under severe fire weather; (iii) in terms of the input data describing fuels, the assignment of fuel models to Corine land-cover classes is guided by expert opinion, adding additional uncertainty; (iv) the 120-m spatial resolution may not capture fuel bed discontinuities and natural fuel breaks associated with topographic conditions. Related to this point is that we modelled a fuel break that was only a single pixel, and thus where the treatments are linked by adjacent vertices (touching on the diagonal), wildfires can essentially spread through the fuel break without being affected by the fuels treatments. However, this effect would only be observed when the minimum travel time was aligned perpendicularly to the fuel break at that specific pair of vertices; (v) a significant fraction of our study area is dominated by unmanaged eucalypt stands, known for their spotting potential, which may exceed the 10% probability we assumed by default. This would allow fuel breaks to be breached by fire at higher rates than simulated, especially under burning conditions more severe or with longer fire durations than considered here (Fernandes *et al.* 2011; Cruz *et al.* 2012; Alexander and Cruz 2013). For Canadian boreal fires, Amiro *et al.* (2001) found that 1-km-wide fuel breaks would restrict spotting and fires larger than 10 000 ha if 15% of the landscape was treated.

Conclusions

Quantifying transmitted risk demonstrates interdependencies among communities in their potential exposure to wildfire and the importance of collaborative planning at the regional scale with respect to wildland fire policy development. Demonstrating this interdependence through simulation studies can help improve risk perception and build the social capacity required for effective wildfire mitigation efforts (Fischer and Charnley 2012). The present analysis clearly demonstrated the potential benefits of coordinated fuel treatments among the landowner communities. Thus, the results from the study may help motivate the development of national and regional public policies towards an integrated, landscape-based 'fire-smart' approach (Fernandes 2013) to manage wildfire risk. Our analysis suggested that allocating 3% of the territory to an FBN would lower fire exposure and decrease the occurrence of large-fire events. If the goal of the decision-makers is to substantially reduce burned area and fire severity, we suggest further fuel treatment efforts are needed beyond the FBN investment, especially in the frequent-fire (high burn probability) subregions within the study area. These results can now be used to frame local fuel and forest management strategies that include cost–benefit analysis and risk assessment (Finney 2005; Rodríguez y Silva *et al.* 2012; Pacheco *et al.* 2015), to support collaborative decision-making among multiple stakeholders and land-tenure systems in Portugal.

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