A methodology for determining operational priorities for prevention and suppression of wildland fires

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Abstract

Traditional uses of the forest (timber, forage) have been giving way to other uses more in demand (recreation, ecosystem services). An observable consequence of this process of forest land use conversion is an increase in more difficult and extreme wildfires. Wildland forest management and protection program budgets are limited, and managers are requesting help in finding ways to objectively assign their limited protection resources based on the intrinsic environmental characteristics of a site and the site's interrelationship with available firefighting resources and existing infrastructure. A Fire Suppression Priority Index, integrating information on both the potential fire behaviour risk (Potential Fire Behaviour Index) and the fire suppression difficulty (Suppression Difficulty Index), provides managers with fundamental information for strategic planning and development of tactical operations to protect the natural environment. Results in the Córdoba Province, Andalusia's autonomous region, Spain, showed a statistically significant relationship between wildfire size and all three indices, demonstrating the utility of the methodology to identify and prioritise forest areas for strategic and tactical fire management operations. In addition, the methodology was tested and validated by trained and qualified wildfire management personnel in Chile and Israel, obtaining similar results as in Spain.

Keywords: strategic fire management planning, wildfire behaviour, wildfire risk, wildfire suppression difficulty

1. Introduction

Survival of forest diversity in Mediterranean ecosystems is threatened by wildfire; a seasonally permanent problem greatly affected in recent years by climate change (Flannigan et al. 2006; González and Pukkala 2007). Long drought periods seen in Mediterranean ecosystems (Millán et al. 2005), as well as their vegetation associations, set favourable conditions for a recurrent yearly fire problem (Piñol et al. 1998; Pausas 2004). In addition, abandonment of rural areas plays a direct role in the increase of fire-hazardous fuels (González Bernáldez 1991). Agencies with wildfire protection responsibilities require more sophisticated, complex and costly strategies to ensure an effective response for the protection of life, property and natural resources (Vélez 2009).

Decision support systems, such as Behave (Andrews 1986; Andrews and Queen 2001), Farsite (Finney 1998), FlamMap (Finney 2007) and Behave Plus (Andrews et al. 2003) are used in US studies to model fire behaviour. Other software such as Visual Behave and Visual CARDIN (Rodríguez y Silva 1999; Rodríguez y Silva et al. 2010a) have been adapted to Mediterranean conditions. All of these software are based on previous surface fire spread models (Rothermel 1972; Burgan and Rothermel 1984) and some with recently updated fuel models (Scott and Burgan 2005; Rodríguez y Silva and Molina Martínez 2012; see also Keane 2013; Weise and Wright 2014).

Fire spread is a complex phenomenon affected by the combination of meteorological conditions, physiographic factors and fuel model conditions such as fuel load and fuel bed depth (Keane et al. 1998; Perry et al. 1999). Improvements in computerised data collection techniques have allowed the spatial distribution of forest fire danger to be mapped by means of Geographic Information Systems (GIS) (Chuvieco and Salas 1996). In this sense, the use of meteorological factors, physiographic factors and land use characteristics in a national fire risk index is well generalised (Deeming et al. 1977; Lasaponara et al. 1999; Taylor and Alexander 2006). Technological advances have influenced the development of fire risk indices. Improvements in fire risk mapping developed from satellite imagery depend on available spatial resolution (López et al. 2002; Andersen et al. 2005). Recent remote sensing developments have also included additional characteristics such as stand density and height (Kötz et al. 2004; Lasaponara et al. 2006). Other researchers have developed a fire risk assessment based on probability of fire occurrence, fire behaviour and potential consequences (Chuvieco et al. 2010). However, recent developments in the field of fire risk management and risk assessment have coalesced on a more nuanced and quantitative approach to fire risk analysis (Finney 2005; Hardy 2005; Busby 2008; Calkin et al. 2011; Thompson and Calkin 2011; Miller and Ager 2013). In this approach assessment of wildfire risk necessitates understanding the likelihood of wildfire interacting with resources valued, and the size of potential net benefits (damages) (defined as benefits minus damages; see for example Rodríguez y Silva and González-Cabán 2010) to the resources from fire (Finney 2005; Thompson and Calkin 2011). All else equal, other factors such as the accessibility and mobility difficulties of firefighting resources become relevant in determining fire spread (Vélez 2009).

Fuel treatments are necessary to preserve the ecological and socioeconomic values of forest areas (Stephens 1998; Agee et al. 2000; Stratton 2004; Stephens and Moghaddas 2005; Molina Martinez et al. 2011a) and to protect the wildland– urban interface (WUI) (Reams et al. 2005). Wildland fires become a problem of social protection magnitude when large fires escape the forest environment and enter heavily urbanised areas that lack the capabilities to protect themselves (Cohen 2000). An effective and objective budget allocation process and an efficient program for fire prevention and suppression activities are needed to help reduce the socioeconomic impacts of wildfires (Molina Martinez et al. 2011b). Along these lines, we developed a new approach for operational priorities assessment that includes two aspects; potential fire behaviour (see Miller and Ager 2013) and fire suppression difficulty that measures the difficulty in performing suppression actions during the fire incident. The resulting Fire Suppression Priority Index (FSPI) is the sum of these two factors. In this paper we present the conceptual model for FSPI and discuss the different sub-indices created and used to generate the potential fire danger and fire suppression difficulty factors. Finally, we discuss the validation process performed by personnel responsible for wildfire operations in Chile, Israel and Spain. However, before continuing with discussion of the FSPI model it is important to indicate that this is not a fire risk assessment or fire risk analysis. Though our model contains some of the parameters necessary for a fire risk analysis, such as fire ignition or fire spread, our work does not include the three components necessary for performing a wildland fire risk analysis: likelihood, intensity and effects (Finney 2005; Thompson and Calkin 2011; Miller and Ager 2013).

Methodology

Study area

The study area covers 13 761 km^2 in the Spanish Province of Cordoba, Andalusia (Fig. 1). The area is characterised by a continental Mediterranean climate with daytime summer temperatures above 40ºC conducive to fire ignition and propagation, and higher risk of fire occurrence. Córdoba fire statistics show an average of 125 forest fires per year (2001–2010), which burn 833 ha of forest lands.

Córdoba is located in the Guadalquivir valley with Sierra Morena mountain range in the north and Sierras Béticas in the south. Two evergreens, *Quercus ilex and Q. suber*, dominate the forest vegetation. The shrub strata is dominated by *Cistus* spp., *Retama shaerocarpa, Pistacia lentiscus, P. terebinthus, Arbutus unedo, Olea europaea* var. *sylvestris, Q. coccifera*, *Teucrium fruticam* and aromatic plants (*Thymus* spp., *Lavandula* spp. and *Rosmarinus* spp.) (see International Association for Plant Taxonomy, http://www.iapt-taxon.org/index_layer.php, accessed 18 September 2013).

The fire protection infrastructure for the Córdoba Province consists of a main Operations Center near the capital in Sierra Morena, and three Defence Centers (CEDEFOS) located in southern Córdoba in forest areas considered of high ecological, cultural and economic importance.

In addition to Córdoba, we used another location in Spain and locations in Chile and Israel to validate the methodology presented here. In Spain the validation area is in the Huelva Province, with an Atlantic influence and 7500 ha of public lands (Montes de Gamonosa, Castaño y Ribera, Sierra de Rite, and El Saltillo) (Fig. 2b). In Chile we used two provinces most highly prone to fire occurrence: Valparaiso and Viñas del Mar (Region V) (Fig. 2c). This study area is 22000 ha, with climatic, vegetation, topographic, and demographic conditions conducive to a severe wildfire occurrence and propagation problem (Castillo et al. 2009). In Israel, the validation area used was the Hakdoshim National Forest (Fig. 2d). The forest area is 2082 ha, covered principally by stands of *Pinus* spp., *Cedrus* spp. and *Cupressus* spp.

Practical approach

Development of FSPI and the two necessary sub-indices requires information on existing vegetation and identification of fuel models in the study area. We developed a GIS database to study the relationship between fuel model and vegetation composition and structure. The information from satellite imagery was insufficient for the spatial resolution of the study because the lack of information on the structure and spatial coverage of vegetation, fuel height, fuel load (kg m^2) and canopy volume, density and abundance for tree species. Precise information (< 5 x 5 m) is needed for each fuel present in each defined cell or pixel.

To resolve this problem, we integrated the satellite imagery information with information from Spanish National Forestry Inventory, Forest Map (http://www.magrama.gob.es/ es/biodiversidad/servicios/banco-datos-naturaleza/informaciondisponible/ifn3.aspx), Land Use and Vegetation Cover Map (http://www.magrama.gob.es/es/biodiversidad/temas/ecosistemasy-conectividad/mapa-forestal-de-espana/) and field inventories (http://www.ign.es/ign/layoutIn/corineLandCover.do, all websites last accessed on 15 September 2013) for all study areas. This integration resulted in a final product of much higher quality. Fuel models identification is done using the methodology of Scott and Burgan (2005) adapted to the Mediterranean ecosystems (Vélez 2009; Rodríguez y Silva and Molina Martínez 2012).

The objective of a fire suppression and prevention index (FSPI) approach is to develop a map to prioritise the necessary prevention and suppression actions as well as the efficient mobilisation of firefighting resources within a fire management program. Two important factors are relevant for prioritising the suppression actions: the potential fire behaviour (Potential Fire Behaviour Index, PFBI), and the difficulties arising from the presence of fire in a specific area (Suppression Difficulty Index, SDI). The combination of these two indices produces the FSPI. GIS data can be used to identify four qualitative areas based on the FSPI: Low (FSPI < 20), Moderate (FSPI 20–50), High (FSPI 51–75) and Very High (FSPI > 75).

Potential fire behaviour index

This index describes the level of fire danger to the vegetation based on ignition potential and the dynamic behaviour and energy release component of the vegetation (Rodrı´guez y Silva 2009). The PFBI is the sum of three sub-indices: ignition, dynamic behaviour and energy behaviour.

Ignition sub-index (I_{ig})

This indicates the capability of accumulated dead fine fuels to ignite given a heat source, showing the fuels' predisposition to accept heat and start combustion (Eqn 1).

$$I_{ig} = [\Sigma (P_i * C_i * F_i) * A_i/A_t] \qquad (1)$$

where Pi is the ignition probability computed using the NWCG Fireline Handbook Appendix B Fire Behavior (USDA Forest Service 2004) and is a function of the fine and dead fuels moisture content, ambient temperature and degree of shade. Ten values in ascending order express every 10% probability, Ci is the ignition coefficient for each fuel category (Table 1) and is computed as Ci = W1h / (W1h + W10h + W100h) 10^{-1} ;

the 1-h, 10-h and 100-h fuel categories. Fi is the flammability coefficient based on five levels of flammability: 1, slightly flammable; 2, flammable; 3, moderately flammable; 4, very flammable and 5, extremely flammable (Hernando 2009), Ai is the area of each fuel model distribution and At is the size of total study area managed within each cell or pixel.

Dynamic behaviour sub-index (I_{cd})

This evaluates how easy or difficult it is for ignited fuels to provide continuity to the oxidation reactions as a function of their own combustibility, the influence from terrain slope and wind speed. It is computed by a weight (W in Table 2) assigned to the fire rate of spread calculated from BEHAVE (Rothermel 1972; Burgan and Rothermel 1984) adapted to Mediterranean conditions (Rodríguez y Silva et al. 2010a), with terrain slope and wind speed for each fuel model distribution (Eqn 2).

$$I_{cd} = [\Sigma\ (CD_i)* A_i/A_t] \qquad (2)$$

where CDi is the assigned weight from Table 2 rate of spread; all other variables as defined previously.

Energy behaviour sub-index (I_{ce})

This sub-index incorporates the complete consolidated combustion phase once the fire started and the oxidation phase is completed (Eqn 3).

$$I_{ce} = [\Sigma\ (2* FL_i * HUA_i / (FL_i + HUA_i)) * A_i/A_t] \qquad (3)$$

where FLi is the assigned weight from the flame length (Table 2), and HUAi is the assigned weight from the heat per unit area (Table 2). All Ice variables were calculated with the BEHAVE system.

Suppression difficulty index

The SDI combines the penetrability, accessibility and mobility sub-indices, line production capabilities by firefighting resource (including hand and mechanical line corrected for model slope in each fuel model distribution) and a new sub-index measuring aerial resources contribution (Eqn 4). To date, only land firefighting resources had been considered.

$$SDI = [\Sigma (I_{ce}) / \Sigma (I_a + I_m + I_p + I_{ar} + I_c)] \qquad (4)$$

where SDI is the suppression difficulty index; I_{ce} is the energy behavior sub-index, obtained from the formula to compute the Potential Risk Index; I_a is the accessibility sub-index; I_m is the mobility sub-index; I_p is the penetration sub-index; I_{ar} is the aerial resources sub-index and I_c is fire-line construction sub-index.

Accessibility sub-index (I_a)

This is used to compute the density of road network available for accessing forest areas to suppress and control a forest fire. It is computed as an assigned weight depending on the length (m) of the access road network in each different fuel model distribution (Table 3). Information obtained from satellite images or aerial photos.

Mobility sub-index (I_m)

Except in rare instances, mobility refers to the access capacity the forest area provides through the existing fire prevention firebreaks network (lineal and area). That is, the ease with which fire suppression equipment can actually move off-road in the forest area. The mobility sub-index is computed as a weight assigned as function of the length of existing fire prevention firebreaks in each fuel model distribution (Table 3). Information obtained from satellite images or aerial photos.

Penetrability sub-index (I_p)

This refers to how easy or difficult it is for firefighters to access the forest area on foot. Measuring this characteristic is difficult. However, having an easy-to-use index would allow incorporating variables that are important to defining how difficult it is for humans to walk through the forest area. Among these variables, we include slope, the shallow soil structure in relationship to its hardness (loose or compact soil), existing fuel density, hill slope aspect and pre-suppression trails (Eqn 5).

$$I_p = [\Sigma [(s_i * d_i * sh_i + e_i)/pt_i] * A_i/A_t] \quad (5)$$

where s_i is the weight assigned to the percentage slope of the fuel model area i (Table 4), d_i is the weight assigned to the difficulty caused by fuel model i for firefighters to walk in the area (Table 1), sh_i is the weight assigned to soil hardness (Table 4), e_i is the weight assigned to the fuel model i slope aspect (Table 4), and pt_i is the weight assigned to existing presuppression trails (Table 4).

Aerial resources sub-index (I_{ar})

This includes three variables related to the different type of aerial resources used in fire suppression. It incorporates variables for helicopter, amphibious aircraft and land-based aircraft services (Eqn 6).

$$I_{ar} = I_h + I_{aa} + I_{la} \quad (6)$$

where I_h is the helicopter variable, I_{aa} is the amphibious aircraft variable and I_{la} is the land-based aircraft variable. Each of these terms is derived from the assigned weights in Table 5.

Fireline opening sub-index (I_c)

This represents the fireline production rate achieved by hand crews using hand tools and machinery, corrected for the fuel model slope (Eqn 7).

$$I_c = [\Sigma (Ih_i + Im_i) * CP_i] \qquad (7)$$

where Ih_i is the weight assigned to the fireline production rate by fuel model using hand tools (Table 1), Im_i is the weight assigned to the fireline production rate using machinery (Table 1) and SC_i is an adjustment coefficient depending on the model slope (Table 4).

Furthermore, we used the Pearson correlation test (IBM SPSS Statistics 2010) to test for potential correlations between each index value (PFBI, SDI and SPI) and fire size or the presence or absence of a large fire in each of the three validating sites. We further used the ‘odds’ ratio (OR) statistic (Morris and Gardner 1988) to analyse and measure the degree of the relationship.

Results

Potential fire behaviour index

To determine PFBI, it was necessary to compute the three subindices identified previously. First, the analysis of the ignition sub-index showed a high value ($I_{ig} >2$) for almost 54% of the Córdoba Province. The difference in this sub-index resulted more from the ignition coefficient and flammability than from the ignition probability. The small fluctuation in the ignition probability is due to lack of variability in relative humidity and temperature in the study area during summer. Thus, the main factor determining the ignition probability was the fuels shading, making necessary a correction to only 1% of the study area. The type of material present and its compactness determined the ignition coefficient. The coefficient took high values for grasslands and pioneer shrublands, and lower values for large concentrations of litter and silvicultural debris. Flammability depended on the floristic composition of the area. In our case, most of the area took on the highest possible value (5) due to the presence of seasonal grasses or the dominance of *Cistus* spp. and *Erica* spp.

Information on the meteorological conditions and physiographic parameters of the study area was necessary to compute the dynamic and energy behaviour sub-indices. Meteorological information was obtained from a geostatistical analysis of historical records for 16 weather stations in the area for an 11-year summer period from 2000 to 2010. GIS was used to gather the study areas physiographic conditions based on a 20-m^2 digital model of the terrain. The meteorological and topographic information was then uploaded into the BEHAVE model resulting in a potential fire rate of spread greater than 20m/min for almost 35% of the forest area. That is, the Ice sub-index reaches levels>5 (fire rate of spread > 20m/min) for more than 35% of the study area, the heat per unit area being the principal limiting factor, meaning that a potential fire with a higher energy release output could result in a potentially higher Ice. Under potential meteorological conditions, flame length was > 2 m over most of the forest area, except in dehesas with cattle or swine present.

The structure of the forest area was very complex, because of the general presence of a multi-layered canopy with dense understorey and trees of variable height and age below the main canopy. The PFBI showed a wide variability. The maximum value was 21.23 for 47% of the forest area, and a minimum of 12 over 34% of the forest area (both stand and treeless areas). Another 19% of these areas were classified as dangerous (values >15).

Suppression difficulty index

The road network is generally good in the central area of the Córdoba Province, but it decays progressively with increasing distance from the central zone. The presence of fire-breaks (mobility sub-index) was higher than 700 m per fuel model in areas in the centre of the province and in some public lands close to one military base, also in some areas of the lower northern and southern sectors of the province. The penetrability sub-index showed that there was difficulty to work on a little over 11% of the study area (values < 2). These difficult areas were located in the central part of the Province and inside the Subbéticas Natural Park. Moving away from those areas the difficulty level decreased. The opening sub-index is given by both the fuel model and the slope. It is important to note that in the study area there is a very narrow zone in which 12% of the total area slope is > 30% (16.78). Combining the slope information and potential fireline production rates for each fuel model, we found low fireline production rates using both hand tools and machinery on 32% of the area, because of the environmental conditions for fireline opening (values < 25m/h) for manual tools and < 1000m/h for bulldozer). In addition to SDI calculation, there was no difficulty in using helicopters in the study area because of the abundance of water sources. For example, there are six water reservoirs over 400 m in length that can accommodate amphibious aircraft, and also four areas for land-based airtankers.

All these sub-indices must be considered for the appropriate planning of prevention program actions. The SDI can be used as an objective way to develop a better fire operational suppression planning for both ground and aerial resources. In this case, SDI showed high values for a little over 10% of the forest area (values > 0.5).

Fire suppression priority index

Once PFBI and SDI were developed we combined them to determine the area most susceptible to a fire that could cause severe damage. Therefore, the FSPI is a jointly weighted evaluation of both indices using the same scale value. The contribution of each index to the FSPI is expressed as a percentage. Using a DELPHI method (fire officers' opinions) the weights assigned were 60% for the PFBI and 40% for the SDI. This relative importance was related to the importance of initial fire spread in the WUI and the fire officers' belief of a high probability of transition to crown fire from surface fire due to the high forest density, low hanging branches, underbrush and high fuel loads presents in the Province. A DELPHI approach is also used in the Forest Service Wildland fire Decision Support System (WFDSS) for estimating potential damages by fire intensity categories.

We estimated that almost 35% of the forest area was in the High (15–20) and Very High (> 20) FSPI categories. A high fire danger and fire suppression difficulty resulted from the large quantity of underbrush material (dead and live) and physiographic characteristics of the study area, which created high fire intensity scenarios. The study area would require fuel treatments such as fuel reduction or prescribed fire, and improvements in the area's mobility network to mitigate potential fire impacts. By using the FSPI fire managers can identify those areas requiring fuel treatments to reduce wildland fire hazard. Therefore, application of fuel treatments would result in reducing

extreme fire behaviour in the management areas and increasing the effectiveness of fire management protection programs.

Validation

Córdoba province

Wildland fire management prevention and suppression personnel in Córdoba worked on validation of the PFBI, SDI and FSPI. First they revised the digitised information (fuel model maps, potential fire risk maps and suppression priority maps) and corroborated that they produced reliable results given the fire propagation rates and fire suppression difficulties in real fires. In addition, they used the indices to optimise and prioritise fuel management treatments in the land management plan for the Córdoba public forests. Use of the maps from the methodology application and their field validation by personnel outside of the research team led us to implement the following operational improvements:

The flammability of landscaping material in housing developments is higher than portrayed in previous risk maps. Fire propagates freely through the landscaping plants and natural vegetation present in housing developments. Observations in the most recent WUI fires showed that the fire spread and energy content of the fires approached that of the mixture grass and shrub fuel type model. Housing developments were classified in two categories depending on the distance between houses, using 100 m as the differentiating criteria. Developments having a mean distance between houses of 100mor more are classified as fuel model PM2; those with distance between structures less than 100 m were assigned the classification PM1 (Rodriguez y Silva and Molina Martínez 2012).

Most olive plantations with mean slopes of more than 10% (5.7º) had continuous grass cover between rows. A sampling transect was established to measure fuel load, fuel continuity, compactness and height. This resulted in assigning this fuel condition to fuel type model P4 (Rodriguez y Silva and Molina Martínez 2012).

Housing development road networks were insufficient for fire suppression needs. During a fire, the social alarm caused traffic jams because everyone tried to use the existing narrow escape routes. WUI fires showed that the capacity of the road network during a fire event collapses, preventing or severe delaying firefighting equipment access to the area. Although there is a high road density in the WUI, the accessibility subindex values were low because of escape route difficulties and the technical recommendations for firefighting equipment used to suppress wildfires.

Airtanker operations around housing developments and their immediate surroundings were difficult. Airtanker effectiveness was considered minimal under these circumstances. Dropping water or fire retardant on housing developments caused damage and social unrest. Fire officers' experiences in Cordoba's housing developments suggest that fire retardant drops can be done in a buffer area of 30 m from the house structure to reduce the fire behaviour.

Not all areas treated for fire prevention were incorporated into the original maps. Therefore, all thematic maps of the area were updated. Once this was done, historical fires from 2003 to 2011 for the Province were used for statistical validation of computed indices. All fires were categorised as either small (<150 ha) or large (>150 ha). We randomly selected the last 9 large fires and 177 small fires scattered throughout the Province for the historical period (Fig. 2a). Each fire was classified into one of four categories according to its FSPI, SDI and PFBI (Table 6). We found a significant relationship between large fire occurrence and PFBI (χ=71.08, $P < 0.01$), the SDI (χ=53.62, $P < 0.01$) and the SPI (χ=79.79, $P < 0.01$). The probability of a large fire occurrence was correlated with fire starts in areas with all three indices rated as 'High' and 'Very High': the PFBI (OR=80.5, probability=98.7%), the SDI (OR=80.5, probability=98.7%) and the FSPI (OR=120.72, probability=98.6%). These statistical results might be even higher if WUI fires are deleted from the database, because WUI fires require the use of all firefighting resources available to guarantee population safety. These actions tend to reduce the total area burned in relation to other areas with index values similar to those shown here.

Huelva

In addition to Córdoba, the methodology was used in other forest lands with different spatial and temporal resolutions. We used the same validation procedure for the indices in forest plantations dominated by exotic species such as *Eucalyptus* spp. As before, in the Huelva Province fires were classified as small (<150 ha) or large (>150 ha). From 1990 to 2010 there were only 15 fires in this area. The significant relationship between large fire occurrence and the three indices was not as high as in the Córdoba case: PFBI (χ = 8.18, $P < 0.05$), SDI (χ = 7.33,$P = 0.06$) and FSPI (χ = 8.86, $P < 0.05$). This can probably be explained by the fires small size, the largest fire was 485 ha, and by the homogeneity in suppression difficulty across the study area. The probability of large fire occurrence was correlated with fires in areas rated as ‘High’ and ‘Very High’ for all three indices (Table 7).

Chile

In Valparaiso and Viñas del Mar, from 2000 to 2009, 150 wildfires were identified. As previously, all fires were categorized as small (<150 ha) or large (>150 ha) (Table 8). We found a significant relationship between large fire occurrence and the PFBI (χ = 38.54, $P < 0.01$), the SDI (χ = 45.34, $P < 0.01$) and the FSPI (χ = 48.84, $P < 0.01$). As for Cordoba and Huelva, the probability of large fire occurrence was correlated with fires in areas rated as ‘High’ and ‘Very High’ by all three indices: the PFBI (OR=17.42, probability=94.5%), the SDI (OR=12.43, probability=92.5%) and the FSPI (OR=17.42, probability=94.5%). Interestingly, the sample had small fires that caused loss of human life and greater economic losses than larger ones. To account for this situation, an additional parameter dealing with the potential damage in the WUI was added to the PFBI index (Rodriguez y Silva et al. 2010b).

Israel

The last validation case is in one of the most important forest zones in Israel, the Hakdoshim National Forest (Fig. 2d). Established as homage to the Holocaust, this forest is highly important for cultural, social and tourist reasons. For the 2003 to 2008 period 19 fires were identified. Because fire sizes are smaller than in the other locations studied, fires were divided into small (<50 ha) and large (>50 ha). Seven fires were larger than 50 ha (Table 9). Most fire occurrences were along the highway between Jerusalem and Tel Aviv. Similar to other areas, we found significant relationships between large fire occurrence and the three indices: PFBI (χ = 6.68, P < 0.05), SDI (χ = 6.39, P< 0.01) and FSPI (χ = 9.40, P < 0.05). As in previous validation cases the same pattern was observed for the occurrence of large fires in the area. The probability of large fire occurrence was higher for fires in areas rated as ‘High’ or ‘Very High’: PFBI (OR=12.5, probability=92.5%), the SDI (OR=12.5, probability=92.5%) and the FSPI (OR=30, probability=96.7%).

Taking advantage of a 2010 large wildfire (>3500 ha) in Mount Carmel, Israel, we computed the three indices (PFBI, SDI and FSPI) for the whole fire area. This fire endangered the third largest city in Israel and caused 44 deaths. According to the computed indices the ignition point of the fire was located in pixels with the highest fire danger rating. For the first 45 min the fire burned freely over a surface characterised by a 'High' or 'Very High' Indices in 72% of the area.

Conclusions

The case studies helped us understand better the on-ground application of the indices presented here. Improvements resulting from the validation process undertaken by Córdoba fire management program personnel helped us develop a revised version of the indices used for development of the 'Urban Development Plan for Córdoba', and for establishing fire operational priorities for the Provincial Operations Center.

Abandonment of traditional activities in forest lands with its consequent increase in fuel loads has had a significant effect on wildland fire severity. The increase in fire severity leads to short- and long-term socioeconomic and ecological consequences, which if not corrected can potentially lead to desertification problems. Because of these important consequences and the high frequency of wildland fires, the national, regional and local authorities have requested information on the potential risk and suppression difficulty of wildland fires. The methodology presented here provides precisely that kind of information by identifying sectors in the management areas with the highest degree of fire danger and sectors with a high degree of firefighting difficulty. This information can help fire planners and fire managers to strategically place existing firefighting resources to increase their fire protection effectiveness and minimise the consequences of fire. The intended use of this information is to help in fire management programs and budget allocation in each planning unit.

Given that the final fire growth depends on fire suppression effectiveness, it is important to develop a fire operational plan for both prevention and suppression activities. The FSPI, which combines the PFBI and the SDI, facilitates establishment of an orderly response to wildfire problems, thereby increasing planning effectiveness. This is an important management consideration when the initial actions cannot be implemented because of economic or time constraints. The proposed FSPI is dynamic and applicable to any forest lands exposed to wildland fire. The relative importance assigned to the PFBI and the SDI for determining the FSPI is variable and depends on human factors and the capacity of suppression activities in the area applied.

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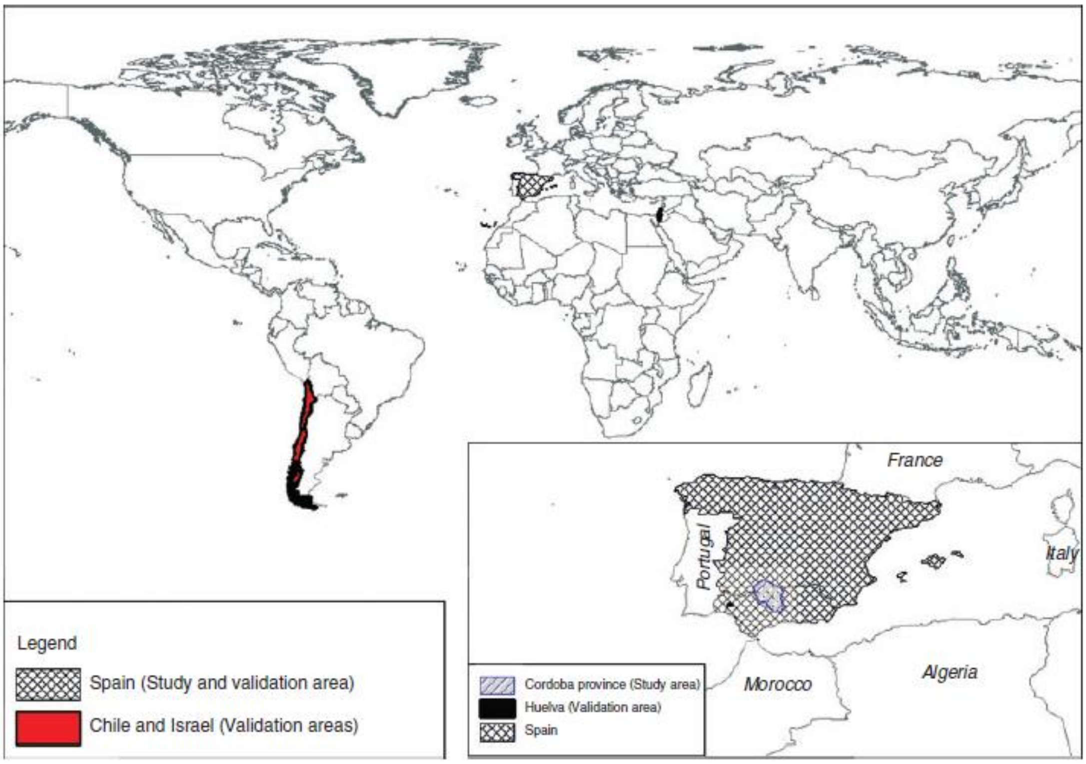
Figure captions

Figure 1. Study area location and validation area in Córdoba, Spain, and validation areas in Chile and Israel.

Figure 2. Fire suppression priority indices (SPI) as calculated across the four validation areas in this study. (*a*) Validation area in Obejo fire, Córdoba, Spain, (*b*) Validation area in ‘Montes de Gamonosa, Castaño y Ribera’, Sierra de Rite’ and ‘El Saltillo’, Huelva Province, Spain, (*c*) Validation area in Valparaiso and Viña del Mar Provinces (Region V), Chile, (*d*) Validation area in Hakdoshim National Forest, Israel.


Legend
Spain (Study and validation area)
Chile and Israel (Validation areas)
France
Portugal
Italy
Morocco
Algeria
Cordoba province (Study area)
Huelva (Validation area)
Spain

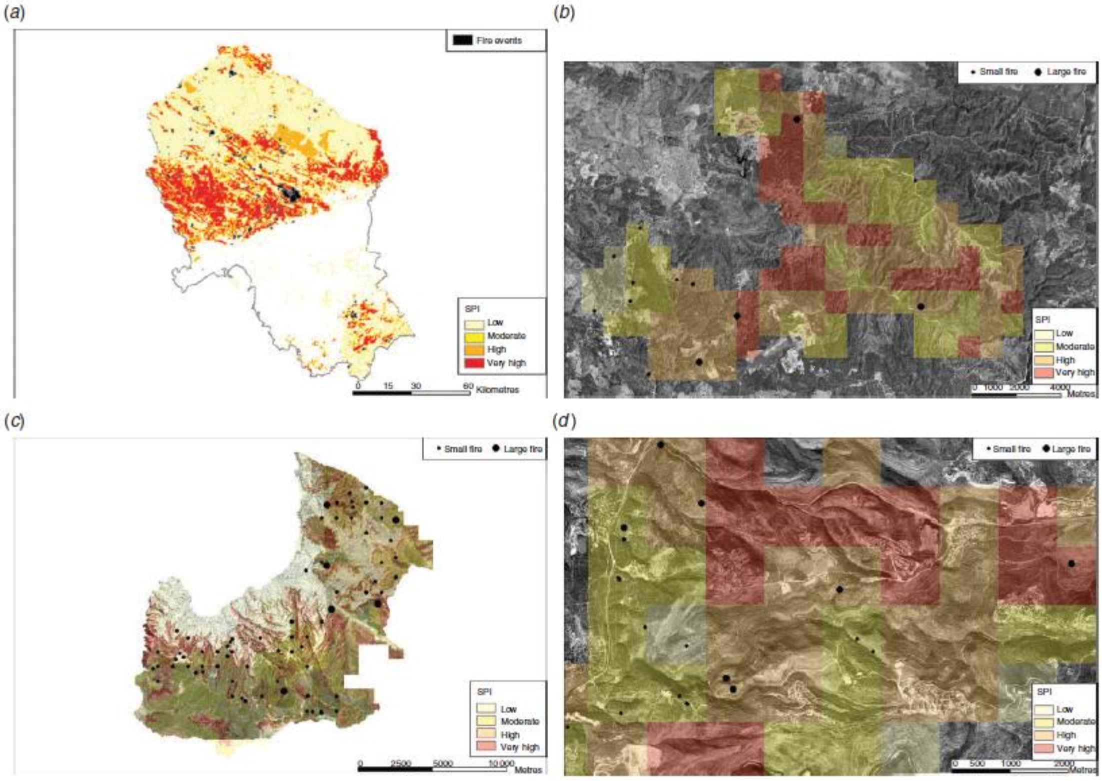

(a)
Fire events
SPI
Low
Moderate
High
Very high
0 15 30 60 Kilometres
(b)
Small fire
Large fire
SPI
Low
Moderate
High
Very high
0 1000 2000 4000 Metres
(c)
Small fire
Large fire
SPI
Low
Moderate
High
Very high
0 2500 5000 10 000 Metres
(d)
Small fire
Large fire
SPI
Low
Moderate
High
Very high
0 500 1000 2000 Metres

Table 1. Values for the ignition coefficient, fuel difficulty weight and fire-line production weight (and rate) for manual or mechanical tools by fuel type

The ignition coefficient is a probability computed using the USDA Forest Service system (USDA Forest Service 2004) and is a function of the fine and dead fuels moisture content, ambient temperature and degree of shade. Ten values in ascending order express every 10% probability. Fuel models are as follows: P1–P9, grass models; PM1–PM4, grass and shrub models; M1–M9, shrub models; HPM1–HPM5, litter; HR1–HR9, grass and shrub litter undercanopy models; R1R4, slash models.

Fuel model	Ignition	Difficulty	Manual rate	Mechanical rate
P1	0.1	10	>46	>1801
P2	0.098	10	>46	>1801
P3	0.096	10	>46	>1801
P4	0.094	10	>46	>1801
P5	0.092	10	>46	>1801
P6	0.09	10	>46	>1801
P7	0.088	9	41-45	1601-1800
P8	0.086	9	41-45	1601-1800
P9	0.084	9	41-45	1601-1800
PM1	0.085	9	41-45	1601-1800
PM2	0.073	9	41-45	1601-1800
PM3	0.061	8	36-40	1401-1600
PM4	0.055	8	36-40	1401-1600
M1	0.018	7	31-35	1201-1400
M2	0.02	7	31-35	1201-1400
M3	0.064	5	21-25	801-1000
M4	0.068	5	21-25	801-1000
M5	0.05	4	16-20	601-800
M6	0.062	5	21-25	801-1000
M7	0.055	3	11-15	401-600
M8	0.048	4	16-20	601-800
M9	0.059	3	11-15	401-600
HPM1	0.03	8	36-40	1401-1600
HPM2	0.035	8	36-40	1401-1600
HPM3	0.04	8	36-40	1401-1600
HPM4	0.04	6	26-30	1001-1200
HPM5	0.045	6	26-30	1001-1200
HR1	0.015	7	31-35	1201-1400
HR2	0.017	7	31-35	1201-1400
HR3	0.018	7	31-35	1201-1400
HR4	0.016	7	31-35	1201-1400
HR5	0.022	7	31-35	1201-1400

HR6	0.019	7	31-35	1201-1400
HR7	0.02	7	31-35	1201-1400
HR8	0.024	7	31-35	1201-1400
HR9	0.028	7	31-35	1201-1400
R1	0.01	2	6-10	201-400
R2	0.0095	2	6-10	201-400
R3	0.009	1	<5	<200
R4	0.0085	1	<5	<200

Table 2. Values assigned for determining the dynamic and energy behaviour sub-indices

Rate of spread (V) category (m/min)	Assigned weight Weight Flame height (FL) (m)	Assigned weight Intensity (I) (Kcal/m/s)	Assigned weight Heat per unit area (HUA) (Kcal/m^2)	
0 – 10	0 – 0.5	0 – 334	0 – 2090	1
11 – 20	0.51 – 1.0	335 – 752	2091 – 4180	2
21 – 30	1.10 – 1.5	753 – 1087	4181 – 6270	3
31 – 40	1.51 – 2.0	1088 – 1421	6271 – 8360	4
41 – 50	2.10 – 2.5	1422 – 1756	8361 – 10450	5
51 – 60	2.51 – 3.0	1757 – 2090	10451 – 12540	6
61 – 70	3.10 – 3.5	2091 – 2424	12541 – 14630	7
71 – 80	3.51 – 4.0	2425 – 2759	14631 – 16730	8
81 – 90	4.10 – 4.5	2760 – 3093	16721 – 18810	9
> 90	> 4.5	> 3093	> 18810	10

Table 3. Assigned weights for elaboration of the accessibility and mobility sub-indices

Length (m)	Weight
0-100	1
101-200	2
201-300	3
301-400	4
401-500	5
501-600	6
601-700	7
701-800	8
801-900	9
> 901	10

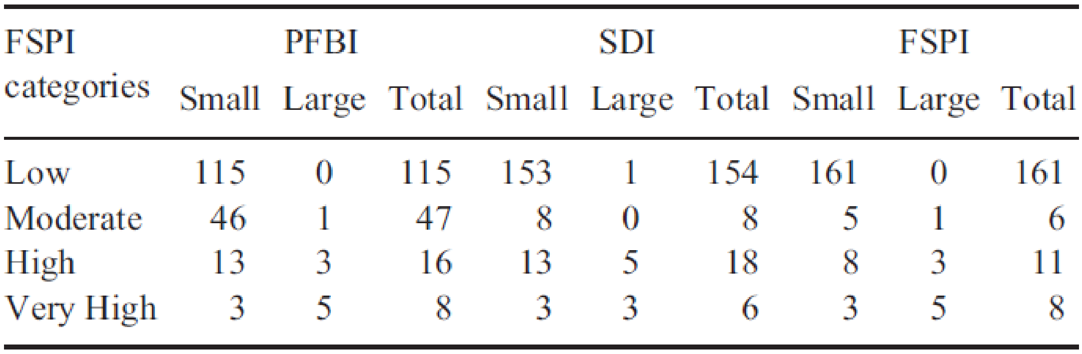
Table 4. Assigned values for elaboration of the penetrability sub-index and the adjustment coefficient depending on the slope for the fire-line construction sub-index

Soil hardness correction (ns) (Cp)	Slope (p) (%)	Exposure (e)	Fuel break trails (s) (m/ha)	Weights category	Slope factor
Hard	0 - 5	N	0 - 5	10	1
	6 - 10		6 - 10	9	1
	11 - 15	NE	11 - 15	8	1
Moderately hard	16 - 20	NW	16 - 20	7	0.8
	21 - 25	E	21 - 25	6	0.8
Moderately loose	26 - 30	W	26 - 30	5	0.8
	31 - 35	SE	31 - 35	4	0.6
	36 - 40	SW	36 - 40	3	0.6
	41 - 45	S	41 - 45	2	0.6
Loose	> 46		> 46	1	0.5

Table 5. Assigned weights for elaboration of the aerial resources sub-index

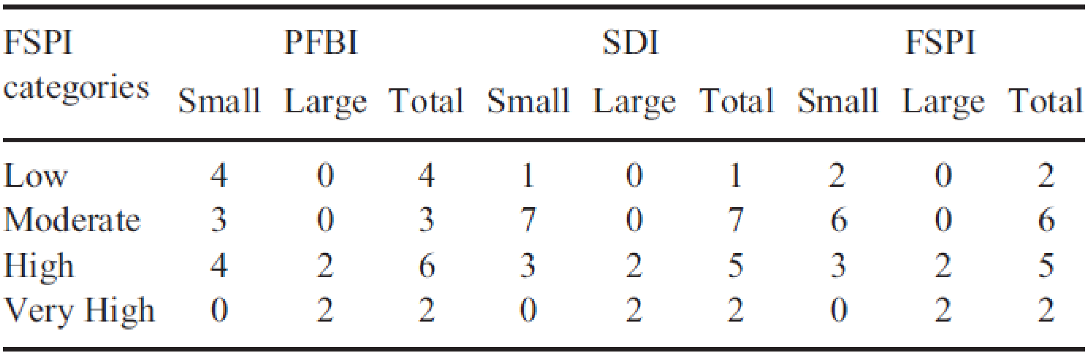
Flying time between drops			
Helicopters	Airplanes		Weight category
	amphibious	land based	
minutes			
< 5	< 20	< 20	10
6-15	21-30	21-40	9
16-25	31-40	41-60	8
26-35	41-50	61-80	7
36-45	51-60	81-100	6
46-55	61-70	101-120	5
56-65	71-80	121-140	4
66-75	81-90	141-160	3
76-85	91-100	161-180	2
>86	>101	>181	1

Table 6. Fire Suppression and Prevention Index (FSPI) category and calculated fire indices for fires occurring in Córdoba Province, Spain (2003–2011)



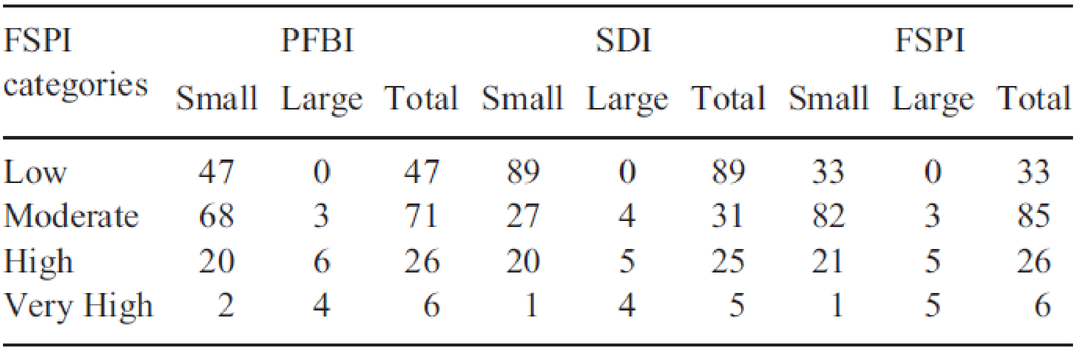
FSPI categories	PFBI			SDI			FSPI		
	Small	Large	Total	Small	Large	Total	Small	Large	Total
Low	115	0	115	153	1	154	161	0	161
Moderate	46	1	47	8	0	8	5	1	6
High	13	3	16	13	5	18	8	3	11
Very High	3	5	8	3	3	6	3	5	8

Table 7. Results for all three indices for the Huelva area



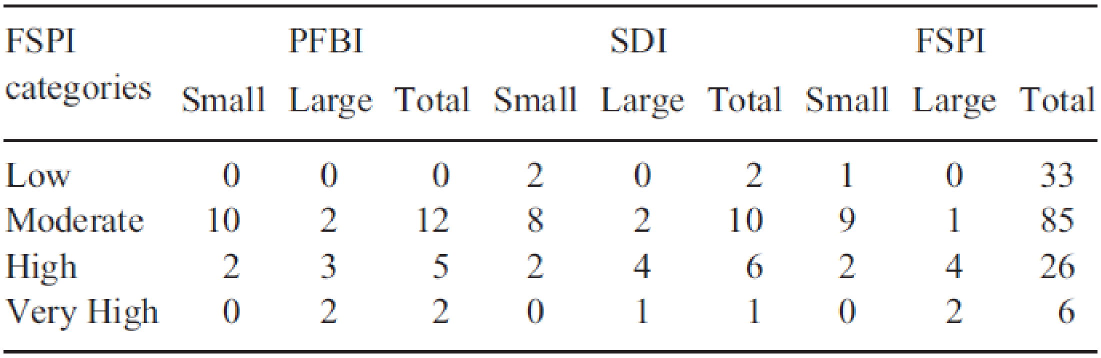
FSPI categories	PFBI			SDI			FSPI		
	Small	Large	Total	Small	Large	Total	Small	Large	Total
Low	4	0	4	1	0	1	2	0	2
Moderate	3	0	3	7	0	7	6	0	6
High	4	2	6	3	2	5	3	2	5
Very High	0	2	2	0	2	2	0	2	2

Table 8. Results for all three indices for Chile areas



FSPI categories	PFBI			SDI			FSPI		
	Small	Large	Total	Small	Large	Total	Small	Large	Total
Low	47	0	47	89	0	89	33	0	33
Moderate	68	3	71	27	4	31	82	3	85
High	20	6	26	20	5	25	21	5	26
Very High	2	4	6	1	4	5	1	5	6

Table 9. Results for all three indices for the Israel area



FSPI categories	PFBI			SDI			FSPI		
	Small	Large	Total	Small	Large	Total	Small	Large	Total
Low	0	0	0	2	0	2	1	0	33
Moderate	10	2	12	8	2	10	9	1	85
High	2	3	5	2	4	6	2	4	26
Very High	0	2	2	0	1	1	0	2	6