Modelling Mediterranean forest fuels by integrating field data and mapping tools

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Abstract:

Fire behavior modelling systems are important in predicting wildfire risk, fire growth and fire effects. However, simulation software requires a new fuel modelling to include fuel treatments, prescribed fire and the transition to crown fire. The thirteen Rothermel models are insufficient in completely representing Mediterranean ecosystems. In this sense, the new American modelling includes five fuel types, requiring the acquisition of hybrid models made up of the mixture of grass and shrub and the grass or shrub mixed with litter from forest canopy. Respecting meteorological conditions and shrub characteristics, field studies have shown significant differences between American and Mediterranean models. As a consequence, the definition of new Mediterranean models requires the adjustment of specific parameters such as fuel load by category (live and dead) and particle size class (1-, 10- and 100-h time-lag), fuelbed depth and surface area to volume ratio. These new parameters were obtained in situ of sample itineraries, prescribed fires and forest fires. The availability of this new modelling, validated on a field of regional scale, will facilitate preventive planning and management as well as an efficient application of suppression techniques, both ground and aerial operations, required in defending a territory against forest fires.

Keywords: Fuel modelling; fuel mapping; fuel management; fire behavior; forest fires

Introduction

Establishing the effects caused in a territory by forest fires requires a set of informative layers. Geographical Information Systems (GIS) data layers and weather information can simulate fire growth and severity (Chuvieco 1999). Different strategies based on these informative layers are fundamental in developing management strategies for the defense of natural resources (Duguy et al. 2007). For this reason, a new fuel modelling which gathers all variables identifying fire progression is an essential task in fire management (Scott and Burgan 2005).

An accurate knowledge of fuel conditions constitutes a primary element of fire risk. A global danger index using meteorological, physiographical and fuel modelling criteria is widely used (Lasaponara et al. 1999; Sebastián et al. 2002). Based on these criteria, decision support systems will show potential fire behavior (spread rate, flame length, fire-line intensity) (Keane et al. 1998). Progression may be similar for different shrub compositions according to the structure, combustibility and inflammability of the species. The information obtained from authentic forest fires allows for a comparison between simulation behavior and field spread. Comparisons between recent large fires in Andalusia and their simulations have transmitted uncertainty, since the simulations did not obtain behavior parameters comparable to those from the real fires (Vélez 2009; Rodriguez y Silva and Molina 2010).

Wildland fire planning requires calculation, display and analysis of fire behavior at landscape-level. In this sense, fuel characterization is a required input for software that simulate fire behavior such as FlamMap© (Finney 2007), Farsite© (Finney 1998), Behave© (Burgan and Rothermel 1984; Andrews 1986) and Behave Plus© (Andrews et al. 2003). Other software like Visual Behave© and Visual Cardin© have adapted the Rothermel models to Mediterranean conditions (Rodríguez y Silva 1999; Rodríguez y

Silva et al. 2010). This study is based on previous studies of surface fire behavior (Rothermel 1972; Albini 1976; Anderson 1982) but with an increase in number and model types in order to provide better fire spread simulations for Mediterranean conditions (Scott and Burgan 2005). This increase in model number arises in answer to the needs of forest managers to increase simulation options or fire behavior changes due to fuel treatments, mainly in the transition from surface to crown fire (Van Wagner 1977).

Scientific precedents used in modelling fuels differ in accordance to the scale used and the available budget (Arroyo et al. 2008). Some studies have attempted to establish a new fuel modelling via the use of remote sensing and Geographic Information Systems (GIS) (Keane et al. 2001; Riano et al. 2002; Chuvieco et al. 2003; Van Wagtendonk and Root 2003; Rollings et al. 2004). Multispectral and hyperspectral images have allowed a more precise modelling based on stand density and height (Lasaponara et al. 2006; Lasaponara and Lanorte 2007a). Continuous improvements in new sensors show steady progress in model resolution levels (Andersen et al. 2005; Lasaponara and Lanorte 2007b). In these cases, and at a local scale due to budget limitations, fuel modelling using laser technology allows us to characterize forest structure (Hyyppa et al. 2008; Pesonen et al. 2008; Popescu and Zhao 2008).

The objective of this paper is stated to be an in-depth study of fire behavior by improving fuel model characterization, fire growth simulation and fuel mapping using Mediterranean parameter adjustments. Its focus is primarily on the development of specific Mediterranean fuel models that can be used in fire spread simulators as a valuable component of fire management. While the new fuel model characterization allows us to assess different management alternatives such as mechanical fuel reduction treatments and prescribed fire, fuel mapping can be used to optimize fuel treatments based on the mitigation of fire impacts, both tangible assets and environmental services and landscape goods.

Methodology

Study area

This research was developed for Andalusia, in southern Spain (87,268 km^2). Its meteorological conditions and socio-economic changes make it suitable to apply to other European countries characterized by high fire risk, such as Portugal, Italy or Greece. We conducted methodology for 37,415 km^2, located in three different provinces: Cordoba, Jaen and Huelva (Figure 1). The provinces chosen as a pilot zone were chosen for their ecological value, landscape diversity and high fire risk. The spatial resolution used complied with the criteria for landscape management and the extrapolation at a national level. However, a greater spatial resolution was used for some important areas because of their history of high fire risk, human activities and prescribed burning activities.

Definition of the vegetation structure

A landscape is a land area composed of a cluster of interacting fuel models (Finney 2001). In Mediterranean areas, landscapes are usually characterized by a fragmented distribution of remnant vegetation with high heterogeneity and complex mixed structures (Agee et al. 2000). Vegetation characterization was based on the different management units, including both stand and treeless areas. The difference between stand and treeless areas corresponds to the amount of downed logs, fallen branches, forest litter and litter with grass and shrub understory. Litter type (broadleaf or needle) and crown cover fraction (dense or isolated forest) were taken into account later in the fuel assignment.

Fuel modelling was defined by analyzing vegetation structure. GIS software has proven to be an indispensable tool in model research because of the wide number of vegetation characteristics that can be assessed. We have developed a GIS database to study vegetation composition and structure in relation to the fuel model. Because the information from a single digital coverage was insufficient for the spatial resolution and objectives sought after, our methodology obtained a final product of much higher quality by overlapping the National Forest Inventory, the Forest Map and the Land Use and Vegetation Cover Map. The Land Use and Vegetation Cover Map presented advantages over other digital mappings, such as updated and greater spatial resolutions of the vegetation; yet, in reference to vertical characterization, the National Forest Inventory and the Forest Map of Andalusia proved more beneficial.

Shrub characterization was assessed according to composition and structure. The combustibility and flammability of the surface vegetation can be discerned through vegetation association (dominant species). On the other hand, shrub structure was determined by three main attributes: density, height and spatial distribution. Density is the most responsible for dangerous behavior induced by fuel load. Height was expressed as an average measure in different quantitative intervals. Spatial distribution was displayed through vegetation associations and density. As an example, while some species present continuous and regular spatial distribution such as *Cistus* spp., *Erica* spp. and *Genista* spp.; other species usually display an irregular distribution showing spatial separation between specimens, such as *Retama* spp. and *Chamaerops* spp.

Landscape analysis required a quick and simple way to characterize the complete vegetation structure. In order to do this, a synthesis of field samplings was considered to facilitate the fuel model assignment. Three characteristics were analyzed to define the new fuel models (Table 1):

- Stand composition (“Stand”). While stand density influences the presence of litter with grass and shrub understory, canopy composition determines litter type (broadleaf, short needle or long needle)
- Shrub composition (“Base”). The species for each vegetation association determines combustibility, flammability and spatial distribution.
- Vertical structure (“Structure”). The depth and height of the fuel are of utmost importance in relation to fire behavior and suppression activity planning.

Definition of the new fuel models

Fuel models are defined by characteristics that contribute to spread rate, flame length and fire intensity (Fernandes 2009). The new modelling (known as "UCO40 system") adapts fuel models revised by the U.S. Forest Service (Scott and Burgan 2005) to those in Mediterranean ecosystems (Vélez 2009; Rodriguez y Silva and Molina 2010). The Rothermel models are classified into four large groups: grasslands, shrublands, litter under canopy areas and silvicultural debris (Anderson 1982). The need for more fuel model options to select from brought about two hybrid fuel types: mixture of grass and shrub (PM) and grass or shrub mixed with litter from forest canopy (HPM). The general carrying fuel type is:

- Nearly pure grass (Group P). There are 9 fuel models in this group based on fuel load, height and herbaceous moisture content.
- Mixture of grass and shrub, up to about 50 percent shrub coverage (Group PM). Four fuel models are distinguished based on fuel load, shrub height and grass continuity.

- Shrub covers at least 50 percent of the site (Group M). There are 9 fuel models based on fuel load, density, height and presence of branched shrub.
- Grass or shrub mixed with litter from forest canopy (Group HPM). There are 5 fuel models based on litter type (broadleaf, short needle or long needle) and grass-shrub load.
- Dead and down woody fuel (litter) beneath a forest canopy; possible existence of live fuel which slightly affects fire behavior (Group HR). There are 9 different fuel models based on litter type (needle or broadleaf) and the load and size of downed fuel.
- Activity fuel (splash) or debris from wind damage or other disturbances (Group R). There are 4 different fuel models based on splash and blowdown size and dead fuel load.

This new classification increased the number of fuel models for forest litter and litter with grass or shrub understory; both of which are important groups to Mediterranean ecosystems. The importance of hybrid model types lies in representing fuel treatments and their progressive evolution from the moment of treatment. Although the number of models is large, they are not all necessarily present in the same province or region. Simple tables help correlate the Rothermel classification to the new Mediterranean modelling (Table 2). Although it is recommended that model correlations be made by an expert user (manager, scientist ...), a fuel model guide is available to help in matching Rothermel models directly to the new fuel modelling (as an example, Figure 2 was used from Rodríguez y Silva and Molina 2010).

Agricultural areas were modelled using plant morphology and crop typology. Although irrigated annual crops or fruit groves maintained a non-burnable condition, there were some agricultural areas that did not keep this non-burnable condition. We suggested a burnable condition for lands where crops were allowed to cure before harvest. Abandoned croplands and ecological crops were modelled as grass or grass-shrub types.

Parameters and variables of the new models

Current software simulations require the use of different fuel models to predict fire behavior. A fuel model is the numerical description of the parameters that characterize each ecosystem in relation to a fire occurrence. We adjusted the fuel model parameters to improve fire behavior outputs. Our modelling required field sampling in order to obtain the best identification, assignment and validation of these model parameters. Knowledge of the spatial distribution of the new fuel model mapping is an essential task in fire management and strategy development. The new modelling was used for current planning, prescribed fire locations or suppression activities.

Field trips and itineraries were carried out from 2005-2010 to obtain a better modelling of the study area. Different sampling plots were established according to the vegetation composition and fuel models found within each location. Line transects and 3 clipped vegetation plots were located within each sample unit (15 meter square plot). Along with vegetation composition, UTM coordinates, density, fuel height, spatial distribution and vertical structure were also identified at each plot. While vegetation composition determined the ecosystem’s combustibility and flammability, vertical structure and spatial distribution were represented by density, height and canopy composition (Ottmar et al. 2007). At the same time, a photographic overview was taken as a visual key for fire officials to recognize the new models.

Fuel load was determined in sampling plots with areas of 40x40 cm or 100x100 cm (based on fuel spatial distribution) that measured 1.70 meters high. Fuel characterization included fuel load by category (live and dead) and particle size (expressed in 1-, 10-, 100-h time-lag). Once all of the samples were collected, and prior to their statistical analyses, the moisture content for each sample was estimated in order to represent fuel load as dry matter content. In this sense, separate live and dead fuel was needed to determine fuel moisture. Each sample underwent a 48-hour drying process in an oven set at 60ºC (Elvira and Hernando 1989), at which this time, fuel weights were constant. The difference in weight before and after drying constituted the moisture content of the sample. Fuel load was transferred to dead fuel after the percentage of moisture was eliminated.

Results

On some occasions, problematic discrepancies were encountered among the different data layers (digital mapping information) used in modelling the forest fuels. One data layer would indicate the presence of one treeless area while another clearly identified one stand area. Vegetation definition of these discrepant areas was achieved by interpreting aerial photos. In those areas, where there was a lack of field plot data, a Cokriging method (geostatistical analysis) was used to interpolate fuel model characteristics based on elevation, slope and aspect.

Mediterranean landscapes are composed of a cluster of interacting land areas, including different stand areas, such as oak, pine and eucalyptus, as well as treeless areas (shrub, grass) and arable crops. With the help of GIS, we were able to determine twenty dense stands, five isolated stands, eight agricultural uses and one use of abandoned cropland. For the first of these, information generated from vegetation composition, including shrub and canopy, was integrated to provide the different land management units (integrating information from "Stand", "Base" and "Structure"). In characterizing shrubland (both in itself and as understory) twenty-four vegetation associations were used based on the combustibility and flammability of the dominant species. In this sense, the combinations between the different stand areas and these different vegetation associations resulted in 159 different forest ecosystems for the study area (integrating the information from “Stand” and “Base”). The addition of the agricultural units, abandoned croplands, shrublands and grasslands amounted to a total of 191 ecosystems. After defining these 191 ecosystems, fuel model definition required the vertical assessment of the ecosystem based on three main attributes: density, height and spatial distribution. Forty-one vertical structures (“Structure”) were used to define possible combinations of these attributes. Finally, the syntheses between the 191 ecosystems (stand, shrublands, grasslands or croplands) and the forty-one vertical structures resulted in more than 350 land management units for the study area, improving considerably the resolution of the cartography currently available in Andalusia.

Fuel model mapping was previously established using the equivalency tables ("Stand", "Base", "Structure" and "Model") and fuel model guide (Rodríguez y Silva and Molina 2010), and then later revised and validated through field work and itineraries. Different vegetation associations and/or vegetation structures were able to define the same fuel model ("Model"), based on the potential surface fire behavior. Similarities or disparities among vegetation associations can be attributed to the combustibility or flammability of the species, fuel load, height, spatial distribution and vertical fuel structure. Some land management units, as were their conversions to fuel models, were detailed in Table 3 (11 stands and 4 treeless areas), stressing the crucial importance of the loads of some hybrid fuel models, such as the PM4 and HPM5 (Table 4). In the first column ("Stand"), canopy cover was characterized by its vegetation composition, influencing the type of forest litter (broadleaf, short needle or long needle). Shrub and/or pasture were defined horizontally by their vegetation associations ("Base") and vertically in height and depth

("Structure"). In two ecosystems with similar fuel load and height, one must not forget other more specific parameters such as particle size (1-, 10- and 100-h time-lag), live woody fuel and live herbaceous fuel that could determine their technical differences. In this case, as a concrete example, one could highlight the differences between the M4 model and the M3 and M5 models (Table 4).

Discussion

A fire spread model constitutes one of the cornerstones in the planning and management of a forest landscape (Rothermel 1972; Albini 1976; Anderson 1982). Among the diverse elements that develop or encourage fire behavior, such as meteorological factors (temperature, relative humidity and wind) and topographic conditions (slope and aspect), surface fuel is the factor which influences combustion (Burgan and Rothermel 1984). Fine dead fuels (1-hour time-lag) greatly influence the predictive models (Andrews 1986).

Technical advances, available cartography and the application of large fire experience in Andalusia have demonstrated the need for further modelling development. The work developed is not a mere map or field inventory, and does not represent a static piece of work, but rather one that should be updated and improved through the experience gained in actual fires. Although the definition and characterization of the different models is not a closed study, but rather one that must be gradually improved, the simulations using software like “Visual Behave"© and" Visual Cardin"© (Martinez Millan et al. 1991; Rodriguez y Silva 1999; Rodriguez y Silva et al. 2010) provided very adequate results for new models. Not only was it crucial for the initial data required by the computerized decision-making support tools, but also for the range of data resulting from their validation. In this sense, validation in Andalusia has relied upon the technical reports and fire behavior studies of the largest fires in Andalusia. The efficiency of the fire behavior in the new fuel modelling was evidenced by fires at the "Rio Tinto Mines" (34,291 ha), Obejo (4,979 ha), Palomas (768 ha), Nerva (566 ha), Estepona (524 ha), Belmez (398 ha), "Sierra Parda" (295 ha), Catena (210 ha), "Los Barrios" (187 ha) and Moro (110 ha). Variations in fire spread can be observed between Rothermel model prediction, new model prediction and field behavior (Table 5). A great similarity between the control points (field studies) and the behavior predicted from the new definition can be observed when comparing simulation results for the new models with actual events. Although these results represent a good validation, the simulator adopts standard or mean values (Table 4) for the model considered, showing some fires closer to the upper or lower fuel load. In the case of Spain’s largest forest fire, the “Rio Tinto Mines” Fire, (34,291 hectares in 2004), while the Rothermel models corresponded to low-lying grass, the "UCO40 system" defined the area as a moderate load of abandoned cropland (Rodriguez y Silva and Molina 2010). Variations in fire behavior can be observed between the Rothermel model prediction, the new model prediction and actual field behavior (Table 5). While fire-line intensity differs 5 times the actual value, spread rate and flame length do not reach these extreme differences, making them of great relevance to firefighting tasks.

The modelling of Mediterranean forest fuels using combustibility, flammability, fuelbed depth, spatial distribution and vertical characterization improved preventive planning which resulted in an efficient economization of fire management by optimizing fuel treatment and prioritizing prescribed burning at the landscape level. This provided critical information for suppression activities and the Incident Command System (ICS). At present, simulator versatility allows for the incorporation of new fuel models, guaranteeing results which are better fitted to reality. As two examples, the Rothermel model simulation and new model simulation ("UCO40 system") were evidenced by the Catena (210 ha) and Palomas (768 ha) fires in relation to field fire behavior (Figure 3). The corrections and adjustments made to the Visual-Behave© and Visual-Cardin© software represent a quick and simple tool for predicting fire behavior, one highly needed by the technicians responsible for preventing and extinguishing forest fires. The programming for Mediterranean forest fuels modelling can be easily extrapolated to other famous software such as “Farsite”© (Finney 1998) and “FlamMap”© (Finney 2007) at any spatial and temporal resolution.

The management of Mediterranean forests requires practices that reduce fire susceptibility (Agee et al. 2000; Stratton 2004; Stephens and Moghaddas 2005; Vélez 2009). Planning mitigation activities, while regarding costs and the importance of the resources to be protected, requires decision tools that offer the greatest degree of veracity. The new modelling is an advance in locating prevention activities and in studying the economic vulnerability of forest resources. Analyzing the potential conditions of a hypothetical fire permitted a simulation of forest resource damage according to its economic value, ecosystem resilience and fire severity (Molina et al. 2009; Rodríguez y Silva and González-Caban 2010; Zamora et al. 2010).

5. Conclusions

Fire behavior modelling systems must be adapted to Mediterranean conditions in order to use the fuel models correctly. In this sense, incorporating hybrid models provides greater simulation reliability and its subsequent application. This fuel modelling can be used in other Mediterranean countries with similar conditions and could easily be extrapolated to other territories with a similar characterization.

The new definition of forest fuel models in Mediterranean ecosystems provides a series of advantages for fire management: facilitating defense planning, detecting potential danger distribution, notifying the organizational levels required to extinguish fires and defining priorities for efficient fire management. The use of the GIS tool can aid managers in developing strategies for wildfire prevention and suppression planning; for which, this new modelling constitutes a dynamic tool (GIS) that can improve and evolve according to the technologies available.

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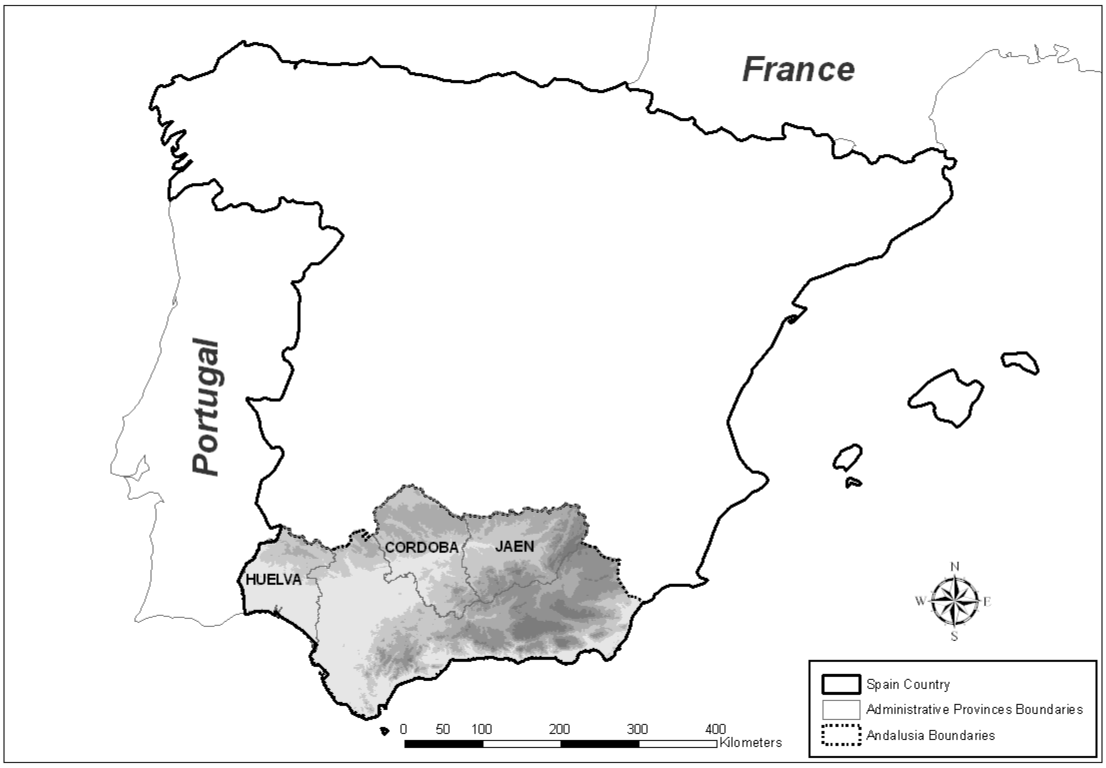
Figure Caption

Figure 1. Study area location

Figure 2. Fuel model guide. Example of the correspondence between fuel model 7 and M3, M4, HPM3 and HPM4

Figure 3. Fire spread simulations (Rothermel and "UCO40" fuel models) at 40 min (Catena Fire) and 210 min (Palomas Fire) in relation to field fire spread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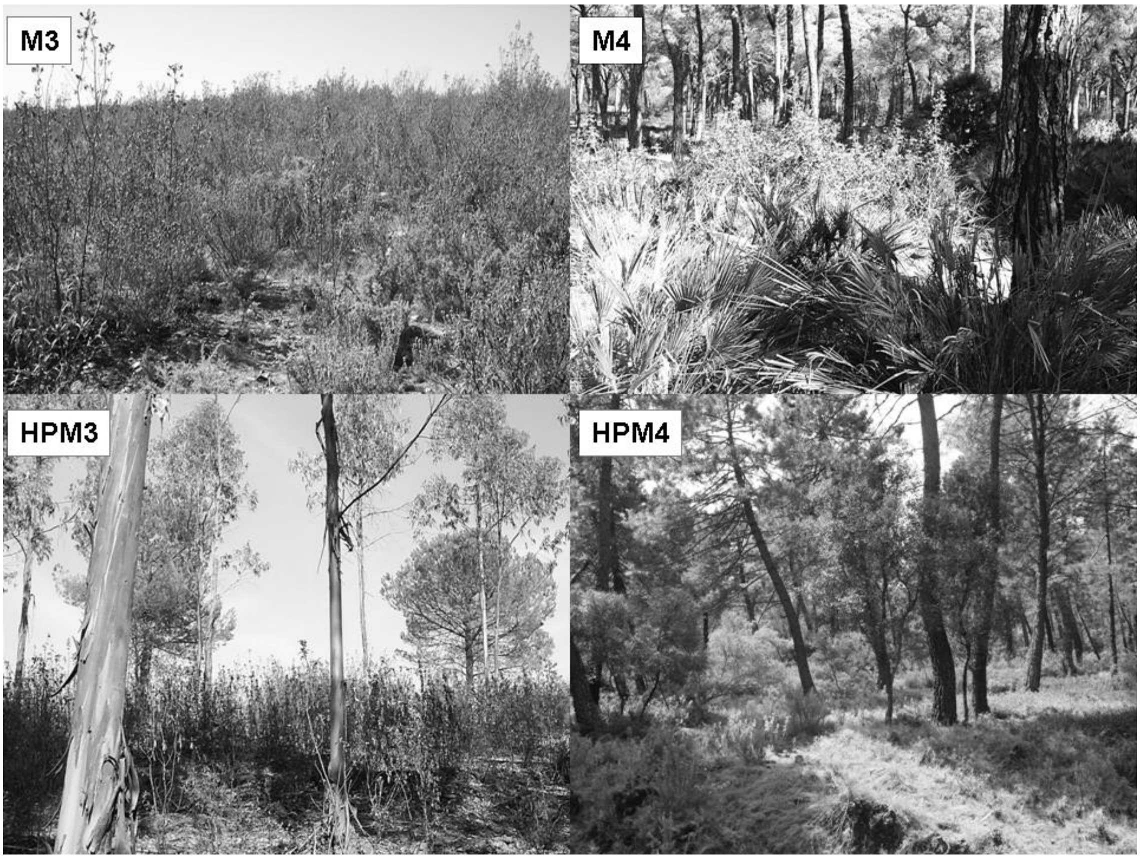
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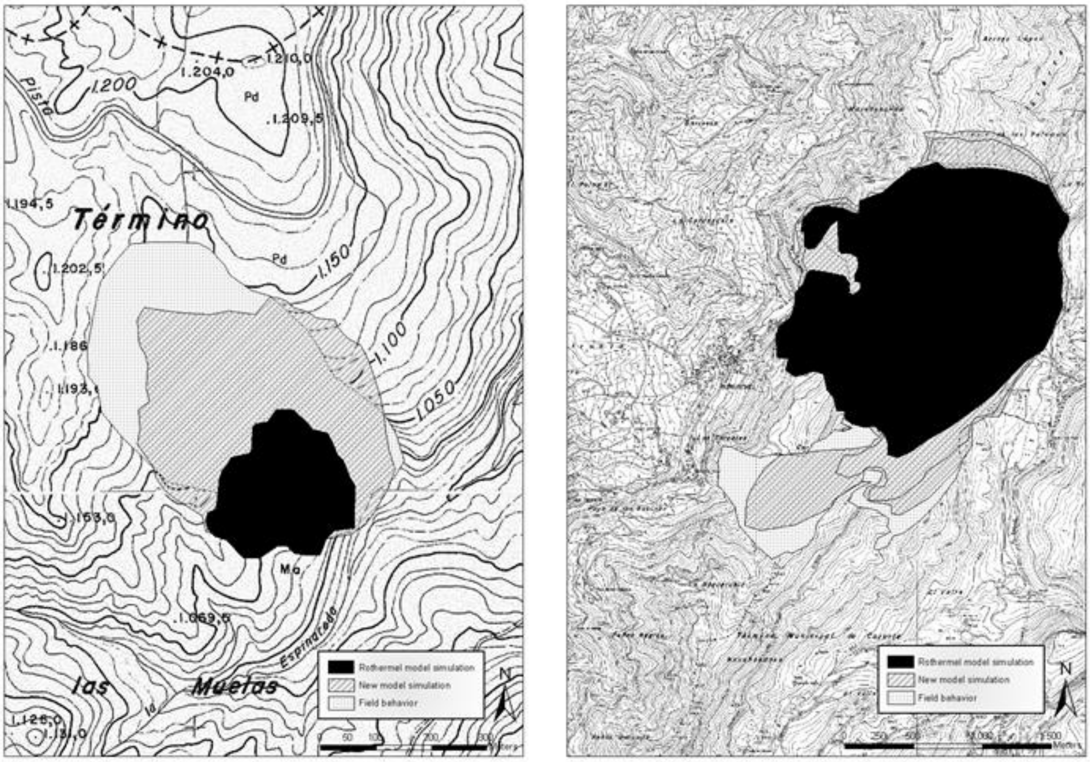
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Table 1. Definition of some land management units (‘‘Stand,’’ ‘‘Base,’’ and ‘‘Structure’’)

Stand	Base	Structure
Pinus pinea	*Cistus* spp.	Very high shrub. Height between 3 to 7 m
Pinus pinea	*Cistus* spp.	Short shrub. Height between 5 to 50 cm
Pinus pinea	*Cistus* spp.	Dispersed shrub on sandy soil
Pinus pinea	*Chamaerops humilis*	Medium shrub. Height between 0.5 to 1.5 m
Pinus pinaster	*Cistus* spp.	High shrub. Height between 1.5 to 3 m
Pinus pinaster	*Cistus* spp.	Medium shrub. Height between 0.5 to 1.5 m
Pinus pinaster	Litter (needle)	Silvicultural debris (post- prescribed fire)
Pinus halepensis	Litter (needle)	Light load of conifer litter
Pinus halepensis	*Cistus* spp.	Medium shrub. Height between 0.5 to 1.5 m
Pinus halepensis	*Ulex* spp.	Medium shrub. Height between 0.5 to 1.5 m
Quercus ilex, Quercus suber	Grass	Short grass. Height between 5 to 50 cm
Quercus ilex, Quercus suber	*Cistus* spp.	Litter, grass and discontinuous shrub
Eucalyptus globulus	Litter (broadleaf)	Moderate load. Depth about 10 centimeters
Eucalyptus globulus	Litter with dispersed shrub	Moderate litter load. Shrub between 0.5 to 1.5 m
Q.suber	*Erica arborea, Quercus coccifera*	Short shrub with grass. Height between 5 to 50 cm
Q.suber	*Erica arborea*	Medium shrub. Height between 0.5 to 1.5 m
Q.suber	Litter (broadleaf)	Dispersal silvicultural debris (debarking)
Olea europaea var. *sylvestris*	*Pistacia lentiscus, Quercus coccifera*	High shrub. Height between 1.5 to 3 m
Olea europaea var. *sylvestris*	*Arbutus unedo - Phillyrea latifolia*	High shrub. Height between 1.5 to 3 m
Castanea sativa	Litter (broadleaf)	Continous litter presence
Treeless	Grass with *Nerium oleander, Tamarix gallica*	Very high shrub. Height between 3 to 7 m
Treeless	*Retama* spp.	Dispersed high shrub. Height between 1.5 to 3 m
Treeless	*Rosmarinus officinalis, Thymus vulgaris*	Short shrub. Height between 5 to 50 cm
Treeless	Grass *(Festuca, Brachypodium)*	Short grass. Height less than 5 cm
Treeless	Grass and *Lavandula* spp.	Short shrub with grass. Height between 5 to 50 cm
Treeless	*Genista* spp.	Grass continuous presence. Height between 0.3 to 1.2 meters
Treeless	Abandoned cropland	Tall grass. Height between 1-1.5 meters

Table 2. Correlation between the Rothermel classification and the new Mediterranean modeling

Fuel model (Rothermel 1972)	New fuel model ("UCO40 system")
	Grass fuel type
Model 1	P1, P2, P3, P4, P5, P6
Model 2	PM1, PM2, HPM1, HPM2
Model 3	P7, P8, P9
	Shrub fuel type
Model 4	M5, M7, M9
Model 5	M1, M2, PM3, PM4
Model 6	M6, M8
Model 7	M3, M4, HPM3, HPM4
	Canopy fuel type
Model 8	HR3, HR5
Model 9	HR2, HR4, HR6
Model 10	HR7, HR8, HR9, HPM5

Table 3. Some land management conversions to fuel model (‘‘UCO40 system’’)

Stand	Base	Structure	Model
Pinus pinea	*Cistus* spp.	Very high shrub. Height between 3 to 7 m	M9
Pinus pinea	*Cistus* spp.	Short shrub. Height between 5 to 50 cm	HPM1
Pinus pinea	*Cistus* spp.	Dispersed shrub on sandy soil	M1
Pinus pinea	*Chamaerops humilis*	Medium shrub. Height between 0.5 to 1.5 m	M4
Pinus pinaster	*Cistus* spp.	High shrub. Height between 1.5 to 3 m	M7
Pinus pinaster	*Cistus* spp.	Medium shrub. Height between 0.5 to 1.5 m	M3
Pinus pinaster	Litter (needle)	Silvicultural debris (post- prescribed fire)	HR5
Pinus halepensis	Litter	Light load of conifer litter	HR3
Pinus halepensis	*Cistus* spp.	Medium shrub. Height between 0.5 to 1.5 m	HPM5
Pinus halepensis	*Ulex* spp.	Medium shrub. Height between 0.5 to 1.5 m	HPM4
Quercus ilex, Quercus suber	Grass	Short grass. Height between 5 to 50 cm	P4
Quercus ilex, Quercus suber	*Cistus* spp.	Litter, grass and discontinuous shrub	HPM2
Eucalyptus globulus	Litter	Moderate load. Depth about 10 centimeters	HR6
Eucalyptus globulus	Litter with dispersed shrub	Moderate litter load. Shrub between 0.5 to 1.5 m	HPM3
Q.suber	*Erica arborea, Quercus coccifera*	Short shrub with grass. Height between 5 to 50 cm	HPM2
Q.suber	*Erica arborea*	Medium shrub. Height between 0.5 to 1.5 m	M3
Q.suber	Litter (broadleaf)	Dispersal silvicultural debris (debarking)	HR4
Olea europaea var. *sylvestris*	*Pistacia lentiscus, Quercus coccifera*	High shrub. Height between 1.5 to 3 m	M5
Olea europaea var. *sylvestris*	*Arbutus unedo - Phillyrea latifolia*	High shrub. Height between 1.5 to 3 m	M9
Castanea sativa	Litter (broadleaf)	Continous litter presence	HR2
Treeless	Grass with *Nerium oleander, Tamarix gallica*	Very high shrub. Height between 3 to 7 m	PM4
Treeless	*Retama* spp.	Dispersed high shrub. Height between 1.5 to 3 m	M6
Treeless	*Rosmarinus officinalis, Thymus vulgaris*	Short shrub. Height between 5 to 50 cm	M2
Treeless	Grass *(Festuca, Brachypodium)*	Short grass. Height less than 5 cm	P1
Treeless	Grass and *Lavandula* spp.	Short shrub with grass. Height between 5 to 50 cm	PM1
Treeless	*Genista* spp.	Grass continuous presence. Height between 0.3 to 1.2 meters	PM3
Treeless	Abandoned cropland	Tall grass. Height between 1-1.5 meters	P7

Table 4. Parameters of the new Mediterranean modeling

Fuel model	Dead fuel 1hr (lb/ft^2)	Dead fuel 10hr (lb/ft^2)	Dead fuel 100hr (lb/ft^2)	Live herbaceous fuel (lb/ft^2)	Live woody fuel (lb/ft^2)	Height/Depth (ft)	Surface-area to volume ratio (1/ft)
P1	0.036	0.000	0.000	0.000	0.000	1.0	3800
P2	0.078	0.000	0.000	0.000	0.000	1.0	3800
P3	0.049	0.000	0.000	0.000	0.000	1.5	3800
P4	0.079	0.000	0.000	0.000	0.000	1.2	3800
P5	0.013	0.000	0.000	0.080	0.000	2.6	3800
P6	0.111	0.000	0.000	0.000	0.000	2.5	3800
P7	0.138	0.000	0.000	0.000	0.000	2.8	1800
P8	0.114	0.000	0.000	0.038	0.000	4.0	1800
P9	0.189	0.000	0.000	0.283	0.000	4.0	1800
PM1	0.091	0.042	0.000	0.000	0.044	1.0	2500
PM2	0.206	0.103	0.051	0.000	0.099	2.0	2500
PM3	0.190	0.111	0.023	0.010	0.091	1.2	3000
PM4	0.402	0.201	0.100	0.022	0.169	2.0	2600
M1	0.056	0.000	0.000	0.000	0.151	1.0	2100
M2	0.197	0.000	0.068	0.000	0.152	1.0	2100
M3	0.235	0.059	0.069	0.000	0.125	2.7	2200
M4	0.143	0.325	0.091	0.000	0.104	3.3	1600
M5	0.363	0.125	0.062	0.000	0.216	5.3	1500
M6	0.128	0.088	0.000	0.023	0.122	4.0	2200
M7	0.457	0.246	0.122	0.000	0.272	5.7	2000
M8	0.230	0.125	0.071	0.000	0.149	4.0	2300
M9	0.711	0.202	0.101	0.000	0.387	6.0	2000
HPM1	0.091	0.060	0.000	0.000	0.061	1.0	2000
HPM2	0.164	0.108	0.000	0.000	0.109	1.0	2000
HPM3	0.181	0.139	0.022	0.000	0.147	2.0	1750
HPM4	0.361	0.271	0.024	0.000	0.228	2.5	1750
HPM5	0.420	0.330	0.028	0.000	0.220	2.8	2000
HR1	0.050	0.015	0.084	0.000	0.000	0.1	2000
HR2	0.093	0.029	0.004	0.000	0.000	0.2	2500
HR3	0.025	0.007	0.042	0.000	0.000	0.1	2000
HR4	0.025	0.006	0.045	0.000	0.000	0.4	2500
HR5	0.058	0.018	0.097	0.000	0.000	0.2	2000
HR6	0.144	0.068	0.007	0.000	0.000	0.4	2500
HR7	0.015	0.077	0.071	0.000	0.000	0.6	2000
HR8	0.146	0.025	0.114	0.000	0.000	0.2	2000
HR9	0.291	0.192	0.120	0.000	0.000	0.6	2500

Table 5. Variations in fire spread between Rothermel model prediction, new model prediction, and field behavior

"Rio Tinto Mines" Fire conditions: Fine fuel moisture: 2.5%. Slope 5%. Wind speed: 8 km h^{-1}

	Rothermel model	New fuel model	Field data
Load (kg m^{-2})	0.165	0.55	0.58 (± 0.15)
Rate of spread (m min $^{-1}$)	42.7	93.3	104.1 (± 5.91)
Flame length (m)	1.8	5.3	4.97 (± 0.51)
Fire-line intensity (kw m^{-1})	878.3	9,893.5	8,198.42 (± 2,360.9)
Spotting (m)	40	68.5	69.5 (± 5.29)

Obejo Fire conditions: Fine fuel moisture: 3%. Slope 30%. Wind speed: 24 km h^{-1}

	Rothermel model	New fuel model	Field data
Load (kg m^{-2})	3.59	3.74	4.17 (± 0.44)
Rate of spread (m min $^{-1}$)	56.7	56.6	52.27 (± 4.53)
Flame length (m)	9.1	11.1	10.85 (± 1.3)
Fire-line intensity (kw m^{-1})	31,902.9	48,528	49,752.15 (± 10,868.9)
Spotting (m)	161.1	178.9	172.2 (± 15.07)

Palomas Fire conditions: Fine fuel moisture: 4%. Slope 60%. Wind speed: 38 km h^{-1}

	Rothermel model	New fuel model	Field data
Load (kg m^{-2})	1.09	1.05	1.19 (± 0.79)
Rate of spread (m min $^{-1}$)	30.7	36.1	42.57 (± 1.34)
Flame length (m)	3.2	4.6	5.06 (± 0.93)
Fire-line intensity (kw m^{-1})	3,288.5	7,026.2	9,009.9 (± 3,614.9)
Spotting (m)	150.3	180.3	181 (± 5.54)

Catena Fire conditions: Fine fuel moisture: 4%. Slope 75%. Wind speed: 10 km h^{-1}

	Rothermel model	New fuel model	Field data
Load (kg m^{-2})	1.09	2.52	2.03 (± 0.90)
Rate of spread (m min $^{-1}$)	13.8	25.7	25.63 (± 4.23)
Flame length (m)	2.2	6.4	5.3 (± 1.7)
Fire-line intensity (kw m^{-1})	1,473.2	14,689.9	10,591.13 (± 6,805.82)
Spotting (m)	43.4	74.7	66.8 (± 11.92)

Moro Fire conditions: Fine fuel moisture: 3%. Slope 25%. Wind speed: 11 km h^{-1}

	Rothermel model	New fuel model	Field data
Load (kg m^{-2})	3.59	6.85	6.15 (± 0.61)
Rate of spread (m min $^{-1}$)	24.6	32.4	31.65 (± 1.34)
Flame length (m)	6.2	11	10.8 (± 0.42)
Fire-line intensity (kw m^{-1})	13,913.4	47,936.1	45,743.65 (± 4,288.2)
Spotting (m)	76.4	97.8	96.6 (± 2.26)

Belmez Fire conditions: Fine fuel moisture: 3%. Slope 15%. Wind speed: 8 km h^{-1}

	Rothermel model	New fuel model	Field data
Load (kg m^{-2})	0.89	0.38	0.48 (± 0.18)
Rate of spread (m min $^{-1}$)	16.1	55.3	55.1 (± 0.1)

Flame length (m)	2.4	2.9	2.8 (± 0.60)
Fire-line intensity (kw m^{-1})	1,668.1	2,557.4	2,623.2 (± 1,231.68)
Spotting (m)	42.4	38.1	37.8 (± 4.46)
"Sierra Parda" Fire conditions: Fine fuel moisture: 2%. Slope 60%. Wind speed: 22 km h^{-1}			
	Rothermel model	New fuel model	Field data
Load (kg m^{-2})	1.09	3.74	3.03 (± 1.26)
Rate of spread (m min $^{-1}$)	29.9	60.2	68.5 (± 14.28)
Flame length (m)	3.3	11.8	9.8 (± 1.97)
Fire-line intensity (kw m^{-1})	3,488.3	55,636.1	37,824.7 (± 16,100.26)
Spotting (m)	99.6	186.8	168.15 (± 18.45)
"Los Barrios" Fire conditions: Fine fuel moisture: 4%. Slope 60%. Wind speed: 8 km h^{-1}			
	Rothermel model	New fuel model	Field data
Load (kg m^{-2})	3.59	2.38	1.97 (± 0.62)
Rate of spread (m min $^{-1}$)	20.5	15.7	13.23 (± 8.81)
Flame length (m)	5.4	4.3	3.9 (± 2.66)
Fire-line intensity (kw m^{-1})	10,246.5	6,209.5	7,127.7 (± 2,885.58)
Spotting (m)	56.8	52.7	48.53 (± 17.4)
Estepona Fire conditions: Fine fuel moisture: 8%. Slope 75%. Wind speed: 30 km h^{-1}			
	Rothermel model	New fuel model	Field data
Load (kg m^{-2})	2.69	2.52	1.83 (± 0.14)
Rate of spread (m min $^{-1}$)	5.5	30.6	45.13 (± 0.12)
Flame length (m)	2.1	6.5	6.6 (± 0.29)
Fire-line intensity (kw m^{-1})	1,248.4	14,973.6	16,151.7 (± 1,535.4)
Spotting (m)	98.8	190.6	194.17 (± 4.53)
Nerva Fire conditions: Fine fuel moisture: 6%. Slope 25%. Wind speed: 9.5 km h^{-1}			
	Rothermel model	New fuel model	Field data
Load (kg m^{-2})	0.78	0.80	0.88 (± 0.13)
Rate of spread (m min $^{-1}$)	1.0	1.8	3.0 (± 0.15)
Flame length (m)	0.6	0.8	1.2 (± 0.09)
Fire-line intensity (kw m^{-1})	73.5	179.9	420.2 (± 61.94)
Spotting (m)	22.1	27	32.8 (± 1.98)