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An integrated approach for mapping fire suppression difficulty in three different ecosystems of Eastern Europe

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ABSTRACT

Increased fire activity, related both to human activities and to climate change, necessitates effective fire prevention and suppression strategies. The main purpose of this paper is to model and map fire suppression difficulty using common approaches in three different ecosystems in Eastern Europe by employing very high-resolution satellite imagery and landscape fire behaviour modelling. The integrated approach could allow fire managers to organize prevention and management of firefighting activities more efficiently by implementing both simple and easy-to-use risk and operational fire suppression difficulty indices. The development of cross-border common methodological approaches could foster cooperation between national authorities that would also maximize the efficiency of firefighting procedures.

KEY WORDS

Fire suppression difficulty; fire behaviour; remote sensing; landscape fire modelling; Eastern Europe

1. Introduction

Forest fires are a major concern in many countries in Europe, most notably in the South, in the Mediterranean Region, but also in Central and Northern Europe. Recently, fires are also becoming a major threat in the Eastern part of the European continent, such as the Black Sea region. Increased fire activity in many of these areas has been linked in the past to changes in land-use and land-cover due to the abandonment of the land and consequent socioeconomic changes (Goldammer & Furyaev 1996). Climate changes, by elevating temperatures and reducing precipitation, have prolonged the dry periods that caused intense fire events in France, Greece, Italy, Portugal, Spain and Turkey during the last ten years (EEA 2010). Furthermore, increasing climate (droughts) or weather (heat waves) extremes are additional threats for the coming years and decades (Giannakopoulos *et al.* 2009; Dimitrakopoulos *et al*. 2011). The most current IPCC report (Kovats *et al*. 2014) on climate change projected an increase in the occurrence of high fire danger days (Arca *et al.* 2012;

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Lung *et al.* 2012) and in fire season length in Europe (Pellizzaro *et al.* 2010). While the Mediterranean part of Europe has extensive firefighting experience, the northeastern part of Europe has major problems with this issue. This region is not prepared properly for large fires, since fire danger prediction systems are lacking. In some countries of the region forested areas are quite limited, which makes them a protection priority. The region has also experienced anthropogenic activities for centuries that have heavily impacted forests and extensive fires would substantially decrease the already limited forested areas.

The increase of burned areas in forested ecosystems demonstrates that fires present extreme fire behaviour parameters, such as fire size, fire rate of spread and fireline intensity, thus creating major difficulties in fire suppression efficiency (Kucuk *et al.* 2007; Saglam *et al*. 2008a; Kucuk *et al*. 2012; Mitsopoulos *et al.* 2014). Additionally, increased concern has been raised about the potential impact that climate change may have on fire regime in ecosystems that are not fire-dependent (Piñol *et al.* 1998; Pausas 2004; Flannigan *et al.* 2006). With regard to climate change, Dury *et al*. (2011) stated that the annual burned area is expected to increase three to five times in Southern Europe by 2100. Evidence for this emerges from fires that nowadays spread over higher altitudes and more northern latitudes. In these environments, forest ecosystems are not resilient to fire, as they have not been evolutionarily exposed to its frequent action (Arianoutsou *et al.* 2010). Dimitrakopoulos *et al.* (2011) reported a statistically significant increase in the mean annual number of fires and the area burned in the relatively more humid and colder regions during recent years. In addition, laboratory studies revealed that fire-stricken low-elevation forest species do not demonstrate higher flammability traits than the high-elevation non-fire-stricken species and the main factor in increased fire occurrence in high-elevation Mediterranean forests could be attributed to climate change (Dimitrakopoulos *et al.* 2013).

The development of efficient fire suppression strategies for wildland fires is complex (Rodríguez y Silva *et al.* 2014). Fire managers and firefighting officials are required to consider threats to socioeconomic and environmental resources and need to identify, in real time, the likelihood of a fire affecting valuable resources. The efficient deployment of suppression resources requires the consideration of multiple decision factors such as potential fire behaviour, topography, firefighter safety and exposure, transportation logistics, resource availability, and productivity. This decision-making process is characterized by great uncertainty. The difficulties are especially prevalent with respect to potential fire behaviour, the effects of fire on valued resources, relative priorities across valued resources and suppression efficiency (Haight & Fried 2007). Spatial fire behaviour parameters can be important inputs for fire suppression strategy and fire management (deployment of fire suppression resources, firefighter safety and exposure, transportation logistics), by quantifying the effect that the expected fire behaviour can have on fire suppression difficulty in natural landscapes (Rodríguez y Silva *et al.* 2014)

An important component of forest firefighting strategies is related to the accurate prediction of fire behaviour and growth, as determined by fuel, weather and topography. Wildland fuel composition and structure are of particular interest to wildland fire management. Based on the knowledge of the spatial extent of the fuels, national authorities and fire managers can design fire management strategies (Mallinis *et al.* 2008a). The wide range of the natural fuels' physical characteristics (i.e., load, size, bulk density, etc.) found within an area and the need for standardization in fuel description across different areas in terms of fuel type maps that are used as input to fire behaviour modelling have resulted in the development of fuel models (Lutes *et al.* 2009). Fuel models can be described as simulated complexes of fuel elements with physical and chemical parameter values representative of the typical fuel conditions (combustible materials) of a certain vegetation type (Anderson 1982). There are an abundance of fuel models worldwide; the most widely known in the USA are the 13 National Forest Fire Laboratory (NFFL) fuel models, which are used as inputs to FARSITE (Finney 1998), BEHAVE Plus (Andrews *et al.* 2003) and FlamMap (Finney 2006, 2007) fire behaviour simulators. These simulators are used for the National Fire Danger Rating System (NFDRS) and the Canadian Forest Fire Behavior Prediction System (FBP), which is composed of 16 fuel models. Researchers around Europe have developed seven fuel models using a modified version of NFFL fuel models (Arroyo *et al.* 2008). This new fuel classification system, called Prometheus, simplifies and adapts NFFL classification for the fuels found in Mediterranean ecosystem (Arroyo *et al.* 2008) in order to be used in decision-support software such as Visual Behave and Visual CARDIN (Rodríguez y Silva 1999; Rodríguez y Silva *et al.* 2010). Fuel maps are an essential tool in fire management since they characterize, at landscape level, the only factor that fire and land managers can control over many scales – fuel parameters (Scott & Burgan 2005). The creation of coarse-resolution fuel maps is useful in global and national fire and fuel hazard assessments because they help fire managers effectively plan, allocate and mobilize suppression resources (Burgan *et al.* 1998). Regional fuel maps are useful as inputs for simulating fire behaviour, fuel consumption, carbon release and smoke dispersion scenarios, as well as for describing fire hazards to support fire suppression and resource deployment (Keane *et al.* 2001; Rodríguez y Silva *et al.* 2014). Medium- and fine-resolution fuel maps are important for proposing and evaluating tactical fuel treatments, assessing fire hazard and risk, helping in environmental assessments and computing fire danger. Recently, the substantial development and improvement of tools for risk analysis have resulted in software improvements, systems integration, greater data availability and improved GIS and simulation techniques. Computer models can now perform spatially explicit fire simulations over heterogeneous fuels and map fire behaviour characteristics across large landscapes (Thompson *et al.* 2011). Most of the spatial fire behaviour modelling studies found in Europe use the FlamMap simulator and Minimum Travel Time (MTT) algorithm in order to address and inform fire risk management, landscape planning and people safety in the vicinity of the wildland urban interface (WUI) and other high-value resources and assets (HVRs) such as industry and infrastructure (Alcasena *et al.* 2015; Mitsopoulos *et al.* 2015; Salis *et al.* 2015).

Spatial distribution maps of wildland fuels can be obtained using many alternative approaches (Keane *et al.* 2001; Arroyo *et al.* 2008; Saglam *et al.* 2008b). Remote sensing technologies can provide improved estimates of the wildland fuels spatial extent using an efficient approach. Various forms of remote-sensing data at multiple scales including digital orthoimagery, medium-high optical imagery such as LANDSAT and ASTER images, hyper-spectral data such as those provided by AVIRIS images and active sensor products such as microwave-radar images and LIDAR datasets have been employed for fuel type mapping on global, regional and local scales (Keane & Reeves 2012; Yavuz & Saglam 2012).

The main purpose of this study was to develop a methodology that maps fire suppression difficulty by using fine-scale fuel sampling with very high-resolution (VHR) fuel maps and spatial fire modelling simulation in three different fire-prone landscapes of the Eastern Europe region.

2. Material and methods

2.1. Study areas

The study was conducted in three different ecosystems of Greece, Turkey and Ukraine (Figure 1).

Menoikio Mountain, Greece, is included in the NATURA 2000 Network (GR1260004) (Figure 1a). The mountain marks the western border of the Prefecture of Drama and is a continuation of Mount Falakro towards the south. The mountain is characterized by its distinctive terrain ranging from mountains and sub-alpine meadows with rich flora to forests of beech (*Fagus Sylvatica*) and beech mixed with Macedonian fir (*Abies borisii regis*), forests of centuries-old chestnuts (*Castanea sativa*) and the rich bird life to which it plays host. The flora consists of plants that are found at high altitudes including beech, chestnut, Macedonian fir, the black pine (*Pinus nigra*), oaks (*Quercus* ssp.), hornbeam (*Carpinus orientalis* and *betulus*), willow (*Salix* ssp.), alder (*Alnus glutinosa*), sorbus (*Sorbus* ssp.), maple (*Acer* ssp.), ash (*Fraxinus* ssp.), dogwood (*Cornus mas*), wild roses (*Rosa* ssp.) and whortleberry (*Vaccinnum* ssp.). During the period 1984–2009 (26 years) a total of 106 fires burned 2208 ha of the Menoikio protected area.

The Bayam Forest District in Turkey covers an area of 16,006 ha of which 80 percent is forested (Figure1b). The remaining 20 percent is used for agricultural, hay production and residential purposes. The terrain is hilly and the elevation ranges between 500 m and 1500 m above the mean sea level with an average slope of 25 percent. The major species in the site include black pine (*Pinus nigra supsp. pallasiana*), Scotts pine (*Pinus Silvestris*), oriental beech (*Fagus orientalis*), common hornbeam (*Carpinus betulus*), field elm (*Ulmus minor*) and various

Figure 1. The location of the three study sites in the Black Sea region.

oak (*Quercus*) species. During the period 1962–2014 (53 years), a total of 54 fires burned 497 ha of the Bayam Forest District.

The Yalta Mountain-Forest Natural Reserve (Yalta MFNR) occupies the southern slope of the main ridge of the Crimean Mountains that extends from west to east (Figure 1c). The vegetation of the area is highly variable with four altitudinal zones. From the seacoast to a height of 400–450 m above sea level pubescent oak (*Quercus pubescens*) forests are dominant. At an altitude of 400 to 900 m wide stretches of forest of black pine grow. Above 900 m and up to 1200 m the third zone of forests is formed with Caucasian pine (*Pinus kochiana*) combined with Scots pine and typical beech forests. During the last 21 years in the Yalta Mountain Forest Natural Reserve, more than 1000 wildfires occurred that burned a total area of 2550 ha.

2.2. Fuel sampling

The study sites were stratified on vegetation maps based on the dominant vegetation type. All the stratified areas were surveyed on site and 40 representative locations with typical ('average') fuel conditions for each area were randomly selected. Surface fuel load was estimated with the Brown *et al.* (1982) method for inventorying surface fuel biomass. Eleven fuel parameters were measured in each location as follows (Brown *et al.* 1982):

(1) The 1-h, 10-h, 100-h, 1000-h and total fuel loads were measured with the planar-intercept method (four 30-m-long transects). The 1-h, 10-h, 100-h and 1000-h fuels correspond to plant parts (branches) with diameters of 0.0–0.5, 0.6–2.5, 2.6–7.5, and > 7.5 cm, respectively (Brown *et al*. 1982).
(2) Foliage load, litter load and depth and shrub (up to 2.0 m in height) and herbaceous (live and dead) vegetation loads were measured in six 10-m^2 sampling plots with the clip and weigh method.
(3) The height of the shrub and herbaceous vegetation layers was also measured in the sampling plot.

The clip-and-weigh method was used to determine all fuel loads by size category. The percentage of the total area covered by each fuel type (shrub, herbaceous, litter, etc.) was determined with the planar intercept method in the fuel transects (30 m long) that were used for fuel measurements (Bonham 1989). All fuel loads (fuel weight per unit surface area) were expressed on a dry-weight basis.

2.3. Fuel mapping

Fuel type mapping in both the Greek and Ukrainian study sites was carried out on the basis of RapidEye imagery acquired in 2012. RapidEye is a commercial optical Earth observation mission. The RapidEye sensor has a nominal ground sampling distance (GSD) of 6.5 m, with five spectral bands: blue (440–510 nm), green (520–590 nm), red (630–685 nm), red edge (690–730 nm) and near infrared (NIR, 760–850 nm).

For the Turkish study site, Astrium Pleiades-1A imagery, also acquired in 2012, was used for delineating fuel models. The Pleiades-1A sensor provides one 50-cm panchromatic (480–830 nm) and four 2-meter multispectral bands over the visible–near infrared part of the electromagnetic spectrum (blue, 430–550 nm; green, 490–610 nm; red, 600–720 nm; near infrared, 750–950 nm).

All three images were orthorectified using digital elevation models with 10 m resolution and GCPs identified over cadastral maps or very high-resolution orthoimagery.

Prior to the classification the green normalized difference vegetation index (GNDVI), the normalized difference vegetation index (NDVI) and the normalized difference red-edge index (NDRE) (only for the RapidEYE images) were calculated and considered along with the original satellite data.

$$GNDVI = \frac{nir - green}{nir + green}$$

$$NDVI = \frac{nir - red}{nir + red}$$

$$NDRE = \frac{nir - rededge}{nir + rededge}$$

The RapidEye images were processed through a geographic object-based image analysis approach (GEOBIA) (Mallinis *et al.* 2008b), while the Pleiades-1A image was classified originally using an unsupervised pixel-based procedure followed by an expert-based refinement of the identified clusters.

For the GEOBIA approach, three different levels of objects were developed in each site. The first was developed following a vector-based segmentation (Mallinis *et al.* 2014) using existing cadastral data to identify urban and agricultural areas. The second was derived from image-based segmentation as the main classification level while the third was developed following image-based segmentation in order to provide texture information in the classification process. The refinement of the classification processes was carried out with reference sets of points obtained through field visits and photo-interpretation of available VHR datasets.

3. Fire behaviour modelling

In order to assess fire behaviour parameters, we used a landscape fire behaviour modelling approach. Simulated wildfire behaviour was performed with Rothermel's (1972) fire spread equation as implemented in the FlamMap software (Finney 2006). The algorithm replicates fire behaviour according to the Huygen's principle, where the growth and behaviour of the fire edge are a vector or wave front (Finney 2002). The simulations were conducted by using as input data the digital terrain model (DTM) of the areas, the spatial extent of the fuel models and the fuel parameter values of each fuel model in the study areas. Fuel models were mapped at a very fine scale of 5 metres pixel size (resulted from RapidEye image analysis), while 20 m × 20 m raster input files were used for the fire behaviour simulation purposes. The basic fire behaviour mode which calculates fire behaviour under a constant set of environmental conditions for an entire landscape was used for the simulation purposes. Heat content and surface area-to-volume ratio values for the fuel models developed were obtained by Dimitrakopoulos and Panov (2001). The dominant wind speed and wind direction values in each burning condition were obtained from the historical fire occurrence data observed

Table 1. Weather and fuel moisture parameters used in the fire simulations in each study area.

Parameters	Menoikio Mountain	Bayam Forest District	Yalta Mountain-Forest Natural Reserve
1-h fuel (0–0.64 cm) (percent)	8	11	10
10-h fuel (0.65–2.5 cm) (percent)	10	14	12
100-h fuel (2.51 – 7.5 cm) (percent)	14	22	16
Live woody fuel (percent)	100	100	120
Live herbaceous fuel (percent)	120	140	140
Wind speed (km/h)	25	20	32
Wind direction	NE	NE	N

in each study area. Fuel moisture per fuel category, in each fuel model found in the area for each burning condition, was estimated by using the specific fuel moisture prediction equations developed by Aguado *et al*. (2007) and Dimitrakopoulos and Bemmerzouk (2003) for dead and live fuel moisture values, respectively (Table 1). The results consisted of surface fire behaviour outputs, since crowning and spotting modules in FlamMap software were not activated. The outputs resulted from the FlamMap runs were shapefiles of the simulated fire perimeters and ASCII files of the simulated fire behaviour. By processing these outputs in a GIS environment, the following information was obtained: fire rate of spread and fireline intensity. The spatial explicit values of the above-mentioned spatial layers were reclassified into four distinct fire suppression difficulty classes. These classes were based on Andrews and Rothermel's (1982) rate of spread fire suppression difficulty classes and Andrews *et al.*'s (2011) fireline intensity classes. From the combination of the two maps (i.e., fire rate of spread and fireline intensity) and the category rating of the factor values, the fire suppression map was obtained.

4. Results

Table 2 presents the fuel models that resulted from field measurements in each study area. In the Greek site six fuel models resulted from the field sampling and represent all the major vegetation types of the study area. The dense shrubland fuel model incorporates maquis with heights up to 2.0 m. This fuel model includes a high proportion of the foliage load, and a substantial part of the fuel load distributed in the large size class (> 2.5 cm branch diameter). The sparse shrubland fuel model is characterized by low height and ground-cover shrubs. The understorey of conifer forests is mainly composed of fine twigs. The litter of the beech, oak and other broadleaved forest species demonstrated limited spatial heterogeneity in terms of fuel loads per fuel category. Finally, the grassland fuel model featured the lowest values of total fuel weights in every category.

In the Turkish site, six fuel models also resulted from the field sampling. The litter layer of the young Anatolian black pine fuel model that has a crown closure less than 70 percent incorporates mostly planted 3-m-tall Anatolian black pine trees. This model is responsible of an average proportion of the foliage load. The second fuel model of the litter layer of the young Anatolian black pine and Scots pine (crown closure 40–70 percent) has the least effect on fuel load (0.13 percent of total fuel load). The third fuel model is the litter layer of the young Anatolian black pine (crown closure > 70 percent). It covers 13 percent of the study area and is responsible for 29 percent of the total fuel load. The fourth fuel model is the litter layer of the mature Anatolian black pine with an understorey (crown closure 40–70 percent).

Table 2. Fuels models resulting from field sampling in the three study areas.

Fuel model	Average height (cm)	Fuel load by category (t/ha) 0.0–0.5	0.6–2.5	2.6–7.5	>7.5	Live foliage (t/ha)	Litter depth (cm)	Litter weight (t/ha)
Menoikio Mountain								
FM1: shrublands (up to 2 m height)	152	8.7	4.5	3.1	0.0	6.6	2.4	2.1
FM2: litter layer of conifer forests	4	3.1	0.7	0.3	0.0	0.0	0.8	6.2
FM3: litter layer of oak forests	6	2.2	1.1	0.6	0.0	0.0	2.6	3.9
FM4: litter layer of beech forests	4.5	3.5	0.9	0.3	0.0	0.0	0.6	4.4
FM5: litter layer of mixed broadleaf forests	5	2.6	0.4	0.2	0.0	0.0	1.6	5.5
FM6: grasslands	25	1.36	0.4	0.0	0.0	0.0	4	8.3
Bayam Forest District								
FM1: litter layer of young Anatolian black pine (crown closure >70)	4.0	0.8	0.2	0.9	0.0	0.0	1.8	2.5
FM2: litter layer of young Anatolian black pine and Scots pine (crown closure 40–70)	5.1	0.44	0	0	0.0	1.9	0.4	1.0
FM3: litter layer of young Anatolian black pine (crown closure >70)	3.8	1.1	0.9	3.4	0.0	0.0	2.6	3.2
FM4: litter layer of mature Anatolian black pine with understorey (crown closure 40–70)	5.2	0.2	0.6	1.2	0.0	0.4	2.4	2
FM5: litter layer of mature Anatolian black pine (crown closure >70)	4.9	1.1	1.4	0.7	0.0	0.0	3.1	3.5
FM6: open area oak fuel type	2.7	1.7	0.8	0.0	0.0	1.3	0.4	1.5
Yalta Mountain-Forest Natural Reserve								
FM1: litter layer of Crimea pine forest >100 years old	3.7	0.6	1.1	0.6	0	0.2	3.7	4.2
FM2: litter layer of Crimea pine forest >100 years old with understorey	5.5	0.3	0.9	0.5	0	5.1	5.5	4.4
FM3: litter layer of Scots pine forest >100 years old	7.1	0.4	0.9	0,0	0	0.0	7.1	3.6
FM4: litter layer of Crimea pine forest >100 years old with dense natural regeneration	4.4	0.4	1.5	0.0	0	0.0	14.4	12.5
FM5: litter layer of Crimea pine forest >100 years old on rocks	4.4	0.8	2.7	0.0	0	0.0	24.4	21.3
FM6: litter layer of Crimea pine forest <100 years old	4.2	1,1	1.8	0.0	0	0.1	4.2	3.1
FM7: litter layer of Crimea pine forest <100 years old with understorey	4.2	1.6	2.2	0.0	0	5.3	4.2	2.9
FM8: litter layer of Scots pine forest <100 years old with understorey	4.2	2.5	2.9	0.0	0	11,2	4.2	4.4
FM9: litter layer of broadleaf forest	1.7	0.8	0.3	1.1	0	0.0	1.7	1.1
FM10: litter layer of beech forest	2.8	0.8	2.5	0.0	0	0,0	2.8	1.8
FM11: Yaila (grassland)	1.5	1.62	0	0	0	7.56	0	0
FM12: litter layer of Scots pine forest <100 years old	4.3	1.9	2.1	0	0	0.1	4.3	3.3

It covers 24 percent of the study area while representing 17 percent of the total fuel load. The fifth fuel model, litter layer of the mature Anatolian black pine (crown closure > 70 percent), covers 17 percent of the study area and is attributed 22.8 percent of the total fuel load. The least contribution comes from the sixth fuel model, the open area oak fuel model: 6.5 percent of the total fuel load is represented by this model although it covers 24 percent of the total study area. The remaining portion of the area (19.65 percent) is covered by rural infrastructure and agricultural and pasture lands.

The Yalta site had 12 fuel models that resulted from the field sampling. Crimea pine forests located mostly at elevations up to 600 m are quite heterogeneous and have low productivity. Depending on stand structure the total fuel load changes from 0.34 t ha^{-1} in middle age forests to 21.7 t ha^{-1} in mature forests. The large amount of natural regeneration of Crimea pine also significantly increases the total fuel load. Scots pine forests are mainly pure stands or with artificially planted broadleaf shrubs. Old Scots pine stands due to their location are mostly mixed with beech or hornbeam. Beech forest has the largest amount of fuel load and no wildfires compared to other broadleaves (oak, hornbeam, poplar). Fuel model 11, named Yaila (grassland), has the lowest fuel load in the area and is represented by grasses. The fuel values represented by the models fall well within the range reported for vegetation types

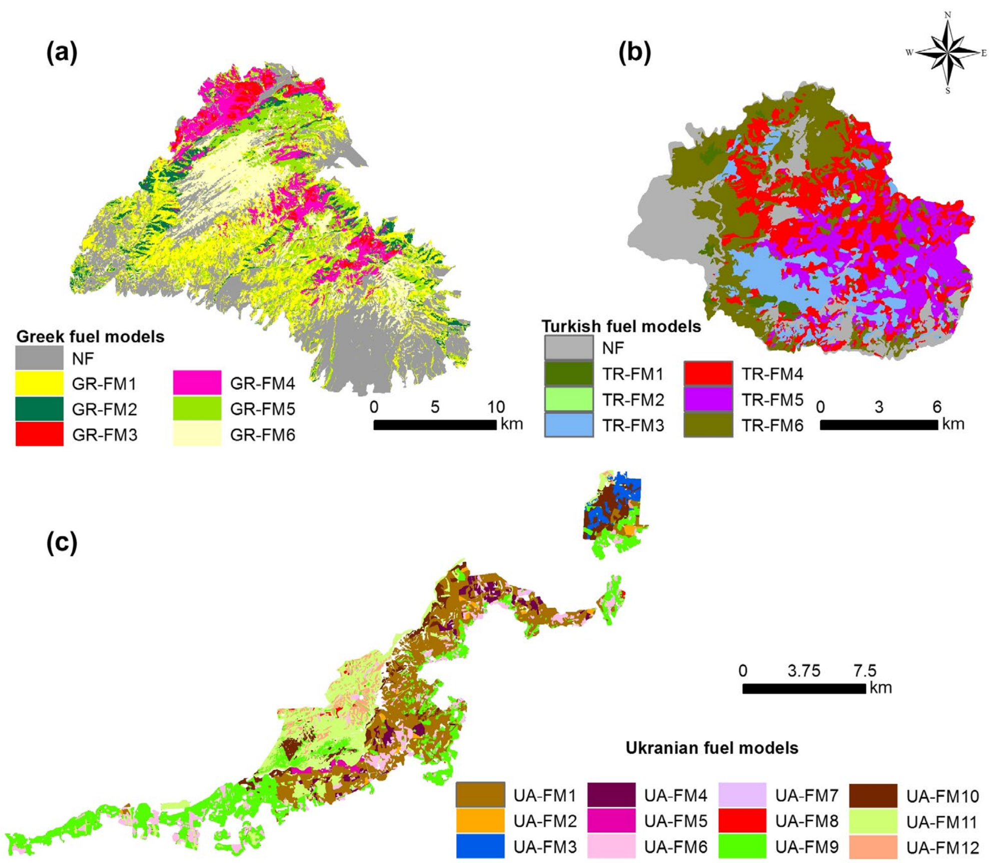

Figure 2. The fuel model maps of the three study sites.

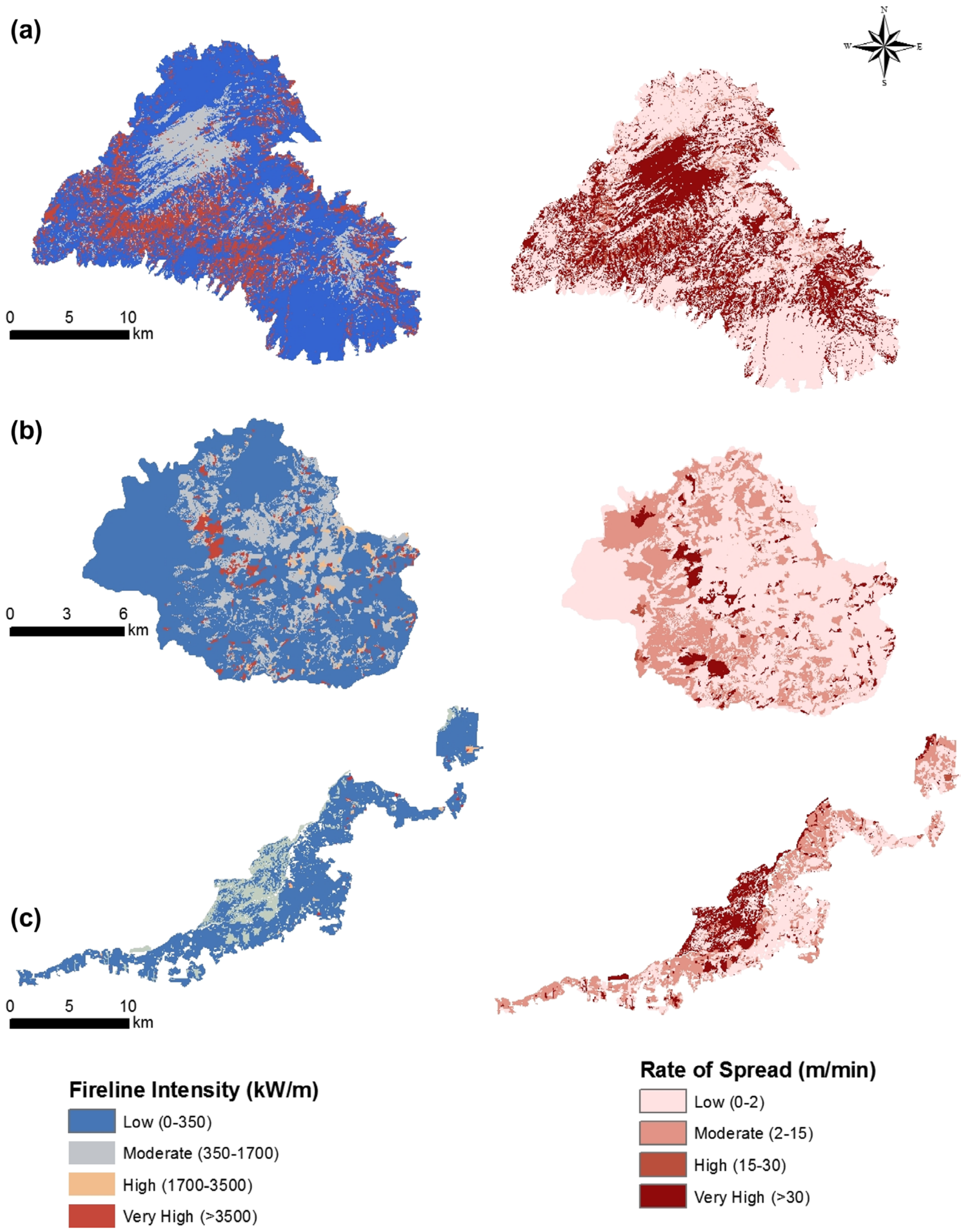

Figure 3. The fireline intensity and fire rate of spread in the three study sites that resulted from FlamMap simulations.

in Greece (Dimitrakopoulos 2002) and for Mediterranean vegetation types in other parts of the world (Scott & Burgan 2005).

Figure 2 presents the fuel model spatial extent in each study area. The majority of the area in the Greek site is occupied by non-fuels (31 percent) and shrublands (20 percent). Grasslands (15.6 percent), broadleaves (15 percent) and beech forests (10 percent) also occupy a significant part of the study site (Figure 2a). In the Turkish site, the majority is occupied by Anatolian black pine at 30 percent. The Scots pine is the second major species and occupies 13 percent of the area (1061 ha), followed by Calabrian pine (33.5 ha), oriental beech (98.5 ha) and oak (98 ha) as the main vegetation, and the area has a semi-continental climate (Figure 2b). In the Ukraine site, the main fuel model dominating the area is the litter area of pine forests (Figure 3c).

Figure 3 shows the fire rate of spread and fireline intensity maps that resulted from fire behaviour simulations. As expected, topography has the largest influence on rate of spread and fireline intensity values. In the Greek site the dense shrubland fuel model demonstrated the most intense fire potential in the fire behaviour simulations due to the heavier fuel load. The grassland fuel models produced low-intensity and high-speed fires due to the reduced fuel load that was composed of dry fine fuels (Figure 3a). In the Turkish site half of the study area (74.9 percent) demonstrated fireline intensity values less than 350 kW m^{-1} due to low fuel load in agricultural areas, pasture lands and openings in the forested lands. In addition, 19.2 percent of the site produced moderate fireline intensity (350–1700 kW m^{-1}). High and very high fireline intensities (>3500 kW m^{-1}) resulted from the six fuel models that each cover 2.3 percent to 3.7 percent of the area, respectively (Figure 3b). In the Ukrainian site, the Yaila (grassland) and some stands of Crimea pine fuel models demonstrated the most

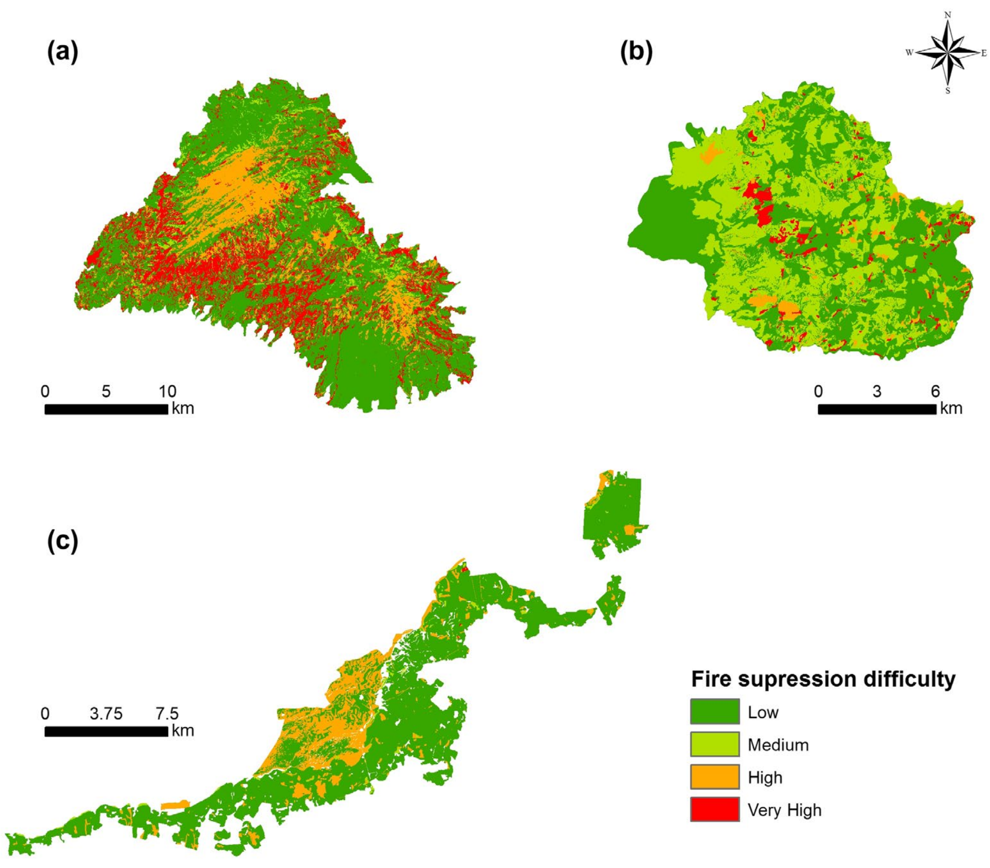

Figure 4. The fire suppression difficulty maps of the three study sites.

intense fire potential due to their physiographic (i.e., slope, aspect) features. At the same time all other models due to the quite dense fuels also showed intense burning conditions (Figure 3c).

The fire suppression difficulty maps developed for each study area are depicted in Figure 4. Fire simulation outputs for fire suppression difficulty showed complex patterns that were generally related to the dominant fuel model and topography in each study site. In the Greek site the shrubland fuel model presented the most difficult fire suppression classes (Figure 4a). In the Turkish site, areas with high potential were found in several locations around the study area, although the largest concentration was in the litter layer of young Anatolian black pine with a canopy cover between 40 and 70 percent in the middle part of the study area. The areas that had been burned previously and replanted right after the fire contributed a heavy fuel load that created conditions favourable for intense fire growth. This is due to the overcrowded young trees and lack of thinning practices. Fire suppression difficulty potential was lower in the surrounding areas that had been recently burned numerous times by wildfires, especially in the vicinity of the grassland and sparse shrubland region (Figure 4b). A similar pattern was observed in the Ukraine site, where Crimea pine fuel demonstrated high fire suppression difficulty compared to the other fuel models in the area (Figure 4c).

5. Discussion

Maps that combine the potential fire rate of spread and fireline intensity provide the necessary information to foresee both prevention of fires and well-structured firefighting operative planning, by taking into consideration the increasing risk of fire spread and intensity (Rodríguez y Silva & González-Cabán 2013). In this framework the four classes created express the growing complexity of landscape management in terms of before and during fire suppression management. The fire suppression difficulty is affected by the surface classified in each different class; the larger it is, the more complex the integrated management of the two aspects is. For the first two classes, giving a general low level of risk, the surface extension is not so relevant, in contrast with the last two classes. The integration approach followed in this study has been joined by analysing all possible combinations (pixel by pixel) of the two variables and the results have been classified into four fire suppression difficulty classes (low, medium, high and very high).

The obtained fire suppression difficulty classes are an expression of different concepts from the point of view of territory planning and management because the first gives a risk level of fire spreading, i.e., fire rate of spread, while the second expresses the difficulty in allocating and deploying fire suppression means, since fireline intensity is directly correlated to the flame length; both aspects are critical for fire suppression activities (Sharples *et al.* 2009). However, it should be noted that the approach used in this study takes into consideration only the fire environment (fuels, topography and meteorology) and it does not account for other factors which influence fire suppression difficulty, such as road density, firefighting operational capabilities and available infrastructures (water tanks, fire towers, etc.).

As reported by other authors (van Wilgen *et al*. 1985; Arca *et al.* 2007) Rothermel's (1972) fire rate of spread equation, as it is embedded in the FlamMap fire simulator, has been extensively validated on areas different from those where the models were originally developed. Still they stated that a validation of the model needs to be developed to account for both the fuel characteristics and the high heterogeneity of different vegetation types of the area of interest. Arca *et al.* (2007) also suggested that localized, site-specific fuel models give more reliable fire behaviour predictions than using the FlamMap simulator. Similarly, studies performed using landscape fire simulation modelling highlight the fact that local-specific fuel data and custom fuel models increase the accuracy of the predicted fire behaviour (Miller & Yool 2002). The validation of fire simulation accuracy has been also conducted with historical fires and data in Mediterranean ecosystems with satisfactory results (Arca *et al.* 2007). However, these efforts are characterized by high uncertainty due to the fact that it is extremely difficult to obtain accurate fire and weather data of real wildfires (Paz *et al.* 2011). Mitsopoulos *et al*. (2013) evaluated FlamMap simulator performance and accuracy based on the real fire perimeter of the 2009 large fire event in Attiki, Greece. Their analysis showed that FlamMap predicted correctly 88 percent of the total burned area. Fire behaviour values that resulted from the simulations were found to be similar to values reported in typical Mediterranean ecosystems (Dimitrakopoulos 2002; Arca *et al*. 2007). Fire behaviour models used in this simulation are semi-empirical. Nevertheless, they have been tested in high-intensity experimental fires with satisfactory results (Stocks *et al.* 2004). Furthermore, the variability in fuel complex characteristics used during the model conception and the physical fuel (i.e., load) and weather parameters should make them applicable to other fuel complexes as well. New landscape fire modelling efforts use the MTT algorithm in order to assess spatial wildfire risk and high-value resource asset exposure to fire in Mediterranean fuel complexes (Arca *et al*. 2012; Salis *et al*. 2013, 2014). Although that approach is suitable for assessing the important scale-related factors that drive wildfire likelihood at multiple ignition points, it does not present essential inputs (e.g., time of arrival, rate of spread, etc.) for fire suppression strategies, such as distribution and allocation of available firefighting resources, fire towers and water-tank construction locations.

The high spatial resolution imagery used in this study generated fine-scale measurements of fuel models, which allowed the mapping of the fuel models' spatial extent in the three study sites, and consequently the creation of detailed fire suppression difficulty maps. The large growth that fires can achieve in these areas is mainly attributed to the high rates of spread in areas which are covered by fuels with substantial fine load components. The potential for high intense fires seen in the simulations highlighted the need for fire management activities in specific locations of the three study areas. This will allow wildfire managers to be effective and efficient in their fire management strategies.

6. Conclusions

This study presented an integrated approach for assessing fire suppression difficulty in three different forest ecosystems in Eastern Europe. Localized fuel models have been developed based on extensive fieldwork. FlamMap simulation results showed that shrubland ecosystems under typical summer burning conditions have a high fire suppression difficulty risk. The proposed methodology presents an integration of fuel sampling, VHR fuel mapping and landscape fire behaviour simulation for fire management planning across the landscape. The final maps are the end product, and they can be fully exploited operationally by local fire management authorities without further processing. The outputs created from this study can be used as valuable components of judicial short- and long-term wildland fire suppression in Eastern Europe.

The modelling approach used in this study represents a first attempt at mapping fire suppression difficulty at local and very fine scale in different complex-fuel natural landscapes. Although the number of the study sites is still not sufficient to represent the complexity of fire behaviour in a wider regional context, the broad gradient of conditions that exist in the study sites allow one to highlight the benefits of using fire spread models for simulating wildfires in the region. This operational approach can be applied to large areas with diverse characteristics considering the relatively low number and easy availability of input data and can also be managed by territorial and public agencies and organizations devoted to forest fire planning and suppression.

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