Modelling and analyzing the surface fire behaviour in Hyrcanian forest of Iran

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ABSTRACT: The purpose of this study was to assess the forest fire behaviour and investigate the impact of different parameters on the spread of surface fire in the Hyrcanian forest of Iran. Surface fire was simulated using mathematical models in Microsoft Visual Basic 6.0 environment during a 30-minute time period. Several parameters that contributed to the speed of surface fire such as slope, wind velocity and litter thickness in the forest floor and various types of forest litter associated with hornbeam (*Carpinus betulus* L.), Persian ironwood (*Parrotia persica* C.A.M), beech (*Fagus orientalis* L.) and maple (*Acer velutinum* L.) were investigated. The results indicated that the maximum burned area was associated with beech litter. Forest surface fire demonstrated similar behaviour for the litter types of beech and Ironwood, whereas in the case of maple and hornbeam litters, the fire spread parallelly and perpendicularly to contour lines, respectively. The burned area increased in an irregular pattern as the forest floor slope gradient was increased. Moreover, the skewed pattern of the burned area for the forest floor composed of maple, beech, ironwood and hornbeam litter was described as high, low, moderate and low, respectively. The fire spread angle in forest floor associated with maple and beech litters changed with litter thickness. Finally, litter thickness had a significant effect on the direction of fire spread and this was more prominent with hornbeam litter.

Keywords: burned area; forest fire; litter thickness; simulation; slope; soft modelling; wind speed

Forest fires were described as a real disaster from ecological, physical and environmental standpoints (Rajaeev et al. 2002; Böhm et al. 2011), and so it is important to accurately assess and carefully manage their impacts whenever and wherever they occur; they represent one of the most critical issues that concern forest resources globally (Kandya et al. 1998; Tuia et al. 2008).

The forest managers in many areas of the Hyrcanian forests have increasingly been focusing on efforts to mitigate damage from forest fires. Many researchers including Giglio (2005) employed GIS (Geographical Information System, ESRI, Redmont, USA) based predictive models for forest fire behaviour. Demagistri et al. (1995) used the capability of RS (Remote Sensing) forest fire simulator software in order to investigate active data defined as physical parameters such as land cover, topography and wind, as well as inactive data associated with maps, aerial photos, SPOT and Landsat satellite images. They improved the software capability using a diffusion model and intermediate graphics.

Jaber et al. (2001) applied intelligent software to prevent fire in forest after data formulation. The built-in capabilities of the software included initial routing, danger evaluation and appearance, simulation, recommendation for initial programming and fire suppression. A simulation system of forest fire using ESRI ArcSDE was introduced by Qizhi et al. (2004).

In an earlier work in Slovakia, a method was presented for the forest fire modelling using FARSITE software. In this research, vegetation type and moisture level were also introduced as the two most important variables to investigate forest fire behaviour.

Reinhaedt and Crookston (2003) reported that the Fire and Fuel Extension (FFE) to the Forest Vegetation Simulator (FVS) simulated fuel dynamics and potential fire behaviour over time, in the context of stand development and management. After a brief review of fire spread models Ferragut et al. (2010) focused on physical models. These models took into account some of the main variables impacting fire spread, namely water content of the litter, radiation, wind and topography effects.

Muge et al. (2008) used Lidar and Farsite simulator for modelling the forest fire behaviour. He used specific data such as elevation, slope gradient, slope direction, surface fuel model, canopy cover and wind velocity and inserted them into the software. It was demonstrated that fuel distribution was an important factor for the prediction of fire occurrence. Perminov (2010) developed a mathematical model for describing heat and mass transfer processes at crown forest fire initiation, taking into account their mutual influence. Lee et al. (2010) simulated and visualized forest fire to estimate forest damage. They reported that fuel models and climate data in regional fires were useful for simulation.

The use of satellite imagery to measure the impact of forest fire on vegetation communities has become a popular topic of discussion in recent years. It was demonstrated that a relationship between fire severity and soil damage could be deduced in eucalypt forests (Shakesby et al. 2007). Smith et al. (2005) showed that, in the case of Savanna fires, surface spectral reflectance increased with increasing fire severity due to the formation of increasing quantities of white mineral ash. Moreover, they studied linear relationships between fire duration and post-fire surface spectral reflectance. Conedra et al. (2011) utilized Monte Carlo simulation to examine the relative likelihood of forest fire initiation as a function of vegetation type, forest land physiography and proximity to the wilderness-urban interface (WUS).

Banj Shafiei et al. (2010) conducted a study in the Chelir forest of northern Iran in order to investigate the impact of fire on forest structure, tree species quality, and regeneration composition. Their results showed that forest fires changed the structure and had different effects on the tree species composition between burned and control areas. Thin barked species such as oriental beech (*Fagus orientalis* Lipsky) and coliseum maple (*Acer cappadocicum* Gled.) have been affected more than those with thick bark, like hornbeam (*Carpinus betulus* L.) and chestnut-leaved oak (*Quercus castaneifolia* C.A. Mey). The density of oriental beech regeneration in the unburned area was greater than in the burned area, while the quantity of regeneration of hornbeam, coliseum maple and velvet maple (*Acer velutinum* Boiss) was higher in the burned area.

Hyrcanian forests of Iran are primarily composed of deciduous species and a major type of forest fire occurring there is actually surface fire (Jazirehi 2010; Marvie-Mohadjer 2011). However, most of the models for predicting forest fires have been developed by other researchers for crown fires of conifers in countries other than Iran. Obviously, these models could not be applied for predicting the surface fire behaviour in Hyrcanian forests of Iran.

This study attempted to assess forest fire behaviour and investigated the effects of different parameters in relation to the spread of surface fire based on parameters such as slope, wind velocity and litter thickness, and litter types associated with species such as hornbeam (*Carpinus betulus* L.), Persian ironwood (*Parrotia persica* C.A.M), beech (*Fagus orientalis* L.) and maple (*Acer velutinum* L.) were investigated.

The main objectives of this study were to (1) provide the simulator mathematical models which were developed based on factors influencing surface fire and (2) investigate the surface fire behaviour specifically for some of the main species of Hyrcanian forest.

MATERIAL AND METHODS

Study area. The study was conducted in Darabbkola forest. The forest covers an area of 2,612 ha and is located in watershed district No. 74. The site is located on the southeastern edge of the city of Sari in Mazandaran province. The latitude, longitude and elevation ranges of this forest are 36°33'20'' to 36°33'30''N, 52°14'40'' to 52°31'55''E and 180–800 m a.s.l., respectively. Due to increasing occurrence and high frequency of surface fires in Hyrcanian forests in recent years, it became beneficial to investigate the forest fire behaviour in these forests (Fig. 1).

Mathematical models and numerical methods. The impact of wind velocity was produced artificially by the rpm-adjustable ventilator. The ventilator rpm was controlled by ultrasonic wind gauge on different slope classes. Sufficient heat was applied to the litters to simulate natural conditions of surface forest fires using ENK capsule. Then, the speed and direction of surface fire were measured at different wind velocity, slope classes

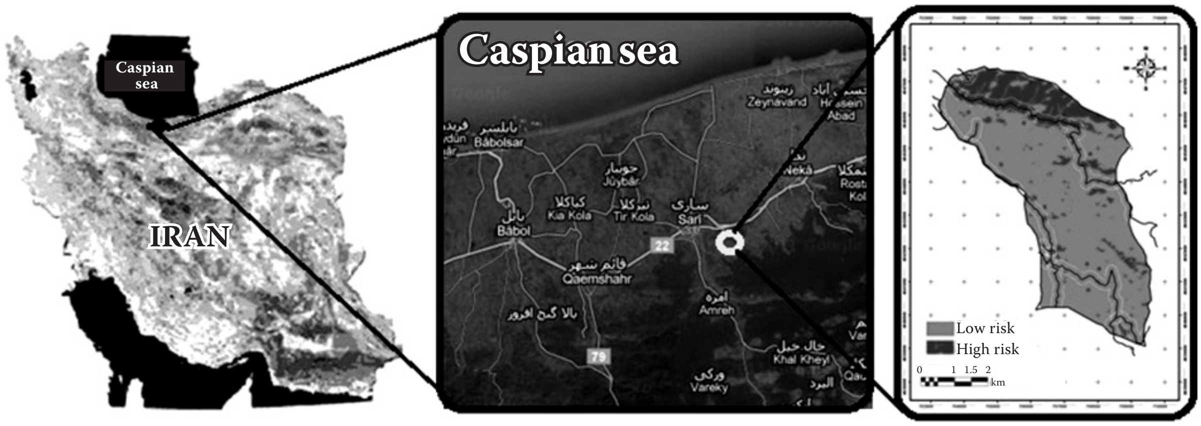

Fig. 1. Maps showing the geographical location of the study area

and litter thicknesses (Nasiri et al. 2012). These measurements were used to develop mathematical and numerical models. The models were then used as source codes and fed into a simulator in order to obtain the associated simulated surface fires (Tables 1 and 2).

Surface fire was simulated using mathematical models in Microsoft Visual Basic 6.0 environment. The simulator was actually a supplementary program designed to be used with FORENG 1.0.0, forest engineering software. The software simulated the behaviour of forest fires at different times, spread, direction and angle shown by 3D visualization system. Each of the proposed functions had several variables. So, a combo box was used to provide a realistic and distinct investigation for each of the functions (Fig. 2).

Using a combo box. To investigate the effect of litter type and slope classes on the burned area, some factors such as litter thickness (3–4 cm) and wind velocity (4–8 m·s^{-1}) were considered fixed. Assuming the fire spread time of 30 min, average fire speed (Table 2), rotation of fire (Table 2), mathematical equations (Table 1) and burned area were calculated with changing combo box options (Fig. 2) for litter type, litter thickness and slope class at any given time. When litter thickness and slope classes were considered fixed at 5–6 cm and 15–30%, respectively, wind velocity impacts on the direction of fire spread and fire progression were calculated. Alternatively, when litter thickness was considered as variable, the wind velocity and slope classes were kept fixed at 9–12 m·s^{-1} and 15–30%, respectively. Using a combo box, 256 different probable forms of fire occurrence (4 litter types × 4 slope classes × 4 wind speed classes × 4 litter thicknesses) were considered probable. In many cases, fire behaviour was the same. Accordingly, with repeated testing, the combo box technique showed significant differences between many of the possible cases of surface fire behaviour.

Table 1. Mathematical models for the effects of wind velocity and litter thickness on controlled fire

Wind velocity (m·s^{-1})	Mathematical models	R^2	Litter thickness (cm)	Mathematical models	R^2
1–3	$y = 11.39 \times x^{0.637}$	0.96	1–2	$y = 42.47 \times \ln(x) - 50.64$	0.87
4–8	$y = 12.84 \times x^{0.747}$	0.92	3–4	$y = 86.72 \times \ln(x) - 133.4$	0.78
9–12	$y = 61.04 \times x^{0.614}$	0.99	5–6	$y = 70.54 \times \ln(x) - 106$	0.91
13–16	$y = 26.34 \times x^{1.083}$	0.97	7–8	$y = 31.72 \times \ln(x) - 12.31$	0.82

Table 2. Fire progression angle and mean spread speed of controlled surface fire in different litter types

Litter type	Average speed (m·h^{-1})	Rotation (degree)	
		minimum	maximum
Maple	59.7	10	45
Beech	51.83	25	55
Hornbeam	47.5	25	60
Persian ironwood	57	55	85

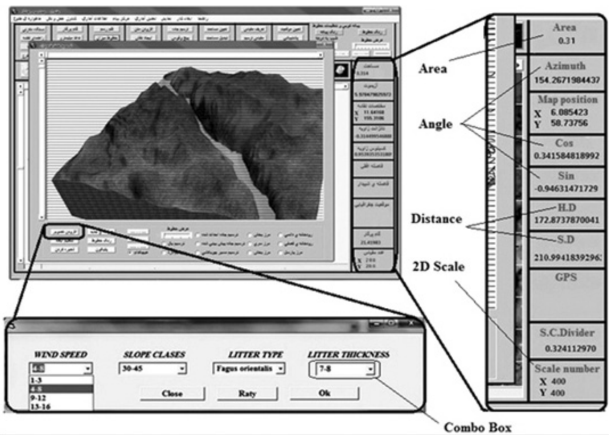

Fig. 2. Simulator software (FORENG 1.0.0) of surface fire

Data analysis. Completely Randomized Block (CRB) Design was used for the analysis of the experiments in this study and the data were analyzed using SPSS (Sciences Statistical Package for the Social, IBM, New York, USA) computer program. The effects of litter type and slope classes on burned areas were investigated using univariate linear regression along with Tukey's HSD mean comparison test. In order to examine the effect of wind speed and litter thickness on the fire spread angle, multivariate regression analysis was used together with Tukey's HSD mean comparison test.

RESULTS

Surface fire spread

Mathematical models were computer simulated to determine the size of burned area during a 30 min period at a fixed topographic condition. Results indicated that the maximum burned area was associated with beech litter (Fig. 3). The type of fire spread in beech and Persian ironwood was approximately the same (Fig. 3e–h and Fig. 4a–d). Surface fire on the forest floor with beech litter remained steady after spreading for a short period of time, whereas under Persian ironwood litter the fire spread continuously. Fire spread in the case of maple (Fig. 3a–d) and hornbeam (Fig. 4e–h) litters was linear and perpendicular to the contour lines, respectively.

Surface fire behaviour

Maple litter

As for the forest floor with maple litter, the results indicated that a small change occurred in the spread angle. Initially, the forest fire was spreading slowly in an upward direction with 10–25 degree angle. However, later the spread angle of the fire and wind velocity were increased. As a result, the fire moved in the upward direction of the slope. When the surface fire was simulated on maple litter, the fire seemed to spread easily around the trees. The angle of fire spread changed as the litter thickness changed. The minimum and maximum angles of fire spread were observed in litter thicknesses of 7–8 cm and 3–4 cm, respectively (Fig. 5).

Beech litter

In the case of the forest floor with beech litter, the fire spread upward at an angle of 45 degrees. The spread angle increased to 55 degrees outward with increasing wind speed. A small change in fire spread was observed with beech litter forest floor and the spread was apple-shaped. Also, the fire spread angle changed as the litter thickness

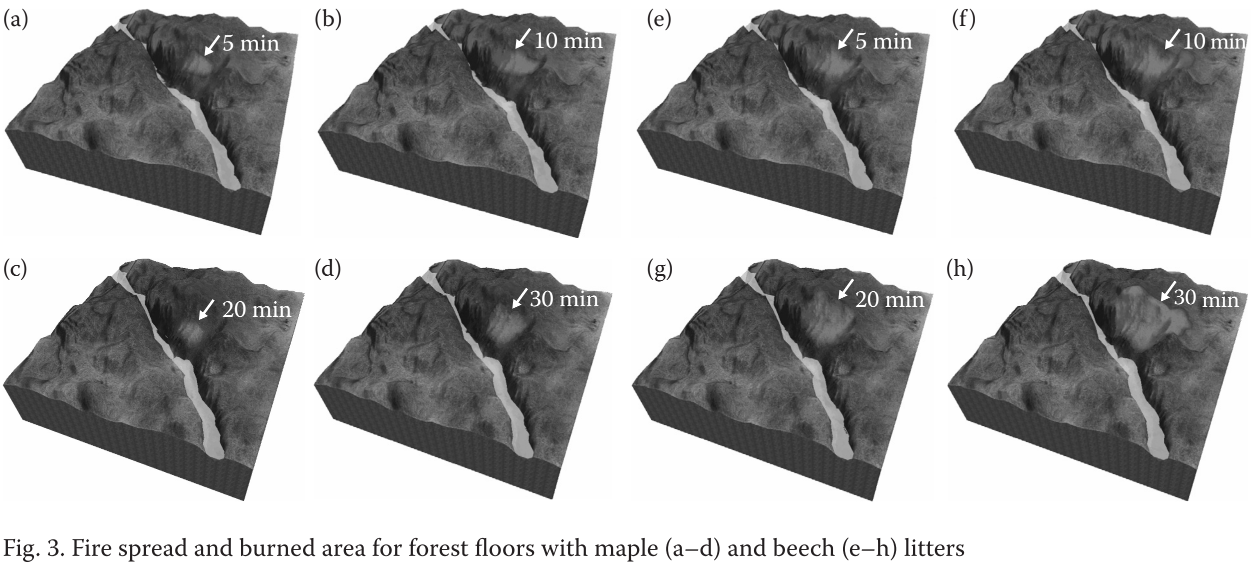

Fig. 3. Fire spread and burned area for forest floors with maple (a–d) and beech (e–h) litters

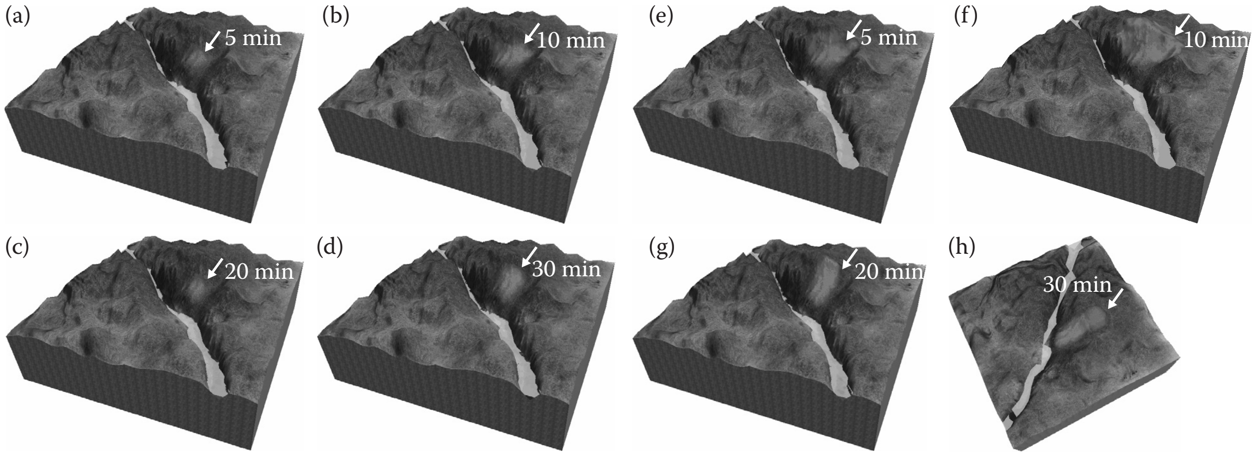

Fig. 4. Fire spread and burned area for forest floors with Persian ironwood (a–d) and hornbeam (e–h) litters

changed. When the litter thickness increases from 1–2 cm to 3–4 cm, the spread angle of fire was lowered by 20 degrees (Fig. 5).

Persian ironwood

For the forest floor with Persian ironwood, the spread angle of fire changed suddenly from 25 degrees to 60 degrees outward with increasing wind velocity. Moreover, in this case the fire spread around the trunks of the trees somewhat easily and the angle of fire spread changed slowly from 30 to 45 degrees with decreasing litter thickness (Fig. 6).

Hornbeam

As for the forest floor with hornbeam litter, the results showed that a small change occurred in the fire

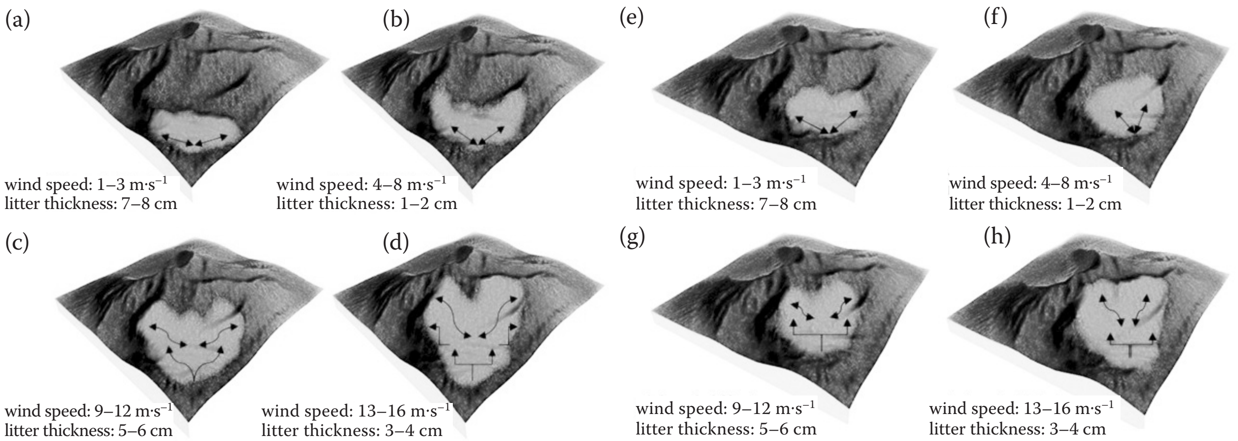

Fig. 5. Surface fire behaviour for maple (a–d), beech (e–h) litter

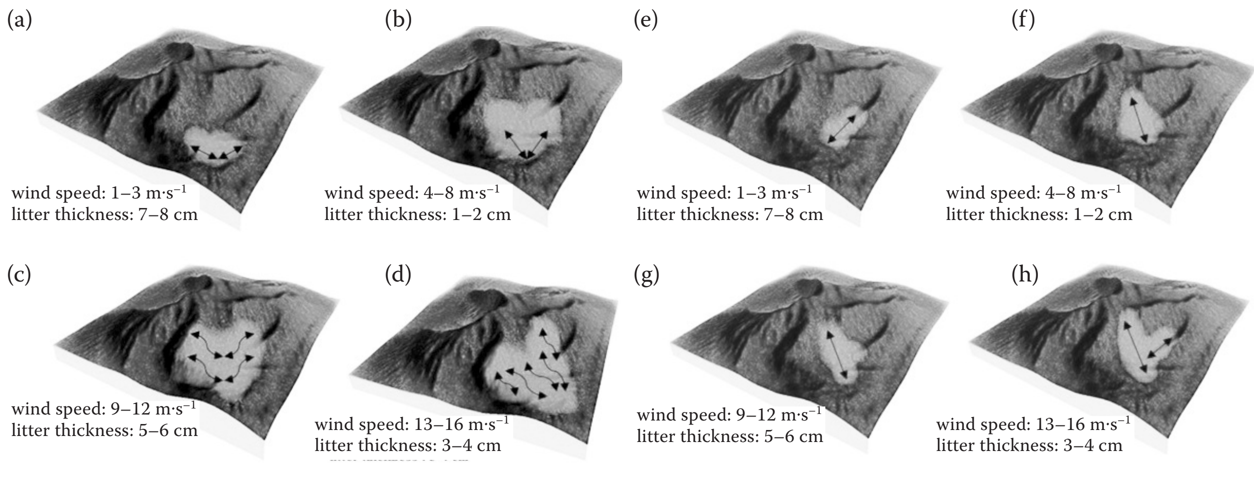

Fig. 6. Surface fire behaviour for Persian ironwood (a–d), hornbeam (e–h) litter

Table 3. Numerical results of burned area with different forest floor litter types and slope classes (fixed parameter: litter thickness = 3–4 cm, wind velocity = 4–8 $m \cdot s^{-1}$)

Slope (%)	Litter type of burned area (ha)			
	maple	beech	persian ironwood	hornbeam
0–15	0.3	0.34	0.23	0.08
15–30	0.48	0.54	0.38	0.2
30–45	0.52	0.56	0.46	0.23
45 <	0.9	1.26	0.71	0.44

spread angle. The fire spread upward with 55 to 85 degree outward angle. A small change was observed during the burning of hornbeam litter in the forest floor. In most cases the surface fire was also simulated in a general upward slope direction. Ironically in this case, the fire spread angle did not change as the litter thickness changed (Fig. 5).

Numerical results and statistical analyses

Burned area

There was a significant difference between burned area sites with hornbeam, beech and Persian ironwood litters (Table 4). It was demonstrated that the slope had a significant effect on the surface fire spread. In similar topographic conditions, the burned area increased irregularly with increasing slope gradient (Table 3). The burned areas in slope classes of 15–30% and greater than 45% increased two and four times, respectively compared to those in the slope class of 0–15% (Table 3). The burned areas associated with the slope class of 15–30% to 30–45% were not significantly different from one another and this was caused by irregularity in the progression of burned area. With the exception of the slope class > 45%, there were no significant differences between burned areas in the remaining slope classes of 0–15%, 15–30% and 30–45% (Table 4).

Fire progression angle

The spread angle of surface fire increased with increasing wind velocity (Table 5). There was no significant difference between Persian ironwood and beech stands in terms of the fire spread angle on their litter under a fixed slope and fixed wind velocity condition (Table 6). Moreover, the statistical analysis showed that there were no significant differences between Persian ironwood, maple and beech stands in terms of their litter thickness effect on the spread angle of surface fire, whereas litter thickness had a significant effect on the spread angle of surface fire in hornbeam stand as compared with the other three species (Tables 5 and 6).

DISCUSSION

Mapping fire risk zones and simulation of surface fire dynamics and fire spread behaviour provides important information for decision-making (Nasiri et al. 2011). In recent years, frequent forest fires with high rates of tree mortality have inflicted extensive damage to Hyrcanian forests of Iran. The new methods of forest fire modelling provide very useful information for improving the forest fire prediction accuracy and fire management planning (Catchpole et al. 1998). Simulation programs are potentially capable of facilitating information about dynamics of forest fire behavioural forecasts that may occur in forest stands. Most of tree species in northern forest regions of Iran are broadleaved deciduous species and the type of fire is usually surface fire (Marvie-Mohadjer 2011). So, the model presented in this study is believed to suit the forest areas with more or less similar vegetation types.

Conversion of the nominal data to numeral data may decrease model accuracy. Besides, there are varieties of models that due to differences in conditions of forests may not exactly be applicable to other forest regions in other counties or even the same country.

Table 4. Statistical test for litter type impact on the burned area

Treatment	Litter type				Slope classes (%)			
	hornbeam	persian ironwood	maple	beech	0–15	15–30	30–45	45 <
Burned area	0.237^{c*}	0.445^{b}	0.55^{ab}	0.672^{a}	0.23^{b*}	0.4^{b}	0.4^{b}	0.827^{a}

a–c mean parameters, *significantly different at 0.05 probability level

Table 5. Numerical results of the fire progression angle at different wind speed, litter thicknesses

Wind speed ($m \cdot s^{-1}$) (fixed parameter: litter thickness = 5–6 cm, slope classes = 15–30%)	Litter type (degree)			
	maple	beech	persian ironwood	hornbeam
1–3	10	35	25	55
4–8	25	45	40	60
9–12	35	50	50	85
13–16	45	55	60	85
Litter thickness (cm) (fixed parameter: slope classes = 15–30%, wind velocity = 9–12 $m \cdot s^{-1}$)	**Litter type (degree)**			
	maple	beech	persian ironwood	horn-beam
1–2	10	25	30	60
3–4	40	45	45	65
5–6	35	45	35	65
7–8	25	30	30	60

Fire behaviour

The shape of leaves had significant effects on the fire spread behaviour. The similarities observed in the surface fire behaviour of beech and Persian ironwood stand on the one hand, and different behaviour observed in the surface fire of maple and hornbeam strands on the other hand may be attributed to the shape and structure of the leaves of these species. The types of leaf litter influence the spread angle of fire, as thinner leaves like those in beech and wide like those in maple facilitated the fire transmission to the adjacent litter by bending and decreasing the spread angle of fire. However, smaller leaves, like those in hornbeam, increased the spread angle of fire due to the lack of rapid transmission of fire to the neighbouring litter (Wotton et al. 1999; Jazirehi 2010). Also, the shape of leaf had a great impact on the fire spread angle. So, hornbeam with tiny and nearly strip-shaped leaves caused the linear fire spread. But the species like maple with wider leaves had a lower fire spread angle.

Table 6. Statistical test for the impact of wind speed and litter thickness on the fire progression angle

Treatment	Litter type			
	hornbeam	ironwood	maple	beech
Wind speed	71.25[a*]	43.75[b]	28.75[c]	46.25[b]
Litter thickness	62.5[b*]	35[a]	27.5[a]	36[a]

*significantly different at 0.05 probability level

Sometimes surface fires are controlled by using non-living or living firebreaks (Jazirehi 2010). The exact location for establishing firebreaks depends on the species itself. For instance, in the case of maple stands with wider leaves and transverse manner of fire spread, the fire break needs to be established in a transverse manner as well.

Burned area

The influence of fuel properties on the fire behaviour and fire regime is a critical research theme in relation to the ecology and management of fire-prone vegetation types. The complementary studies of Ganteaume et al. (2011) contributed to the topic in forests of southeastern France, woodland and shrub-land types, namely in cork oak (*Quercus suber*), mixed oak, pine-oak and Aleppo pine (*Pinus halepensis*) stands. The fire-carrying ability of undisturbed litter was addressed experimentally in controlled conditions to compare flammability, both between vegetation types and past fire frequency.

In this study, the maximum burned area in a given duration was recorded for beech litter type forest floor (Fig. 7a). Leaf thickness and area were the key factors to determine the intensity and duration of litter burning in beech forest floor. Long leaves of broadleaved species were more sensitive to fire than short leaves (Scarff, Westboy 2006). Because of having the leaf areas large enough, maple and Persian ironwood litters allowed to spread fire rather rapidly around their main trunks. The fire spread rate in hornbeam was low. This situation, however, did not occur for beech litter despite the relatively large size of its leaves.

Simulations showed that the burned areas were larger in higher slope classes (Fig. 7b). It was demonstrated that the effect of slope on the spread of low intensity surface fires was more pronounced than for higher intensity surface fires (Swanson 1978). As low intensity surface fires are rather common in Hyrcanian forests of Iran, the slope impact on the spread rate of surface fire has an important applicability in northern forest regions of Iran. The wind velocity had a smaller impact on the rotation angle for surface fires associated with beech and hornbeam litter, whereas the slope gradient had a significant effect on fire spread and rotation. In gentle slopes, the spread speed of surface fire decreased with increasing litter thickness, whereas the speed of fire increased as the

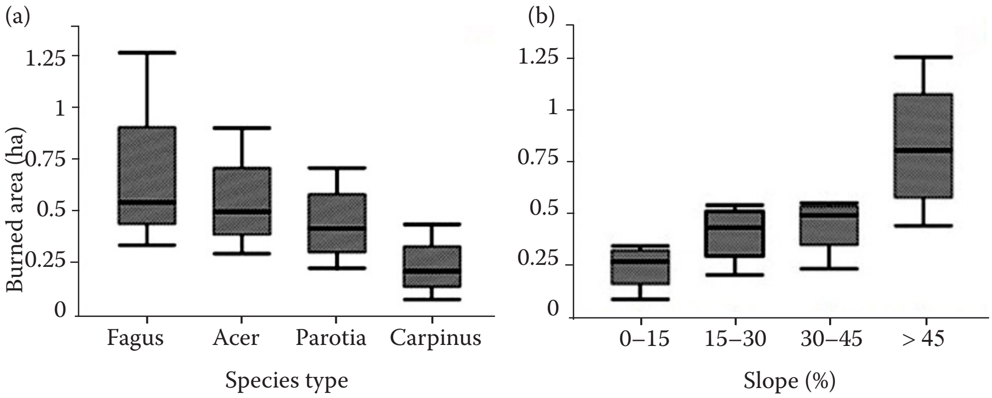

Fig. 7. Comparison of burned areas in different species (a) and slope classes (b)

slope became steeper. In a given slope class, the speed of surface fire initially increased and then it decreased (Nasiri et al. 2012).

Fire progression angle

Wind and slope are commonly known to be major factors affecting the manner in which wildfires progress. Most wildfire behaviour models and fire behaviour prediction systems take into account the wind velocity and slope effects in estimating the rate of fire spread. The US, Canadian and Australian fire behaviour prediction systems are based on semi-empirical or empirical fire models which take into account the combined effects of wind and slope (Pimont et al. 2010).

The progression angle of fire changed with increasing wind speed (Fig. 8a). The fire showed uncommon behaviour when increasing the wind velocity (Morandini et al. 2006). When the wind velocity reached 13–16 m·s^{-1}, the mean fire spread rate changed from 630 m·h^{-1} to 1,832 m·h^{-1} (Nasiri et al. 2012). Under low wind velocity, maple and ironwood litters due to their relatively larger size of leaves allowed fire to revolve easily around the tree trunks. Besides, the revolving rate decreased with increasing wind velocity. Under these conditions the fire was spread in a straightforward manner (Weise, Biging 1996; Boboulos, Purvis 2009).

The role of forest floor litter in relation to surface fire has been studied by many researchers (Bradstock, Cohn 2002; Scarff, Westboy 2006). Several factors such as type of plant debris, moisture and thickness of forest floor litter have an impact on how it is burnt. Morandini et al. (2001) reported that the spread rate of fire will be different in dependence on the composition of organic matter in litter layer.

Contrary to hornbeam where litter thickness had a low effect on the fire spread angle, in the case of maple, litter thickness had a significant impact on the spread angle of fires (Fig. 8b). This may be due to the relatively higher speed of fire spread observed in maple litter as opposed to that in hornbeam (Table 2). The spread rate of fire increased with increasing litter thicknesses up to as much as 4 cm after which it decreased (Nasiri et al. 2012). This would have important implications in the Hyrcanian vegetation zone where the thickness of forest floor litter varies in different seasons (Marvie-Mohadjer 2011). Excessive thickness of litter, however, can prevent oxygen to reach to the bottom layer and it may eventually cause the fire to suffocate (Ormeno et al. 2009; Jazirehi 2010).

CONCLUSIONS

Computer simulation of mathematical models indicated that this approach is useful in prediction of surface fire speed, spread angle and rotation. The results

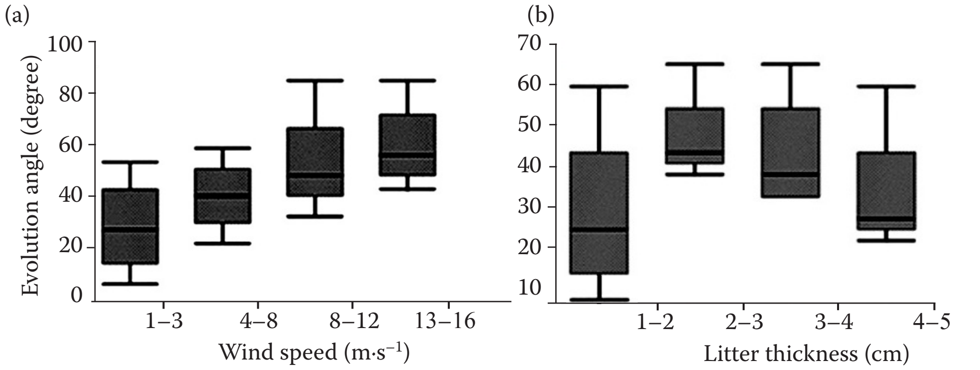

Fig. 8. Comparison of the fire spread progression angle at different wind speed (a) and litter thickness (b)

obtained from a simulation can be used to build a database in which the surface fire could be spread without any attempt to suppress it. These mathematical models may be used to evaluate critical conditions for forest floor fire initiation and spread and thus provide effective means to better understand the behaviour of surface forest fire, which could be helpful in preventing fires in Hyrcanian forests of Iran.

Acknowledgment

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