Carpathian Journal of Earth and Environmental Sciences, August 2015, Vol. 10, No 3, p. 247 - 254

FIRE-RISK EVALUATION OF AUSTRIAN PINE STANDS IN HUNGARY – EFFECTS OF DROUGHT CONDITIONS AND SLOPE ASPECT ON FIRE SPREAD AND FIRE BEHAVIOUR

Péter CSONTOS & Imre CSERESNYÉS

Institute for Soil Sciences and Agricultural Chemistry, Centre for Agricultural Research, Hungarian Academy of Sciences, Herman Ottó. út 15, Budapest, H-1022, Hungary; E-mails: csontos.peter@agrar.mta.hu, cseresnyes.imre@agrar.mta.hu

Abstract: Plantations of the alien *Pinus nigra* are considered among the highly flammable vegetation types in Hungary. The fire risk of such plantations was examined using McArthur's empirical forest fire danger model. Present paper focuses on the effects of drought conditions and terrain inclination on fire behaviour. Fire danger index (FDI) and fire behaviour [flame height, spotting distance and rate of spread (ROS)] were examined by changing the drought factor and terrain inclination within specified intervals meanwhile the other input parameters of the model were kept constant. Results showed that increasing drought factor causes linear growth of the FDI, flame height, spotting distance and ROS. Terrain inclination had no effect on FDI, flame height and spotting distance, but influenced ROS. Upslope fire spread velocity increased exponentially with increase in terrain's inclination, however, downslope ROS was independent of slope angle and was equal to ROS detected on plain ground. Modelling results confirmed a serious fire risk of Austrian pine plantations. The results provided by the McArthur model were in good agreement with that of other fire models and also corresponded to the results of artificial needle litter burning experiments. Therefore, McArthur's model was recommended for studying wildfires in European pine forests.

Keywords: drought factor, fire danger index, flame height, McArthur's model, *Pinus nigra*, rate of spread, slope aspect, spotting distance

1. INTRODUCTION

Austrian pine (*Pinus nigra* Arn.), a native to the Mediterranean and the Balkans, was repeatedly planted in Hungary during the last 150 years. Today its stands extend to 63000 ha throughout the country. At the beginning of Austrian pine introduction the main goals were to prevent soil erosion on overgrazed slopes of hilly regions of the country and to stabilize quick sand dunes on the plains. The wood production of these plantations raised importance later (Tamás, 2003). In the latest decades Austrian pine was also used for recultivation of abandoned open air mines (Cseresnyés et al., 2014).

Recently, Austrian pine plantations received strong criticism from the side of nature conservation, because these stands seriously impoverished the formerly existing species rich, high diversity grassland vegetation on which they were planted to (Csontos et al., 1996).

However, the most pronounced objection against pine plantations is rooted in their flammability that involves not only nature conservation problems but also economic harms. In several countries, pine forest fires showed increasing frequency during the last 30 years (Viegas et al., 1999, Niklasson & Granström, 2000, Zumbrunnen et al., 2011, Ganteaume et al., 2013), and the same tendency appeared in Hungary (Ghimessy, 1991, Zambó, 1995). In the background three major reasons can be mentioned.

First, the high resin content of Austrian pine and the low decomposition rate of its needle litter make its stands flammable (Küçük et al., 2007), since fire risk and fire behaviour are strongly related to the amount and physico-chemical properties of the accumulated fuel (Viegas, 1998, Ganteaume et al., 2011, Alvarez et al., 2012). *Pinus nigra* plantations in Hungary are monocultures and have almost completely closed canopy, resulting in a higher rate of litter accumulation (Cseresnyés et al., 2006, Csontos et al., 2007), than observed in its native stands where Austrian pine grows in mixture of broadleaved trees and forms a less closed tree layer (Horvat et al., 1974).

Second, the ever increasing number and activity of human population also facilitate fire ignition. Millán et al., (1998) and Zumbrunnen et al., (2011) reported that a considerable percent of wildfires can be linked with direct or indirect human activities.

Third, the recent trend of global warming increases the frequency and total length of extreme dry meteorological conditions that makes *P. nigra* stands vulnerable to fire (Hufnagel & Garamvölgyi, 2014). Therefore, investigations on the relationship between recent climatic conditions and fire risk could serve useful information to the discussion on future perspectives of Austrian pine plantations in Hungary and neighbouring territories.

Previously, we reported the effects of temperature and wind speed on the fire risk of Austrian pine plantations using McArthur's forest fire danger model (Cseresnyés et al., 2011). This paper focuses on the effects of drought status and slope conditions on fire ignition and fire behaviour.

2. MATERIALS AND METHODS

Modelling objects were Austrian pine forests planted on dolomite hills of Pilis Mts. and Budai Mts., Hungary (Fig. 1). Data on accurate localities and age of the stands (that ranged from 21 to 108 years) were known from local forest inventories. Each stand was larger (considerably larger in most cases) than 5 ha in area.

The applied modelling tool was originally developed by McArthur, as an empirical forest fire danger model of eucalypt forests, and was later expressed as equations (Noble et al., 1980). Recently, the model is widely used in fire danger forecasting, and forms an important part of the development of fire prevention technologies in Australia (Weber, 2001, Cheney et al., 2012). Pastor et al., (2003) has already proposed the application of McArthur's model for European conifer forests, and our previous study also suggested its efficiency in modelling forest fires of Hungarian pine stands established on dolomite bedrock (Cseresnyés et al., 2011).

The model's input data requirements are: temperature, relative humidity, wind speed, drought factor, terrain's slope angle and amount of fuel, from which it calculates the fire danger index (FDI), the flame height, the spotting distance and the rate of fire spread (ROS; Fig. 2). FDI expresses the risk of fire ignition in numeric form, and has the following verbal categories: low: 0-4, medium: 5-11, high: 12-23, very high: 24-49, extreme: >50.

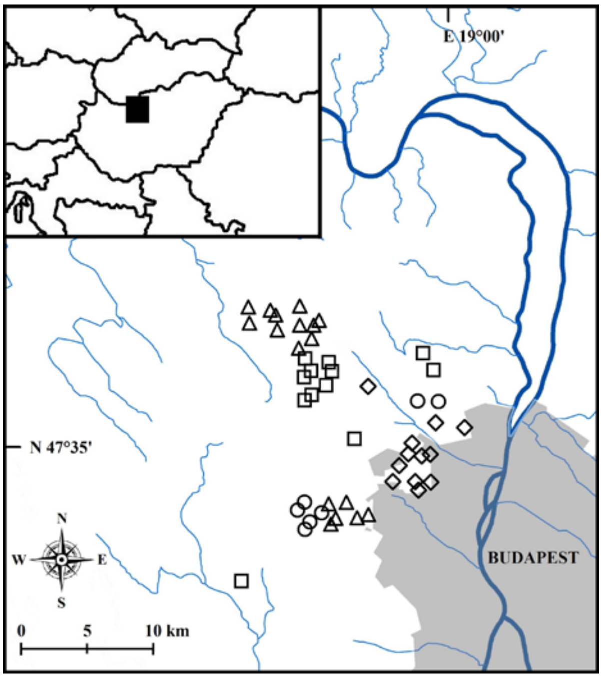

Figure 1. Geographical positions of the studied Austrian pine plantations on dolomite hills of Pilis Mts. and Budai Mts., Hungary. Pictograms indicate age classes as follows: circle= 20-35 years, triangle= 35-60 yrs, square= 60-80 yrs and diamond= 80< yrs.

In the present paper the effects of drought factor and terrain's slope angle was studied. Ordered stepwise changes in the value of drought factor (or slope angle) was applied meanwhile the remaining five input parameters were kept constant, and the resulting four outgrowths of the model were examined. For determining the applied values of the constant input parameters and the ranges of the changing parameters, data were gathered from reports of the Hungarian Meteorological Service and from direct field studies in the Austrian pine plantations of the dolomite region of Pilis Mts. and Budai Mts., Hungary.

The following constant values and intervals of change were used:

1) Temperature: Its fixed value was set at 30°C, because this temperature prevails frequently during the most fire sensitive periods of the year (Mersich et al., 2001).

2) Relative humidity: 30% was applied. Similar or lower air humidity value occurs frequently in Hungary between July and September (Mersich et al., 2001).

3) Wind speed: 30 km/h (grade 5 in Beaufort-Köppen Scale). Such strong wind is frequent in each season of the year, especially on sharp ridges and exposed mountain tops. Steep slopes and sharp ridges are typical of dolomite hills, thus when examining these areas we have to reckon with strong squalls even on relatively calm days.

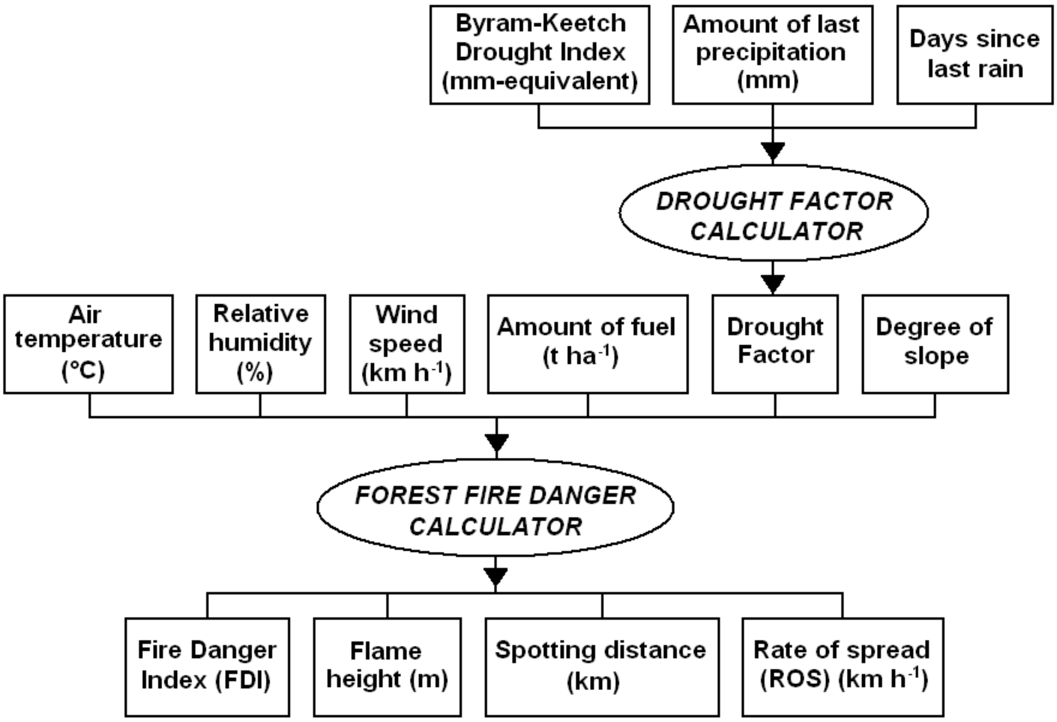

Figure 2. Schematic diagram of the McArthur's Forest Fire Danger model.

4) Amount of fuel: The McArthur's model considers the amount of litter only with diameter less than 6 mm (Noble et al., 1980). This fine fuel fraction responds quickly to changes in weather conditions and it burns out quickly in the fire front thus determining the ROS (Noble et al., 1980, Sağlam et al., 2008). In a previous study we determined the fine fuel fraction in four age classes of Austrian pine stands, that are: 10574 kg ha^{-1} in the age class of 20–35 years, 14024 kg ha^{-1} in the age class of 35–60 years, 18564 kg ha^{-1} in the age class of 60–80 years and 13056 kg ha^{-1} in stands with age above 80 years (Cseresnyés et al., 2006). Although the probability of combustion (namely the FDI) is independent of the amount of fuel, higher amounts of litter mass generally increases the flame height, the rate of spread and the spotting distance. Since the amount of fuel reached a maximum mass in the 60–80 years old stands, this age class can be considered the most threatened by forest fires. In the present modelling work the stand age class above 80 years was ignored, firstly because such old monodominant Austrian pine forests are rare. Secondly, according to our former statistical analysis, the amount of accumulated fuel in this age class corresponds essentially to fuel mass in the stand age of 35–60 years (Cseresnyés et al., 2006).

5) Drought factor: Its value is an integer number between 0 and 10, and it indicates the dryness of upper soil layer including litter and dead part of standing vegetation. Drought factor calculation requires the actual value of *Byram–Keetch Drought Index* (BKDI), amount of the last precipitation event and the number of days elapsed since that event (see Keetch & Byram, 1968 for details). In the Temperate climate zone, both BKDI and drought factor follows characteristic changes within a year, what is more pronounced when data of several years are averaged (Fig. 3). For the studied region of Hungary, seasonal changes of the drought factor was already reported, based on data from 1985 to 2009 (Cseresnyés et al., 2011). In the light of the 25 years average, August and September were characterized by the highest drought factor (around 7), but in the individual years drought factor often reached the maximum for certain periods. In the driest year (2000), the total length of drought factor 10 period lasted for 99 days (Cseresnyés et al., 2011). Therefore, when it was a constant input parameter (and degree of slope was the changing one) we fixed the drought factor at the highest value (=10). Using drought factor as the changing parameter its whole range was investigated.

6) Degree of slope: As a fixed parameter, its value was set to 30° as being a frequently occurring slope angle in the dolomite region of both the Pilis Mts. and the Budai Mts. Degree of slope was altered gradually from –30° (fire spreads downhill) to +30° (fire spreads uphill). Dolomite areas are abounding in steep slopes, therefore this topographical effect contributes significantly to fire-risk conditions. Besides enhancing the flame height, increasing degree of slope is also often a driving factor for crown fire initiations (Santoni & Balbi, 1998).

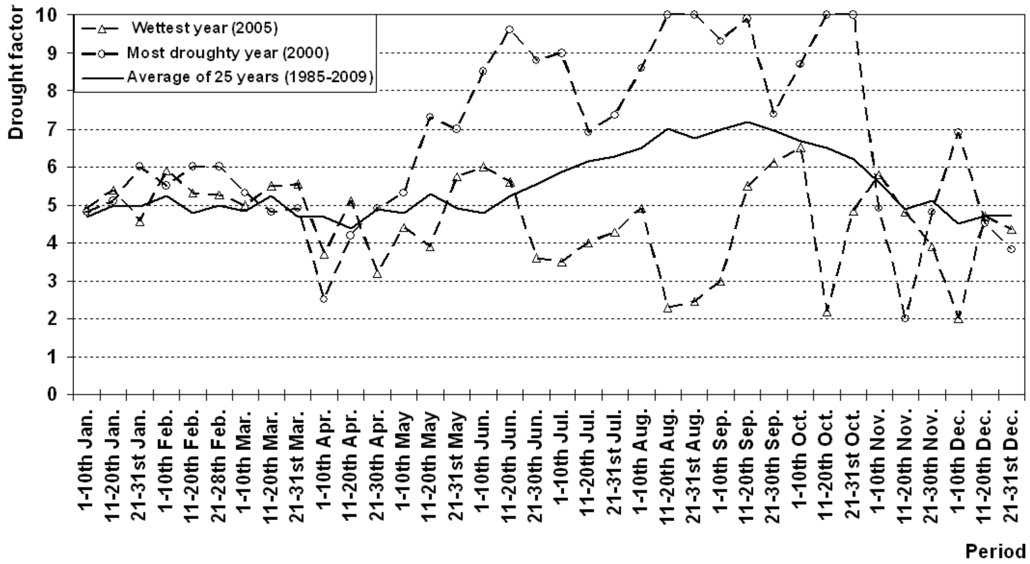

Figure 3. Annual changes of the mean value of drought factor as the average of years between 1985 and 2009, as well as in the wettest year (2005) and in the most droughty year (2000) of that period.

3. RESULTS

Modelling runs showed clearly the considerable influence of the drought factor on fire initiation and fire behaviour. Fire ignition probability (FDI) is independent of the mass of fuel, therefore, stand age effect cannot be studied in this respect (Figs 4a, b).

Fire danger index increased linearly to the increasing drought (Fig. 4a). Under the given constant parameters, medium level fire danger (FDI=5) was achieved at drought factor 2, and high fire danger (FDI=12) appeared at drought factor 5. At drought factor 7 – a level of aridity often prevails during summer season in Hungary (see Fig. 2) – FDI can be as high as 17, and under severe drought (with drought factor=10) we have to face a very high risk of fire (FDI=24). FDI proved to be independent of slope angle (Fig. 4b). At changing slope angle the model predicts very high fire dander (FDI=24) under the inputted meteorological conditions together with the drough factor kept constant at value 10.

Expected flame height increased linearly with the drought factor (Fig. 4c). Since fire does not occour at zero drought factor (FDI=0), therefore flame height (as well as spotting distance and ROS) can only be modelled between drought factor 1 and 10. Flame height is increased by the available quantity of fuel, consequently the shortest flame height was predicted for the age class 20–35 years and the highest was calculated for the age class 60–80 years. On an average summer day (with drought factor 7), expected flame heights are 3.38 m, 5.12 m and 7.44 m for pine stands aged 20–35 years, 35–60 years and 60–80 years, respectively. In case of severe drought (when drought factor 10 prevails), the predicted flame heights were 4.57 m, 6.70 m and 9.54 m in order with increasing stand age classes. Flame height proved to be independent of slope angle expressing the same values at any inclination, but depending on the available fuel (Fig. 4d).

Spotting distance behaves similar to flame height in the sense that it depends from fire intensity, so thus its value was increased by both the increasing drought and the increasing amount of fuel (Fig. 4e). It is notable that a critical level of fire intensity is required to initiate fire's spotting activity, therefore, this outbreak point differed among age classes. Under the adjusted meteorological conditions the model predicted the outbreak of fire spotting at drought factor 4 for 20–35 years old stands, at drought factor 3 for 35–60 years old stands and already at drought factor 2 for 60–80 years old stands, where the highest amount of fuel accumulated. At drought factor 7 (on an average summer day), spotting distance was predicted as 0.47 km, 0.71 km and 1.00 km for 20–35, 35–60 and 60–80 years old pine stands, respectively, whereas under severe drought (at drought factor 10) 0.83 km, 1.16 km and 1.58 km of spotting distances were calculated for the same order of stand age classes. Similarly to flame height, spotting distance was not affected by the terrain's slope angle but depended on the available fuel, thus on the stand age (Fig. 4f). Similarly to flame height, spotting distance was also independent of the terrain's slope angle (Fig. 4f), and its predicted constant values were 0.83 km, 1.16 km and 1.58 km for the stand age classes 20–35 years, 35–60 years and 60–80 years, respectively (under the circumstances of input data, as described in the methods section).

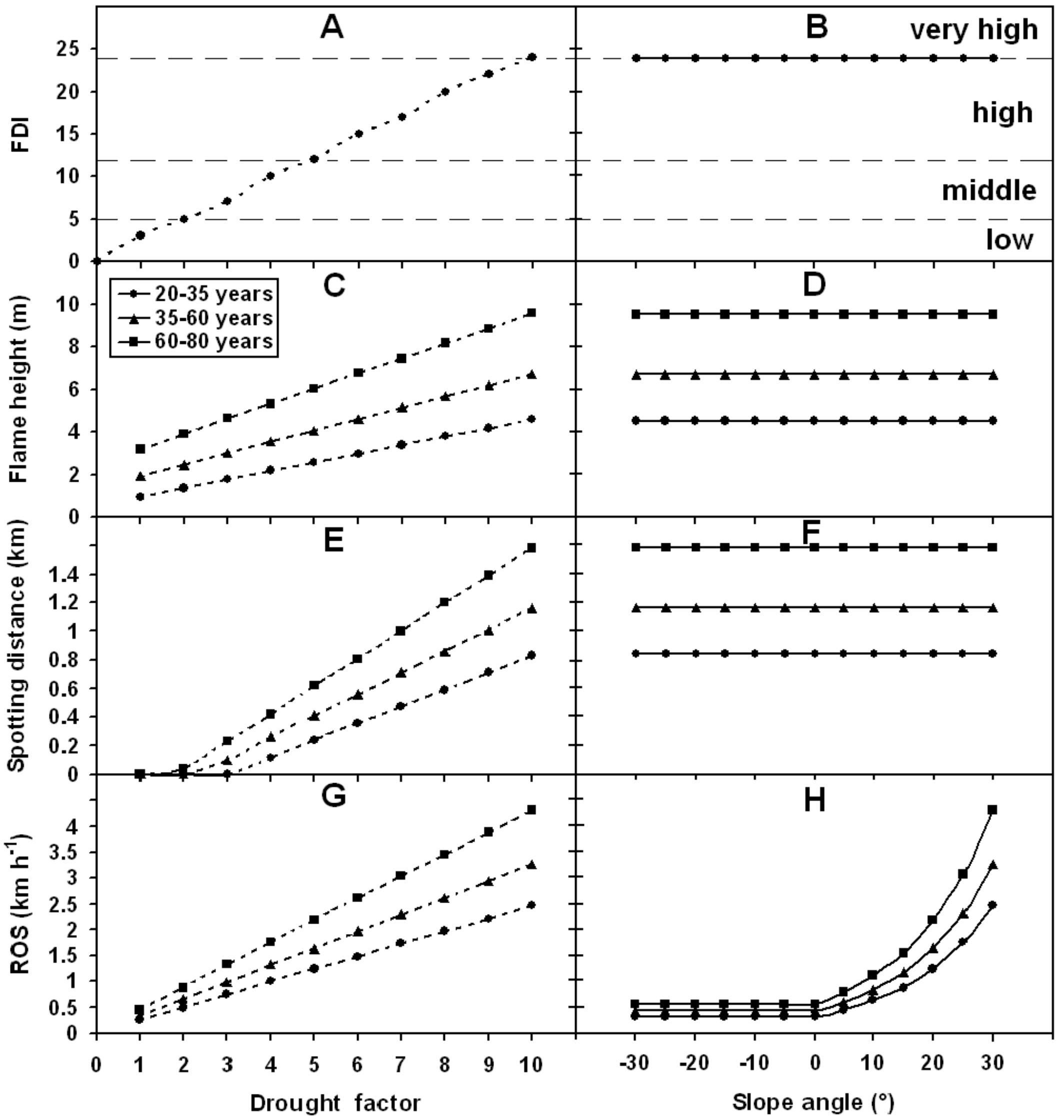

Figure 4. Changes of the Fire Danger Index (FDI), flame height, spotting distance and rate of fire spread (ROS) with the drought factor and slope angle in *Pinus nigra* stands. (Since the FDI is independent of the amount of fuel, age classes are not distinguished in Fig. 4a and 4b.)

Rate of fire spread (ROS) showed linear increase with increasing drought factor, and its actual values as well as the slopes of the lines were influenced by the available fuel, too (Fig. 4g). At drought factor 7, ROS was 1.73 km/h, 2.29 km/h and 3.04 km/h for pine stands belonging to age classes 20–35 years, 35–60 years and 60–80 years, respectively. The rate of fire spread in the three age classes increased to 2.46 km/h, 3.26 km/h and 4.32 km/h, respectively, when the drought factor's value was increased to 10. ROS was also influenced by terrain inclination (Fig. 4h). On plain ground, ROS of 0.31 km/h was predicted in 20–35 years old stands, what increased to 0.41 km/h in 35–60 years old stands, and we can expect 0.54 km/h in pine stands with age between 60 and 80 years. When fire spreads downhill (indicated by negative angles of slope on the graph), ROS was independent of slope angle, and its actual value was equal to that predicted for plain ground in the corresponding stand age classes. In case of uphill fire spread, the ROS increased exponentially with the slope angle. Compared to the plain ground rate, speed of fire spread was doubled at slope 10°, four-fold higher at slope 20° and eight-times faster spread occurred at slope 30°.

4. DISCUSSION

According to McArthur's model, an increase in drought factor increases the fire danger index, the flame height, the spotting distance and also the rate of spread. Earlier studies revealed that in years with usual pattern of precipitation, drought factor's value around 7 is typical for the late summer – early autumn season, what is the period of year with the highest risk of forest fires in Hungary (Cseresnyés et al., 2011). In the same season of the year, if a longer period of rainless weather prevails, drought factor can reach value 10, and in this case we can expect "very high" fire danger (FDI=24). At this rate of fire danger predicted flame height is almost 10 m, spotting distance is above 1.5 km and speed of upslope fire spread on a 30° terrain is around 4.3 km/h in the most threatened 60–80 years old pine plantations.

Several studies support interrelationships between drought conditions and wildfire risk. In the Mediterranean, direct relationships were found between rain deficit of summer months and the wildfire events: in years drier than the average, size and frequency of wildfires were above the average (Viegas et al., 1990, Alvarez et al., 2012). Viegas et al., (1992) also reported that number of wildfires and size of area burnt increased exponentially with the decrease of litter humidity. Large forest fires are linked with litter humudity of 10% or below, whereas at litter humidity of 20–30% forest fires occur with considerably lower frequency and also the size of area burnt become one order of magnitude smaller. Around litter humidity of 35–40% fires usually stop spreading, then the fire is extinguished (Viegas, 1998). One of the physical principles of wildfire spread is that the heat produced by the fire is transmitted (mainly by radiation and convection) to the intact litter lying in front of the fire, evaporates its water content and increases its temperature up to the ignition temperature (what is about 300 °C for needle litter) (Rothermel, 1972). If weather conditions reduce the humidity of the intact litter, fewer energy is needed to make the litter dry, and it also fasten the heating up procees of the litter to the ignition temperature. Therefore, fire intensity increases together with the related attributes like flame height and spotting distance. Linear decrease of the ROS with increase of litter humidity was also demonstrated in needle litter burning experiments under controlled circumstances (Viegas & Neto, 1991). Litter humidity was reported as the second most important factor (after wind speed) in determining the ROS when needle litter of *Pinus nigra* was experimentally burnt (Bilgili & Sağlam, 2003, Küçük et al., 2008).

According to the McArthur's model, slope angle has considerable influence on the rate of fire spread, but has no effects on the flame height and the spotting distance. For upslope fire spread, the model predicts exponential increase in speed with increasing slope angle of the terrain, however, downslope fire spread rate proved to be independent of the terrain inclination and was equal to the ROS predicted for level ground (Cheney et al., 2012). Similar effects of slope angle were considered in some further fire danger models – including the widely used Rothermel's model – and results of burning experiments under controlled circumstances confirmed that (Rothermel, 1972, Viegas & Neto, 1991, Viegas, 1998). During upslope fire spread, flame is tilted forward and its angle to the unburned fuel decreases. As a result, the radiative heat transfer increases towards the unburned fuel located ahead of the flame front, thus the fire spread accelerated (Rothermel, 1972, Morandini et al., 2001, Simeoni et al., 2001). The relationship between terrain inclination and upslope fire spread in equation form is $V= V_0(1 + \varphi_s)$ where V_0 is the fire velocity measured on plain ground, and φ_s is a slope-depending coefficient. Santoni & Balbi (1998) and Boboulos & Purvis (2009) experimentally determined the φ_s (using Mediterranean pine needles) and the values showed a fairly good agreement with that of predicted by the McArthur model. According to our results, upslope fire velocity on a 30° inclined terrain is eight times faster than fire velocity on plain ground. Results of needle litter prescribed burning experiments indicated 5–8 times higher ROS on slopes around 30° inclination under both laboratory and field conditions (Viegas et al., 1994, Santoni & Balbi, 1998, Gonzalez et al., 2008), although in some cases 8–10 times increase in velocity were detected depending on the experimental circumstances (mainly the bulk density and humidity of the litter) (Morandini et al., 2001).

There are rather few opportunities to compare fire spread data produced by the McArthur model with that of published in the literature, mainly because literature sources contain incomplete lists of the input parameters required by the model. For example, Santoni & Balbi (1998) and Morandini et al., (2001) reported ROS between 0.16 and 0.30 km/h in their *Pinus* needle litter burning experiments, in which the completely dried needle litter – that represented a 4000 kg/ha fuel density – was lit under circumstances of 20°C air temperature and 30° terrain inclination in the absence of wind. In a similar artificial litter burning experiment, detected ROS was around 0.17–0.27 km/h when needle litter amount and wind speed were raised to 12000 kg/ha and 11 km/h, respectively, but terrain inclination was reduced to 10° (Morandini et al., 2001). Unfortunately, relative air humidity was not reported in these cases. However, if input data sets from the two papers mentioned above were improved with relative air humidity values between 30% and 70% (what is the range of the most probably prevailing humidity for the studied region), the ROS predicted by the McArthur model proved to be practically the same as were observed in the burning experiments.

Based on results published in the literature, the McArthur model predicts the relationship between fire danger risk and drought conditions or terrain inclination very similarly to that of other models, and its results also in accordance with that of reported about needle litter burning experiments, carried out either in laboratory or field conditions. In our earlier studies, similar agreement was found between McArthur's model and other fire risk models when predictions for the effects of temperature and wind speed on the fire danger probabilities were analysed (Cseresnyés et al., 2011). From these findings, the McArthur model seems to be suitable for studying the fire risk and fire behaviour of European pine forests, but further testing of its applicability is recommended under various habitat conditions.

5. CONCLUSIONS

Results showed that increasing drought factor causes linear growth of the fire danger index, flame height, spotting distance and rate of fire spread. Terrain inclination had no effect on FDI, flame height and spotting distance, but influenced ROS. Upslope fire spread velocity increased exponentially with increase in terrain's inclination, however, downslope ROS was independent of slope angle and was equal to ROS detected on plain ground. Modelling results confirmed a serious fire risk of Austrian pine plantations, reaching the highest fire sensitivity in the 60-80 years old stands. The results provided by the McArthur model were in good agreement with that of other fire models and also corresponded to the results of artificial needle litter burning experiments. Although, there are some sophisticated fire models which might outperform McArthur's model in terms of accuracy, but the usability easiness of the latter offers satisfactory compensation for that. Therefore, McArthur's model was recommended for studying wildfires in European pine forests.

Acknowledgements

We are grateful to the reviewers' for their comments on the first version of the manuscript. Our study was partly supported by the Hungarian National Scientific Research Found (OTKA-T037732).

REFERENCES

Alvarez, A., Gracia, M., Vayreda, J. & Retana, J., 2012. *Patterns of fuel types and crown fire potential in Pinus halepensis forests in the Western Mediterranean Basin*. Forest Ecology and Management, 270, 282-290.

Bilgili, E. & Sağlam, B., 2003. *Fire behaviour in maquis fuels in Turkey*. Forest Ecology and Management, 184, 201-207.

Boboulos, M. & Purvis, M. R. I., 2009. *Wind and slope effects on ROS during the fire propagation in East-Mediterranean pine forest litter*. Fire Safety Journal, 44, 764-769.

Cheney, N. P., Gould, J. S., McCaw, W. L. & Anderson, W. L., 2012. *Predicting fire behaviour in dry eucalypt forest in southern Australia*. Forest Ecology and Management, 280, 120-131.

Cseresnyés, I., Csontos, P. & Bózsing, E., 2006. *Stand age influence on litter mass of Pinus nigra plantations on dolomite hills in Hungary*. Canadian Journal of Botany, 84, 363-370.

Cseresnyés, I., Szécsy, O. & Csontos, P., 2011. *Fire-risk of Austrian pine (Pinus nigra) plantations under various temperature and wind conditions*. Acta Botanica Croatica, 70, 157-166.

Cseresnyés, I., Cseresnyés-Bózsing, E., Tamás, J., Barina, Z. & Csontos, P. 2014. *Effect of Austrian pine on naturalness and succession of vegetation in reclaimed bauxite quarries*. Applied Ecology and Environmental Research, 12, 931-946.

Csontos, P., Horánszky, A., Kalapos, T. & Lőkös, L., 1996. *Seed bank of Pinus nigra plantations in dolomite rock grassland habitats, and its implications for restoring grassland vegetation*. Annales Historico-naturales Musei Nationalis Hungarici, 88, 69-77.

Csontos, P., Rocchini, D. & Bacaro, G., 2007. *Modelling factors affecting litter mass components of pine stands*. Community Ecology, 8, 247-255.

Ganteaume, A., Jappiot, M., Lampin-Maillet, C., Curt, T. & Borgniet, L., 2011. *Effects of vegetation type and fire regime on flammability of undisturbed litter in Southeastern France*. Forest Ecology and Management, 261, 2223-2231.

Ganteaume, A., Camia, A., Jappiot, M., San-Miguel-Ayanz, J., Long-Fournel, M. & Lampin, C., 2013. *A review of the main driving factors of forest fire ignition over Europe.* Environmental Management, 51, 651-662.

Ghimessy, L., 1991. *Forest fires in 1990 (In Hungarian).* Erdészeti Lapok, 126, 140-142.

Gonzalez, J. R., del Barrio, G. & Duguy, B., 2008. *Assessing functional landscape connectivity for disturbance propagation on regional scales. A cost-surface model approach applied to surface fire spread.* Ecological Modelling, 211, 121-141.

Horvat, I., Glavač, V., & Ellenberg, H., 1974. *Vegetation Südosteuropas*. Gustav Fischer Verlag, Stuttgart.

Hufnagel, L. & Garamvölgyi, Á., 2014. *Impacts of climate change on vegetation distribution No. 2 – Climate change induced vegetation shifts in the new world.* Applied Ecology and Environmental Research, 12, 355-422.

Keetch, J. J. & Byram, G. M., 1968. *A drought index for forest fire control*. USDA Forest Service Research

Paper SE-38. USDA Southeastern Forest Experiment Station, Asheville, NC.

Küçük, Ö., Bilgili, E. & Baysal, I., 2007. *Fire development from a point source in surface fuels of a mature Anatolian black pine stand*. Turkish Journal of Agriculture and Forestry, 31, 263-273.

Küçük, Ö., Bilgili, E., Sağlam, B., Başkaya, S. & Dinç Durmaz, B., 2008. *Some parameters affecting fire behavior in Anatolian black pine slash*. Turkish Journal of Agriculture and Forestry, 32, 121-129.

Mersich, I., Práger, T., Ambrózy, P., Hunkár, M. & Dunkel, Z., 2001 (eds.). *Climatic atlas of Hungary (In Hungarian)*. Nemzeti Tankönyvkiadó, Budapest.

Millán, M. M., Estrela, M. J. & Badenas, C., 1998. *Synoptic analysis of meteorological processes relevant to forest fire dynamics on the Spanish mediterranean coast*. In: Moreno, J. M. (ed.), Large forest fires, 1-30. Backhuys Publishers, Leiden.

Morandini, F., Santoni, P. A. & Balbi, J. H., 2001. *The contribution of radiant heat transfer to laboratory-scale fire spread under the influences of wind and slope*. Fire Safety Journal, 36, 519-543.

Niklasson, M. & Granström, A., 2000. *Numbers and sizes of fires: long-term spatially explicit fire history in a Swedish boreal landscape*. Ecology, 81, 1484-1499.

Noble, I. R., Bary, G. A. V. & Gill, A. M., 1980. *McArthur's fire-danger meters expressed as equations*. Australian Journal of Ecology, 5, 201-203.

Pastor, E., Zárate, L., Planas, E. & Arnaldos, J., 2003. *Mathematical models and calculation systems for the study of wildland fire behaviour*. Progress in Energy and Combustion Science, 29, 139-153.

Rothermel, R. C., 1972. *A mathematical model for predicting fire spread in wildland fuels*. USDA Forest Service Research Paper INT-115. USDA Intermountain Forest and Range Experiment Station, Ogden, UT.

Sağlam, B., Küçük, Ö., Bilgili, E., Dinç Durmaz, B. & Baysal, B., 2008. *Estimating fuel biomass of some shrub species (maquis) in Turkey*. Turkish Journal of Agriculture and Forestry, 32, 349-356.

Santoni, P. A. & Balbi, J. H., 1998. *Modelling of two-dimensional flame spread across a sloping fuel bed*. Fire Safety Journal, 31, 201-225.

Simeoni, A., Santoni, P. A., Larini, M. & Balbi, J. H., 2001. *On the wind advection influence in the fire spread across a fuel bed: modelling by a semi-physical approach and testing with experiments*. Fire Safety Journal, 36, 491-513.

Tamás, J., 2003. *The history of Austrian pine plantations in Hungary*. Acta Botanica Croatica, 62, 147-158.

Viegas, D. X., 1998. *Weather, fuel status and fire occurrence: predicting large forest fires*. In: Moreno, J. M. (ed.), Large forest fires, 31-48. Backhuys Publishers, Leiden.

Viegas, D. X., Viegas, M. T. P. & Ferreira, A. D., 1990. *Characteristics of some forest fuels and their relation to the occurrence of fires*. Proceedings 1st International Conference on Forest Fire Research, Coimbra, Portugal, 1-13.

Viegas, D. X. & Neto, L. P. C., 1991. *Wall shear-stress as a parameter to correlate the rate of spread of a wind induced forest fire*. International Journal of Wildland Fire, 1, 177-188.

Viegas, D. X., Viegas, M. T. P. & Ferreira, A. D., 1992. *Moisture content of fine forest fuels and fire occurrence in Central Portugal*. International Journal of Wildland Fire, 2, 69-86.

Viegas, D. X., Varela, V. G. M. & Borges, C. P., 1994. *On the evolution of a linear fire front in a slope*. Proceedings 2nd International Conference on Forest Fire Research, Coimbra, Portugal, 301-318.

Viegas, D. X., Bovio, G., Ferreira, A. D., Nosenzo, A. & Sol, B., 1999. *Comparative study of various methods of fire danger evaluation in Southern Europe*. International Journal of Wildland Fire, 9, 235-246.

Weber, R. O., 2001. *Wildland fire spread models*. In: Johnson, E. A., Miyanishi, K. (eds.), Forest fires. Behavior and ecological effects, 151-169. Academic Press, San Diego.

Zambó, P., 1995. *Forest fires in years 1993 and 1994 on the territory of Pilis Forest Inventory, degree of losses and efforts for restoration (In Hungarian)*. Erdészeti Lapok, 130, 152.

Zumbrunnen, T., Pezzatti, G. B., Menéndez, P. & Bugmann, H., 2011. *Weather and human impacts on forest fires: 100 years of fire history in two climatic regions of Switzerland*. Forest Ecology and Management, 261, 2188-2199.

Received at: 21. 01. 2015
Revised at: 04. 06. 2015
Accepted for publication at: 25. 07. 2015
Published online at: 28.07. 2015