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Modeling wind adjustment factor in Mediterranean stands of Southern Europe

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Abstract

Wind speed, that is strongly affected by terrain and vegetation, is one of the most important factors on fire spread. Fire simulators calculate wind speed as open 10-m wind speed multiplied by the wind adjustment factor (WAF). In forested sites, the sub-canopy wind speed plays a keystone role in low intensity fire or prescribed burn, and therefore, in prescribed burn plan. This research aims to estimate a WAF model based on in-stand wind speed at 2-m above ground and forests characteristics. Different sampling sites were established for WAF training and test. WAF range from 0.03 and 0.84, showing significant differences due to stand characteristics. Our findings showed canopy cover as the most influenced variable in WAF. On the one hand, the non-linear WAF model reached a coefficient of determination of 87.4%, including a second variable: the vertical distance between surface vegetation and the canopy base height. This approach proposes a novel method for the identification of WAF for prescribed fire implementation without the source of error could be generated using fixed WAF for each fuel model. The proposed model can be used to simulate different canopy management alternatives both fuel treatments and timber harvesting.

1. Introduction

Wind is affected by terrain, vegetation and the heigh above the ground (Andrews, 2012). The wind adjustment factor (WAF) has been widely used to identify a midflame wind from the 20-ft wind speed (Andrews, 2012). The midflame wind, which is used by several fire simulators, such as Behave Plus and FlamMap, is calculated as the product between 20-ft wind speed ("free wind") and WAF. In the case of Europe, weather station observations at 10-m height, clear ground, are used in opposition to 20-ft height following meteorological standards of the World Meteorological Organization (Brock, 2001). However, WAF depends on the vegetation characteristics and roughness (Mueller et al., 2014). The WAF, which is dimensionless (< 1), is reduced based on forest canopy and roughness (Albini and Baughman, 1979).

WindNinja software models wind speed according to terrain exposure and vegetation type. Other computational fluid dynamics (CFD) approaches, such as FIRETEC (Pimont et al., 2011) and WFDS (Mueller et al., 2014), can modify the wind speed based on fluid physical analysis. Although wind simulation using fluid dynamics is very realistic, a great time is required to run. Some approaches have been developed to simplify WAF calculation and to minimize the running time. Firstly, Deeming et al. (1977) assigned a mean WAF for each fuel model according to free wind at 20-ft height. Albini and Baughman (1979) proposed two mathematical models based on sheltered and unsheltered vegetation from the wind. Subsequently, Baughman and Albini (1980) modified the initial WAF for each fuel. Finney et al. (2011) proposed a WAF based on surface fuel bed depth.

Although wind speed profile is adjusted as a logarithmic function in open areas (Andrews, 2012), a complex wind profile is shown in forested areas due to the vegetation height, canopy cover and plant are density profile (Queck et al., 2010, 2012). Some authors (Gillies et al., 2002) have even proposed differences between species, but they suggested that is not be large enough to have a practical implication. However, a simplified wind profile simulation assumes a constant sub-canopy WAF when canopy gaps and topographical position could increase wind speed due to Venturi effect (Molina et al., 2022). Therefore, WAF could be also affected by wind speed (Moon et al., 2019). All the above antecedents, subcanopy WAF plays a keystone role in surface fire spread in low intensity fires and prescribed fires, but a source of error could be generated using fixed WAFs for each fuel model.

This research aims to propose a mean wind adjustment factor (WAF) at 2-m above ground based on canopy characteristics. We attempt to find the relationship between reference wind (open area) and wind speed at 2-m height with different forests characteristics. In this sense, the identification of canopy characteristics that can affect wind speed and, therefore, fire intensity is essential for improving fire behavior models and prescribed burn plans.

2. Material and methods

2.1. Study area

Different forested sites were selected across southern Spain, covering two administrative regions (Andalusia and Castilla la Mancha) (Figure 1). Forested areas were dominated by *Pinus* species with and without understory. While 53.66% of the sampling sites were sheltered sites, 46.34% of the sampling sites were in unsheltered sites. One hundred meters was established as threshold to compare open wind speed and in-stand wind speed.

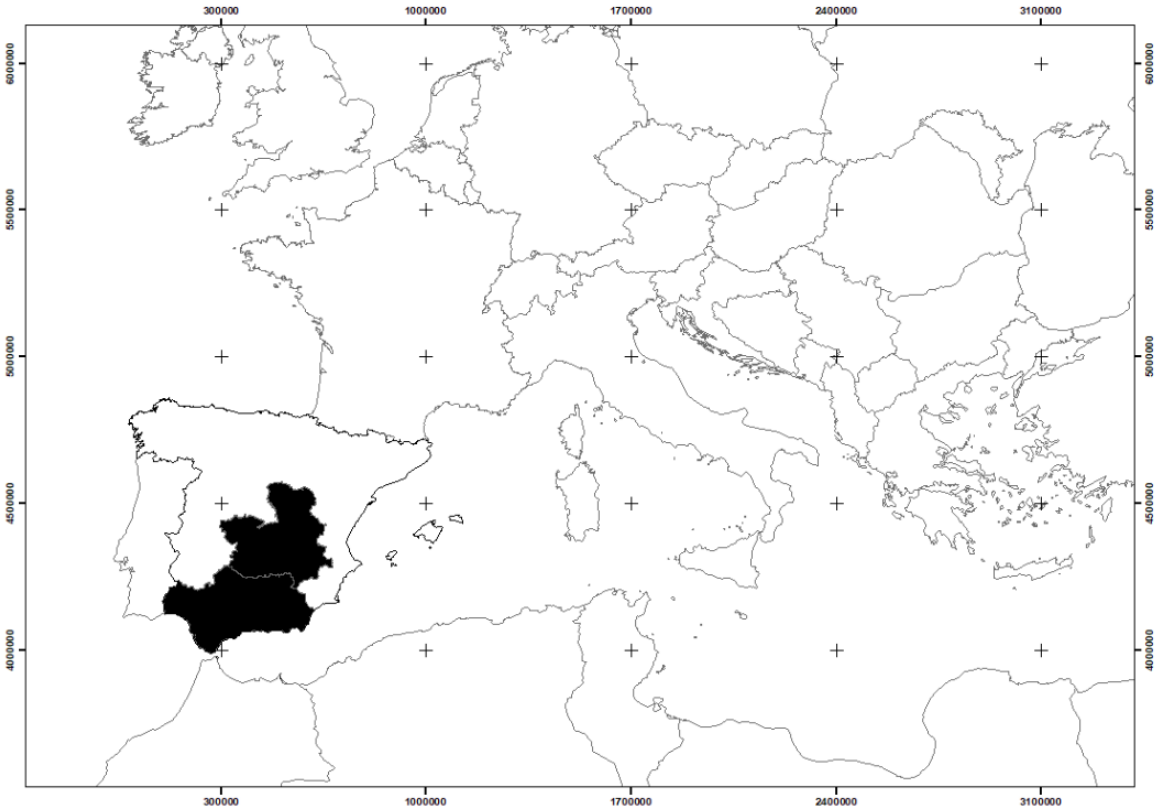

Figure 1- Study area location

Vegetation data was collected using circular plots of 20 m de radius. The vegetation inventory included variables such as stand density, stand height, canopy base height (live branch and dead branch), diameter at breast height, crown diameter and understory height. Basal area was calculated based on diameter at breast height and stand density. Canopy cover was estimated using the sum of tree crown vertical projection divided by the total area. The range of the vegetation characteristics was defined in Table 1.

Table 1. Range of the dependent and independent variables

Variable	Range
Wind adjustment factor	0.03 – 0.89
Wind speed (km/h)	0 – 47.2
Canopy cover (%)	10 – 100
Stand density (trees/ha)	10 – 1,205
Diameter at breast height (cm)	14 – 38.56
Stand height (m)	4.5 – 14.40
Basal area (m^2/ha)	13 – 65.53
Canopy base height (m)	4.5 – 15.3
Canopy dead base height (m)	0.1 – 71.91
Crown length (m)	0.44 – 7.57
Crown ratio	0.44 – 6.00
Undergrowth height (m)	1.10 – 9.01
Vertical distance between surface vegetation and the canopy base height (m)	0 – 7.57
Vertical distance between surface vegetation and the canopy dead base height (m)	0 – 5.63
Topographical stand position (unsheltered and sheltered stand)	1 = stand on flat or near base of mountain 2 = stand on high ridges

2.2. Wind speed measurements

Wind speed measurements were carried out from 2014 to 2020 using a meteorological vehicle and ThiesClima weather stations at open-canopy sites and guyed-mast with SkyWatch weather stations at sub-canopy wind speed (Figure 2). Wind speed was measured at height of 2 and 6 m (sub-canopy sites) and 10 m (reference open sites). Although the weather stations recorded data each ten seconds, the data were analyzed as ten minutes averaging interval to reduce effects of canopy cover. Our research has the limitations of the use of cup anemometer in-stand measures with turbulence patterns.

Figure 2- Weather stations used in this approach

2.3. WAF calculation

Although WAF can be modified by wind speed, this research identified an average WAF for a wide range of wind speed due to the reduced wind speed traditionally used for prescribed burns. WAF is calculated as the ratio between in-stand wind speed at 2-m of height (U_c) and open wind speed at 10 m above ground (U_o) (Equation 1).

$$WAF = U_c / U_o \qquad \text{Equation 1}$$

2.4. Statistical analysis

Some statistical tests were performed using SPSS© software. Multi-linear and non-lineal models were tested to identify the best adjustment for WAF based on forest characteristics. A subsample of 70% of the dataset was used for model training and 30% of the dataset for model test. The coefficient of determination, the mean absolute error (MAE), and the root mean square error (RMSE) were used to select the best model. Finally, a Wilcoxon test was used to identify significant differences in WAF based on canopy cover and unsheltered and sheltered fuels (< or > 50% of canopy cover).

3. Results

The wind adjustment factor (WAF) ranged from 0.01 to 0.84 for the different sampled sites. Canopy cover (CC) was the most related variable for WAF. Although basal area and stand density were the most important variables immediately following CC, they were strongly correlated with CC. The proposed model included two independent variables: canopy cover and the distance between surface vegetation and the canopy dead base height (z) (Table 2). While CC was negatively related to WAF, z was positively related to WAF. The coefficient of determination reached a value of 0.780 with only one variable. RMSE ranged from 1.21 m to 4.94 m and MAE was between 1.39 m and 5.85 m based on the training and test dataset, respectively.

Table 2. WAF model based on vegetation characteristics

Model	Parameter	Estimation	R^2	RMSE	MAE
WAF = a*FCC + EXP (b*CC)	a	2.594	0.780	0.29	0.11
	b	-0.033			

Note: FCC is the canopy cover (%) and CC is the canopy cover (%)

4. Discussion

Drag coefficient depends on wind speed, air density and contact area (Queck et al., 2010). Our findings observed higher WAF with light winds than heavy winds due to higher contact area like other studies (Queck et al., 2012). Considerable heterogeneity was found in vertical wind profiles based on vegetation structure and characteristics (Cassiani et al., 2008). Our findings showed canopy cover as the most influenced variable in WAF, like other approaches (Pimond et al., 2011). While some authors (Mueller et al., 2014) showed WAF range in canopies between 0.15 and 0.37, other studies (Moon et al., 2019) showed a wide WAF variation between open woodlands and dense forests. In our study area, WAF ranged from 0.03 to 0.89, showing differences more than nine times in dense stands than in open woodlands. Pimont et al. (2011) identified significant differences in treated areas with canopy cover lower than 25%, but they did not find significant differences with cover higher than 50%. We found significant differences with canopy cover lower than 30% and higher than 50%. Further studies would focus on the WAF adjustment based on the canopy fuel load.

There was a significant variation in the range of the WAF when they are compared to reference values or fuel model values used by fire simulators. We wonder that the limited sampling could be an issue here as possibly the adjustment could be different in different regions. BehavePlus offers the possibility to consider unsheltered o sheltered fuel models (Andrews, 2012). While fully sheltered WAF from BehavePlus varied from 0.1 (dense stands) to 0.2 (open stands), unsheltered WAF ranged from 0.3 to 0.4 from timber-understory and timber-litter fuel models. The reference WAF for canopy cover higher than 50% is like our WAF for very dense stands (cover higher than 90%) and other values found in literature from sheltered stands (Queck et al., 2012). Finally, although Baughman and Albini (1980) and NWCG (2006) performed significant WAF differences between shade-intolerant and shade-tolerant species, in our study are they were did not found due to the usual presence of Mediterranean mixed stands.

Wind speed at low canopy layer plays a keystone role in prescribed fire implementation. Canopy cover can be estimated by satellite images, hyperspectral images, and LIDAR data to improve economically the cartography required by WAF and fire simulation. With the help of LIDAR data and Geographic Information System, we performed WAF for different prescribed burns based on our test model. WAF variation implies a change in fire behavior, mainly in spread rate, flame length and fire-line intensity. A change in rate of spread and flame length would promote a higher fire-line intensity (Byram, 1959), and therefore, a higher scorch height and damages to trees (Molina et al., 2022). The wind speed modeling is a very complex phenomenon (Moon et al., 2019). Although computational fluid dynamics can precisely model the air flow (Pimont et al., 2011), forest managers demand easy tools for use "in situ" or "on the fireline" for supporting changes in fire-ignition patterns of prescribed burns. The proposed model can be used to simulate different management alternatives and for discerning the most appropriate canopy cover to the achieve the trade-off between canopy fuel load and wind speed.

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