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Influence of changes in meteorological conditions on the moisture content of dead fine fuel in the mixed pine forest

Vplyv zmien meteorologických podmienok na obsah vlhkosti odumretého jemného paliva v zmiešanom borovicovom poraste

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Abstract:

The moisture content of fine fuels is one of the key indicators for assessing the danger of forest fires. It is the most critical factor influencing the ignitability of vegetation and fire behaviour. The aim of this pilot study was to determine the relationship between fine fuel moisture and weather parameters. The dependence was studied using data obtained during a field survey in a mixed pine forest in Slovakia. The Wiltronics fine fuel moisture meter ME2000 was used to determine the moisture content of the fine fuel. Statistical analysis of fine fuel moisture content and weather parameters data was provided. The results of the regression analysis showed that changes in weather parameters had a significant effect on the moisture content of fine fuels. The greatest influence on the moisture content in fine fuels had the combination of weather parameters, namely air temperature, relative air humidity, and wind speed. Here presented results of measurements were performed in the period without precipitation. Those will be supplemented with further measurements in the future and compared with existing data, continue previous measurements. Prediction of fine fuel moisture content through the models developed and presented here is the first step to understand how the fine fuel moisture content values are changing with changing weather conditions. These models should serve to fill the gap in the prediction of daily moisture content in fine fuel for forest areas in Slovakia and to the forest fire danger index itself.

Keywords: *dead fine fuel; forest fire; fuel moisture content; meteorological conditions*

Influence of changes in meteorological conditions on the moisture content of dead fine fuel in the mixed pine forest

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Abstrakt:

Obsah vlhkosti v jemných palivách je jedným z kľúčových ukazovateľov pre posudzovanie nebezpečenstva vzniku lesných požiarov. Je to najkritickejší faktor ovplyvňujúci zapáliteľnosť vegetácie a správania sa požiaru. Cieľom tejto pilotnej štúdie bolo hodnotenie závislosti medzi vlhkosťou jemného paliva a meteorologickými parametrami. Závislosť bola hodnotená prostredníctvom údajov získaných počas terénneho prieskumu v zmiešanom borovicovom poraste na Slovensku. Na stanovenie obsahu vlhkosti v jemnom palive sa použil merač vlhkosti jemného paliva ME2000 od spoločnosti Wiltronics. Bola vypracovaná štatistická analýza obsahu vlhkosti jemného paliva a údajov o parametroch počasia. Výsledky regresnej a korelačnej analýzy ukázali, že zmeny meteorologických parametrov mali významný vplyv na obsah vlhkosti v jemných palivách. Najväčší vplyv na obsah vlhkosti v jemných palivách mala kombinácia meteorologických parametrov, konkrétne teploty vzduchu, relatívnej vlhkosti vzduchu a rýchlosti vetra. Tu uvádzané výsledky meraní boli vykonané v období bez úhrnu zrážok. Tie budú v budúcnosti doplnené o ďalšie merania a v porovnaní s existujúcimi údajmi budú pokračovať v predchádzajúcich meraniach. Predikcia obsahu vlhkosti jemného paliva prostredníctvom tu vyvinutých a prezentovaných modelov je prvým krokom k pochopeniu toho, ako sa hodnoty obsahu vlhkosti jemného paliva menia s meniacimi sa meteorologickými podmienkami. Tieto modely by mali slúžiť na vyplnenie medzery v predikcii denného obsahu vlhkosti v jemnom palive pre lesné oblasti na Slovensku a na samotný index nebezpečenstva lesných požiarov.

Kľúčové slová: *odumreté jemné palivo; lesný požiar; obsah vlhkosti paliva; meteorologické podmienky*

1. Introduction

Forest fires destroy thousands of forests around the world every year with serious consequences for the atmosphere, biodiversity, ground use change and soil degradation [1]. Currently, forest fires are the main environmental threats that affect not only forest ecosystems but also air quality over long distances [2,3]. They are also one of the most important factors threatening the extinction of wild animals and natural vegetation [4]. These uncontrolled fires of forest vegetation, grasslands and crops are becoming a more common global problem in response to ongoing climate change and the geographical development of the population [5]. They are also one of the most studied natural phenomena due to their character and adverse effects [6]. The frequency and intensity of forest fires vary across countries due to climate, vegetation and initiation patterns [7]. However, current fire regimes in many areas are heavily influenced by humans which often increases the number of ignitions and the frequency of fires. Such deviations from natural regimes threaten biodiversity and ecosystem dynamics as well as human life and infrastructure [8].

In general, forest fires require four factors, namely the source of ignition, fire weather (types of weather that create favourable conditions for the start and spread of wildfires), fuel load (sufficient combustible material to sustain combustion), and low fuel moisture [9]. It is the moisture content of fine fuel that is the most important parameter for determining the flammability of fuel and is directly affected by climatic and weather conditions with which it can change rapidly [10]. The moisture content of the fuel represents the amount of water present in the fuel expressed as a percentage of the weight of the dried fuel [11]. In the absence of precipitation, dead fine fuels (less than 0.6 cm in diameter) have a moisture content from 3% up to 35%. This upper limit is known as the fibber saturation point and is the moisture content reached at 100% relative air humidity. However, when exposed to precipitation, water will also be stored in the cell cavities and on the surface of the fuel, where in this case the moisture content of the fuel can reach values of up to 300% [12].

The moisture of small dead branches (fuel with a diameter <25.4 mm), shrub leaves, and litter (referred to as living and dead fine fuel moisture with a particle diameter <6 mm) has a major impact on forest fire behaviour by controlling fuel flammability, spread rate, the intensity of the fire and the amount of consumed fuel [12,13,14,15,16,17,18]. The specific heat capacity of water is approximately 4180 $J \cdot kg^{-1} \cdot K^{-1}$, indicating that a significant amount of energy will be used to raise the water temperature to the boiling point that would otherwise be consumed to raise the fuel temperature to the ignition temperature and to the formation of flammable gases which promote flame combustion [19].

The content of water presented in fine fuels is one of the key indicators for assessing the danger of forest fires. Assessment of the moisture content of the fuel is also an important aspect of fire control procedures such as prescribed fires, where a certain fire behaviour is required in advance [20]. For dead fuels, the dynamics of moisture content is assumed to be dependent mainly on the relative air humidity, air temperature, wind, sunlight and precipitations. These variables have been incorporated into several systems that predict fuel moisture and are also the input for almost all fire models [14,21]. Also, the moisture content of fine fuel is one of the key parameters for determining the so-called fire danger index and for assessing the risk of fire in general and predicting the spread of fire [8,22,23,24]. Fuel moisture is the most critical factor affecting the ignitability of vegetation [25]. According to Flamigan et al. [26], weather is more likely to be the best predictor of regional fire activity for periods longer than a month. Liu et al. [27] found that climate and weather variability affects not only the occurrence and spread of fires but also the severity in different time scales [28]. The climate directly affects the type and amount of vegetation and weather conditions determine the humidity levels present in the air and subsequently the moisture content levels in the fuel [10]. The use of fuel moisture content value estimations derived from meteorological indices is suitable for dead fine fuels because their water content is highly related to weather conditions. However, in living fuels the physiological properties of the species and the adaptation to drought mean a great variety of humidity conditions at the same meteorological inputs [29]. The role of moisture in living fuels is indeed crucial in predicting fire behaviour, as it can prevent or promote the spread of fires [30,31]. Estimation moisture of vegetation is one of the most difficult tasks in assessing the risk of fire because the interactions of water with plants are complex and difficult to generalize [32]. When a dead fine fuel is exposed to an environment of constant temperature and relative air humidity, its moisture content increases or decreases until it eventually reaches a steady moisture content called the equilibrium moisture content, which is a function of the fuel temperature, relative air humidity and fuel type as well as on whether the particle has been adsorbing or desorbing moisture [33].

Boer et al. [34] in their study point out that fire risk assessment systems in forest stands should be based on a reliable prediction of the fuel moisture content of the so-called critical value of fuel moisture. They reached this value based on research carried out in central Portugal in June 2017, where catastrophic forest fires broke out shortly after the fuels reached a critical moisture content. There are currently several ways to predict the moisture content of fine fuel. One method is an equilibrium moisture content, the value of which depends on the relative humidity and temperature of the air to which the fuel is exposed [20,35]. Another method is the method of regression analysis with weather elements (air temperature, relative air humidity) based on repeated measurements of moisture content in the fuel [36,37]. Moisture estimation using remote sensing [36] and process modelling [38] can also be included here. Newer models that apply to different fuel size classes include the model described by Nelson [39], which requires data on solar radiation and precipitation in addition to air temperature and relative air humidity data. The moisture content of the fuel is thus derived from an iterative scheme rather than from a direct evaluation of a specific function. Currently, used tools include the Fosberg Fire Hazard Index which assesses fire hazards based on air temperature, relative air humidity, wind speed and total precipitation. By adjusting this index, Goodrick [40] also seeks to include the effects of drought. Zhu et al. [22] based on experiments achieved a modified model by modifying the Catchpole method to predict the moisture content of fine fuel. They used different values of tree canopy cover to adjust the temperature and relative humidity of the air near the fuel surface as stands with different degrees of canopy transmit different intensities of sunlight. This has a significant effect on the water content of the fuel. For this reason, occurs the water content of the fuel is significantly affected. Therefore, it is essential that models for predicting the water content of fuels also consider this factor.

Despite the fact that the relationships between weather and the moisture content of dead fine fuel have been studied for more than a century, in Slovakia only a few people have dealt with this issue so far, where reliable methods for predicting changes in fuel moisture content have not yet been developed. There is also little information about the moisture dynamics of surface fuel in forests. This poses a serious problem for assessing the risk of forest fires. In their study, Majlingová and Schallerová [23] analysed the relationship between the relative air humidity and moisture content of fine fuel based on the measurement of the litter moisture content directly in the field survey in the Low Tatras Mts. region. They aimed to obtain a conversion index, the value of which would be used to calculate the moisture of the litter based on the actual relative air humidity. The results of the analyses confirmed that it was not possible to determine the conversion factor between the relative air humidity and the litter moisture content, because the input data were very variable. However, the direct measurement of the moisture content of the fuel in large forests with a tendency to fire is extremely difficult, requiring a long time, considerable financial cots and staffing, especially when extensive estimates are needed [41,42].

The aim of this pilot study carried out in Slovakia is to investigate the sensitivity of fine fuel moisture in a mixed stand formed by tree species *Pinus sylvestris* L., *Quercus cerris* L., and *Carpinus betulus* L. to changes in air temperature, relative air humidity and precipitation total.

2. Material and Methods

2.1. Study area description

For the experimental area of the pilot study was selected the territory of the University Forestry Enterprise of the Technical University in Zvolen, Slovakia. As part of the field survey to measure the moisture of fine fuel and meteorological conditions a forest stand with the number 366b was selected, which is displayed in Figure 1.

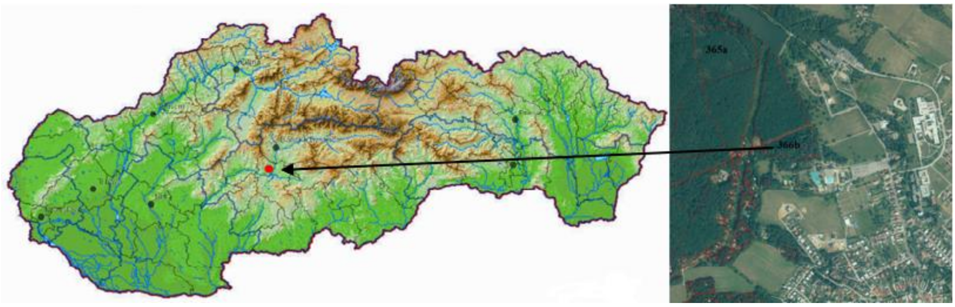

Fig. 1 Location of the study area in Kováčová, Slovakia [43]

The forest area belongs to category B – forests with a medium degree of fire risk. Table 1 shows the basic forest management data for the selected stand.

Tab. 1 Basic data about forest stand [43]

Forest stand	Stand 366b
Wood composition of the forest (%)	*Pinus sylvestris* L. – 90 *Quercus cerris* L. – 3 *Carpinus betulus* L. – 7
Age of stand (years)	135
Age class (years)	81+
Area (ha)	2.17
Density of stocking	0.60
Aspect	E
Slope (%)	10
Altitude (m. a. s. l.)	325 – 360
Fuel model	23

2.2. Fuel Sampling

The measurement of the moisture content of dead fine fuel took place in the summer season from 1.8.2019 to 3.8.2019. We used a ME2000 fine fuel moisture meter (Wiltronics Research Pty. Ltd., Australia) to measure the moisture content of fine fuel. The fine fuel moisture meter is used for fast and accurate determination of the percentage moisture content in leaves, twigs and bark located on the soil surface in the forest as well as the moisture content of living fuel, e.g. bushes. Fuel such as grass, leaves, needles, herbs is called a fine fuel, which is one of the most important factors in determining the intensity of the fire, the speed of the fire front and the probability of spot fires. The principle of measuring the moisture content of the fuel is based on electrical resistance. The moisture meter measures resistance up to 10^{12} ohm, which corresponds to the moisture content in the fuel of at least 2% by weight after it has been dried in the dryer [44].

The fuel was taken during the day from 7:00 a.m. to 6:00 p.m. at hourly intervals. The samples consisted of dead leaves, needles and branches up to 0.5 cm in diameter. Before each measurement, the fuel samples were picked and used in this fresh form for measuring their actual moisture content. While the moisture content of the fine fuel can vary even in a small area of forest, three repeated measurements were made every hour for each type of sample.

2.3. Weather measurements

On days when intensive sampling and measurement took place, we installed a portable professional meteorological station at the sampling site (Oregon Scientific WMR3000, USA). This professional weather station gathers and automatically uploads accurate and detailed weather data for ease of access in tracking long-term weather patterns. Customizable recording interval settings allow users to capture and store information via the data logger at selected intervals for improved usability in research and study. The saved data can be transferred to a computer, where the data can be analysed using the Weather OS PRO control software. The temperature accuracy of the station is ±0.5 °C and the measuring range from -40 °C to 60 °C. The relative air humidity values have an accuracy of ±3%. The device was installed at a height of 1.5 m.

2.4. Statistical analysis

We used a simple linear regression and correlation analysis to evaluate the relationship between dead fine fuels and relative air humidity, air temperature and wind. All analyses were performed using a statistical tool (Statistica 12, StatSoft, CR). In total, we examined the following statistical indicators: arithmetic mean, minimum, maximum, variance, standard deviation, standard error, correlation coefficient and regression coefficient.

3. Results and Discussion

Figures 2 to 4 show the daily course of moisture content in fine fuels (%) and the changing weather conditions: average wind speed ($km \cdot h^{-1}$), air temperature (°C) and relative air humidity (%). No precipitations occurred during the measurement of fine fuel moisture but in the few days before the field survey implementation, there were more intense precipitations, which resulted in higher fuel moisture values on the first day of the measurement, compared to the other days. Air temperature and relative air humidity show typical trends during the day, i.e. the relative air humidity decreases with increasing air temperature. The lowest relative air humidity was reached between 12 a.m. and 4 p.m. To compare the moisture content of individual fuels (litter – leaves, needles, branches), during the all-day measurement the highest average moisture content (Figure 2) was achieved in the case of the litter formed by leaves (27.93%), followed by litter formed by needles, which average moisture content was of 24.23%. The moisture content of dead branches was of 20.33%. From the comparison, it is apparent that fine fuel (leaves and needles) responds to precipitations more sensitive, compared to a woody fuel (branches).

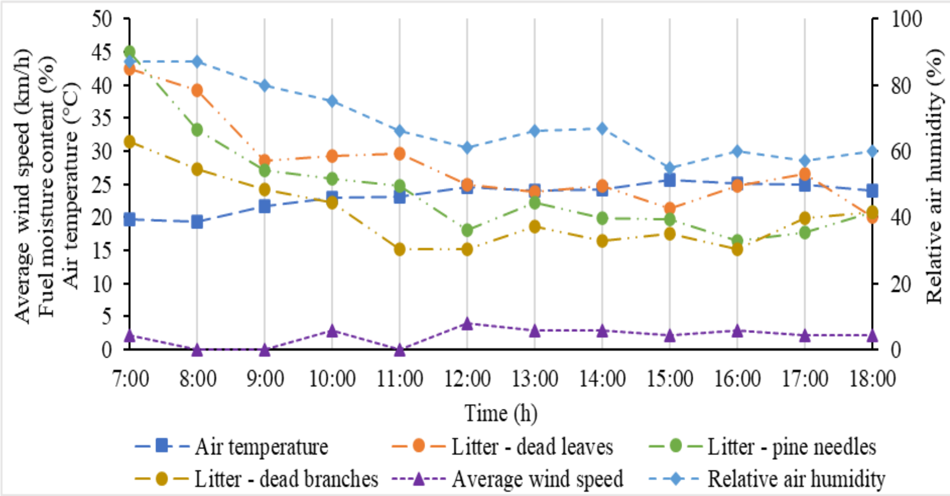

Fig. 2 Time course of fine fuel moisture and weather development during the day 1.8.2019 [Source: Author]

On the second day of the measurement (figure 3), the average fuel moisture content was lower (leaves 21.20%, needles 16.9%, branches 15.9%), which can be explained by the fact that sunny weather prevailed. On the last day of the measurement (figure 4), the moisture content of the fuel decreased again (leaves 17.1%, needles 15.3%, branches 14.2%), which was caused by persistent sunny weather without precipitation again. The largest decrease in fuel moisture content compared to the first day of measurement was achieved at litter formed by leaves (10.83%), followed by litter formed by needles (8.93%), and at least values of the moisture content showed the coarser fuel – branches (6.13%). This is confirmed by the fact that fine fuel is more prone to changes in moisture content when compared with coarser fuels. The process of water adsorption and desorption in fine fuels is influenced not only by weather parameters but also by the chemical and physical properties of the fuel.

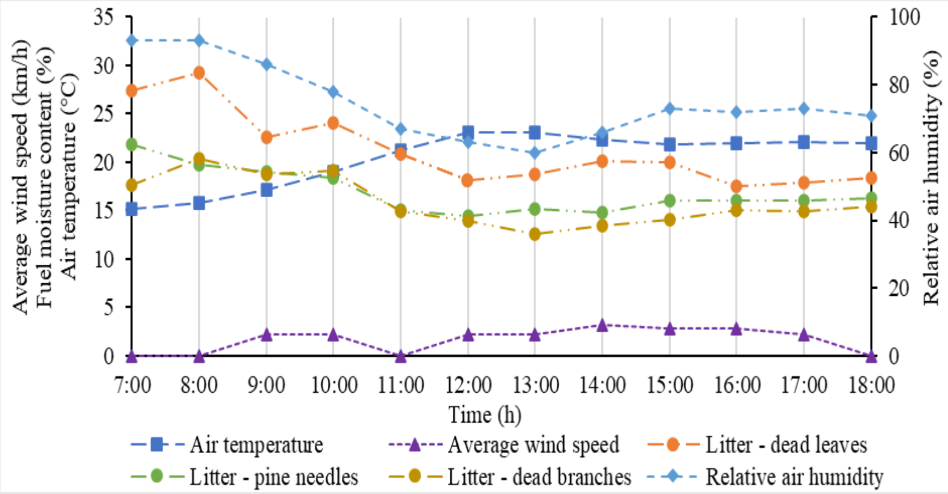

Fig. 3 Time course of fine fuel moisture and weather development during the day 2.8.2019 [Source: Author]

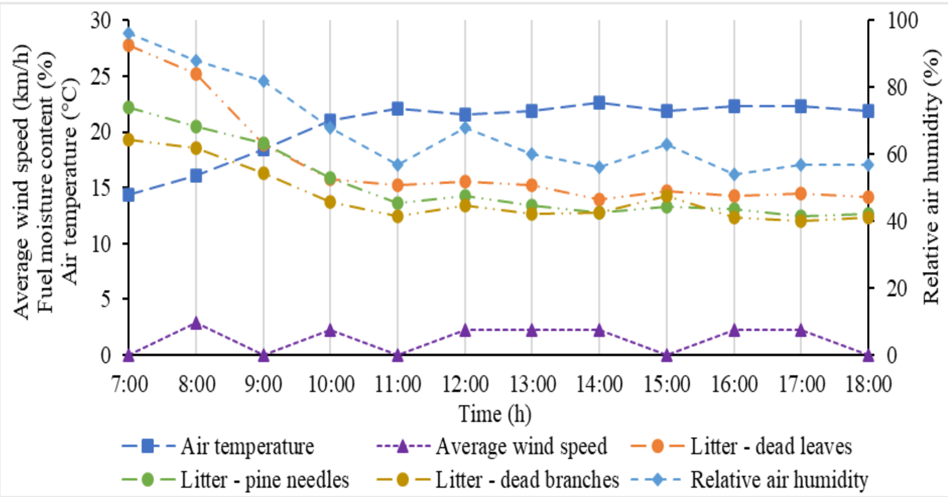

Fig. 4 Time course of fine fuel moisture and weather development during the day 3.8.2019 [Source: Author]

Table 2 shows the values of weather parameters and moisture content of fine fuel obtained by field survey. The results of the pilot study indicated a relatively wide variation of all measured parameters. These values represent weather characteristics typical for the territory of Slovakia. The recorder air temperatures at the time of sampling ranged from 14.4 °C to 25.6 °C, relative air humidity from 54% to 96%, and average wind speed from 0 to 4 km·h^{-1}. The values of the moisture content of the fine fuel ranged as follows. For dead leaves from 13.7% to 45.7%, for needles from 12.3% to 47.1% and for dead branches from 11.9% to 33.2%.

Tab. 1 Descriptive statistics for weather parameters and fine fuels moisture contents [Source: Author]

Statistics parameter	T	RH	W	FMC dead leaves	FMC pine needles	FMC dead branches
No. of samples	36	36	36	108	108	108
Minimum	14,4	54,0	0,0	13,7	12,3	11,9
Maximum	25,6	96,0	4,0	45,7	47,1	33,2
Mean	21,4	70,1	1,7	22,1	18,8	16,8
Standard deviation	2,8	12,1	1,2	6,9	6,5	4,5

T: temperature (°C); RH: relative air humidity (%); W: average wind speed ($km \cdot h^{-1}$); FMC: fuel moisture content (%).

Table 3 shows the calculated values of the correlation coefficients, which define the dependence between the moisture content of the fine fuel and the weather parameters. Correlation coefficients were calculated at the 95% level of significance. The analysis indicated that the moisture content of the fine fuel correlated mostly with the relative air humidity (r = 0.62, 0.57, 0.61) and the least with the wind speed (r = 0.10, 0.11, 0.11). In the case of providing a correlation analysis to evaluate the dependency between fuel moisture content and relative air humidity measured during individual days the field survey, the results showed a medium to the strong dependence of those variables. The values of the correlation coefficients (r) were of 0.87, 0.86, 0.95 for dead leaves, 0.88, 0.95, 0.98 for needles and 0.84, 0.88, 0.97 for branches. In this case, we can observe the differences in the expression of dependence during the whole period or the individual days of sampling.

Tab. 2 Correlation coefficients between weather conditions parameters and fine fuel moisture contents [Source: Author]

Parameter	T	RH	W	FMC dead leaves	FMC pine needles	FMC dead branches
T	1,000000	--	--	--	--	--
RH	-0,862482	1,000000	--	--	--	--
W	0,435543	-0,313053	1,000000	--	--	--
FMC dead leaves	-0,288342	0,622039	-0,103171	1,000000	--	--
FMC pine needles	-0,242647	0,570445	-0,109020	0,916391	1,000000	--
FMC dead branches	-0,289438	0,609526	-0,111759	0,887430	0,924666	1,000000

Table 4 shows the results of the regression analysis between the moisture content of the fine fuel and the weather parameters. The results of the regression analysis indicated that the addition of several weather variables increased the percentage variability of fuel moisture, which is explained by the influence and fluctuations of relative humidity, air temperature and wind speed. According to Saglam et al. [41], it is important in the regression analysis to supplement the data from the period since the last precipitation as another independent variable that will improve the explanation of the variability of fine fuel moisture content.

Tab. 3 Regression models used for the prediction of the fuel moisture content based on weather conditions [Source: Author]

Regression models	r^2	$S_{y.x}$
FMC – dead leaves (%) = – 2.0403 + 0.3445*RH	0.39	5.39
FMC – dead leaves (%) = 36.9037 – 0.6923*T	0.08	6.59
FMC – dead leaves (%) = – 84.2251 + 0.8073*RH + 2.3262*T	0.63	4.26
FMC – dead leaves (%) = – 87.1397 + 0.8190*RH + 2.4606*T – 0.4643*W	0.63	4.29
FMC – pine needles (%) = – 2.2104 + 0.2999*RH	0.33	5.37
FMC – pine needles (%) = 30.6303 – 0.5530*T	0.06	6.34
FMC – pine needles (%) = – 80.6031 + 0.7413*RH + 2.2189*T	0.57	4.36
FMC – pine needles (%) = – 84.2854 + 0.7562*RH + 2.3886*T – 0.5866*W	0.58	4.37
FMC – dead branches (%) = 1.4594 + 0.2187*RH	0.37	3.53
FMC – dead branches (%) = 26.4157 – 0.45028*T	0.08	4.27
FMC – dead branches (%) = – 49.2424 + 0.5043*RH + 1.4351*T	0.57	4.35
FMC – dead branches (%) = – 51.2633 + 0.5124*RH + 1.5283*T – 0.3219*W	0.60	2.92

r^2 – R-squared; $S_{y.x}$ – standard error of the estimate.

The accuracy of the regression coefficients and the regression model itself needs to be interpreted in these cases with a certain amount of caution for several reasons. The first reason is the short time interval used for measuring the values of moisture content of fine fuel and weather parameters. Another reason is that the data were taken from one stand and cannot be interpreted for the whole territory of Slovakia with a similar type of fuel. The moisture content of fine fuel is also affected by the weather parameters, further there are also topographic conditions, especially the terrain slope, terrain morphology, and last but not least, the terrain aspect, i.e. the orientation of the slope to the sun. This is especially important in the relationship between solar heating and faster fuel drying.

Conclusion

The paper deals with the analysis of the dependence between the moisture content of fine fuel and the weather conditions in a mixed pine stand. For this purpose, measurements of fine fuel moisture content and weather parameters in the selected area were provided. A linear regression and correlation analysis were performed to determine the dependency between fine fuel moisture content and weather parameters. The results showed that changes in weather parameters had a significant effect on the moisture content of fine fuels. The greatest influence on the moisture content in fine fuel was the combination of weather parameters, namely air temperature, relative air humidity, and wind speed. As the measurements were performed in the period without precipitation, it is necessary to supplement this weather parameter with further measurements in the future. Prediction of fine fuel moisture content through the models developed and presented here is the first step to understanding the behaviour of fine fuel moisture depending on the weather parameters. These models should serve to fill the gap in the prediction of daily moisture content in fine fuel for forest areas in Slovakia. At the same time, it presents the input information needed to develop forest fire alerting systems providing the information on forest fire danger which assessment requires the information on the actual moisture content of vegetation (fuel).

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