# ADVANCES IN FOREST FIRE RESEARCH

## 2022


**Edited by**

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# Fuel Moisture Content in Croatian wildfire spread simulator AdriaFirePropagator

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**Keywords**

Dead Fine Fuel Moisture Content, Wildfire Spread Simulation, AdriaFirePropagator

**Abstract**

Fuel moisture content (FMC) is the mass of water contained within vegetation in relation to the dry mass. It is one of the most important variables in all wildfire prediction and spread simulation models. FMC has great influence on wildfire ignition and combustion. For accurate wildfire spread simulations and wildfire risk index estimations, fuel moisture is a very important input variable. Since 2016, Croatian firefighters in everyday practice use Web based System for wildfire behaviour modelling and wildfire spread simulation named AdriaFirePropagator. The simulator is based on semi-empirical Rothermel's surface fire spread model for wildfire behaviour modelling and cellular automata for wildfire spread simulation. Fuel moisture, both live and dead is a very sensitive parameter in wildfire behaviour modelling. Live fuel moisture defines the moisture content of live fuels and dead fuel moisture is defined as moisture of dead fuels with time-lag of 1 hour, 10 hour and 100 hours. In Croatia there is no organised service for daily measurement of fuel moisture content, so values of these variables has to be estimated from meteorological parameters. This paper compares three approaches to fine dead fuel estimation, all implemented in AdriaFirePropagator. The first one, used in most wildfire simulation software, was based on standard mathematical models that relate air temperature, air humidity, 24-hours rainfall and wind speed with fine dead fuel moisture (FFMC). The second one was based on standard Fire Behavior Analysis Tables (FBA Tables) and the third one was based on intensive experimental research of dead fine fuel moisture content of Aleppo pine (*Pinus halepenses* Mill.). After intensive experimental research new Croatian fine dead fuel model PhFFMC was developed, tested in selected pine species stand and applied in AdriaFirePropagator for fuel regions where this pine species dominate. Croatian model is much better correlated with experimental data, therefore for more accurate wildfire simulations, similar models have to be developed also for other typical vegetation fuel types.

## 1. Fuel Moisture and wildfire spread simulation

Fuel moisture, both live and dead, is a very sensitive parameter in wildfire spread simulation. Live fuel moisture defines the moisture content of live fuels (Moist_live), and dead fuel moisture is usually defined as moisture of dead fuels with time-lag of 1 hour (Mois_dead_1h), 10 hour (Mois_dead_10h) and 100 hour (Mois_dead_100h). To illustrate how important fuel moisture is for wildfire simulations, in Figure 1 we show wildfire spread simulation results where all parameters are the same except live and dead fuel moisture content. The moisture content of **dead fuels** (DFMC) is controlled by fuel properties and external weather conditions: relative humidity, precipitation, temperature, and solar radiation, and the moisture content of **live fuels** (LFMC) is controlled largely by internal physiological mechanisms, so it is difficult to predict them only from meteorological parameters.

## 2. Determination of Fuel Moisture Content without direct measurement for AdriaFirePropagator simulations

**AdriaFirePropagator** is a Web base simulation tool for wildfire behaviour modelling and wildfire spread simulation. Since 2016. it is in everyday practice used by Croatian firefighters as one of modules of advanced wildfire surveillance and monitoring system named OiV Fire Detect AI (OiV (2022)).

AdriaFirePropagator is based on semi-empirical Rothermel's surface fire spread model for wildfire behaviour modelling and cellular automata for wildfire spread simulation.

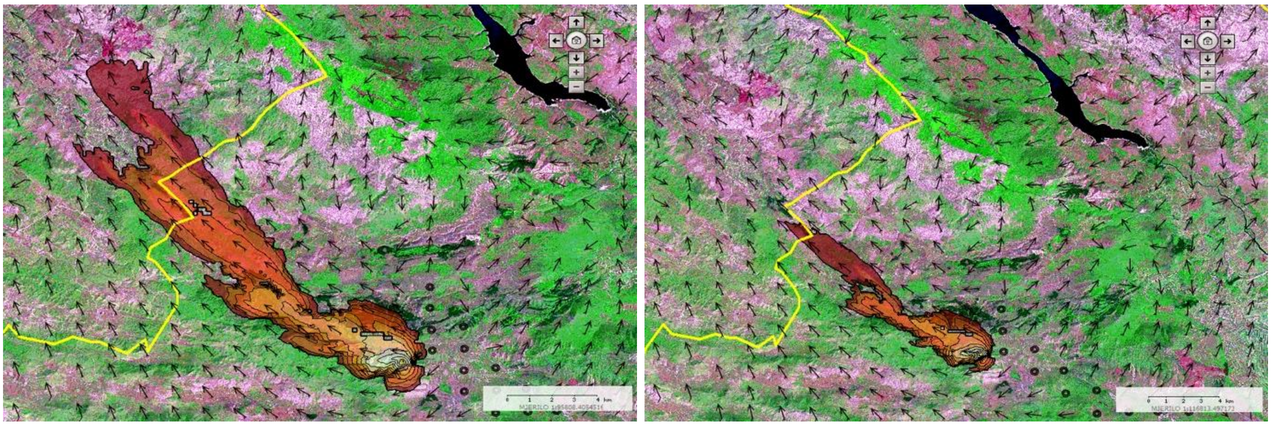

***Figure 1 - Wildfire spread simulation using AdriaFirePropagator with the same input parameters except live and deal fuel moisture. In the left simulation the moisture content was 50% of the moisture content used for the right simulation).***

In AdriaFirePropagator estimation of the moisture content of dead fuels is estimated by two models. The first one is based on Canadian FWI and its Fine Fuel Moisture Content (FFMC) calculation using air temperature, relative humidity, wind speed and 24-h rainfall. Van Wagner (1987) has proposed the scale equation that connect fine dead fuels moisture content m in % and FFMC:

$$m\ (\%) = 147.2\ (101 - FFMC)/(59.5+FFMC) \qquad (1)$$

Formula is valid for the whole FFMC range FFMC $\in$ [ 0, 100 ].

Viegas also has shown in Viegas (2005) the correspondence between FFMC and fine dead fuel moisture:

$$m\ (\%) = (9*10^{9})/(FFMC^{4.54}) \qquad (2)$$

but this formula is valid only for FFMC $\in$ [ 65, 95 ].

In AdriaFirePropagator moisture content m (%) is related to Mois_dead_1h.

Van Wagner (1987) has also proposed scales between Duff Moisture Code (DMC) and real moisture content in %, but AdriaFirePropagator moisture simulation is based on time-lag fuel moisture models corresponding to fuel particle size and not on fuel position used in Canadian FWI moisture codes, therefore here only correlation between FFMC and 1h fuel moisture was used. Other coarser dead fuel particles moisture content (Mois_dead_10h, Mois_dead_100h) is calculated by correlation models based on Scott and Burgan (2005) dead fuel moisture scenarios (very low, low, moderate and high) using simple equations:

$$\text{Mois\_dead\_10h}\ (\%) = \text{Mois\_dead\_1} + 1 \qquad (3)$$

$$\text{Mois\_dead\_100h}\ (\%) = \text{Mois\_dead\_1} + 2 \qquad (4)$$

Additionally, according to report published in Scott (2012) we have implemented weighting factors used to combine 1-, 10-, and 100-hr timelag class moisture contents into a single characteristic dead fuel moisture content for standard Scott–Burgan fuel model classes.

The second model for fine dead fuel moisture content estimation was based on standard Fire Behavior Analysis Tables (FBA Tables), published in Rothermel's (1983) guide on fire behavior prediction and implemented in BehavePluse utility named *Fine Dead Fuel Moisture Tool*. In these tables dead fuel moisture content is estimated using as input variables air temperature and relative air humidity. Tables are different for daytime and nighttime with additional corrections for season, time of day, elevation of the projection point relative to the weather observation, slope steepness class, aspect, and whether the fuelbed is shaded as reported in Scott (2012).

Meteorological data for both models are automatically collected from Croatian Meteorological and Hydrological Service server two times a day together with weather predictions calculated by ALADIN forecast model for the next 12 hours in the time resolution of 2 hours.

Moisture content of live fuels unfortunately could not be estimated from meteorological parameters. It is entirely based on field observations using approach published by Scott (2005, 2012) based on estimated by the percentage of cured leaves and introduced in simulator manually.

## 3. New Croatian model for dead Fine Fuel Moisture Content of two pine species typical for Croatian Adriatic vegetation

In order to improve the models for fine dead fuel moisture estimation, intensive experimental research was initiated at the Faculty of Forestry and Wood Technology, University of Zagreb (Bakšić 2017, Bakšić et al. 2017). As a case study, a typical Adriatic pine species, Aleppo pine (*Pinus halepensis* Mill.) was selected. Equilibrium moisture content (EMC) and response time of dead Aleppo pine needles were determined in the laboratory. These species-specific values were used to modify the Canadian hourly FFMC model. Thus, the basic modifications were changes in the EMC equations and changes in the response time equations of the hourly FFMC model. The input variables were hourly weather data: temperature, relative humidity, and wind speed. At this stage of model development, precipitation phase was not considered, so in case of precipitation the original equation from hourly FFMC should be used. A detailed explanation of the materials and methods as well as the final equations of the new model named PhFFMC (*Pinus halepensis* FFMC) can be found in Bakšić et al. (2017).

For model validation, intensive destructive sampling for moisture content determination was conducted in a mature Aleppo pine forest on Lastovo Island in July 2013. During sampling, a portable weather station was installed in the study site. Figure 2 shows the model validation results: the estimated moisture content for both the hourly FFMC model and the Croatian PhFFMC model compared to the actual observed moisture content.

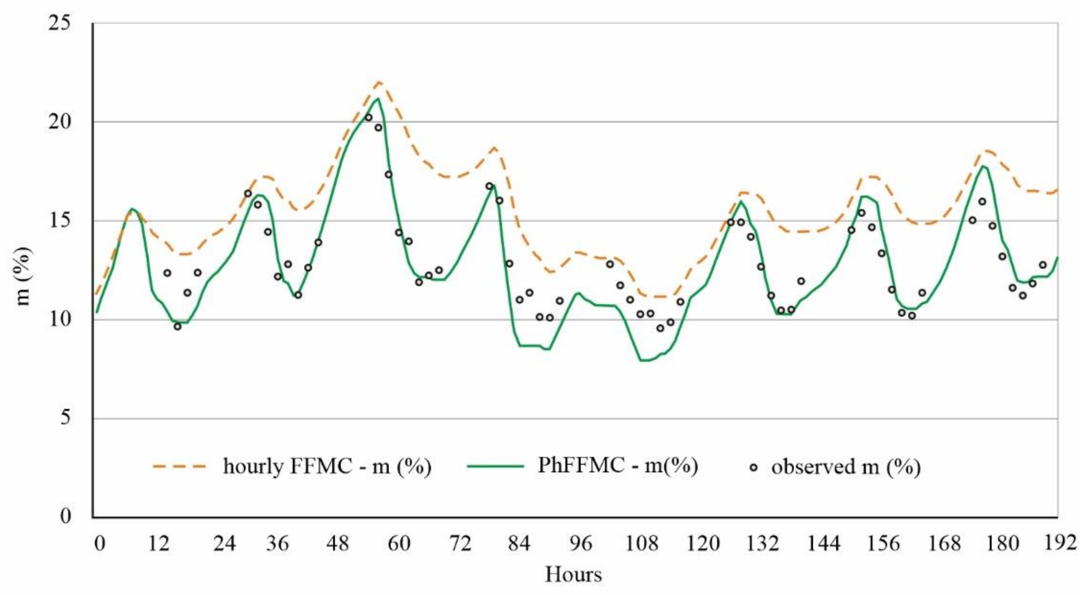


***Figure 2 - Estimated moisture content (m) from hourly FFMC and Croatian PhFFMC models compared to actual moisture content (m) (Bakšić 2017).***

Model validation results showed that the hourly FFMC model continuously overestimated the moisture content of Aleppo pine needles. Aleppo pine needles lose and gain moisture faster than the hourly FFMC model suggests. This is particularly evident when the actual moisture content reaches a minimum value, as this is when the largest average deviation from the hourly FFMC model occurs. On the other hand, the PhFFMC model follows the moisture content of Aleppo pine needles more closely throughout the period and reduces the mean absolute error in predicting moisture content to only 1%.

## 4. Comparation of various dead fuel models in AdriaFirePropagator simulator

Croatian model for dead fine fuel moisture content was implemented in AdriaFirePropagator and compared with other standard fuel moisture models based on Van Wagner equation and FBA tables. For testing purposes, we have used the large fire that occurred on the island Lastovo at 0:30 on Sept 4, 2003 and lasted almost 8 days. This fire was very well documented, so we were able to reconstruct its development. Figure 3 shows one of fire images taken by firefighters and ignition point location.


***Figure 3 – Lastovo wildfire that has started on Sept 4, 2003 and lasted almost 8 days (left). Ignition point (right).***

The weather conditions at the time of fire ignition were: Temperature T = 19.4 $^{0}$C (66.92 $^{0}$F), Atmospheric pressure at sea level SLP = 1024.7 hPa, Relative Humidity H = 29 %, Total Rainfall PP = 0 mm, Wind Speed W = 27 km/h, Wind Direction WD = 75$^{0}$ ('bura' wind). In simulations we have used Albini-Anderson vegetation categories. In its initial stage, fire propagated through vegetation class *"Long Needles and Hardwood Litter"*. Simulation was satisfactory regarding shape, but unfortunately not regarding time as Figure 4 shows. The fire front reaches real fire front in 360 min instead of 150 min. Therefore, we have changed fuel parameters to better fit the real fire spread. The difference was in fuel load and fuel bed depth, that has to be increased.

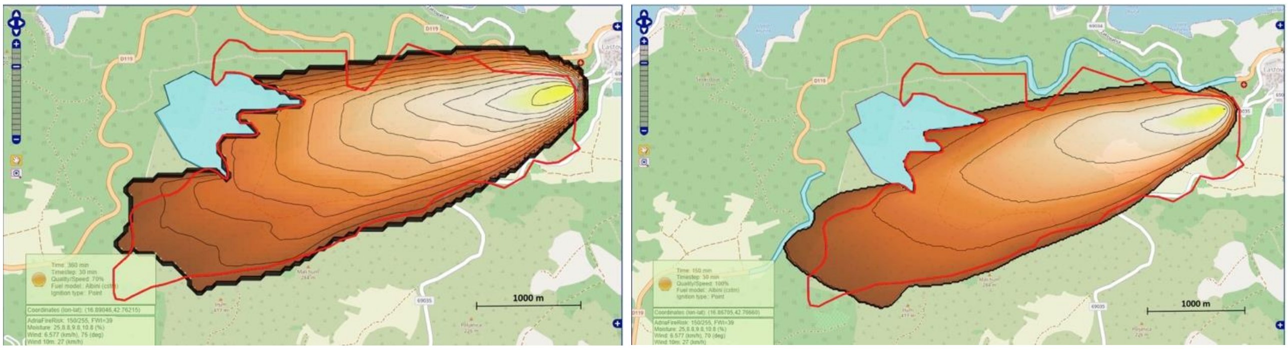


***Figure 4 – With original Albini-Anderson fuel model parameters the fire front reaches real fire front (red line) in 360 min (left) instead of real 150 min. After fuel parameters adaptation satisfactory simulation was obtained (right).***

Our next step was comparison of various dead fine fuel moisture content models. Live fuel moisture in all simulations was estimated to 80%. Three model for fine dead fuel moisture were compared:

a) Moisture model based on Canadian Fine Fuel Moisture Content (FFMC) calculation: Moisture 1h: 9.6; Moisture 10h: 10.6; Moisture 100h: 11.6 (same for the whole simulation)
b) Croatian model based on PhFFMC (Dominant vegetation on Lastovo island is Aleppo pine): Moisture 1h: 8.8; Moisture 10h: 9.8, Moisture 100h: 10.8 (same for the whole simulation)
c) Moisture model based on standard Fire Behavior Analysis Tables (FBA Tables): Moisture 1h: 6; Moisture 10h: 7; Moisture 100h: 8 (same for the whole simulation)

Figure 6 shows AdriaFirePropagator simulations for various moisture content models in comparison with real fire front recorded by firefighter commander Miloslavić (2003).The red line represents the real fire front.

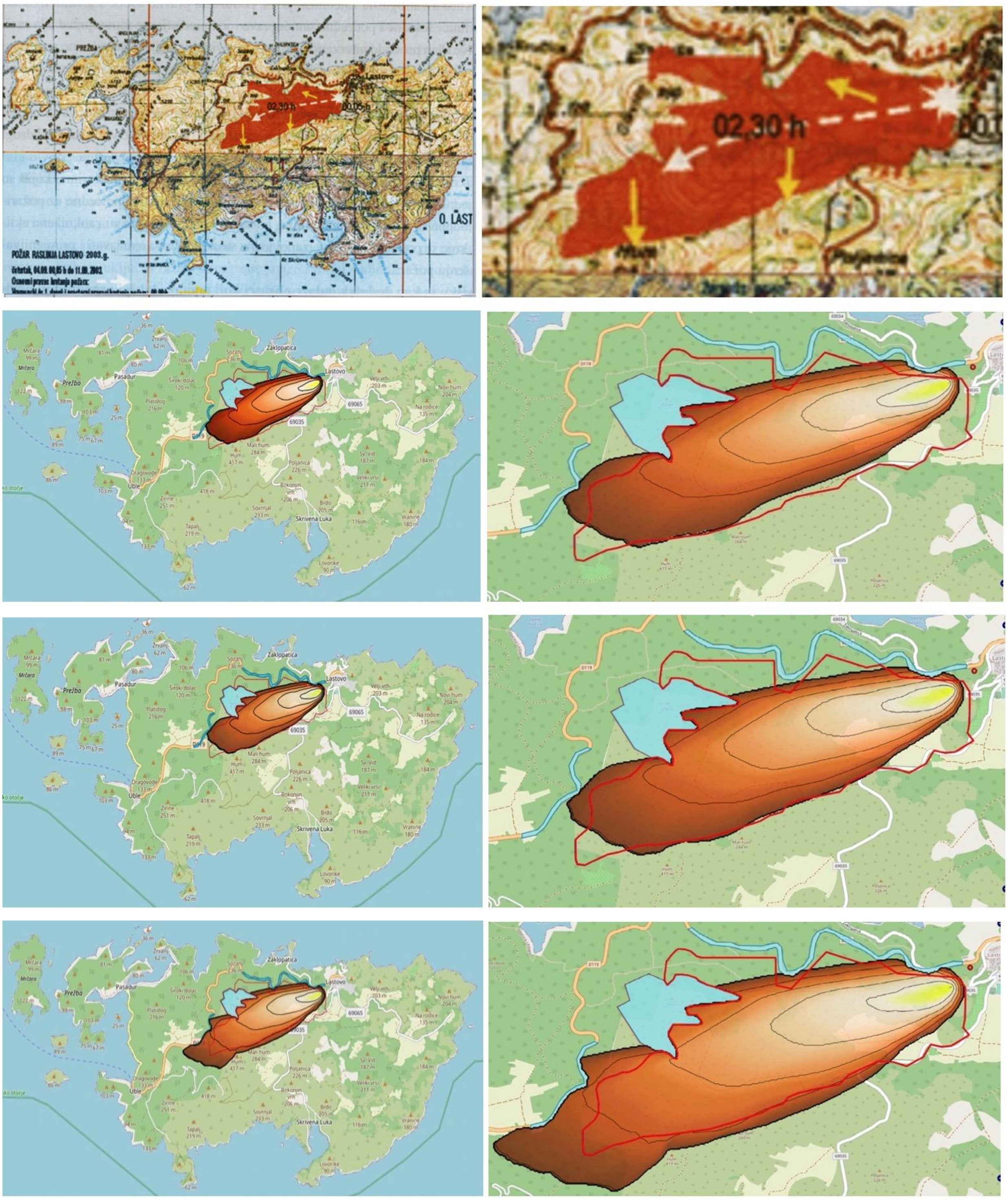


***Figure 6 – Comparison of real fire front (1st row and red line on simulations) and AdriaFirePropagator simulations for various moisture models: 2nd raw – Canadian FFMC, 3rd raw– Croatian PhFFMC model, 4th raw – FBA Tables.***

Table 1 summarise obtained results and shows precision, recall, F1 score and Intersection over Union (IoU).

***Table 1 – Statistical comparison of simulation results from Figure 6 for various moisture models***

| | Precision | Recall | F1 score | IoU |
|---|---|---|---|---|
| **Canadian FFMC** | **0,93811805** | 0,79243403 | 0,854375306 | 0,753069534 |
| **Croatian** | 0,929727814 | 0,827800566 | **0,880604881** | **0,779056441** |
| **FBA tables** | 0,742912923 | **0,878384288** | 0,804988789 | 0,673624466 |

Simulation based on Croatian PhFFMC model gave the best result in cumulative measures, because simulated fire front for this model was the closest to the actual fire front. FFMC based model gives the biggest moisture content, therefore the simulated fire front is smaller than the actual fire front. The situation is opposite for FBA tables model: the moisture content is the smallest and the simulated fire front is bigger than the actual one.

## 5. Conclusion

AdriaFirePropagator is a wildfire simulation software used in everyday practice by Croatian firefighters as a part of the advanced wildfire surveillance and monitoring system named OiV Fire Detect AI. Fuel moisture, both live and dead is a very sensitive parameter in wildfire spread simulations. Paper compares three different models for dead fuel moisture estimation: model based on Canadian FFMC, model based on Fire Behavior Analysis Tables (FBA Tables) and a new Croatian model based on intensive experimental and field research for fine dead fuel model for Aleppo pine PhFFMC. A well-documented 2003 Lastovo fire was used as a case study. From aforementioned models, the Croatian PhFFMC model has shown the best fit with real fire front, therefore our suggestion is that similar models should be made for all other vegetation categories characteristic for Adriatic region. The authors of PhFFMC model also have developed the similar model for Dalmatian black pine (*Pinus nigra* (Arnold) subsp. *dalmatica* (Vis.) Franco)) named PnFFMC (Bakšić 2017, Bakšić & Bakšić 2022). We hope that similar models will be develop for all other typical Adriatic vegetations. Also, we have shown that the original parameters of Albini-Anderson vegetation models do not give good results, especially in relation to the time component of fire spread, therefore we had to adjust them to match the actual fire spread. We hope that new vegetation models proposed through FirEUrisk project will resolve this problem.

## 6. Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003890.

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