

Estimation of dead fuel moisture content from meteorological data in Mediterranean areas. Applications in fire danger assessment

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Abstract. The estimation of moisture content of dead fuels is a critical variable in fire danger assessment since it is strongly related to fire ignition and fire spread potential. This study evaluates the accuracy of two well-known meteorological moisture codes, the Canadian Fine Fuels Moisture Content and the US 10-h, to estimate fuel moisture content of dead fuels in Mediterranean areas. Cured grasses and litter have been used for this study. The study was conducted in two phases. The former aimed to select the most efficient code, and the latter to produce a spatial representation of that index for operational assessment of fire danger conditions. The first phase required calibration and validation of an estimation model based on regression analysis. Field samples were collected in the Cabañeros National Park (Central Spain) for a six-year period (1998–2003). The estimations were more accurate for litter (r^2 between 0.52) than for cured grasslands (r^2 0.11). In addition, grasslands showed higher variability in the trends among the study years. The two moisture codes evaluated in this paper offered similar trends, therefore, the 10-h code was selected since it is simpler to compute. The second phase was based on interpolating the required meteorological variables (temperature and relative humidity) to compute the 10-h moisture code. The interpolation was based on European Centre for Medium Range Weather Forecasting (ECMWF) predictions. Finally, a simple method to combine the estimations of dead fuel moisture content with other variables associated to fire danger is presented in this paper. This method estimates the probability of ignition based on the moisture of extinction of each fuel type.

Additional keywords: dead fuel moisture content, fire danger assessment, meteorological data.

Introduction

Most operational fire danger rating systems base their estimation of fuel moisture conditions on meteorological data (Stocks *et al.* 1989). Commonly, meteorological danger indices try to estimate fuel moisture content of dead materials present in the forest understorey or lying on the forest floor, which are the driest and most likely to ignite (Viegas *et al.* 1992). Dead fuel includes a wide range of materials (senescent grasses, dry leaves, small twigs and organic material in the topsoil).

The water content of fuels is inversely related to the probability of ignition, because of the fact that part of the energy necessary to start a fire is used up in the process of evaporation right before the fire starts to burn (Dimitrakopoulos and Papaioannou 2001). On the other hand, water content also affects fire propagation since the source of the flames is reduced with humid materials, therefore, flammability is reduced (Viegas 1998).

The moisture content of dead fuel changes frequently, as a result mainly of atmospheric conditions (Simard 1968). Loss or gain of water content will vary depending on the physical and chemical characteristics of the fuel and the presence of varying atmospheric activity (rain, condensation, etc.).

Most commonly in the forest fire literature, water content is expressed as a percentage of the dry weight, and it is usually referred to as 'fuel moisture content', FMC (Viney 1991). Dead

FMC is determined by various methods: field sampling, standard fuels and meteorological indices being the most common (Viney 1991; Camia *et al.* 2003).

Field sampling provides accurate estimation, but it is costly and labour intensive, especially when wide area estimations are required. In addition, this method does not provide an instantaneous estimation, since the samples must be oven-dried for a certain number of hours (24 or 48 h are common).

The use of standard fuels has been suggested by some authors (Simard 1968). This method is based on monitoring weight changes of previously calibrated wooden sticks that are assumed to be good representatives of certain fuel sizes. It reduces the effort of field sampling and provides an instant estimation of FMC, but also has little spatial significance, because the measurements are local. In addition, the standard fuels can lose their calibration quite quickly.

Meteorological danger indices (MDIs) have been commonly used to estimate dead FMC. These indices rely on current and past weather conditions, since they try to estimate the degree of dryness of different forest fuels. MDIs have the advantage of frequent updating and, in addition to estimating FMC, provide other critical variables for fire ignition and fire propagation assessment. The MDIs vary in complexity and in the number of required variables, from those that only need temperature and

relative humidity to those that are based on complex numerical models (see Viney 1991 for a review). There are two main difficulties associated with MDIs in FMC estimation: spatial significance and calibration. The former is caused by the location of weather stations that may not be very appropriate for fire danger estimation, since they are commonly associated to monitoring agricultural or urban parameters. Consequently, spatial interpolation techniques are required. These interpolation methods always introduce a certain estimation error, which is added to the actual estimation of FMC.

Another difficulty of using MDIs operationally for the estimation of dead FMC conditions is linked to the lack of calibration of moisture codes to different ecosystem or climate characteristics. The most well known MDIs were developed by the Canadian and US Forest Services, and in spite of their soundness, little information is still available on their applicability to different ecosystems. For instance the Canadian Fire Weather Index (FWI) is being used in a wide range of countries from Mexico and Indonesia to Mediterranean Europe, with good results (Viegas *et al.* 1996), although these countries include very different environmental conditions to those where the system was developed.

This paper aims to test the efficiency of two well-known moisture codes to estimate the FMC of dead fuels in Mediterranean areas. This is part of a larger project that aims to develop an operational fire danger assessment system.

A two-step process was adopted in this work. First, the suitability of the two meteorological indices to estimated Mediterranean conditions was tested, and an empirical model to estimate dead FMC from meteorological data was developed. Second, the selected index was mapped for our study region using spatial interpolation techniques from weather forecasted data. Since the final goal of our project is the integration of moisture status with other factors of fire danger (potential lightning, human factors, potential spread, values at stake, etc.), the paper also discusses a simple method to convert the estimated FMC values of dead fuels into a standard scale of fire danger. The synthetic fire risk index is described in Chuvieco *et al.* (2003). The system was developed for the whole autonomous region of Madrid (around 8000 km²) located in Central Spain (Fig. 1). This



Fig. 1. Location of the study areas.

semi-operational system was developed for the summer of 2003, but it will be tested in more detail during the 2007 fire season.

Materials and methods

Field sampling

To test which MDI provided a better estimation of dead FMC in Mediterranean conditions, a calibration phase was undertaken based on field sampling. The samples were collected in the Cabañeros National Park (central Spain), located 200 km south of Madrid (Fig. 1). The area had been used for other projects by our group (Chuvieco *et al.* 2004b), and provides a good sampling scenario because of being a natural reserve. On the other hand, this area has similar climatic characteristics to the Madrid region. The average annual temperature is 12.5°C, with warm summers that occasionally reach more than 40°C. The average precipitation reaches 700 mm, the highest levels being in autumn and winter. The summer (June to September) is the driest period, with periodic summer rainstorms.

The field work was done between April and September from 1998 to 2003. The samples were collected between 1200 and 1400 hours GMT in order to reflect the hours of maximum fire danger. Field sampling was of both live and dead vegetation species, but only the latter will be used in this paper (see Chuvieco *et al.* 2004b for a description of the FMC of live species). The plots were sampled every week between 1998 and 2000 and every other week from 2001 to 2003. Three of the field plots were covered by grasslands, two by shrubs species and one by deciduous oaks species (mainly *Quercus faginea*). Within the scope of this paper, only plots where grasslands and oak leaves were collected will be used.

Grassland plots were ~50 × 50 m² in size, and the three plots were distributed in a 10-km range to cover the global variation of FMC conditions within the National Park. Grassland samples were taken from whole plants in these plots, three samples per plot. They were considered dead fuels only when the measured FMC was below 30%, which is a common threshold to define the senescence of grasslands (Schroeder and Buck 1970). The deciduous oak plot was sampled for live and dead leaves, but only litter samples were used for this paper. Dead oak leaves are considered a good representative of dead materials lying on the Mediterranean forest floor, since they are widely found in these ecosystems. Each sample was of ~100 g of each fuel type. The samples were put into an envelope and then weighed in the field with a field scale (±0.1 g precision). Afterwards, they were dried in an oven for 48 h at 60°C and then weighed again on the same scale, following procedures described by Desbois *et al.* (1997). The dry weight (W_d) was subtracted from the fresh weight (W_f) in order to obtain the FMC using the following equation:

$$FMC = 100 \times (W_f - W_d) / W_d. \quad (1)$$

A total number of 56 periods were available for senescent grasslands and 92 for litter. Seventy percent of these measurements were used for calibrating the model and the remaining for validation. Average values of the three plots of grasslands and the oak plots were used for the statistical analysis, since we were interested in multitemporal rather than spatial variability of FMC with meteorological data.

Meteorological indexes

Since our model was intended to estimate the FMC of cured grasses and litter, it should be based on those meteorological indices associated to the finest dead fuels. Two moisture codes with this attribute were selected from the Canadian and the US fire danger indices: the Fine Fuel Moisture Code (FFMC) and the 10-h code, respectively. Both the CFFWI (Canadian Forest Fire Weather Index) and the NFDRS (National Forest Fire Danger Rating System) have been used for fire prevention in several Mediterranean areas (Viegas *et al.* 1996; Sebastian-Lopez *et al.* 2002).

The FFMC is part of the CFFWI, and tries to estimate moisture content of the top layer on the ground (L-layer) from measurements of temperature, relative humidity, wind velocity and precipitation registered in the last 24 h (Van Wagner 1987). This moisture code has an empirical character derived from the relationship between these meteorological variables and the water content of a standard fuel. Jack pine (*Pinus banksiana*) and Lodgepole Pine (*Pinus contorta*) were used to calibrate the index. The index also integrates the cumulative effect of atmospheric conditions in the hours previous to the measurements. This index has a timelag of ~ 0.66 days. The estimated FMC, which was derived from the FFMC, was obtained using the equation proposed by Van Wagner (1987):

$$\text{FMC(FFMC)} = 147.2 \times (101 - \text{FFMC}) / (59.5 + \text{FFMC}) \quad (2)$$

The 10-h moisture code is part of the NFDRS. This code estimates the water content of fuels with a width of 1.2 to 2.5 cm (Bradshaw *et al.* 1983), using the concept of equilibrium moisture content (EMC). The EMC is a function of the temperature and the relative humidity (Simard 1968), as well as the atmospheric conditions present at the time the samples are measured. The 10-h code was estimated applying the equation proposed by Bradshaw *et al.* (1983):

$$\text{FMC (10-h)} = 1.28 \times \text{EMC (\%)} \quad (3)$$

The EMC was calculated from the temperature and relative humidity in the fuel atmosphere interface using the formula proposed by Simard (1968). This model is derived by applying a regression on published values for woods. These input parameters are modified to adjust the standard exposed instrument readings of relative humidity and temperature to fuel level. The adjustment parameters for air temperature and air relative humidity were applied as recommended by Bradshaw *et al.* (1983).

The meteorological data used to calculate the meteorological indices was obtained from an automatic weather station operated by our department. The station is located within the Cabañeros National Park, and in the vicinity (<7 km) of the field sampling plots. The meteorological indices correspond to the measurements obtained at 1400 hours GMT. The time periods where no data was available were not used in this study.

Statistical analysis

The selection of the most efficient index to estimate the FMC of senescent grasses and litter was based on a multitemporal correlation between the field data and the meteorological moisture codes. Yearly correlations were computed for each fuel type.

Linear regression analysis was conducted to obtain an empirical model for the estimation of FMC. Two separate models were created for grasses and litter, plus another one that mixed the two fuel types. For all the regression models a random sample of 70% of the study periods were selected to calibrate the model, and the remaining 30% were used for validation.

The performance of each index was measured by the Pearson r value and the root mean standard error (RMSE):

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1,n} (\text{FMC}_{\text{obs}} - \text{FMC}_{\text{est}})^2}{n}} \quad (4)$$

where FMC_{obs} and FMC_{est} are, respectively, the observed and estimated FMC values and n is the number of periods considered.

Spatial estimation of FMC

Once the most suitable meteorological index to describe the FMC trends of dead materials was found, the second phase of our study was addressed to apply the model to the whole autonomous region of Madrid (8000 km²). To do so, spatial interpolation techniques were used. Considering that the FMC of the dead fuels changes in short periods of time, the index needed to be computed and updated quickly. Considering the current difficulties to obtain and process data that comes from numerous weather stations, it was decided to base the spatial interpolation on forecasted variables, instead of on actual measured variables. Short-term forecast (6 h) provides reliable estimates of most meteorological variables, and is, therefore, commonly used in operational fire danger systems (Carlson and Burgan 2003).

Estimated fields of 1400 hours GMT meteorological input variables for the Madrid region were obtained by applying a two-step method. First, downscaling and interpolation of the surface temperature and relative humidity forecasts provided by the European Centre for Medium Range Weather Forecasting's (ECMWF) numerical weather prediction model (NWPM) were performed. This model determines parameters of the future state of the atmosphere using a numerical integration of hydrodynamic equations from an initial state (ECMWF 1991). Forecasts were obtained by means of numerical solution (temporal integration) of mass, momentum and energy fluxes among points of a three-dimensional grid that covers the atmosphere domain. Because of computational limitations, the horizontal grid resolution (0.5° × 0.5° in the ECMWF model) is not high enough to depict important topographical features. For this reason, in topographically complex regions like Madrid, it became necessary to downscale the NWPM output of surface variables. A statistical downscaling method, based upon empirical relationships between ECMWF forecasts and observations in 35 weather stations in the Madrid region were applied.

Once the original 0.5° × 0.5° ECMWF forecasts were transformed into forecasts for 35 specific sites in the region, it was necessary to perform the spatial interpolation itself. The final output fields had a spatial resolution of 500 × 500 m². The interpolation algorithm took into account horizontal distances between the grid point and the surrounding stations (quadratic inverse distance algorithm). The effect of altitude of each grid point over the value of the variable (temperature or humidity) was also considered by means of the variable altitude gradient

detected in the former prediction for the 35 sites (that obviously have different altitudes).

Conversion of FMC values to fire ignition danger

Once the estimation of the dead FMC was accomplished and the spatial interpolation generated, the final step of the project was to integrate the predictions with other factors of fire risk (not considered in this paper). To do so, a common scale of fire danger was required. This common scale was defined in terms of probability of fire occurrence, either related to human factors or physical factors. To do so, we decided to transform all the danger variables into a common scale of danger, which ranged from 0 (null probability) to 1 (maximum probability). In the case of the FMC of dead fuels, the probability of fire occurrence was based on the concept of moisture of extinction (ME), which had been successfully tested in a previous project (Chuvieco *et al.* 2004a). ME is defined as the threshold moisture content above which a fire cannot be sustained (Rothermel 1972). In spite of some criticism, this concept is widely used in the forest fire literature (Simard 1968; Deeming *et al.* 1978; Burgan *et al.* 1998). Following the BEHAVE fire behaviour prediction system (Burgan and Rothermel 1984), the ME of dead fuels varies between 12 and 40% depending on the fuel types developed for this program; NFFL, National Forest Fire Laboratory fuel classification system (Burgan and Rothermel 1984). For the types of dead fuels used in this study, we used standard BEHAVE values of ME for grasslands of 12% (NFFL model 1) and 15% (NFFL model 2), and litter 25% (NFFL model 9).

We assumed that ME values act as relative thresholds to ignition for each fuel, above which the ignition potential dramatically decreases. Although, the ignition probability (IP) for FMC values higher than ME should be zero, a conservative approach was followed, which assumed that a marginal IP existed even at high values of FMC. For this reason, we proposed to assign a maximum IP of 0.2 to the FMC that equals the ME value of each fuel. Dead fuel FMC values lower than ME would have IP values in the range of 0.2 to 1, the IP being linearly inversely proportional to FMC values. For FMC values greater than the ME, IP values would range from 0.2 to 0. Null ignition potential (IP = 0) was assigned to the maximum FMC value recorded in the historical series of FMC field measurements (1998–2003). Schematically this method is based on the following algorithm:

If $FMC > ME$ then

$$IP = (1 - ((FMC - ME)/(FMC_{max} - ME))) \times 0.2$$

else

$$IP = 0.2 + ((ME - FMC)/(ME - FMC_{min})) \times 0.8$$

where FMC_{max} and FMC_{min} are the maximum and minimum FMC values of each fuel type derived from field FMC samplings (see next paragraph). Although these values are site specific, they can reasonably be applied to relatively large regions that have similar environmental conditions.

Results

Estimation of FMC

The maximum and minimum values of FMC of the two types of dead fuels sampled were 364.36 and 0.72% for grasslands

Table 1. Pearson *r* values of Meteorological Danger Indices (MDIs) and fuel moisture content (FMC) in grassland and litter. In bold are 0.05 significant correlations. Number of observations available are shown in parentheses

Code	FMC (Grassland)/MDI					
	1998 (10)	1999 (13)	2000 (12)	2001 (7)	2002 (7)	2003 (7)
FFMC	-0.75	-0.63	-0.18	0.25	-0.60	-0.06
10-h	0.67	0.61	0.09	-0.36	0.66	0.19
	FMC (Litter)/MDI					
	1998 (19)	1999 (20)	2000 (21)	2001 (11)	2002 (11)	2003 (10)
FFMC	-0.88	-0.85	-0.78	-0.90	-0.37	-0.78
10-h	0.70	0.85	0.83	0.70	0.64	0.67

and 30.39 and 0.07% for dead leaves. It is important to note the high water content of the grassland species, which is a result of healthy plant conditions during most of the vegetative cycle. As mentioned earlier, grasslands were only considered dead fuels when the FMC was below 30%.

Table 1 shows the results obtained from applying the Pearson correlation between the moisture codes FFMC and 10-h against the FMC in grassland and litter fuels during the six-year study. The significance level was fixed at 0.05.

The highest correlation was found between meteorological indexes and leaf litter. In this type of fuel the correlation values were always higher than 0.64, reaching 0.90 in 2001 with the FFMC code. The correlation in 2002 was not significant with this code, but the signs were consistent. As for the grassland species, the correlation was significant in the years 1998–1999, while during the other years the rate of correlation was lower but the signs agreed with the expected trends, except for the year 2001.

The correlation values between the FMC derived from the FFMC and the field measured FMC showed a tendency to overestimate the water content in both grass and litter, and in some cases gave higher than expected values for dead fuels (>30%). In both cases the estimations did not provide high confidence. The RMSE values are 8.1% and 17.1% for the cured grass species and the litter, respectively. As we have stated, the coefficients of this equation are simply empirical, since they came from measurements in Canada of a standard fuel (pine), which probably explains this overestimation. In order to correct this deficiency, coefficients derived from the regression analysis between the FMC and the FFMC and 10-h codes during our study period (1998–2003) were used. The results of the estimation from FFMC improved for both types of fuels, and reduced the RMSE to 5.43% for the cured grass and to 2.89% for the litter.

The same analysis was performed for the 10-h moisture code (Eqn 3). The fitting in this case provided an RMS of 7.28% and 2.97% for the dead fuels (cured grass and litter, respectively). The results were better adjusted than those obtained from the CFFMC. As in the case of the estimation of FMC from the FFMC, the next step was to use the coefficients that resulted from the regression analysis between the field samples and the 10-h index in order to obtain an estimation that applies to the environmental characteristics of the target site. This analysis reduced the RMS to 5.75% for the grassland and 2.82% for the leaf litter.

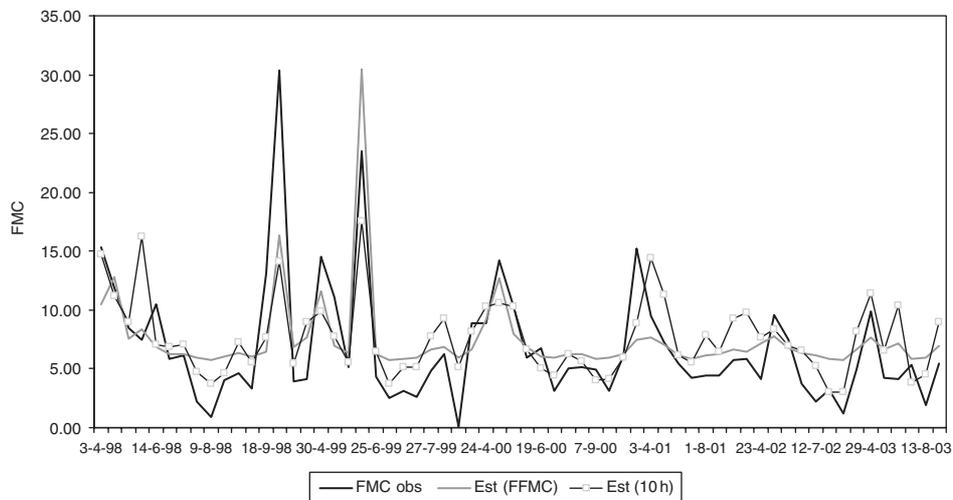


Fig. 2. Temporal trends of real and estimated fuel moisture content (FMC) of litter in the Cabañeros area (calibration data).

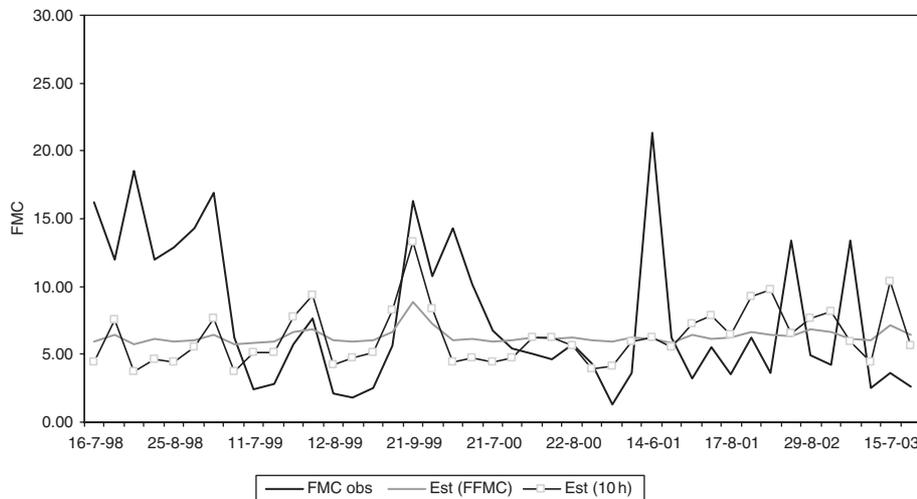


Fig. 3. Temporal trends of real and estimated fuel moisture content (FMC) of grassland in the Cabañeros area (calibration data).

To further advance the operational use of the FMC estimation we assessed the potential of using a common equation for both grass and litter. The resulting coefficients were:

$$\text{FMC}_{\text{est}} = 10\text{-h} \times 1.0317 + 2.1608 \quad (5)$$

$$\text{FMC}_{\text{est}} = \text{FFMC} \times 0.2068 + 5.3087 \quad (6)$$

Figs 2 and 3 show temporal tendencies between the observed and estimated values of FMC in these two types with the calibration data. For litter, there is, in general, a strong fit between the observed and the estimated values with both meteorological codes. Most of the errors show an overestimation of ~3–4%. The RMSE value ranged from 3.75 for the 10-h code to 3.41 for the FFMC code. On the other hand, in 1998 there was a time period with an underestimation of the FMC of 15% for both codes used. The hours in which the samples were collected registered high

relative humidity and even a few millimetres of precipitation. However, the estimated FMC was lower (15%), as they did not take into consideration the atmospheric conditions. The rest of the estimations don't show any outstanding difference.

The estimation of the FMC for the senescent grass (Fig. 3) showed a lower fit than for the leaf litter, as was anticipated in the correlation analysis. In general there is an underestimation of the FMC of 10% in some periods, in both the FFMC and the 10-h. Residuals for 1998 were higher with an underestimation of the FMC values close to 15%. RMSE values offered similar values for both codes, 5.59% for the 10-h and 5.36% for the FFMC. The results of the data used to validate the model (30% of the sample) did not differ from the rest of the sample (Table 2). Maximum residuals were higher for litter (17.01%) than for cured grass (13.22%). However, average residual values show better results for litter fuels (2.74%) than for senescent grass (4.10%). RMSE

Table 2. Fuel moisture content (FMC) residuals for the validation data. Estimations from 10-h code
 Absolute residual refers to the difference between actual and estimated percentage of FMC without considering the sign

Fuel	Parameter	FMC observed	FMC estimated from 10-h	Absolute residual 10-h	Relative residual 10-h	RMSE
Grass	Maximum	24.60	13.22	12.70	1.59	5.26
	Minimum	1.67	3.66	0.92	0.12	
	Average	8.00	6.70	4.10	0.67	
Litter	Maximum	30.25	14.56	17.01	4.21	4.35
	Minimum	0.93	4.33	0.07	0.01	
	Average	6.24	7.24	2.74	0.66	

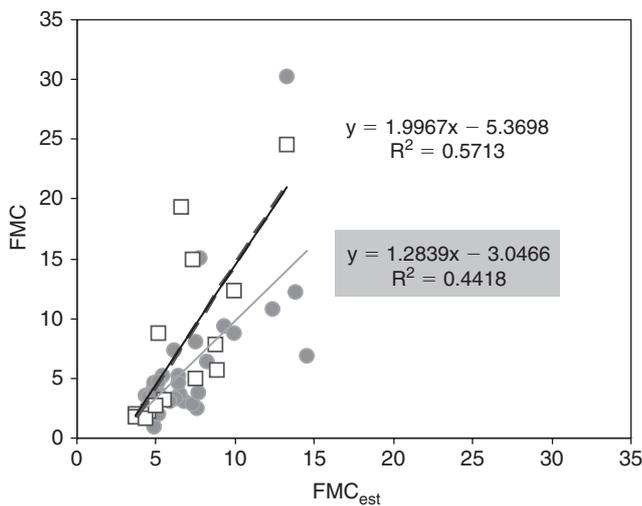


Fig. 4. Observed and predicted fuel moisture content (FMC) values for the validation data. (□) Cured grass, (●) litter.

values offered similar values for both types of fuels: 5.26% for cured grass and 4.35% for litter fuels. An underestimation of the FMC of litter was observed, which is coincident with a period when the water content of this fuel reached its maximum value (30.25%). In this case, there was a registered precipitation a couple of hours right before sampling. It was probable that the fuel contained its maximum water content while the indexes did not reflect the same information.

Estimations from both FFMC and 10-h moisture codes did not show significant differences. Consequently, the 10-h code was selected for the remaining phases of this study, as it required fewer meteorological variables for its calculation.

Fig. 4 shows the fit between observed and predicted FMC values for the validation data using the 10-h code. The adjustment is stronger in the cured grass because of no outstanding deviations in the estimations. In terms of the litter fuels, there was a deviation between observed and estimated values of the FMC because of anomalous high FMC values for one study period. The remaining time periods showed a generalized tendency toward overestimation of the water content value for this type of fuel.

Spatial estimation of FMC

Estimated fields of 1400 hours GMT temperature and relative humidity (at 2 m from the surface) for the Madrid region were obtained by applying the two-step method previously described. The original ECMWF input were H+24 forecasts (that is the ECMWF prediction was initialised at 1200 hours GMT of the previous day). This method is currently operative to supply high-quality, high-resolution forecasts of forest-fire related meteorological variables in many regions of Spain. The quality expected from the method can be assessed in Figs 5 and 6, where a 24-h forecast series of 1400 hours GMT temperature and relative humidity are plotted against the synchronic observed values in a weather station in the Madrid region.

Conversion of FMC to IPd

To obtain the ME of each grid of the estimation region, a fuel type map of the Madrid region was provided by the Regional Environmental Directorate. The ME for the different surface fuels of the region were derived from those proposed in the BEHAVE fuel models (Burgan and Rothermel 1984).

Fig. 7 shows an example of FMC estimation, as well as the IP computed for dead fuels during the same day (15 July 2003), as an example of the operational product that is intended to be derived operationally. The maps show low values of FMC for dead fuels. Most of the region had FMC values under 9.5%, with higher values occurring at the northern sector, where higher altitudes are found. Conversely, the IP was maximum in the south-eastern, central and north-western areas. Areas with no forest fuels or fuels type others than NFFL 1, 2 or 9 have been masked out, using a forest map of the Madrid region.

Conclusions

Meteorological indexes have been extensively used in fire danger estimation. Today there are a wide variety of indexes, many of which can be applied in environments very different from those in which they were developed.

This study has compared the performance of two meteorological moisture codes commonly used for fire danger estimation in Canada (FFMC) and the United States (10-h). We have tested whether they correctly predict temporal variation of the FMC of dead fuels in Mediterranean areas. The two codes were compared by taking measurements in the field over a period of six years. The results did not show a significant difference between the

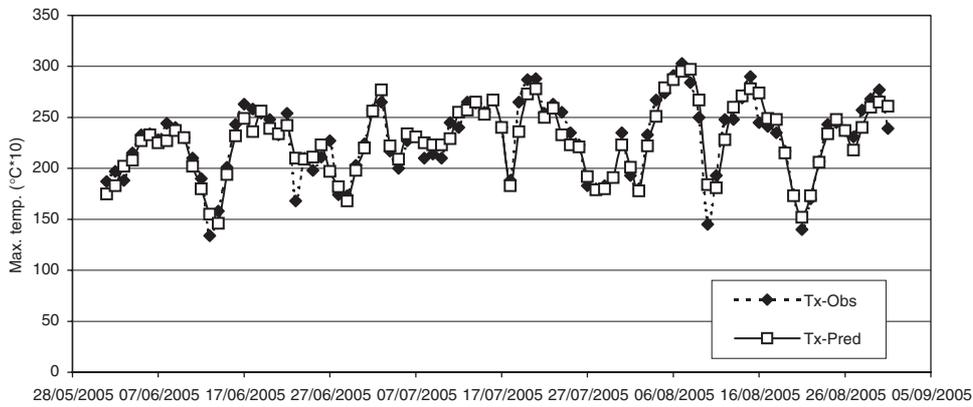


Fig. 5. Forecast series of 1400 hours GMT temperature and observed values in Navacerrada weather station (Madrid). Temperature is expressed in tenth of degree.

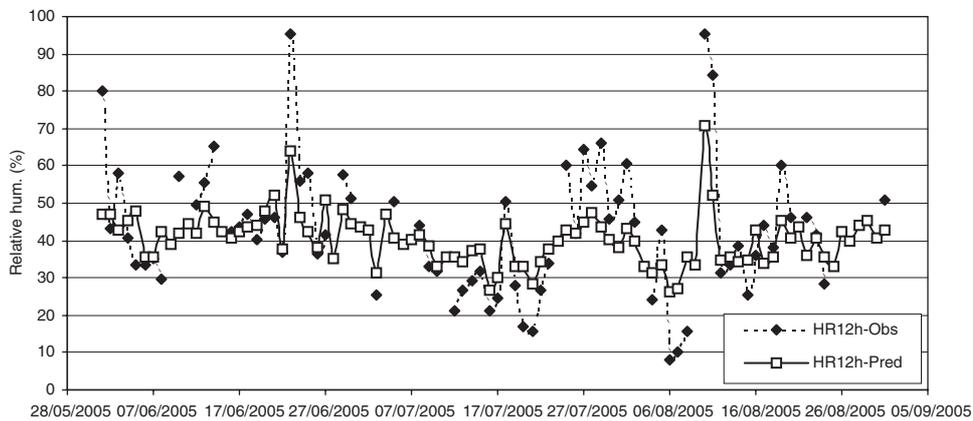


Fig. 6. Forecast series of 1400 hours GMT relative humidity and observed values in Navacerrada weather station (Madrid).

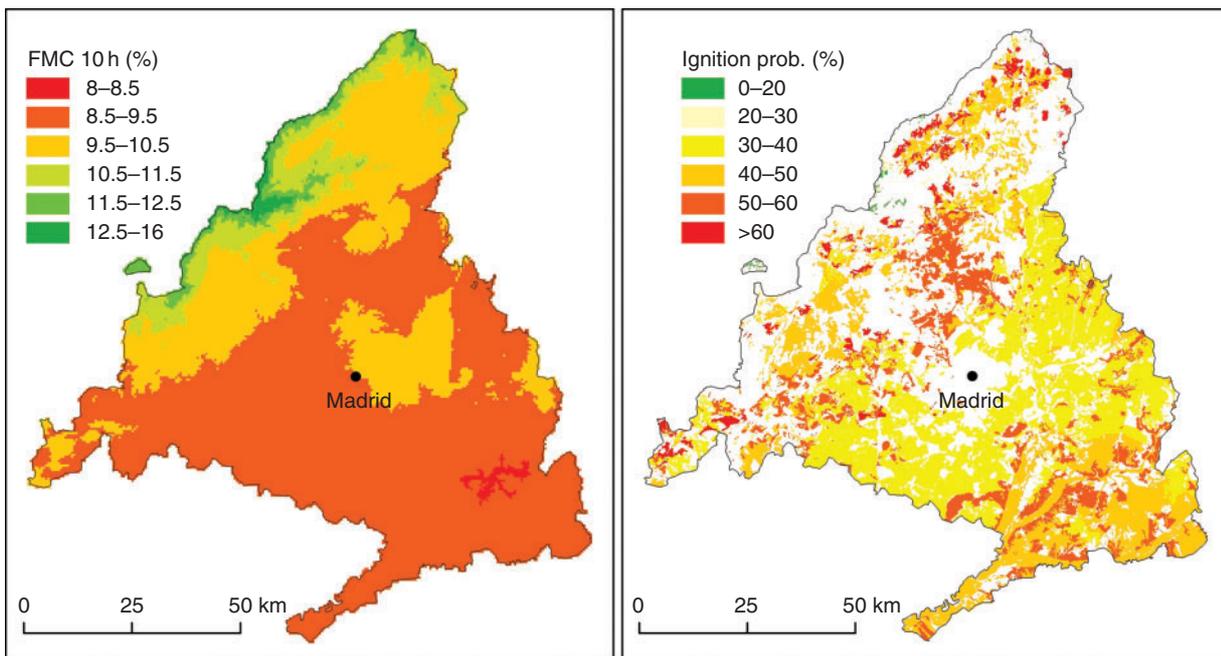


Fig. 7. Fuel moisture content (FMC) maps estimated from Eqn 5 (left) and ignition probability of dead fuels (IP) related to FMC values in the Madrid region (right). White areas in the IP map refer to either non fuel areas or where the fuel model is not included in the study.

two. Therefore, the index that required less inputs, the NFDRS 10-h code, is recommended for operational purposes. This index allows an estimation of the FMC of flammable dead fuels with an RMSE close to 5%.

In addition, the spatial variation of the 10-h code was obtained using interpolation techniques. Target estimation variables, which in this case were air temperature and relative humidity, were generated for our study region. This estimation was based on a two-step method of (1) downscaling and (2) interpolation of ECMWF predictions. The method is currently operative to supply high-quality high-resolution forecasts of forest-fire related meteorological variables in several regions of Spain.

Finally this paper has presented a proposal to obtain the ignition potential associated to dead FMC. We propose to transform the original scale of FMC into an IP, defined as the likelihood of a fire starting, in the range of 0 to 1, using the concept of ME, which should be adapted to each fuel type.

Since FMC can be mapped by gridded meteorological data, IP can also be mapped and, therefore, the assessment of ignition danger can be performed spatially. Moreover, this information can be easily integrated with other sources of danger (lightning or socio-economic causes), within the framework of the geographic information systems derived for this purpose.

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