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Modeling moisture content in shrubs to predict fire risk in Catalonia (Spain)

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Abstract

We measured the moisture content in small branches and leaves of *Cistus monspeliensis* in four Mediterranean locations of Catalonia (Spain), from 1998 to 2000. The moisture of the measured fraction is also known as live fine fuel moisture, and it provides the most significant fuel in wild fires in this region. The aim of the study was to model the live fine fuel moisture based on meteorological variables from automatic weather stations close-by, and several components of the Canadian index of forest fire danger. We wanted to generalize the estimates of live fine fuel moisture from this species to other localities throughout the region from the data obtained by the network of automatic weather stations. We developed two models. The second model, independent of the actual sampling date, was more general, but the addition of the temporal component improved the predictive ability of the first model. We validated the models with data collected at two locations in 2001 and 2002. The resulting adjustments reached R^2 of around 80%, for the predicted against the observed values for the test period. Therefore, the methodology developed provides a reliable tool to predict forest fire risk throughout the year.

Keywords: Forest fire; Live fine fuel moisture; Drought index; *Cistus monspeliensis*

1. Introduction

The moisture content of small branches and leaves of shrubs (referred to as live fine fuel moisture, M) growing in fire prone regions determines the inflammability of the vegetation and therefore the potential for the outbreak and spread of wild fires. The lower the moisture content of the vegetation, the more difficult it is to prevent the advance of fire. Live fine fuel moisture in plants is conditioned by parameters related to environmental factors, and to the life history and ecophysiology of the particular plant species. Plants develop both morphological and physiological mechanisms in order to regulate their water content, and these adaptations are particularly apparent in plants from geographical areas regularly experiencing drought periods, such as the Mediterranean region. Live fine fuel moisture integrates variables related to species characteristics, climate, topography, and soils. Several authors have related live fine fuel moisture to flammability in Mediterranean species (Elvira and Hernando, 1989; Valette, 1993; Moro and Le Corre, 1993; Rochas, 1994), and have considered it to be an

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index of fire risk. Therefore, it is of interest because it can be used as a entry value in fire simulators such as BEHAVE (Burgan and Rothermel, 1984) or FARSITE (Finney, 1995). However the difficulty of determining this parameter has limited, till now, its generalized use over extensive areas. The direct determination of live fine fuel moisture is complex, and requires field sample collection, and gravimetric processing in the laboratory.

Cistus monspeliensis is a shrub that grows in Europe in the Mediterranean area, from Greece to the Iberian Peninsula (Tutin et al., 1978), mostly in warm and open environments. In Catalonia, the species is abundant in the shrublands developing on acid soils on areas close to the seashore (Bolòs et al., 1998). It is very common in the first stages of regeneration of the vegetation after wild fires. High temperatures associated with fires break the dormancy of its seeds (Aronne and Mazzoleni, 1989; Trabaud and Oustric, 1989; Trabaud, 1995). In areas where wild fires are very frequent, with a 6 years recurrence, *C. monspeliensis* can dominate the whole shrubland. The leaves of the species show few mechanisms to regulate transpiration, and under strong drought conditions, they wilt (Folch, 1981). Therefore, it is expected that the moisture content of small branches and leaves will show a strong variation following changes in the environmental conditions.

The Catalan Service of Fire Forest Protection established, in 1995, a network of localities where samples from several Mediterranean woody species were regularly collected during the summer, and live fine fuel moisture determined, following Countryman and Dean (1979), and Norum and Miller (1984). After 1998, the sampling methodology was improved, and moisture was sampled throughout the year. Previous studies found three different models for live fine fuel moisture dynamics, related to the functional types of the plants (Piñol and Ogaya, 1997). Sclerophyl species showed moisture variations during the budding period, remaining relatively constant during the rest of the year; soft-leaved species were highly dynamic in their moisture content all year around; and for *Pinus halepensis* it was always constant (Piñol and Ogaya, 1997). These results highlight the interest of species such as *C. monspeliensis*, whose moisture content changes with environmental conditions throughout the year, as indicators of fire risk. *C. monspeliensis* moisture decreased with the increase of the summer drought, and showed a good correlation with climate parameters from several meteorological observatories (Viegas et al., 1998).

The objective of the present study is to model variations in live fine fuel moisture of *C. monspeliensis* as a function of meteorological variables, and include data from several localities in order to assess to what extent the site effects have been described by the climatic variables (Connolly and Wachendorf, 2001). If we are able to successfully model variations in live fine fuel moisture for this species, which is common over a wide part of the most fire-prone Catalan region, based on meteorological variables routinarily obtained from automatic weather stations, and independent of the specific localities, we could predict a component of fire risk quite accurately at the regional scale without having to measure the actual live fine fuel moisture content of the plants.

2. Methods

2.1. Species and experimental design

C. monspeliensis is a Mediterranean shrub commonly around 1 m high, with soft leaves that fall if drought is very intense. It has been shown that its water content is very sensitive to seasonal changes and variations among years, and it is highly correlated to meteorological variables (Piñol and Ogaya, 1997; Viegas et al., 1998, 2001).

The Catalan Service of Fire Protection (Direcció General de Protecció de Riscos del Medi Natural) has a network of sites spread throughout the region of Catalonia where plant samples have been collected in a standard way since 1998. The sites were evenly distributed in areas of Mediterranean fire-prone woody vegetation, on sunny slopes less than 30%, with tree canopy less than 10%, and acidic substrate. Five sites with a good cover of *C. monspeliensis* were considered in the present study (Table 1). At each site, we defined beforehand transects along which we collected 20 branches from the upper part of the plant, with basal diameter less than 0.6 cm (Andrews, 1986) and more than 0.4 cm, because of high variability found on smaller branches in previous measurements. Samples were taken at noon every 15 days in summer, and once a month during the rest of the year. Dead matter remaining on the plant and fruits were eliminated.

Table 1
Sampling sites and their closest meteorological observatories

Site	Vegetation	Latitude	Longitude	Altitude (m)	Observatory	Altitude (m)	Latitude	Longitude	Distance apart (km)
Barcelona	Cisto-Sarothamnetum scoparii	41°26′52″E	02°08′39″N	310	Viladecans	13	41°17′58″N	02°02′23″E	19
Caldes	Lavandulo-Ericetum scopariae	41°48′56″E	02°50′58″N	160	Cassà de la Selva	176	41°52′33″N	02°55′42″E	9
Piera	Erico-Thymelaetum hirsutii	41°31′40″E	01°43′51″N	340	Sta C. de Queralt	718	41°31′52″N	01°22′06″E	30
Vilajuïga	Cisto-Sarothamnetum scoparii	42°20′43″E	03°06′28″N	150	Cabanes	31	42°18′26″N	02°57′21″E	13
Port de la Selva	Cisto-Sarothamnetum scoparii	42°20′52″E	03°13′05″N	140	Cabanes	31	42°18′26″N	02°57′21″E	23

The branches were stored in hermetically sealed plastic bottles and transported in a portable fridge to the laboratory, where they were weighed and oven-dried to constant weight. We determined live fine fuel moisture as

$$M = \frac{100(W_f - W_d)}{W_d}$$

where M is the live fine fuel moisture (%), W_f the fresh weight (g) and W_d is the dry weight (g).

2.2. Predictive variables

For each sampling site we selected a nearby meteorological observatory from the automatic meteorological network of the Catalan Department of the Environment, representing the climate of the site (Table 1). Automatic weather stations gave us hourly data with eight sensors for measuring the following variables: temperature, relative humidity, global solar radiation, net solar radiation, wind direction and velocity, rainfall and soil temperature at 50 cm. In the variable selection procedure, we built in many different variables by several methods (Table 2). Besides maximum, minimum and mean daily values, for several meteorological variables we calculated the mean value over different time periods (3, 7 and 15 days). We also calculated the sum of the daily variables over the same periods. In some cases, for the chosen period, we used the maximum or the minimum of the data too.

We added variables representing soil water reserve, R_{150} and R_{10} (Carrega, 1991). This is a meteorological calculation, and it is independent of soil depth and soil characteristics. However, it allowed us to compare the sites of the different automatic weather stations. Soil water reserve increased or decreased every hour as a function of the hourly Penman–Monteith evapotranspiration (E_{toh}, mm), and the hourly rainfall (P_{Vh}, mm), following the algorithm.

Case (a):

$$R_{act} = R + (P_{Vh} - E_{toh}) \quad \text{if } (E_{toh} - P_{Vh}) \leq 0$$

Case (b):

$$R_{act} = R - \left(R \times \frac{(E_{toh} - P_{Vh})}{R_{max}}\right) \quad \text{if } (E_{toh} - P_{Vh}) > 0$$

where R_{act} is the actual reserve (mm) (considering 150 or 10 mm the upper threshold for R_{150} and R_{10}, respectively, and 1 mm minimum for both), R the previous reserve (mm), and R_{max} is the maximum possible value (150 or 10 mm for R_{150} and R_{10}, respectively).

We also used as predictors of M several components of the Canadian Forest Fire Weather Index (Van Wagner, 1987), fine fuel moisture code (F_{FMC}), duff moisture code (D_{MC}), drought code (D_C) and buildup index (B_{UI}), calculated according to Van Wagner and Pickett (1985) from the mean meteorological values between noon and 1300, solar time. The Canadian Forest Fire Weather Index is an empirical index calculated for the Canadian fuel models. However, its use as a meteorological index of fire risk is in general use, even for Mediterranean countries. Some of its sub-indexes

Table 2
Variables initially considered for modeling the live fine fuel moisture (M) of *C. monspeliensis*

Meteorological variables	Symbol
Sum of daily maximum, minimum and mean temperatures 3, 7 and 15 days before sampling (°C)	T_{max3}, T_{max7}, T_{max15}, T_{min3}, T_{min7}, T_{min15}, T_{mean3}, T_{mean7}, T_{mean15}
Mean daily mean and minimum air relative humidity 3, 7 and 15 days before sampling (%)	H_{Rmean3}, H_{Rmean7}, $H_{Rmean15}$, H_{Rmin3}, H_{Rmin7}, H_{Rmin15}
Mean daily maximum wind speed 3, 7 and 15 days before sampling (m/s)	V_{max3}, V_{max7}, V_{max15}
Total rainfall over 3, 7 and 15 days before sampling (mm)	P_{V3}, P_{V7}, P_{V15}
Total evapotranspiration Penman–Monteith over 3, 7 and 15 days before sampling (mm)	E_{to3}, E_{to7}, E_{to15}
Total global radiation over 3, 7 and 15 days before sampling (MJ/m^2)	G_{R3}, G_{R7}, G_{R15}
Soil water reserve (mm)	R_{150}, R_{10}
Canadian Forest Fire Weather Index: fine fuel moisture code, duff moisture code, drought code, buildup index	F_{FMC}, D_{MC}, D_C, B_{UI}

have been found useful as predictors of M of different species under Mediterranean conditions (Viegas et al., 1999). These sub-indexes are daily indexes and they are related, mainly, to the moisture content of a given kind of dead fine fuel. In F_{FMC}, the fuel represented is a layer of pine needles, which dry quickly. The calculation requires air temperature, air humidity, wind speed and rainfall. D_{MC} represents slow-drying fuels and it can be related to the lower organic layer. To calculate this sub-index, temperature, air humidity, rainfall and a day-length factor are needed. D_C represents very slow-drying forest fuels and it can be related to some deep and compact organic layers. The calculation is based on air temperature, rainfall and a day-length factor. B_{UI} is an intermediate sub-index, calculated from the harmonic mean of D_{MC} and D_C. The calculation methodology of these sub-indexes is complex, and more than 20 equations are involved (Van Wagner and Pickett, 1985). We obtained the Canadian Forest Fire Weather Index by working with output data from the weather stations.

It is well known that plant moisture varies in relation to the plant's phenology, and M varies with the seasonal growth cycle (Schoeder, 1970). In order to take into account the intrinsic dynamics of the species, we also introduced into the modeling a function of the day of the year:

$$D_t = \cos\left(\frac{2\pi D}{365} - 0.59\right)$$

where D_t is a function of date (date), and D is the day of year between 0 and 365.

Overall, we initially considered 33 potentially predictive variables (Table 2). Because of the large number of initial meteorological variables, we performed an exploratory Principal Component Analysis to identify the main groups of independent variables (Table 3) (Hair et al., 1999).

2.3. Modelling process

To calibrate the models, we used M data from March 1998 to October 2000 for the localities of Barcelona, Caldes, Piera and Vilajuiga. We used multiple linear backwards regression and confirmatory general linear modelling (GLM) to explore the relationships between the live fine fuel moisture (M) and the predictive variables. Previously, we checked for normality and homogeneity of variance.

Initially, we introduced site as a fixed factor. The meteorological predictor variables chosen from the first three factors from the results of Principal Components Analysis were air temperature, air humidity and soil water reserve (Table 3). We used date as an independent variable. All second order interactions were incorporated into the initial models. Higher order interactions, and interactions with site were not included in the modeling. In accordance with the objective of the present study, the parameter estimates for the different sites in the final models are not to be different from zero, after removing variables with a P-value over 0.05. In order to make the model even more general, we also tried modeling M without introducing the variable date. This variable was replaced by an air temperature component because of the high linear relationship between date and T_{max15} ($r = -0.93$, $P < 0.001$).

The models were validated by testing the M data at two localities, Caldes and Port de la Selva, from January 2001 to March 2002.

Table 3
Variables with load higher than 0.45 into the six factors obtained from principal components analysis, and interpretation of the factors

Factors	Cumulative explained variance (%)	Variables
Air temperature	36	B_{UI}, D_{MC}, D_C, T_{max3}, T_{mean3}, T_{min3}, E_{to3}, T_{max7}, T_{mean7}, T_{min7}, E_{to7}, T_{max15}, T_{mean15}, T_{min15}, E_{to15}, R_{150}, G_{R3}, G_{R7}, G_{R15}
Air humidity	55	H_{Rmean3}, H_{Rmin3}, H_{Rmean7}, H_{Rmin7}, $H_{Rmean15}$, H_{Rmin15}
Soil water reserve	64	R_{150}, B_{UI}, D_{MC}, D_C, P_{V15}
Rainfall	73	F_{FMC}, P_{V3}, P_{V7}, P_{V15}, R_{10}
Wind speed	82	V_{max3}, V_{max7}, V_{max15}
Radiation	90	G_{R3}, G_{R7}, G_{R15}, E_{to3}, E_{to7}, E_{to15}

Table 4
Model coefficients stimates (B), standardized coefficients (β), t-statistic (T) significance (Sig.), and Tolerance is one minus the variability portion explained by the rest of the predictors (Tolerance) for the two proposed models on live fine fuel moisture in *C. monspeliensis* when the T-values are significant at less than 0.05

Model	Variables	Parameter estimates			T	Sig.	Tolerance
		B	S.E.	β			
1	Intercept	99.1	7.8		12.7	0.000	
	Fifteen last days sum of daily minimum air temperature (T_{min15}, °C)	−1.6E−02	0.04	−0.042			0.109
	Soil water reserve (R_{150}, mm)	0.34	0.04	0.396	8.3	0.000	0.552
	Date (D_t)	10.4	8.8	0.218			0.036
	Daily minimum air relative humidity, average 7 last days (H_{Rmin7}, %)	1.6E−02	0.13	0.005			0.739
	T_{min15} (°C) × date (D_t)	0.23	0.03	0.829	7.5	0.000	0.102
	H_{Rmin7} (%) × date (D_t)	−0.51	0.17	−0.515	−3.0	0.003	0.043
2	Intercept	68.4	16.0		4.3	0.000	
	Buildup index (B_{UI})	−0.30	0.03	−0.466	−9.4	0.000	0.564
	Fifteen last days sum of daily maximum air temperature (T_{max15}, °C)	0.60	0.11	1.63	–	–	0.016
	$(T_{max15})^2$	−1.2E−03	0.000	−2.09	−7.0	0.000	0.016

The T-significance values have been omitted for the variables in a significant interaction. Using the calibration data for Barcelona, Caldes, Piera and Vilajuïga for the period March 1998 to October 2000.

3. Results

3.1. Calibration

We developed two models, successfully accounting for site variability. Model 1, which included date, predicted that the effect of temperature and air moisture on live fine fuel moisture is mediated by the time of year (Table 4). This model can be represented graphically by a plane characterizing the effect of T_{min15} and H_{Rmin7} upon the M. The slope of such a plane varies depending on the time of the year due to the interaction with date. Soil water availability (R_{150}) was another important predictive variable in this model; M increased lineally with R_{150}, after fixing the other variables (Fig. 1). According to this model, M in *C. monspeliensis* can be calculated as

$$M_1 = 99.1 + 0.016T_{min15} + 0.34R_{150} + 10.4D_t + 0.016H_{Rmin7} + 0.23T_{min15}D_t - 0.51H_{Rmin7}D_t$$
$$(\text{adjusted } R^2 = 0.82,\ P < 0.000)$$

Model 2 was constructed without introducing the variable date. Instead, a quadratic component of maximum temperature was added, which was significant and appeared in the final model (Table 4). Therefore, because of this quadratic component, M can increase or decrease with temperature. The second model included also the B_{UI} (*buildup index*), which integrates the effects of temperature, soil water reserve and air moisture (Fig. 2). According to this model, M in *C. monspeliensis* can be calculated as

$$M_2 = 68.4 - 0.30B_{UI} + 0.60T_{max15} - 0.0012(T_{max15})^2$$
$$(\text{adjusted } R^2 = 0.79,\ P < 0.000)$$

where

$$B_{UI} = f(P_v, T_n, H_{Rn}, D_l)$$

and P_v is the rainfall over last 24 h (mm), T_n the temperature at noon (°C), H_{Rn} the relative humidity at noon (%) and D_l is the day-length factor.

No self-correlation of errors can be observed in any of both models, with a Durbin–Watson statistic of 1.8 for the first model and of 1.7 for the second one. The typified residues extend from −3 to 3 and are normally distributed among both models. Model 2 had some collinearity problems, and showed higher errors than model 1 for the calibration series (Table 5). The

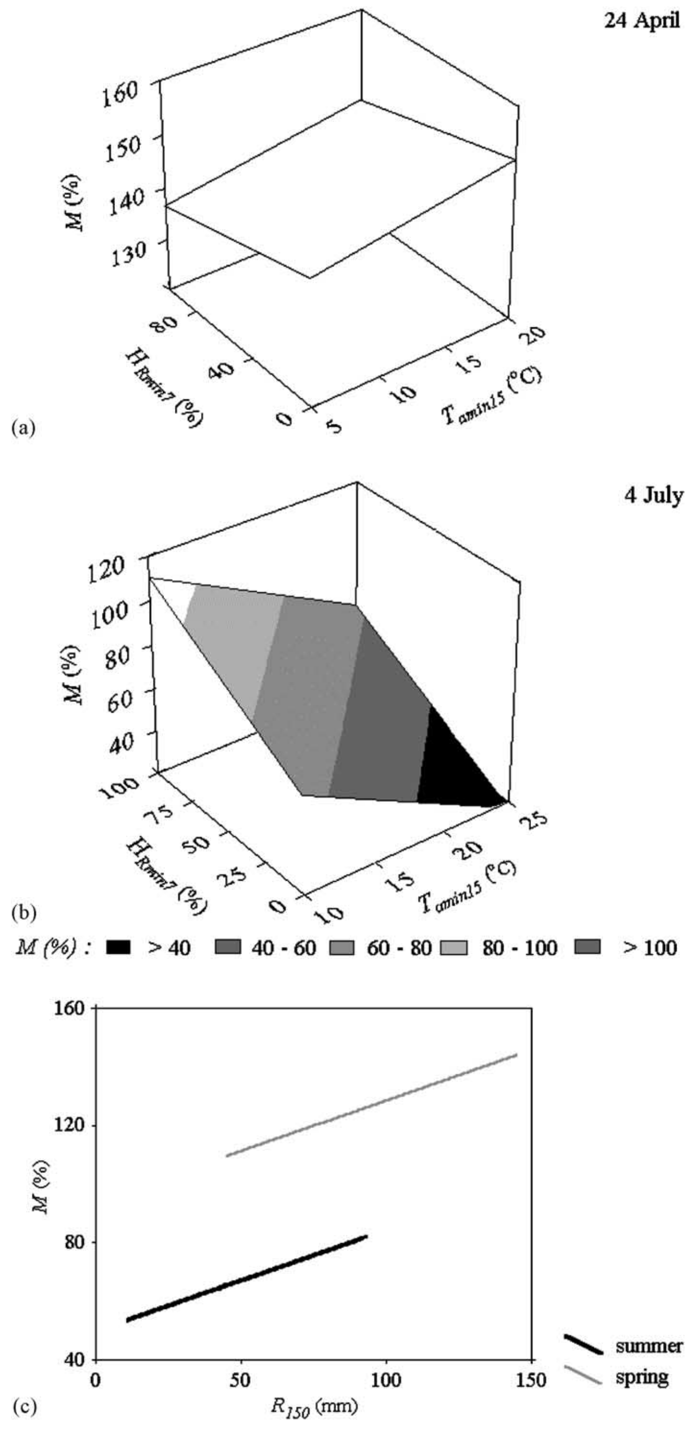

Fig. 1. Partial results for model 1. Effect of the averaged daily minimum relative air humidity the last 7 days (H_{Rmin7}), and average of the minimum daily air temperature the last 15 days (T_{amin15}) on live fine fuel moisture (M) in model 1, within the range of values of the other variables in the model. $T_{\mathrm{amin15}} = T_{\mathrm{min15}}/15$. The results are shown for two different seasons: (a) spring (24 April; soil water reserve ($R_{150} = 120$ mm), and (b) summer (4 July; $R_{150} = 20$ mm). (c) Effect of R_{150} on M in model 1, within the range of values of the other variables in the model (4 July; $T_{\mathrm{amin15}} = 17.6\,^{\circ}\mathrm{C}$; $H_{\mathrm{Rmin7}} = 35\%$; and 24 April; $T_{\mathrm{amin15}} = 15\,^{\circ}\mathrm{C}$; $H_{\mathrm{Rmin7}} = 60\%$).

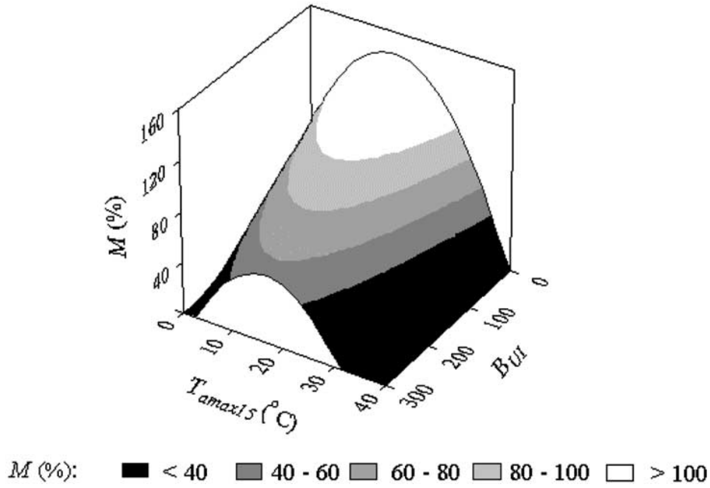

Fig. 2. Partial results for model 2. Effect of buildup index (B_{UI}) and average of the daily maximum air temperature the last 15 days (T_{amax15}) on live fine fuel moisture (M) in *C. monspeliensis* in model 2; $T_{\mathrm{amax15}} = T_{\mathrm{max15}}/15$.

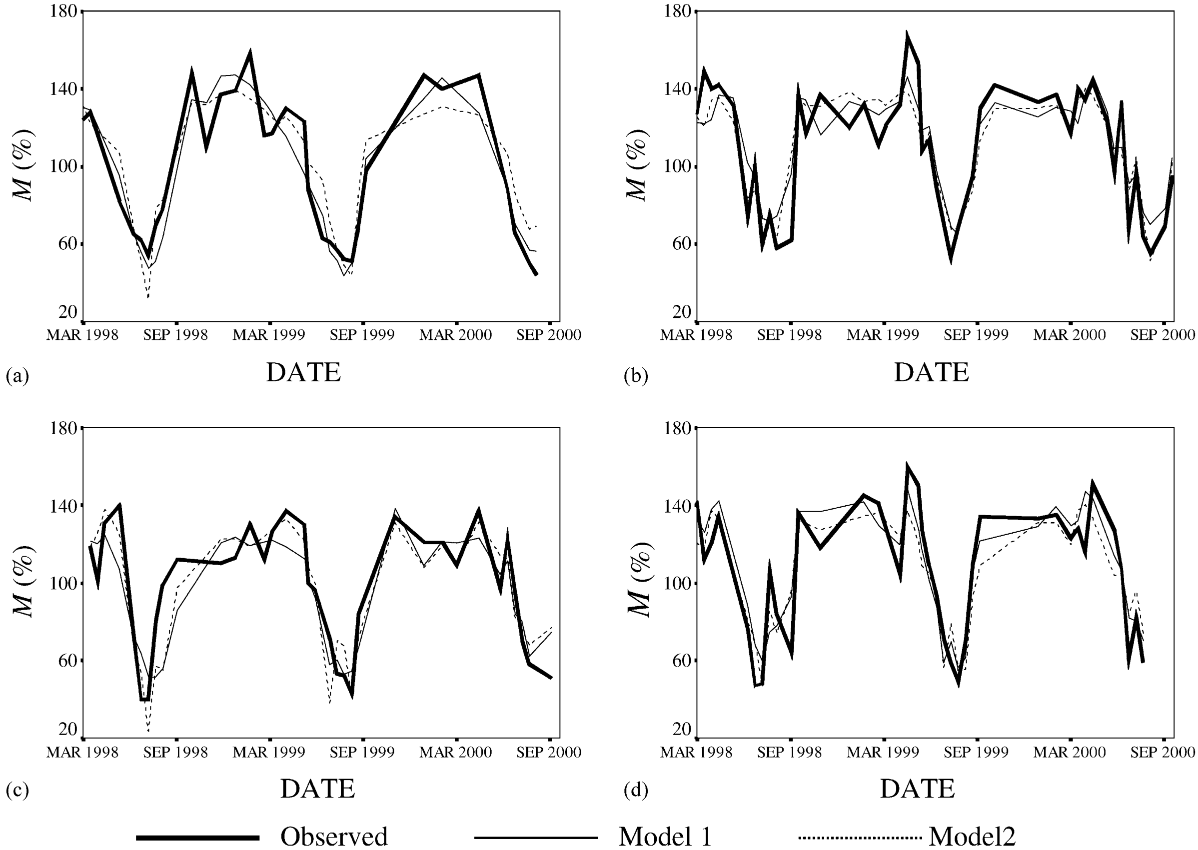

Fig. 3. Observed and predicted values of live fine fuel moisture (M) in *C. mospeliensis* at four locations in Catalonia using calibration period. Both the predictions by models 1 and 2 are shown: (a) Barcelona, (b) Caldes de Malavella, (c) Piera and (d) Vilajuïga.

Table 5
Mean error and mean absolute percentage error (MAPE) for the two proposed models of the live fine fuel moisture in *C. monspeliensis*

Site	Data	N	Model 1		Model 2	
			Mean error	MAPE	Mean error	MAPE
Barcelona	Fitting	33	1.1	10.5	−3.3	15.8
Caldes	Fitting	44	−2.0	12.3	0.2	10.3
Piera	Fitting	36	3.2	14.8	1.6	14.7
Vilajuïga	Fitting	37	−1.6	13.0	1.3	14.4
Total	Fitting	150	0.0	12.7	0.0	13.6
Caldes	Testing	20	5.9	12.8	13.0	15.0
Port de la Selva	Testing	15	8.0	10.9	19.3	19.7
Total	Testing	35	6.8	12.0	15.7	17.0

Using the calibration data for the period March 1998 to October 2000 (fitting) and the validation data for the period January 2001 to March 2002 (testing). N is the number of sampling dates.

main deviations from actual data in both models corresponded to the budding period. Both models underestimated live fine fuel moisture in this period, particularly model 2 (Fig. 3).

3.2. Validation

The values predicted of M in *C. monspeliensis* for the years 2001 and 2002 follow the same pattern as the fitting ones, not only in the site used for the calibration (Caldes) but also for another one not used in this calibration (Port de la Selva). Model 1 gives a better prediction than model 2 (Table 5), with a correlation coefficient for the predicted values against observed values for the test period of 0.85 as contrasted with a coefficient of 0.83 in model 2.

4. Discussion

The two final models included components related to temperature, soil water availability and atmospheric water content (Table 4). These factors are related to the water economy of the plants, particularly critical in Mediterranean regions. Water balance in the plants depends on water flux inputs by root absorption and water flux losses by leaf transpiration. Both soil and atmospheric water shortages can induce stomatal closure, as shown by Castell and Terrades (1993) for several Mediterranean species.

It is important to point out the dependence of the interactions between meteorological variables and biological processes on the date. In the Mediterranean spring, with medium to high R_{150} values, an increase in air temperature stimulates primary production, and enhances bud growth. Buds have high water content, and increase M. In summer time, during the dry season, the potentials necessary to extract the low water available in the soil are very high and, for the same increase in temperature, the plant cannot compensate the water lost by the increased transpiration; therefore, M decreases (Figs. 1 and 2). For the same reason, the fall of atmospheric humidity in summer has a great impact on M, and for this period the meteorological situations increase fire risk. Therefore, the model can simulate episodes of high E_{to} that can occur in synoptic situations of high risk of forest fires (Montserrat, 1999).

Nonetheless, the inclusion of the variable date in the models limits their generalization, because in different sites plants can shift phenological rhythms. For this reason, modeling based on the calendar has to be carefully considered (Connolly and Wachendorf, 2001). However, at the scale considered in this study (Catalonia, NE of Spain), model 1 can be considered perfectly suitable to predict M of the studied species.

Because of the introduction of the variable date, model 1 can generate errors when infrequent meteorological situations occur. Consequently, rain episodes in July 2001, very rare in a Mediterranean summer and non-existent in the series used for calibration to fit the model, were better predicted by model 2, whereas moisture increases in the budding period and strong fuel moisture decreases in summertime were better predicted by model 1 (Fig. 4).

One of the characteristics of Mediterranean climate is the presence of periods of frequent storms. This phenomenon can be very localized, distorting water availability calculations. This could explain discrepancies between predicted and observed values in some periods for all the sites, as the weather stations were not located at exactly the same sites where plants were sampled (Fig. 3).

Nowadays, the Catalan Service of Fire Forest Protection uses a map of live fine fuel moisture of *C. monspeliensis* as an auxiliary tool to evaluate fire risk. The models presented here can be used to estimate M in

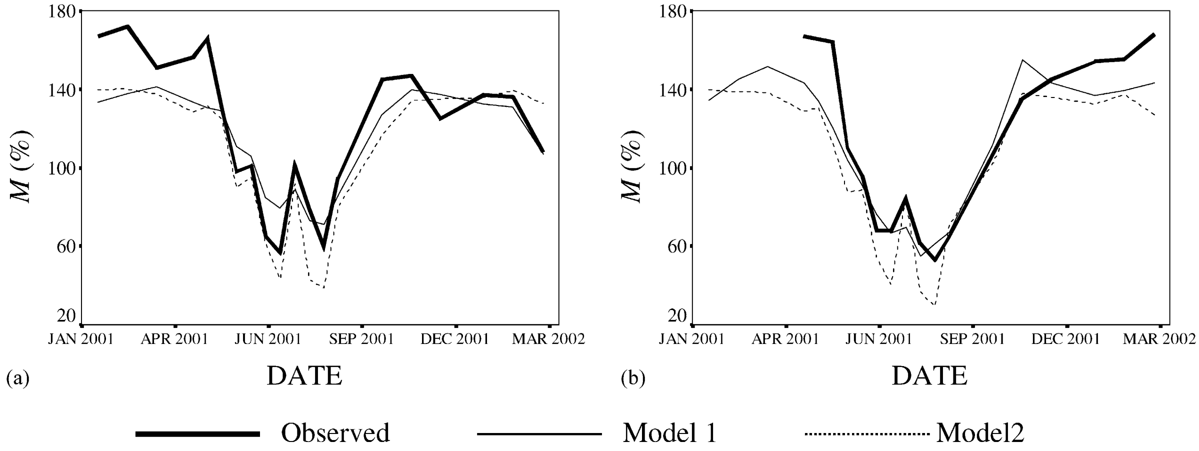

Fig. 4. Observed and predicted values of live fine fuel moisture (*M*) in *C. mospeliensis* at two locations in Catalonia using validation period. Both the predictions by models 1 and 2 are shown: (a) Caldes de Malavella and (b) Port de la Selva.

historical fires, calculate the current fuel moisture and, combined with methods of meteorological prediction, forecast how present-day conditions can affect the fire risk later in the year.

5. Conclusions

Seasonal variations in moisture content of *C. monspeliensis* could be simulated using mathematical models that included temperature, atmospheric moisture, estimates of water availability, and their interactions with time. The resulting adjustments reached R^2 of around 80% for the predicted against the observed values for the test period, and were independent of the particular sampling location.

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