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Combining NDVI and surface temperature for the estimation of live fuel moisture content in forest fire danger rating

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Abstract

This paper presents an empirical method for deriving fuel moisture content (FMC) for Mediterranean grasslands and shrub species based on multitemporal analysis of NOAA–AVHRR data. The results are based on 6 years of field measurements of FMC. The empirical function was derived from a 4-year series and includes multitemporal composites of AVHRR's normalized difference vegetation index (NDVI) and surface temperature (ST) values, as well as a function of the day of the year. It was tested using data from 2 other years on the same site as well as other sites with similar species but very distant from each other and with different elevation ranges. The results show that the model provides a consistent estimation of FMC, with high accuracies for all study sites and species considered, with r^2 values over 0.8 for both grasslands and shrub species. This performance enables the model to be used to derive spatial estimator of FMC, which is a key factor in operational fire danger management in Mediterranean conditions.

Keywords: Multitemporal analysis; Fuel moisture content; Surface temperature; Forest fires; AVHRR

1. Introduction

Most research concerning the use of remote sensing techniques for forest fire applications have focused on detecting active fires, mainly using middle-infrared images (Ahern et al., 2001; Martín et al., 1999). In recent years, burned land mapping is also widely extended on both local and global scales with a wide range of sensors (Grégoire et al., 2003; Justice et al., 2002). However, fewer activities have been reported regarding the pre-fire phase, which is critical to better manage fire suppression resources, to reduce accidental fire ignitions and mitigate fire propagation rates. Within this approach, remote sensing tools may greatly help the characterization of the fuel bed, with respect to both biomass loads and structural properties commonly referred to as fuel types (Chuvieco et al., 2003b; Keane et al., 2000; Riaño et al., 2002) on one hand, and fuel water status on the other. The latter will be the basis for this paper.

The moisture content of fuel is a critical parameter in fire ignition because flammability is closely dependent on it (Dimitrakopoulos & Papaioannou, 2001). Dead fuels lying on the forest floor (fallen branches, litter, foliage) are the most dangerous because they are drier than live fuels and more dependent on rapid atmospheric changes. The moisture content of live fuels has a marginal role in fire ignition, but it is critical in fire propagation modelling because the amount of water is directly related to the rate of fire spread (Carlson & Burgan, 2003; Sneeuwjagt & Peet, 1985; Viegas, 1998). Commonly, the estimation of dead fuel moisture content (FMC) is based on meteorological danger indices, which attempt to account for the adsorption–

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evaporation relationships in inert materials (Simard, 1968). Applying those indices to live fuel moisture trends is complex because live plants are much less dependent on atmospheric conditions than dead materials, given their mechanisms to extract water from the soil reserve and reduce evapotranspiration. Recent research have obtained strong nonlinear relationships between live fuels moisture content and long-term meteorological codes (Castro et al., 2003; Viegas et al., 2001), but their results are species-dependant. Additionally, meteorological data are frequently not available for fire prone areas, which require the application of spatial interpolation techniques that may introduce additional noise.

Remote sensing data have been frequently used to estimate the water status of plants, both in agricultural and ecological research (Carter, 1991). In the forest fire danger literature, the water content of plants is commonly expressed as fuel moisture content (FMC), defined as the percentage of water weight over sample dry weight:

$$\mathrm{FMC} = \left(\frac{W_\mathrm{w} - W_\mathrm{d}}{W_\mathrm{d}}\right) \times 100 \qquad (1)$$

where W_w is the wet weight and W_d is the dry weight of the same sample. This variable is mostly obtained through field sampling using gravimetric methods (wet samples are weighed, then oven-dried at 60 or 100 °C; Viegas et al., 1992) and weighed again to determine the dry weight). FMC can be referred to for both live and dead species.

Within the context of fire danger estimation, good correlations between live FMC and multitemporal series of NOAA–AVHRR data have been found for herbaceous species using normalized difference vegetation index (NDVI) data (Chladil & Nunez, 1995; Paltridge & Barber, 1988), but problems were found for shrubs and trees (Chuvieco et al., 1999; Leblon, 2001).

However, in the remote sensing literature, water content is usually expressed as the equivalent water thickness (EWT: water content/leaf surface), instead of FMC, because EWT is directly related to the absorption depth of the leaf. Laboratory spectral measurements have been performed to estimate EWT, showing divergent results in the visible and near infrared (NIR) depending on whether they were done at leaf or canopy level, because of the indirect effects of water content changes on the whole plant (mainly through the modification of the leaf area index [LAI]). However, short wave infrared bands (SWIR: 1.1–2.5 μm) have proven to be the most sensitive to EWT variations (Bowman, 1989; Cohen, 1991; Datt, 1999), although additional bands are required to reduce the uncertainty caused by other variables affecting SWIR reflectance. Simulation studies based on radiate transfer models have recently identified a ratio of the near infrared (NIR) and SWIR band as the most appropriate for retrieving EWT at leaf and canopy levels (Ceccato et al., 2001, 2002b), as previous experimental studies had suggested (Hunt & Rock, 1989). In spite of this progress, to estimate EWT from reflectance measurements, additional efforts need to be made to derive FMC from satellite data in fire danger studies because the amount of water per area is not as critical in fire propagation as the quantity of water per dry mass. Assuming that the specific leaf weight (SLW = dry leaf weight/leaf area) is constant over time for single species, FMC may be considered a function of EWT (Chuvieco et al., 2003a). Still, when this relation changes significantly over time, FMC may be indirectly estimated as a result of the effects of plant drying on the decrease in leaf area index (LAI) values (mainly in shrub species) and chlorophyll content (herbaceous species). Therefore, the estimation of FMC from reflectance measurements can be undertaken when the estimation is restricted to single or (physiologically) similar species. This explains why strong empirical relations between FMC and satellite variables have been found by several authors (Ceccato et al., 2003; Chuvieco et al., 2002; Leblon, 2001). Recent studies have shown that by better estimating other factors affecting canopy reflectance in the NIR and SWIR bands, particularly the leaf area index (LAI), it is possible to apply radiative transfer model (RTM) inversion techniques to obtain a reliable estimation of EWT and FMC (Zarco-Tejada et al., 2003).

Additionally, plant canopy temperature is affected by FMC changes because water availability is a critical parameter in plant evapotranspiration. Based on this principle, several authors have tested the use of thermal images to estimate plant water content, mainly on crops (Jackson et al., 1981; Moran et al., 1994). Forest and shrub canopies are more complex, but some workers have shown good relationships between the differences in air and surface temperature (ST) and fire danger hazard (Vidal et al., 1994). Because these differences are closely dependent on the density of vegetation cover, the combined use of surface temperature (ST) and NDVI have shown statistically stronger relationships with water content than either of the two variables alone (Alonso et al., 1996; Chuvieco et al., 1999; Prosper-Laget et al., 1995).

2. Objectives

This paper presents the assessment of an empirical approach to estimate FMC of Mediterranean species based on multitemporal analysis of NOAA–AVHRR images. The proposed method is built on statistical fitting of field collected FMC and satellite data, using a function of the day of the year to take into account the seasonal trends of FMC. The empirical estimation was intended for operational retrieval of FMC in fire danger assessments. Considering the current limitations of meteorological networks and fuel type maps, it was determined that the FMC estimation should not require external data sets other than the information derived from the AVHRR images and very simple vegetation maps. The estimation was targeted at grassland and shrub species, which are the most dangerous in fire propagation of surface fires.

The empirical fitting was based on a long time series of field measurements of FMC for the Cabañeros National Park study site (Central Spain), but it was validated by collecting field measurements at other sites with similar species.

Previous work showed a strong statistical relationship between AVHRR-derived variables and FMC for the Cabañeros study site using only summer images (Chuvieco et al., 2003a). In that paper, 2 years of field data were used for calibrating the model and 2 more years for validation in the same study site. Additionally, strong relations were also found for Landsat-TM images (Chuvieco et al., 2002) and SPOT-Vegetation images, showing consistent trends among the three sensors (Chuvieco et al., in press). This paper follows the same trend towards finding consistent relations between FMC and satellite-derived variables, for operational use of satellite data in fire danger estimation. In this case, the model is applied to both spring and summer data, uses 4 years for calibration and 2 more for validation in the same study site, as well as five additional validation sites, located far away from the calibration area. Additionally, it introduces a function of the day of the year to model the effect of the seasonal trends.

3. Field work

One of the key elements to obtain a sound empirical estimation in remote sensing research is the availability of long time series of field data. In the case of FMC, few studies have been based on field measurements (Chladil & Nunez, 1995; Chuvieco et al., 1999; Paltridge & Barber, 1988) because they are costly and very time consuming. Additional problems arise when these measurements need to be related to coarse spatial resolution images (above 500-m pixel size), which are currently the only source of potential FMC estimation at the required temporal frequency. Field measurements must include valid samples of large areas, on which the satellite images will be acquired. The scaling-up of field measurements has been analysed within the scientific community involved in global change studies (DeFries & Townshend, 1994; Quattrochi & Goodchild, 1997). Nested sampling is a common strategy in this regard, and it involves collecting data from plots of different sizes and levels of detail, while acknowledging the convenience of working with homogeneous areas for calibration purposes.

For this project, the Cabañeros National Park (located in Central Spain: Fig. 1) was used as a calibration site because it offered unique opportunities for testing relations between FMC and satellite-derived variables. First, the central area of the park is covered by grassland and shrublands on very gentle slopes. Because it is a protected area, no agricultural practices are carried out, and therefore, temporal changes are associated to vegetation seasonal trends rather than crop alterations. Fuel types sampled were grasslands (three plots) and several shrub species (two plots): *Cistus ladanifer, Erica australis, Phillyrea angustifolia* and *Rosmarinus officinalis*. Plot sizes were 50 × 50 m, located 3 to 5 km apart, along a range of 20 × 5 km. A complete description of the fieldwork may be found in Chuvieco et al. (2003a). In this paper, results will be reported for grasslands and *C. ladanifer*, a shrub species widely extended across the Mediterranean basin. *R. officinalis*, another well-extended Mediterranean shrub, will only be used in the assessment but not in the empirical fittings. In this way, it will test the potential of extending the empirical method to other species with similar ecological characteristics.

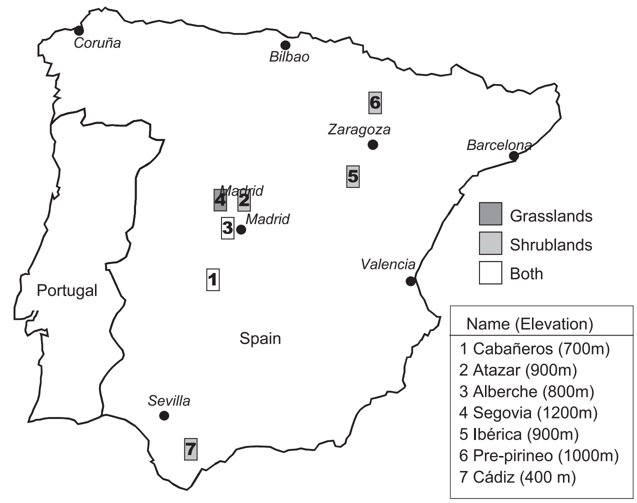

Fig. 1. Location of the sampling plots.

Field measurements were taken from early April to the end of September. For the model calibration, a time series from 1996 to 1999 was used. These samples were collected every 8 days. For validation purposes, another field campaign was carried out in 2001 and 2002. In this case, the samples were collected every 16 days because previous analysis did not show shorter time changes in FMC values. In each plot, three samples per species were collected. Average values per plot and period were computed.

Long-term trends of FMC values were compared for the different grassland and shrubland plots located in Cabañeros in order to test whether they were showing local or regional differences in FMC trends. Considering the large distance between plots (3–5 km apart), if significant differences in average values between plots of grasslands or shrublands were not found, it could be concluded that FMC temporal changes of these two vegetation types are more significant than those changes caused by their spatial diversity. Consequently, field measurements of small plots could be considered as representative of the temporal variation of FMC for large plots. In this way, our field measurements could be soundly related to coarse resolution satellite images.

During 2001 and 2002, a different set of field measurements was taken in other regions of Central Spain for validation purposes (Fig. 1): a site located in the province of Segovia was covered with grasslands; Atazar–Alberche with grassland and shrubs (a mixture of *C. ladanifer* and *R. officinalis*); Iberica and Pre-pirineo with shrubs (*R. officinalis* and other shrub species), and Cadiz with *C. ladanifer*. These plots are 200 to 500 km apart from the Cabañeros site and have different elevations but include similar species as they are part of the Mediterranean ecosystem (with the exception of the Pre-pirineo site). The plots were selected so as to include homogeneous plant coverage on as gentle slopes as possible. However, the shrub species were frequently mixed, even with some trees. Among the different mixtures, only those plots with a significant coverage of *C. ladanifer* or *R. officinalis* (more than 60%) were selected for validation purposes. To assure consistency in the results, the field protocol of these assessment sites was the same as that of Cabañeros.

4. Satellite image processing

AVHRR images were acquired by the University of Alcala's HRPT receiving station. Raw digital to reflectance conversion was based on NOAA coefficients (including degradation rates), and surface temperature (ST) was based on methods proposed by Coll & Caselles (1997). Geometric corrections were based on orbital models and multitemporal matching was improved by manual control points and automatic correlation. Daily data were synthesized into 8-day composites using maximum NDVI values. The median value of a 3×3 pixel window was extracted from each composite and correlated against field measurements.

As mentioned, when comparing AVHRR images and field measurements, the potential noise caused by the great differences within the area covered may be reduced when using average values of species, instead of single plot averages. For instance, average values of grasslands collected in a length of 10 km (three plots separated linearly 5 km each) would be a better representation of what an AVHRR pixel is actually measuring than single plot measurements.

5. Model construction

Several authors have discussed the pros and cons of empirical and theoretical models in remote sensing research (Strahler et al., 1986). Theoretical models have two main advantages: generalizing power and a better understanding of the parameters involved. However, they are complex to generate because they require many input parameters that are often unavailable and are difficult to validate. Empirical models are commonly based on statistical analysis. They are simpler to formulate and provide a quantitative validation on their exactness, but they are difficult to generalize, especially when statistical relations are not based on physical properties.

In the field of water content estimation, a whole range of theoretical models has been proposed in recent years, most of them based on the radiative transfer function (Baret & Fourty, 1997; Ceccato et al., 2001; Ceccato et al., 2002b; Jacquemoud et al., 1996; Zarco-Tejada et al., 2003). They are solid approaches but require further assessment and must demonstrate their operational application with field campaigns. These models estimate the EWT, which is the variable directly associated to leaf water absorption. FMC is equal to EWT divided by SLW. EWT can be estimated using a radiative transfer function, but dry matter content cannot be directly retrieved because the water is masking its effect on reflectance (Jacquemoud et al., 2000). For this reason, Zarco-Tejada et al. (2003) use a simplified inversion model to obtain dry matter for FMC estimation, after deriving EWT from a radiative transfer model.

Empirical fittings for the estimation of FMC from satellite data have been proposed by several authors (Alonso et al., 1996; Chladil & Nunez, 1995; Chuvieco et al., 1999, 2002, 2003a; Hardy & Burgan, 1999; Paltridge & Barber, 1988). Most commonly, these studies were based on AVHRR images, although there are also some examples using Landsat-TM images (Chuvieco et al., 2002).

For this project, the empirical model was based on linear regression analysis, where FMC was the dependent variable and the independent variables were AVHRR variables, NDVI and ST, and a function of the day of the year. Two models were generated, one for grasslands and one for shrubs. The major physiological differences between these two communities made it advisable to split the fittings. As mentioned, *C. ladanifer* was selected as a representative of Mediterranean shrub species because it is widely represented in Spain. Other species of the same family (*Cistus* sp.) are also broadly distributed across the Mediterranean basin.

The statistical model was built from 88 periods (22 periods of 8 days during 4 years: 1996 to 1999), covering spring and summer conditions of the Cabañeros National Park. The time series include a wide range of rain patterns, with some dry years (1999 and 1997 with precipitation close to 200 mm in 6 months), and more humid ones (1996 and 1998), with 250 and 230 mm, respectively.

The equation was validated using data from the same study area (Cabañeros), as well as the other study sites previously described during the 2001 and 2002 spring and summer seasons.

Satellite variables considered in the linear regression were NDVI and ST. The former would be positively related to FMC because the drying of the plant reduces chlorophyll activity in grasslands, as well as leaf area index in shrub species. On the contrary, ST would be expected to be negatively related to FMC because the cooling effect of evapotranspiration is reduced when plants get dry and introduce mechanisms to reduce water loss.

Before obtaining the estimations of FMC from linear regression models, an analysis of trends between FMC and these two variables (NDVI and ST) was undertaken. In a similar way to other study areas (Alonso et al., 1996; Kalluri et al., 1998; Moran et al., 1994; Prosper-Laget et al., 1995), NDVI showed a negative correlation with ST in both grasslands and shrublands for the spring and summer seasons. This trend must be related to the physiological reaction of plants to higher temperatures and lower moisture contents, which, depending on the plants, may change leaf colour, deteriorate leaf structure, modify leaf angle distribution by leaf curling or reduce LAI by leaf loss, and/or decrease evapotranspiration. Based on these relationships, some authors have proposed a regression model of NDVI and ST to estimate plant evapotranspiration (Kalluri et al., 1998) and fire hazard levels (Prosper-Laget et al., 1995). A scatterplot of NDVI against ST for different FMC values observed in the Cabañeros site showed the trend towards the appearance of low values of FMC when low values of NDVI and high ST values occur, both for grasslands and shrublands (Fig. 2). The trends are more evident for grasslands because they present a wider range of both FMC and NDVI values.

Following the logic of Verstraete and Pinty (1996), the design of an optimal index for discriminating different FMC values should be based on lines perpendicular to the main axis of NDVI and ST variation, which show potential sensitivity for discriminating FMC values.

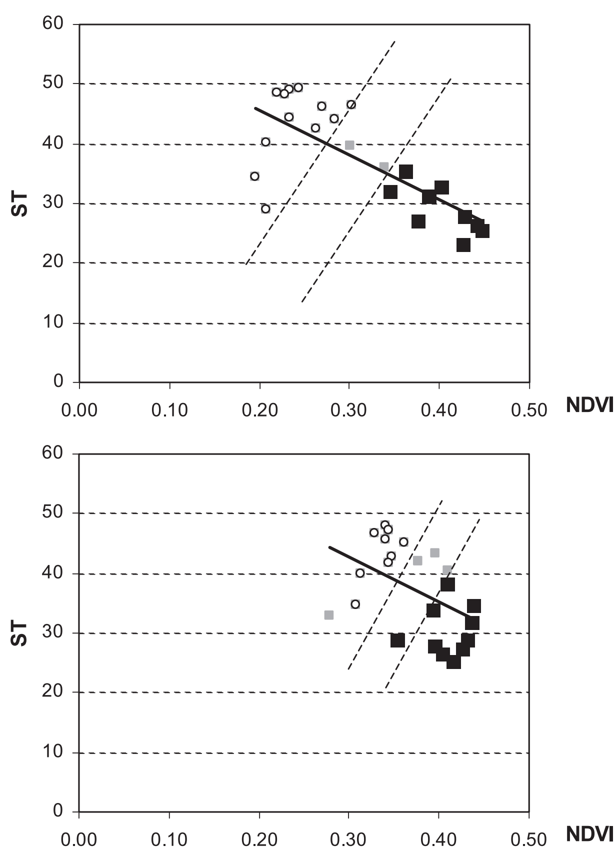

Fig. 2. Relations between NDVI–ST and FMC. Grasslands (top) and shrublands (Bottom). Black boxes refer to FMC > 100% in grasslands and 110% for shrublands; white boxes, FMC < 35% in grasslands and < 80% for the shrublands; and grey boxes, the intermediate values. Solid line is the regression of NDVI and ST. Dotted lines represent ranges of FMC in the inverse relation of NDVI and ST.

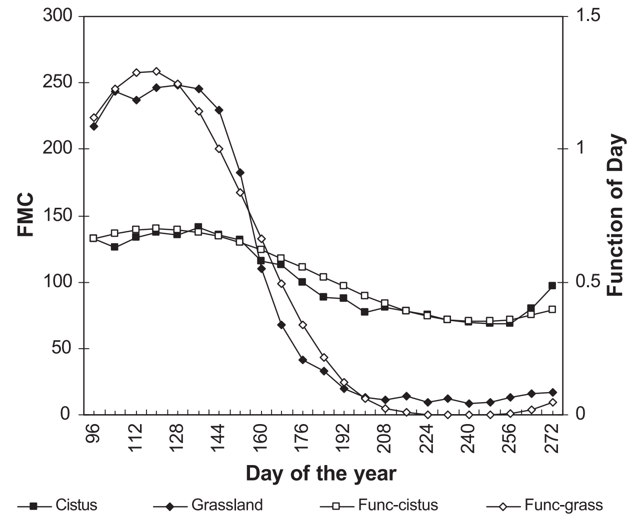

Fig. 3. Average values of FMC for grassland and *C. ladanifer* in 6 years of Cabañeros field data. The function of the Day of the Year for each vegetation type is also included.

Additionally, a temporal variable based on the day of the year (from 1 to 365) was included in the empirical fitting to take into account seasonal trends in FMC, following a logic already tested in Mediterranean conditions (Castro et al., 2003; Chuvieco et al., in press). Considering that these temporal trends are more contrasted for grasslands than shrublands, two different functions were computed:

$$\mathrm{FD_g} = (\sin(1.5 \times \pi \times (\mathrm{Dy} + \mathrm{Dy}^{1/3})/365))^4) \times 1.3 \tag{2}$$

$$\mathrm{FD_c} = ((\sin(1.5 \times \pi \times \mathrm{Dy}/365))^2) + 1) \times 0.35 \tag{3}$$

where $\mathrm{FD_g}$ and $\mathrm{FD_c}$ are the functions of the day of the year (Dy) for grasslands and *C. ladanifer*, respectively, and the sine angle is computed in radians. This function was derived by fitting a periodical function to the temporal average of FMC values of grassland and *C. ladanifer* for 6 years of measurements in Cabañeros (1996–2001), as shown in Fig. 3. The function has a wider variation for grasslands than *C. ladanifer*, which agrees with the stronger contrast in the water content of herbaceous species. The constant terms were used just to scale the functions in a similar range among them.

6. Results

For the 6 years of field data, the *t* tests applied to the temporal differences of the three grassland plots in the Cabañeros site, separated between 3 and 5 km, did not show significant differences among them (Fig. 4). Similarly, the average temporal trends of the two shrub plots located 3 km apart were not significantly different. Therefore, it could

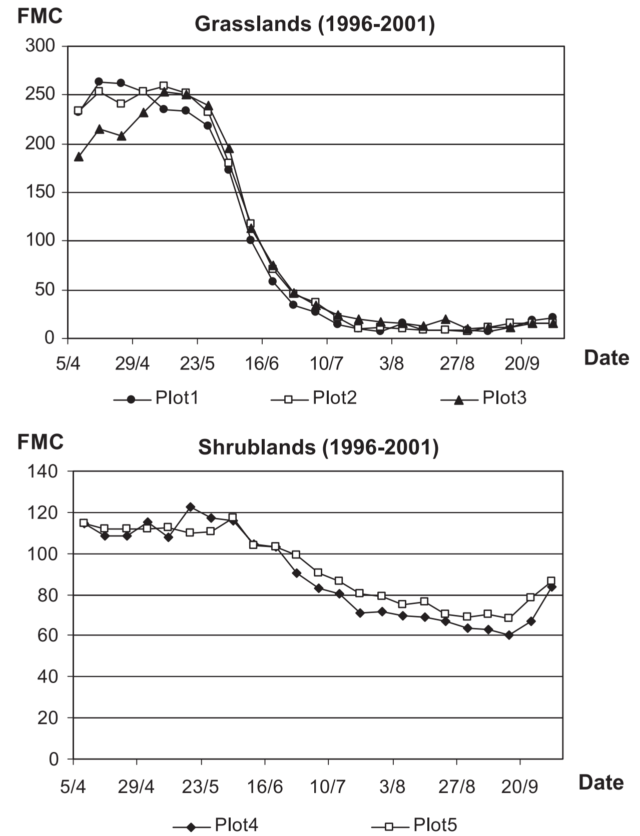

Fig. 4. Average temporal evolution of FMC for grassland and *C. ladanifer* in the different field plots of the Cabañeros National Park.

be concluded that the average FMC values of small plots (50×50 m) are representative of large areas (several kilometers apart), at least in the Cabañeros site, and consequently, temporal data extracted from those small plots can be assumed representative of the large plots observable in AVHRR coarse-pixel size images.

As mentioned above, the equations to estimate FMC from AVHRR data were derived from multiple linear regression analysis, using NDVI, ST and FD for 4 years of Cabañeros field data (1996 to 1999).

The resultant equations were:

$$\mathrm{FMC_g} = -57.103 + 284.808 \times \mathrm{NDVI} - 0.089 \times \mathrm{ST} + 136.75 \times \mathrm{FD_g} \quad (4)$$

$$\mathrm{FMC_c} = 70.195 + 53.520 \times \mathrm{NDVI} - 1.435 \times \mathrm{ST} + 122.087 \times \mathrm{FD_c} \quad (5)$$

where $\mathrm{FMC_g}$ and $\mathrm{FMC_c}$ are the estimated FMC values of grasslands and *C. ladanifer*, respectively; NDVI is the normalized difference vegetation index (range -1 to $+1$); ST is the surface temperature (in Celsius degrees); and FD, the function of the Day of the Year (as stated in Eqs. (2) and (3)). The determination coefficients (r^2) obtained were 0.737 ($p<0.001$) for grasslands and 0.672 ($p<0.001$) for *C. ladanifer*. Significance values of independent variables were lower than 0.01 for NDVI and $\mathrm{FD_g}$ in the case of grasslands, and ST and $\mathrm{FD_c}$ in the case of *C. ladanifer*. ST was not significant for grasslands ($p>0.5$) because most of its discrimination power is included in the $\mathrm{FD_g}$ variable. However, it was incorporated to improve spatial estimations, given that $\mathrm{FD_g}$ does not change spatially. For the same reason, NDVI was kept in the case of *C. ladanifer*, in spite of its low significance ($p=0.187$). The contribution of NDVI to FMC estimation is more significant for grasslands because the drying process in herbaceous species is commonly followed by a loss of chlorophyll activity and a LAI decrease. In both cases, the factor accounting for the seasonal trends (FD) is very significant ($p<0.001$). As expected, NDVI and FMC show a positive correlation, whereas for ST it is negative, confirming the physiological assumptions previously stated.

The assessment of these equations was carried out on other time periods (2001–2002) in the same study site (Cabañeros), as well as on other study sites, and good results were obtained in all cases. Table 1 shows the r^2 values for the different locations. Relations are very coherent at all sites, in spite of being at a distance of over 200 km for Segovia and Atazar–Alberche sites, and more than 500 km for the Iberica site, and with different altitude ranges (up to 500 m of height increase in the case of Segovia). For the Cádiz site, only four observations were available, but r^2 values were also very high (0.96). The Pre-pirineo site did not have samples or neither grasslands nor *C. ladanifer* and was not included in this analysis.

Fig. 5 shows observed and predicted values for both vegetation types in the Cabañeros plots during the time period for assessment. The temporal trends are very well estimated, and deviations of actual versus predicted FMC values are low and have no consistent bias. The worst estimation was observed for grasslands in late spring (early June) and in the middle of the summer (August). The former is related to the sudden decrease in FMC, which in both years, changes from over 170% to just 30–35% in 16 days. This severe decrease is reflected in the reduction of NDVI and increasing ST, but not as steep as the field FMC values

Table 1
Pearson determination coefficients (r^2) and standard errors (S.E.) between estimated and observed FMC values for the different study sites

	Cabañeros		Segovia		Atazar–Alberche		Ibérica	
	r^2	S.E.	r^2	S.E.	r^2	S.E.	r^2	S.E.
Grasslands	0.931	30.59	0.905	34.46	0.881	41.24		
Cistus ladanifer	0.872	9.80			0.794	13.60		
Rosmarinus officinalis	0.853	6.47			0.873	10.70	0.891	8.33
Shrub[a]	0.791	12.55			0.857	11.34	0.665	17.58

All correlations are significant at $p<0.001$.
[a] Shrub here implies a mixture of *C. ladanifer*, *R. officinalis* and other Mediterranean shrub species.

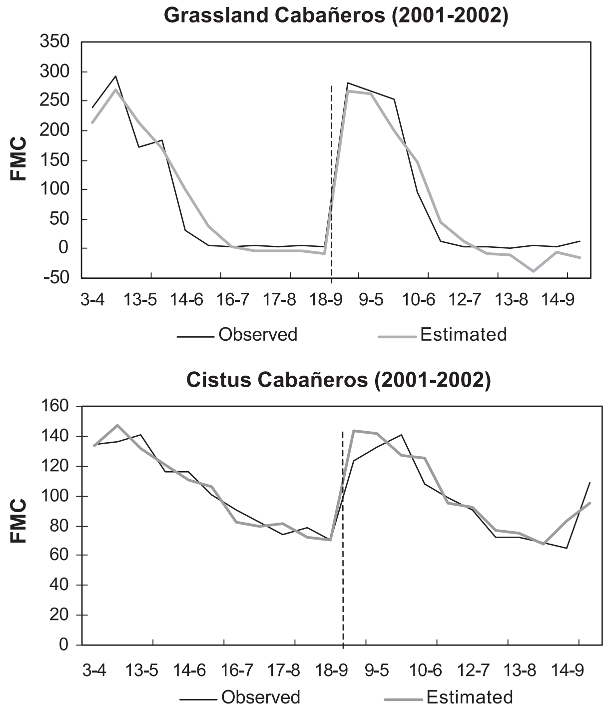

Fig. 5. Observed and estimated FMC values for grasslands (top) and *C. ladanifer* (bottom) in Cabañeros. Validation period (2001 and 2002).

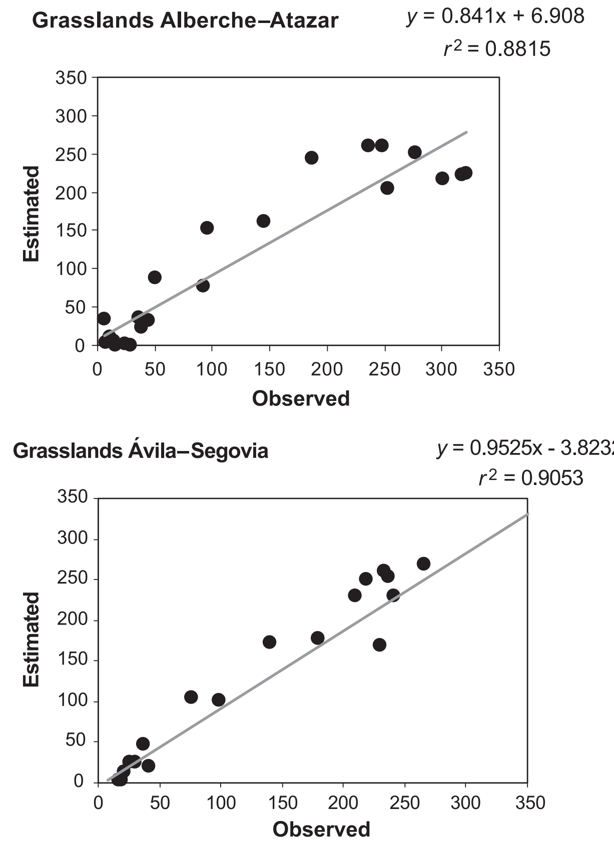

Fig. 6. Observed and estimated FMC values for grasslands in Alberche–Atazar and Avila–Segovia. Validation sites (2001 and 2002).

show. As a result, overestimations in this period reach up to 60% of FMC. Additionally, negative FMC values were estimated in August of the second year, caused by very low NDVI values (below 0.1 for this period). However, negative estimations are not a major obstacle for operational purposes because a simple filter could be applied to the empirical model to avoid them. Additionally, FMC values of grasslands during most of July and August are below 30%, which may be considered the limit for live species. Therefore, for practical purposes, grasslands may be considered as dead fuels for the central part of the summer.

The validation of the *C. ladanifer* showed an even better fitting than grasslands, with very close estimations both in spring and summer in the Cabañeros site. The highest deviations from the observed FMC values never reached 20%, and for most periods, they are under 10% of FMC.

The other two validation sites for grasslands (Avila–Segovia and Alberche–Atazar) also showed very good fittings, with r^2 values of 0.881 and 0.905 (Fig. 6). There is a slight tendency towards overestimation in Alberche–Atazar and underestimation in Avila–Segovia, but the relation in both cases is close to a 1:1. The scattergram also shows a nonlinear estimation trend, especially in Alberche–Atazar, which may be related to the saturation of NDVI in the upper part of the range (Baret & Guyot, 1991). In fact, polynomial equations between observed and estimated FMC values provide r^2 values higher than for lineal trends, with 0.96 for Avila–Segovia and 0.95 for Alberche–Atazar. Nonlinear relationships should also be explored at the calibration stage in the future.

FMC estimation for *C. ladanifer* shows good fittings in all assessment sites (Fig. 7): Alberche–Atazar, Cabañeros and Cádiz, although for the latter, only 4 observations in the summer of 2001 were available. The empirical model has a slight tendency towards overestimation, especially for lower values of FMC. The lower values offer a better fitting between estimated and observed FMC with differences lower than 10% of FMC during mid-summer.

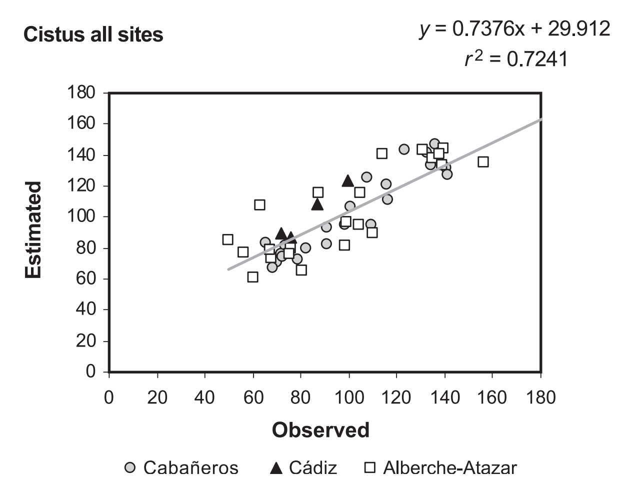

Fig. 7. Observed and estimated FMC values for *C. ladanifer* in Alberche–Atazar and Cádiz. Validation sites (2001 and 2002).

Considering certain physiological similarities between *C. ladanifer* and another widespread Mediterranean shrub, *R. officinalis*, the empirical function was also applied to other study sites where this shrub species had been sampled in the field. The results were very positive for all sites (Cabañeros, Atazar–Alberche and Iberica), with r^2 over 0.85 (Table 1). The temporal trends also show good fittings, with nonsignificant biases (Fig. 8). An underestimation was observed for the spring season, but the fittings improved in the summer, when fire danger is higher, and therefore, the need for accurate estimations is more demanding. The absolute errors were higher for *R. officinalis* than for *C. ladanifer*, especially in the Iberica site, which may also be caused by the mixture of the field plots, where several shrub species grow in the same area.

7. Discussion and conclusions

The empirical model generated from NDVI, ST and function of Day of the Year showed a consistent predictive power to estimate FMC of grasslands and *C. ladanifer*, a typical Mediterranean shrub species. The model was tested in plots located several hundreds of kilometers apart and with different altitude ranges. Therefore, this model may be tested on operational scenarios in Mediterranean conditions,

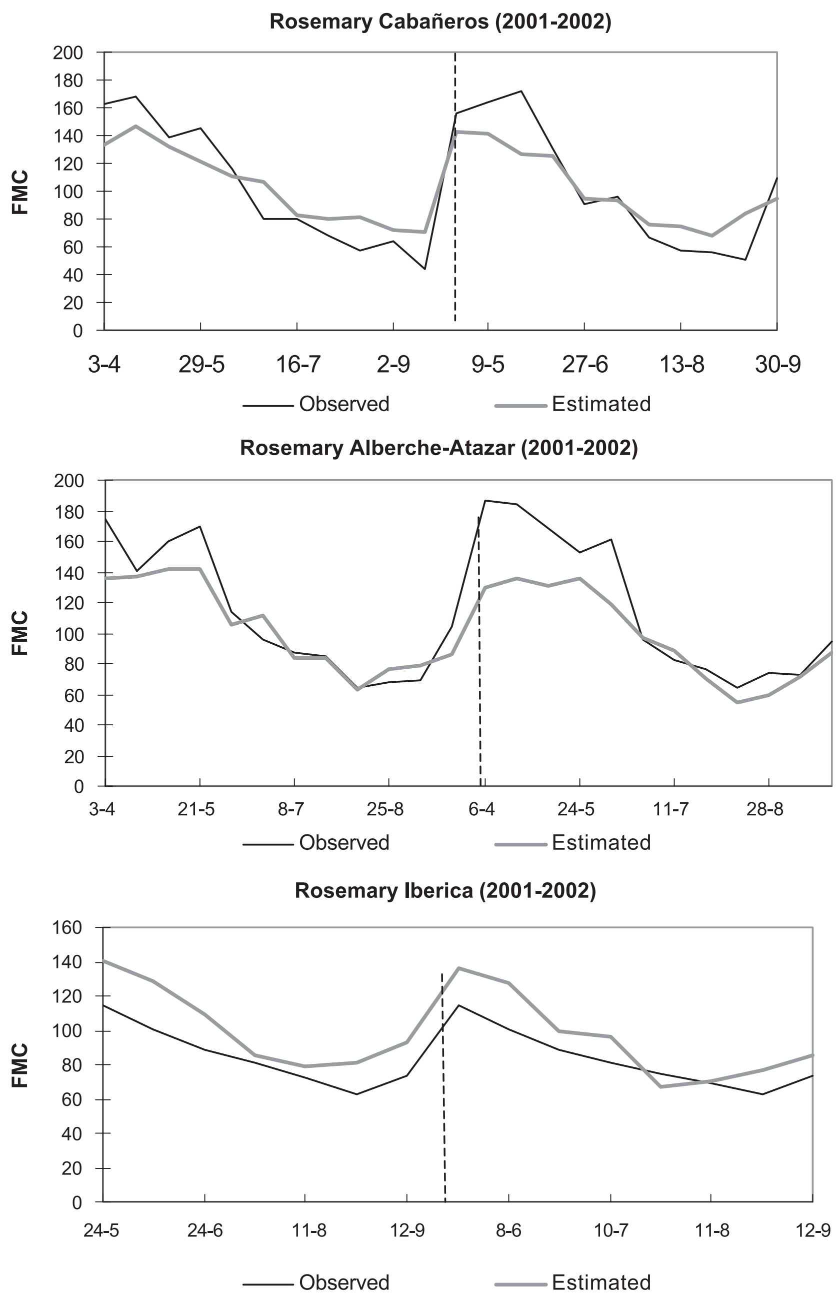

Fig. 8. Observed and estimated FMC values for *R. officinalis* in Cabañeros, Alberche–Atazar and Iberica. Validation sites (2001 and 2002).

applying both spring and summer data. Comparing these results with previous findings (Chuvieco et al., 2003a), the model provides a better estimation of FMC variations, covering a wider temporal series, and has been assessed in other study areas. The model only requires two basic satellite variables (NDVI and ST), the day of the year and a regional map of vegetation types, which distinguishes grasslands from shrublands. This variable could also be derived from the multitemporal classification of AVHRR data, following any of the methods applied to derive global land cover maps (DeFries & Townshend, 1994).

In the case of mixed pixels, a linear mixture of grassland and shrubland FMC functions could be applicable, or alternatively, the function of the most dangerous fuel can be used, according to the experience of local fire managers.

Considering the spatial and temporal resolution of AVHRR images, the empirical index may be used for short-term estimations of FMC. Conversion of FMC values to fire danger rating may be based on ignition delay values for each vegetation species or alternatively on historical relationships between FMC and fire occurrence. The former approach relies on calorimetric methods that estimate the time it takes for a fuel to ignite based on its moisture content (Dimitrakopoulos & Papaioannou, 2001). The latter is more statistical and takes into account critical levels of FMC for different degrees of fire occurrence. The former approach seems preferable because it has a more physical basis, measuring relations between FMC and probability of ignition.

In spite of the great potential and interest that approaches based on RTM have for FMC estimation, empirical fittings are also critical for operational applications because they provide faster and easily operated models of known accuracy. Additionally, RTM models do not include thermal information that is vital, especially in fuels which are more adapted to summer drought, which is the case in most Mediterranean shrubs. In these species, FMC cannot be accurately estimated using just NDVI values because chrolophyll and LAI changes caused by FMC variations are less apparent in shrub species than in grasslands.

The applicability of the empirical model to other shrub species may be based on their physiological similarities with *C. ladanifer*. The paper has shown that FMC trends of *R. officinalis* are also well estimated from the empirical model. A more physical basis to extend this to other shrub species should rely on physiological differences between the reference and the desired species, which may be based on specific leaf weight or LAI factors, but this hypothesis should be tested in future work.

This study has was based on NOAA–AVHRR imagery due to the long time series available. In the near future, FMC estimations based on other sensors should be achievable. Recent studies have shown the potentials of Terra-MODIS (Zarco-Tejada et al., 2003) and Spot-Vegetation (Ceccato et al., 2002a), because both include information in the SWIR water absorption bands. However, these efforts should be extended to longer time series and calibrated in Mediterranean conditions. Additionally, the local reception of AVHRR images facilitates the operational use of their data. The increasing availability of near-real time images and products from the MODIS sensor should also provide a sound alternative in the near future.

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