Effects of Seasonal Weather Variations and Phenology on Live Fuel Moisture Content and Ignitability of Mediterranean Species

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Abstract

Maquis is an important component of Mediterranean vegetation characterized by high specific and structural heterogeneity and complexity. Flammability of vegetation is influenced by several factors (structural and chemical properties, moisture content, etc.) The moisture content of living plants is one of the most critical parameter affecting fire ignition and propagation and represents an important variable in fire behaviour modelling. Plant water content variations depend on both environmental conditions and ecophysiological characteristics of plants. As a consequence, knowledge of seasonal variation of ignitability and vegetation moisture content could contribute to identify critical periods of high ignitability risk in maquis ecosystems. Ignition delay time (ID time) and live fuel moisture content (LFMC) of eight dominant species (*Arbutus unedo* L. *Cistus salvifolius* L., *Cistus monspeliensis* L., *Erica scoparia* L., *Lavandula stoechas* L., *Phillyrea angustifolia* L., *Pistacia lentiscus* L. and *Rosmarinus officinalis* L.) of two areas located in North Sardinia, Italy, were measured during two consecutive years. Phenological phases and meteorological variables were also observed. Seasonal patterns of LFMC were compared with two drought meteorological indices. The aims of this work were to evaluate the influence of weather seasonal variations and phenology on LFMC and to analyze the relations between the seasonal patterns of LFMC and the pattern of two drought meteorological indices. Two typical seasonal patterns of ignitability were identified. *Cistus salvifolius*, *Cistus monspeliensis, Lavandula stoechas* and *Rosmarinus officinalis* seemed to be strongly sensitive to seasonal changes. They showed a clear increase of ignitability, during the drought period. For *Arbutus unedo*, *Erica scoparia, Phillyrea angustifolia* L. and *Pistacia lentiscus* the potential ignition risk of the live fine fuel appeared constantly high during the year and not strongly dependent on seasons. These patterns were strictly related to the seasonal variation of LFMC. Significant regression equations were found between plant moisture content and ID time. LFMC seasonal variations of *Cistus salvifolius*, *Cistus monspeliensis, Lavandula stoechas* and *Rosmarinus officinalis* were also well correlated to the drought indices.

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Introduction

Mediterranean maquis is an important component of Mediterranean vegetation, which is characterized by high specific and structural heterogeneity and complexity. Flammability of vegetation is influenced by several factors including structural properties, chemical properties and moisture content. Moisture content of dead fuel (dead twigs and leaves, fallen branches, litter, etc.) is an important variable in fire ignition and fire propagation modeling, because it is usually the driest and most likely to ignite during the summer season (Chuvieco and others 2004). In Mediterranean shrubland, the main component of the available fuel to fire is represented by live fuel (Sun and others 2006). In addition, depending on the moisture content and the heat flux from a fire, living vegetation may act as a heat source or a heat sink, either contributing to fire energy or retarding fire propagation and intensity (Nelson 2001, Pyne and others 1996). Moisture variations in dead fuel are mainly controlled by air relative humidity and temperature whereas in living vegetation water content are related to both environmental conditions and ecophysiological characteristics of plant species (Castro and others 2003). Since most of fire spread models were designed for fuel bed dominated by dead fuel, the prediction of fire spread in Mediterranean vegetation is difficult.

Several authors have found relationships between vegetation water content and ignition delay time in Mediterranean species (Dimitrakopoulos and Papaioannou 2001, Hernando Lara and others 1994, Xanthopoulos and Wakimoto 1992). In addition, Mediterranean shrubland vegetation has structural and chemical flammable properties that allow live fuels to propagate wildfire even when meteorological conditions and fuel status are not particularly severe (Sun and others 2006). Therefore, a better understanding of seasonal variation of ignitability and vegetation moisture content and their relationships could contribute to improve our knowledge of burning characteristics of maquis species. In addition, seasonal monitoring of vegetation moisture content, relative to the whole vegetation and the single species, can contribute to identify critical periods of high ignitability risk for Mediterranean ecosystems (Viegas and others 2001).

Several studies were recently conducted to estimate live fuel moisture content values from seasonal drought indices related to both meteorological parameters and soil water content variability (Castro and others 2003, Dennison and others 2003; Dimitrakopoulos and Bemmerzouk 2003, Viegas and others 2001).

The objectives of this work were (i) to describe the seasonal pattern of live fine fuel moisture content and ignitability values for some Mediterranean shrubs, (ii) to evaluate the relationships between moisture content and ignitability, and (iii) to evaluate the relationships between two drought meteorological indices and the seasonal pattern of live fuel moisture.

Materials and methods

The study was carried out in two Mediterranean type ecosystems. The first was in a coastal area and the second in an inland hilly site, both dominated by evergreen and semi-deciduous small shrub species.

The first site is located in North-Western Sardinia, Italy, within a nature reserve (40° 36' N, 8° 09' E, 30 m a.s.l.) covering approximately 1200 ha. The climate is semi-arid with a remarkable water deficit from May through September (mean annual rainfall 600 mm, mean annual temperature value 16 °C). The coastal area was an example of regenerating vegetation without disturbs after a fire event occurred in the mid-1970s. The vegetation was mainly characterized by the presence of *Chamaerops humilis* L., *Cistus monspeliensis* L., *Pistacia lentiscus* L., *Genista acanthoclada* L., *Rosmarinus officinalis* L., J*uniperus phoenicea* L., and *Phillyrea angustifolia* L.

The second site is located in a forest area in North-Eastern Sardinia, Italy (40° 42' N; 9° 24' E, 700 m a.s.l.), mainly covered by evergreen and semi-deciduous small shrubs. Rainfall events are concentrated in autumn and winter season with a water deficit from June through September (mean annual rainfall 996 mm, mean annual temperature value 12.9 °C). The inland site represents a highly disturbed ecosystem degraded by frequent and intense fires. The vegetation cover mainly includes *Cistus salvifolius* L., *Lavandula stoechas* L., *Erica scoparia* L., and *Arbutus unedo* L.

Ignition delay time (ID time) and live fuel moisture content (LFMC) of terminal portion of twigs (live fine fuel) were measured on eight dominant species of the study areas that are very common in the Western Mediterranean Basin: *Cistus salvifolius* L., *Lavandula stoechas* L., *Erica scoparia* L., and *Arbutus unedo* L. (inland site) and *Cistus monspeliensis* L., *Pistacia lentiscus* L., *Rosmarinus officinalis* L., and *Phillyrea angustifolia* L. (coastal site).

Samples from each species were collected monthly or bi-monthly during the period October 2003 through October 2004, and weekly between March and December 2005. Phenological stages were observed on the sampling dates. Three samples for each species were dried in an oven for 24 hours at 102 °C to determine LFMC, which was expressed as percentage of dry weight according to the following equation:

$$LFMC = \left[\left(FW - DW\right)/DW\right]100$$

where FW and DW indicate the fresh and dry weight of the plant material, respectively.

Ignitability test samples from each species were collected monthly or bi-monthly from October 2003 to October 2004 and from March to November 2005 in the coastal and the inland site, respectively. ID time was measured using a standard epiradiator of 500 W constant nominal power according to the methodology described by Valette (1990). For each species, 45 samples were tested. According to the methodology proposed by Valette (1990), species were classified as: low or moderately flammable (ID time > 27 s), flammable (ID time ranging from 17 to 26 s), and very or extremely flammable (ID time < 17 s).

In addition, meteorological variables were recorded by an automatic weather station located in the study sites.

Two drought meteorological indices were calculated: the Drought Code (DC) of the Canadian Forest Fire Danger Rating Systems (CFFDRS) (Van Wagner 1987), and the Canopy Drought Stress Index (CDSI) (Baldocchi 1997). DC is mainly related to moisture content of dead fuel. It is calculated from daily rainfall and air temperature and represents very slow drying fuels (time lag response about 52 days) (Van Wagner and Pickett 1985). CDSI is an index formulated to evaluate prolonged period of canopy water stress and is defined as the ratio between the cumulative precipitation (ΣP) and the cumulative reference evapotranspiration (ΣETo) over a period of time. In this paper, ETo was estimated using the Hargreaves equation (1975).

Statistical analysis

A regression analysis was performed to describe the relations between ID time and LFMC values by species. Spearman's rank correlation analysis was also performed to test the significance of relationships between LFMC and CDSI or DC values.

Results

Different ranges and seasonal trends of ID time were observed for the species examined (figure 1). The highest variability was observed for *Cistus salvifolius* (*Cistus s.*) *Cistus monspeliensis* (*Cistus m.*), *Rosmarinus officinalis* (*Rosmarinus*) and *Lavandula stoechas* (*Lavandula*) with the lowest values recorded in summer, and a clear increase in autumn. All species showed the highest values in spring. *Arbutus unedo* (*Arbutus*), *Erica scoparia* (*Erica*), *Pistacia lentiscus* (*Pistacia*) and *Phillyrea angustifolia* (*Phillyrea*) showed ID time values almost constant during the cold period, whereas relatively little decreases were observed in summer.

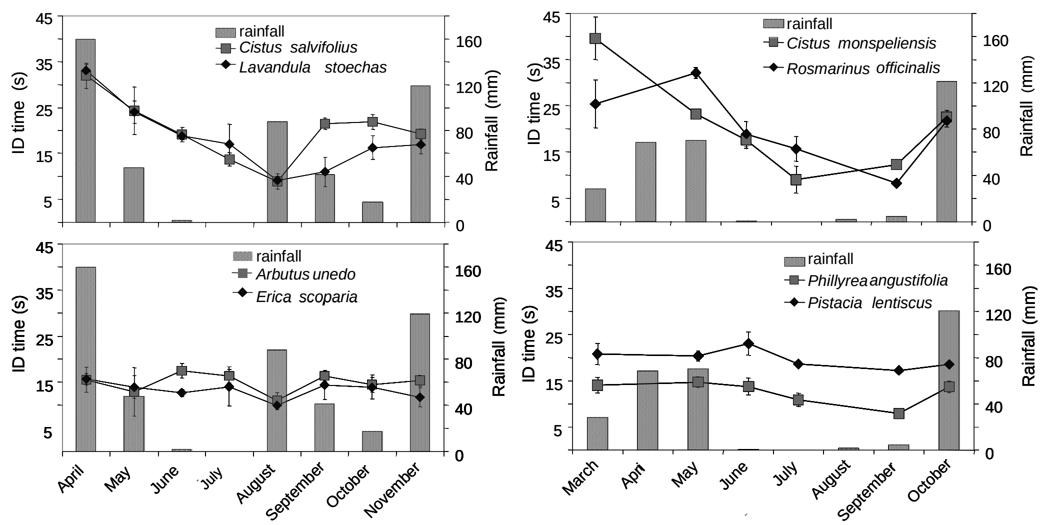

Figure 1—Monthly precipitation and patterns of time to ignition of the studied species

These patterns were strictly related to LFMC seasonal variations. Significant regression equations of ID time versus LFMC were observed for all species (table 1). The moisture content variation accounted for most of the variance in the ID time with R^2 values ranging from 0.64 to 0.94 for *Arbutus* and *Pistacia*, respectively.

***Table 1**— Linear regression statistics of time to ignition vs. moisture content.*

species	Regression model ID time = α +β LFMC			
	α	β	R^2	Sign.
Pistacia	1.78	0.20	0.94	***
Cistus s.	4.13	0.11	0.92	***
Rosmarinus	5.61	0.13	0.85	***
Lavandula	4.85	0.09	0.76	**
Cistus m.	8.7	0.09	0.73	**
Phillyrea	1.52	0.17	0.72	**
Erica	4.82	0.12	0.66	*
Arbutus	4.31	0.09	0.64	*

n.s. $p > 0.05$; * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$

Figures 2 - 5 show the phenological behavior of the observed species, the patterns of LFMC and cumulative precipitation between samplings during 2005. *Cistus m*., *Cistus s.*, *Lavandula* and *Rosmarinus* showed the highest values of LFMC in spring, when plants were in resprouting and flowering phases. From the end of the rainy period until the end of August, when plants reduced their physiological activities during the summer drought period, the LFMC values decreased almost constantly. The lowest values were observed on August. LFMC values increased in late summer when the first rainfall events after the drought period occurred, air temperature started to decrease and the vegetative activities of plants restarted. *Arbutus*, *Pistacia* and *Phillyrea* showed a narrow range of LFMC values throughout the observation period with a slight increase in late spring during the resprouting phase. The pattern of LFMC for *Erica* was constant during the whole experimental period and did not seem related to the phenological behaviors of the species (figures 2 – 5).

The results of correlation analysis performed to test the significance of the relationship between LFMC of the species characterized by high seasonal variability (i.e. *Cistus*, *Lavandula* and *Rosmarinus*), and the drought meteorological indices are reported in table 2. For all these species the moisture content values were significantly well correlated to both CDSI and DC indices.

***Table 2**—Significance of correlation and values of coefficients of correlation between live fuel moisture content and meteorological indices for the period 4/19-9/13 2005.*

species	DC	CDSI
	R	R
Cistus m.	-0.74^{C}	0.72^{C}
Rosmarinus	-0.84^{C}	0.83^{C}
Cistus s	-0.90^{C}	0.83^{C}
Lavandula	-0.84^{C}	0.84^{C}

A: $p \leq 0.05$; B: $p \leq 0.01$; C: $p \leq 0.001$

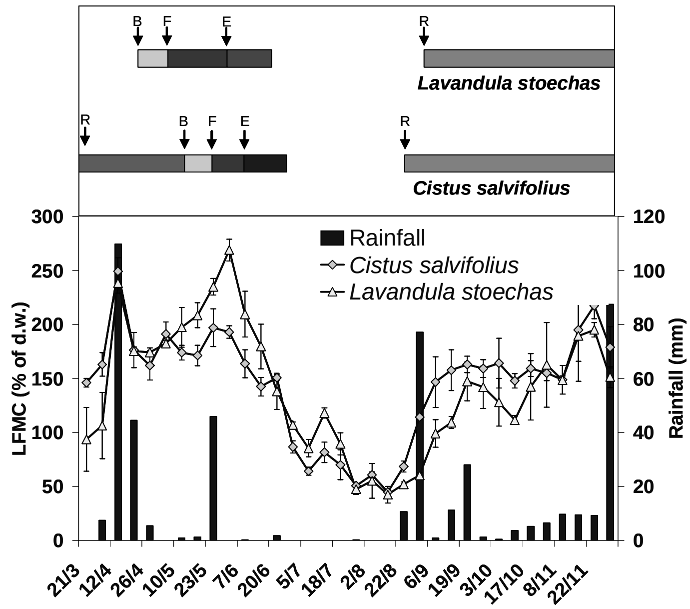

Figure 2— Phenological diagrams (top), live fine fuel moisture content (LFMC) and rainfall totals cumulated between sampling dates (bottom) of *Lavandula stoechas* and *Cistus salvifolius* in the inland site during the period late March - December 2005. B = beginning of flowering, F = full flowering, E = end of flowering, and R = resprouting.

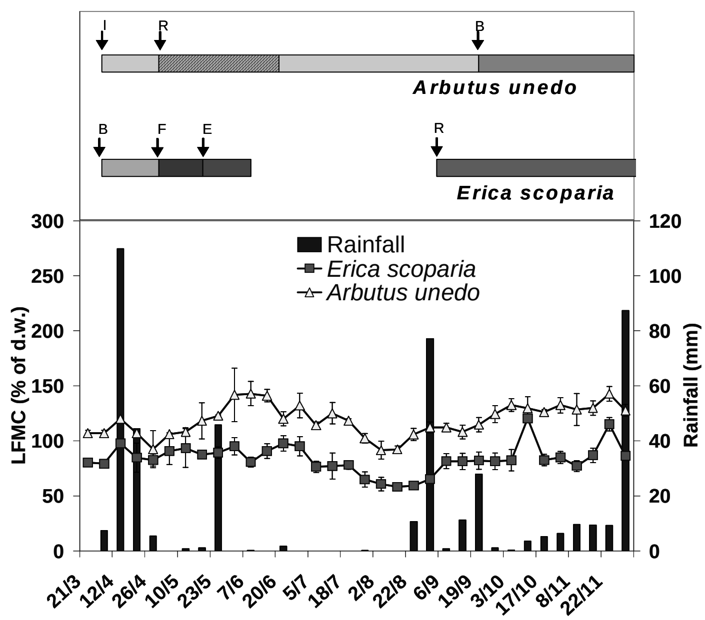

Figure 3— Phenological diagrams (top), live fine fuel moisture content (LFMC) and rainfall totals cumulated between sampling dates (bottom) of *Erica scoparia* and *Arbutus unedo* in the inland site during the period late March - December 2005. I = Inflorescence emission, B = beginning of flowering, F = full flowering, E = end of flowering, and R = resprouting.

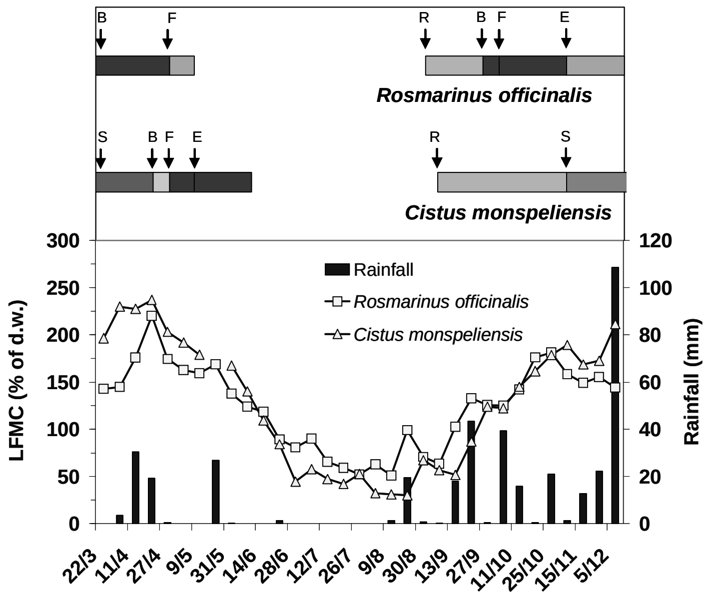

Figure 4— Phenological diagrams (top), live fine fuel moisture content (LFMC) and rainfall totals cumulated between sampling dates (bottom) of *Cistus monspeliensis* and *Rosmarinus officinalis* in the coastal site during the period late March- December 2005. B = beginning of flowering, F = full flowering, E = end of flowering, R = resprouting, and S = shoot elongation.

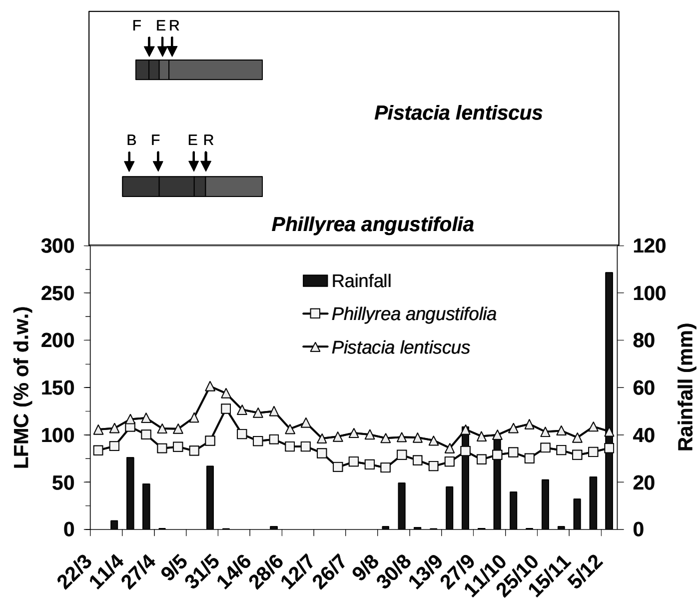

Figure 5— Phenological diagrams (top), live fine fuel moisture content (LFMC) and rainfall totals cumulated between sampling dates (bottom) of *Pistacia lentiscus* and *Phillyrea angustifolia* in the coastal site during the period late March-December 2005. B = beginning of flowering, F = full flowering, E = end of flowering, and R = resprouting.

To evaluate whether or not the meteorological drought indices could be useful to describe the seasonal changes of LFMC, the pattern of the LFMC was compared with the meteorological drought indices variations during the experimental period.

Figures 6 and 7 show the patterns of the indices and the moisture content of *Cistus m, Cistus s.*, *Lavandula* and *Rosmarinus*. CDSI values decreased constantly during the drought period with a pattern similar to LFMC values. The rainfall events occurred in late summer had a little impact on CDSI values, which remained almost at the same level when LFMC increased. DC is more affected by rainfall events and when the first precipitation occurred in autumn, DC values increased. Therefore, the DC pattern was quite close to the variation of LFMC observed for *Cistus m*, *Cistus s.*, *Lavandula* and *Rosmarinus* even when the first precipitation in autumn occurred.

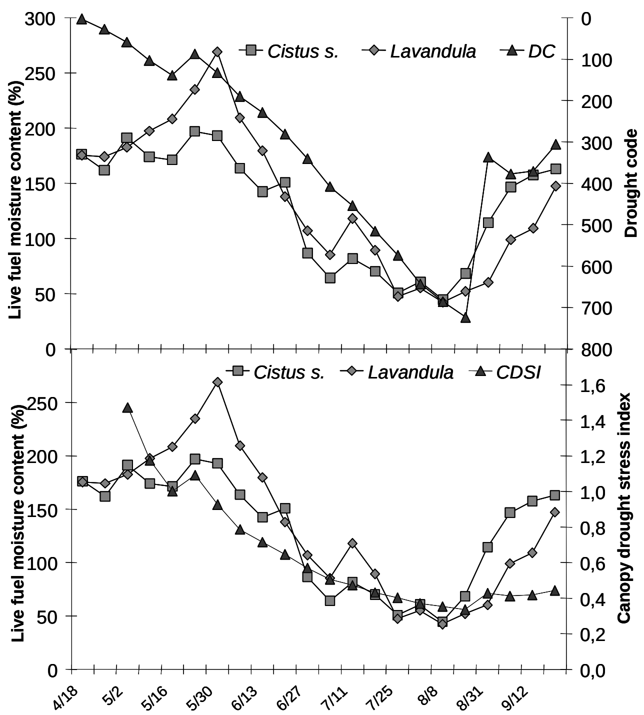

Figure 6—Seasonal trends of the two meteorological drought indices (DC and CDSI) and live fuel moisture content (LFMC) values observed on two shrub species at the experimental inland site during the period late April through September 2005.

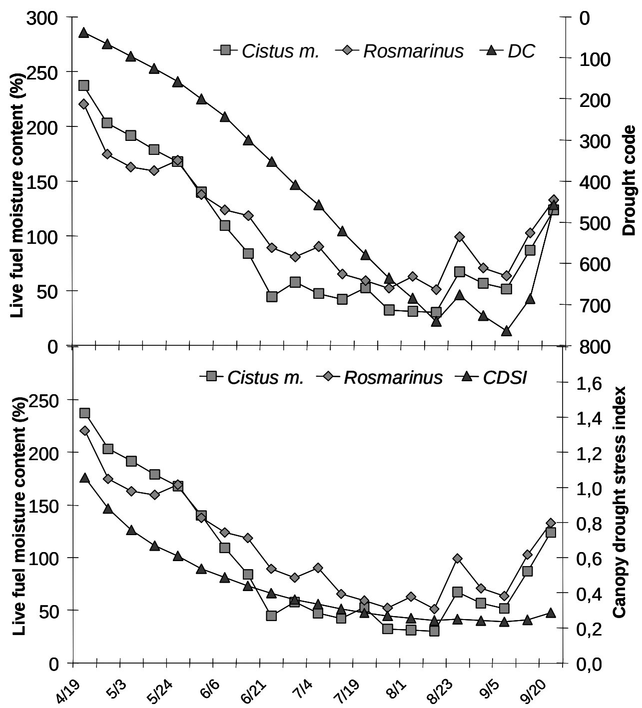

Figure 7—Seasonal trends of the two meteorological drought indices (DC and CDSI) and live fuel moisture content (LFMC) values observed on two shrub species at the experimental coastal site during the period late April through September 2005.

Discussion and conclusions

According to our results, two typical seasonal patterns of ignitability can be identified for the species examined. *Cistus m., Cistus s.*, *Lavandula* and *Rosmarinus* seemed to be strongly sensitive to seasonal environmental changes, showing a clear increase of ignitability during the drought period. In spring, when the plants were resprouting and flowering at the end of the rainfall season, these species showed to be moderately flammable.

For the other species the ignitability of the live fine fuel appeared constantly high during the year and not strongly dependent on seasons.

These patterns were strictly related to LFMC seasonal variation. The relation between LFMC and ID time was strong, as indicated by the regression statistics, with high level of significance and coefficients of determination values ranging from 0.64 to 0.94 (table 1). Our results are similar to the findings on Mediterranean shrubs growing in the Mediterranean Basin reported by other authors (Dimitrakopoulos and Papaioannou 2001, Hernando Lara and others 1994, Trabaud 1976, Weise and others 2005). This suggests that modeling LFMC variations using a consistent data-set could be useful to predict ignition potential for fuel and, consequently, critical periods for high fire potential of Mediterranean shrubland ecosystems (Viegas and others 1992).

As reported in other works (Castro and others 2003, Piñol and others 1998, Viegas and others 2001), the analysis of our results confirms that LFMC can vary among species, mainly due to species-specific adaptive mechanism of vegetation to cope summer drought season, and within species in relation to both environmental conditions and phenological stages. In general, evergreen deep rooted sclerophyllous species, like *Arbutus, Erica, Pistacia* and *Phillyrea* are tolerant to water stress and affected by drought conditions only when particularly severe. For these species, the LFMC values were not particularly high over the year and little dependent on meteorological conditions. Consequently, for practical purposes, it seems not of crucial importance to accurately model their LFMC seasonal variation. Knowledge of both mean moisture content and phenology of plants can be more useful information for fire risk assessment. On the other hand, species that use drought avoidance mechanisms, adjusting the growing period or limiting water losses, like *Cistus, Lavandula* and *Rosmarinus* are particularly affected by soil moisture availability and show LFMC values more dependent on meteorological conditions. An increase of ignitability is observed in these species during the drought period. Therefore, for practical purpose it would be useful modeling LFMC pattern of these species in relation to meteorological data.

Live fuel moisture seasonal variation of *Cistus, Lavandula* and *Rosmarinus* was also well correlated to the seasonal patterns of two drought meteorological indices, the Drought Code and the Canopy Drought Stress Index. This result confirms findings of other authors that reported a strong relation between variation of LFMC in Mediterranean species and some indicators of fine fuel moisture used in the CFFDRS (Castro and others 2003, Viegas and others 2001). In addition, when DC is applied to modeling live fuel moisture variation in Mediterranean species sensitive to meteorological conditions, it seems to be more useful than CDSI. Since first autumn rainfall events have little impact on CDSI, the pattern of this index was not comparable to live moisture variation of *Cistus, Lavandula* and *Rosmarinus* observed in autumn. The variation of DC values, which is more affected by rainfall events, was more comparable to the moisture content of plants, showing a pattern similar to that one observed for LFMC in *Cistus, Lavandula* and *Rosmarinus*. In conclusion, although the DC was formulated to describe changes in moisture content of dead fuel, it seems to be useful to modeling live fuel moisture variation in Mediterranean species that are particularly sensitive to meteorological conditions and characterized by clear and important decrease of moisture content during drought season.

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