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Drought models for the study of the vegetation moisture content; analysis of performance of different models in two mediterranean ecosystems for application in forest fire prevention

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Abstract

Vegetation water content is one of the most important parameters of vegetation status and health, and consequently a natural element that regulates several ecosystems worldwide; moreover, considering vegetation as fuel, this variable is related to wildfires. Forest fires and vegetation resistance to ignition during periods of drought are both strictly related to climate characteristics of the area. The contribution of this work is to evaluate the performance of vegetation drought models using field measured data (data related to local adaptation and phenotypic plasticity), data usually lacking. In the present work, moisture content of shrub vegetation and live foliage (fine fuels) were detected by field measurements of in Tuscany (Italy). In two plots of *Quercus ilex* L. and mixed broadleaves forest, seasonal and inter-annual variations of live fine fuels of several species are analyzed. The selected species constitute two sets (shrubs and trees) of vegetation typology characterized by a representative seasonal variability in mediterranean ecosystems. From nearby stations meteorological data were collected in each study area for the evaluation of fuel moisture indicators, including the Drought Code (DC) used in the Canadian Forest Fire Danger Rating System. The results of the present work have shown that for the summer season the slow response of live fine fuel moisture content (LFMC) to meteorological conditions (namely to precipitation), was well described by the DC. Empirical correlations between LFMC and DC for each species and site are proposed.

Key words: wildfire; fuel; meteorological parameters; models; risk management

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1. Introduction

Wildfires constitute disturbances affecting Mediterranean agroforestry ecosystems (Bond & van Wilgen 1996; Keeley et al. 2011) and represent a complex phenomenon determined by natural and anthropogenic causes. Forest fires destroy around 1 million hectares in the Mediterranean basin; this has a serious impact on the environment and on socio-economic activities (San-Miguel-Ayanz et al. 2009). Climate change, particularly in the Mediterranean basin, will determine more frequent and severe extreme drought events, envisaging episodes of increased fire risk. In consideration of new climatic scenarios, managers and stakeholders are faced with a general trend of increased burnt areas and a rise in the frequency, intensity, and severity of fires; significant efforts have been focused both on active fight and on structural prevention.

Fuel moisture content and flammability are influenced by drought and water stress even if it is possible to record differences in the response mechanisms and adaptive traits in different plant communities.

Mediterranean understory shrub species greatly influences wildfires ignition and spread, this behavior is correlate to climate characteristics, winter precipitation and prolonged summer drought.

For an efficient wildland fuel management, it is crucial to be able to assess fuel moisture content with an effective level of accuracy; fine fuel drought estimation, correlated with information as wind speed, vegetation typology and structure, provides indications on fire potential and fire danger rating (Pellizzaro et al. 2007; Cardil et al. 2019).

Drought measurements based on field data are more accurate but limited in coverage; the application of models based and calibrated on ground-based data allow to merge accuracy and precision with the possibility of deriving information for larger areas. The present work provides information to better monitor drought by filling

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**Corresponding author. Matteo De Vincenzi, e-mail: matteo.devincenzi@ibe.cnr.it* the gap of data measured in representative ecosystems (Zhao et al. 2022).

Considering the large typologies of forest in Tuscany Region (central Italy), representative direct measurements for living parts of vegetation are not easy to collect, as well as taking into account that also living fuels moisture content of foliage and small twigs (Live Fuel Moisture Content – LFMC; Fares et al. 2017; Martin-StPaul et al. 2018) constantly changes in relation with meteorological condition following the rates of water uptake and water loss by transpiration. These rates are driven by multiple physical and biological variables, because of live fuel moisture estimation is more complicated than that of dead fuels; for a more effective modeling it has to be physically measured (Anderson & Anderson 2009). Considering the dependence of the vegetation moisture content on the meteorological factors, it is important to deepen knowledge of the relationships between these two sets of parameters collecting and analyzing the widest number of measurements on different typologies of live fine fuel (Arganaraz et al. 2018).

Many fires danger rating modeling are relied on fuels moisture content, weather, and drought effects to define numerical indices in order to face fire protection needs (Chandler et al. 1983; Torres et al 2018).

The present work has investigated the dependences between LFMC and meteorological parameters in two representative broadleaves forests plots in Tuscany (Central Italy) with the main objective to describe the temporal seasonal variation of the moisture content to determine the possibility of using some indices based on standard meteorological data to estimate LFMC. An additional aim of the study was to model the live fine fuel moisture (based on meteorological variables measured at nearby weather stations) to evaluate the possibility to generalize the estimation of live fine fuel moisture from the selected species to other localities throughout the region.

2. Materials and methods

2.1. Study site

The study was carried out in two different test sites in Tuscany region (central Italy), located one in a Mediterranean coastal area (Follonica – Grosseto Province 42°56’57”N 10°45’56”E altitude 91 m a.s.l.) and the other in a hinterland mid-hill area (Lecceto – Siena Province 43°18’12”N 11°16’19”E altitude 296 m a.s.l.), representative of typologies of ecosystem frequently prone to fire (Fig. 1).

The coastal area of Follonica has a Mediterranean climate with an average annual temperature of 15.7 °C and rainfall of about 690 mm (last 15 years average). The area is characterized by water deficit conditions in summer and more significant rains in spring and especially in autumn and early winter. The meteorological data (air temperature, air relative humidity, rain, global solar radiation) were collected by Follonica weather station (Lat. 42°55’59’’N, Lon. 10°45’54’’E, altitude 15 m a.s.l.), of the Regional Hydrological Service of Tuscany Region (Servizio Idrologico Regionale – SIR) located approximately 1,5 ÷2 km from the sampling site of the experimentation. For Follonica area, 2011 was a year with little rainfall (367 mm of cumulative rainfall) with a sparsely rainy spring and autumn. In comparison to the average annual precipitation of the last 15 years, 2012 was slightly less rainy (622.8 mm), with a less rainy early spring. The average temperatures in both sampling years were generally slightly lower than in the past 15 years.

Lecceto, a mid-hill site, is characterized by a temperate sub-Mediterranean climate. The average annual rainfall recorded in the nearby meteorological stations (located in a radius of 10 km) is between 830 mm and 880 mm (average of the last 20 years); the mean annual temperature is 14 °C. The meteorological data, used for Lecceto, are acquired by the SIR weather station of Scorgiano (Lat. 43°21’58”N; Long. 11°9’4”E; altitude 233 m a.s.l.). The choice was made because it was the closest weather station (10 km), located in similar geographical conditions. In 2011, the cumulative rainfall was decidedly lower than the average of the last 20 years (570 mm about 30% less than the average). In 2012, however, the cumulative rainfall was slightly above average (908 mm). The yearly mean temperatures of 2011 and 2012 were consistent with averages over the past 20 years.

Concerning the soil, Follonica is characterized by Calcaric and Calcaric Leptosol soils with prevalence of clayey, silty clayey (Galestri) with siliceous limestone and Lecceto test area is characterized by Chromic and Hap-

Fig. 1. The two study areas in Tuscany: Follonica (Province of Grosseto) and Lecceto (Province of Siena).

lic Luvisol; Calcaric, Leptic e Stagnic Cambisol; Skeletic Endoleptic Regosol with steep slopes, eroded slopes and articulated forms of karst (Barazzuoli 2006).

2.2. Data collection

In the two test sites we measured in 2011 and 2012 the moisture content of small branches and leaves of *Quercus ilex* L. (young and adult trees), *Fraxinus ornus* L., *Myrtus communis* L., *Arbutus unedo* L., *Rhamnus alaternus* L. and *Phillyrea angustifolia* L. (in Follonica test site) and *Quercus ilex* L. (young and adult trees), *Erica arborea* L., *Ligustrum vulgare* L., *Arbutus unedo* L. and *Viburnum tinus* L. (in Lecceto test site). The moisture of these measured elements is defined as live fine fuel moisture and provides a more significant fuel in wildfires to which these ecosystems are prone (Chandler et al. 1983; Viegas et al. 2001; Ruffault et al 2016). Five apical and lateral shoots of branches are sampled (around solar midday and were not sampled if plants were wet) from different individuals of a given species along transepts of 800 m representative of the surrounding landscape. For each species considered and in each of the two areas, five individual plants were selected on each of which the five samples were collected. Sampled individuals were chosen to be representative of the average status of each species. Samples have been kept in the sampling case cool and dry until they are weighed. The weighing of all samples took place at our experimental site (Santa Paolina Follonica farm) located approximately 90 km (1 hour journey) from the Lecceto area and 2 km from the Follonica area (Norum & Miller 1984; Zahn & Henson 2011).

In the present work, a time window of 7 months from April to October has been considered for the analysis. This is due to the direct effect of climate on fires in Mediterranean areas; when the temperatures start increasing, the vegetation quickly loses moisture, and the forest becomes more prone to early season fires (March and April period) (Turco et al. 2018). Moreover, we have considered that forest fires in the Tuscany region are largely human caused and can be attributed to negligence, agropastoral land use and arson; in this context spring and summer season are the most subject to risk in terms of agronomic and touristic activities (Michetti & Pinar 2019; Resco de Dios et al. 2021). To compare the performance of selected drought indices related to meteorological parameters, this time-window better fits temperature and rain trends in our two coastal and hill test areas.

2.3. Meteorological drought indices

In the test areas, to evaluate the aridity conditions determining forest fire potential risk, some drought meteorological indices have been analyzed and compared with the Live Fuel Moisture Content (LFMC) of the sampled species (Ruffault et al. 2018).

The LFMC is the percentage of dry weight according to the equation:

$$\mathrm{LFMC} = \frac{(\mathrm{FW} - \mathrm{DW})}{\mathrm{DW}} \cdot 100 \qquad [1]$$

FW – fresh weight of the plant material;
DW – dry weight after oven drying at 70 °C for 72 h (constant weight reaching).

Comparison between drought indices outputs is investigated to provide a baseline analysis for potential operative application in the framework of fire risk management. We analyzed three drought indices that incorporate precipitation and evapotranspiration parameters.

The study also explores if there are any temporal correlations and what drought indices better express and fit seasonal variables.

2.4. Drought index overview

The Keetch Byram Drought Index (KBDI) is a drought index to find out forest fire potential risk; this index is based on the soil moisture deficit accumulate in the forest ecosystem and it is expression of rain and evapotranspiration effects on the soil loss humidity (Keetch & Byram 1968).

Defining the available soil water content equal to 203.2 mm and considering the effective precipitation > 5,1 mm (excluding rain intercepted by the crowns or lost for evapotranspiration) the value to reduce the drought rate, KBDI represents an estimation of the rain useful to field moisture capacity recovering.

The KBDI value is computed from air daily max temperature, effective precipitation, average annual rainfall. The KBDI range is from 0 mm (saturated soil) to 203.2 mm (total drought).

KBDI computing formula:

$$\mathrm{KBDI} = \mathrm{Q} + \mathrm{dQ}\ [\mathrm{mm}] \qquad [2]$$

$$\mathrm{dQ} = \frac{(203.2 - \mathrm{Q})[0.968\exp\,(0.0875\mathrm{T}_{\max} + 1.5552) - 8.30]\ \mathrm{dt}}{1 + 10.88\exp\,(-0.001736\mathrm{P}_{\mathrm{a}})} \cdot 10^{-3}$$

where:
Q – KBDI of the previous day [mm] - in detail the drought of the previous day to which the actual precipitation is subtracted (> 5.1mm);
dQ – variation in Q [mm];
$\mathrm{T}_{\max}$ – max air daily temperature [°C];
P_{a} – average annual rainfall [mm];
dt – time increment (set as 1 day).

Two meteorological drought indices, developed by the Canadian Forest Weather Index System, were also applied: Duff Moisture Code (DMC) and Drought Code (DC) (Van Wagner 1987). The DMC expresses the moisture content of loosely compacted, decomposing surface organic matter slowly drying (response to time lag ~ 12 days).

The DC represents a numeric rating of the average moisture content of deep, compact organic layers, drying relatively slowly (response to time lag ~ 52 days). DC expresses the seasonal drought effects on the deep duff layers and large logs. Variables requested by the DC computing are midday air temperature, daily rainfall, and the month in reference to length of day index.

2.5. Missing Data Reconstruction and Environmental and statistical considerations

In the framework of agricultural modelling and hydrological analysis, meteorological data are very important; measuring instrument failures can create missing data in the measurements. For the present work the temperature missing data have been reconstructed (Arca et al. 1999; Benincasa et al. 2009; Shamshirband et al. 2016; Tomaselli et al. 2017) with artificial neural networks (ANNs), using the temperature values recorded in the nearest weather station (Venturina station, far about 20 km); three artificial neural networks were carried out to estimate daily maximum, minimum and mean air temperature (Tmax, Tmin, Tmean).

To make the analysis homogeneous for the two research years, as specified above, samplings of plant species were considered from the beginning of spring (when vegetative growth occurs and the longest dry periods begin) up to mid-autumn (beginning of the heaviest rains after the summer drought period), where the fire hazard is greater.

For the two periods considered, a Spearman's statistical correlation was performed to analyze the significance of the links between the LFMCs of the various sampled species and the meteorological drought indices. The same analysis was carried out to compare LFMC and cumulative rainfalls in 30 days before sampling (ΣP_{30}) and always between LFMC and mean of daily maximum air temperatures in the ten days before sampling ($Tmax_{10}$).

3. Results

3.1. Follonica (Coastal Area)

The comparison between the rainfall data of the two sampling years and the cumulative average of precipitation over the last 18 years highlights that in the coastal area of Follonica the year 2011 was low in precipitation (about 45% less) while 2012 was slightly less rainy (about 6% less). From data analysis, it is observed that the average of $Tmax_{10}$ is higher in spring-autumn 2011 (26.4 °C) than in 2012 (24.2 °C). Moreover, ΣP_{30} is on average higher in spring-autumn 2012 (44.8 mm against 17.6 mm); in particular, in 2012, the values of ΣP_{30} are highest from April to June and from August to November (Fig. 2).

Analyzing the LFMC trend of *Myrtus communis* L. in the spring-autumn period, it can observe that it has the same average value in the two years, with a slightly greater variance in 2011. The LFMC values of the other sampled species are higher in 2011; the greatest differences are observed for *Rhamnus alaternus* L. (27% with a marked variability in 2011), *Arbutus unedo* L. (22% with very high variability) and old and young *Quercus ilex* L. (around 22% and 18%, with a slightly greater variance in 2012 for younger specimens). The difference in the LFMC values of *Phillyrea angustifolia* L. (4.1% with very similar variance in the two years) and *F. ornus* L. (2.9% with greater variance in 2011) was more contained in the two-year period (Fig. 2).

In 2011, the LFMC minimum values for almost all the species of the experimentation were obtained in the sampling at the end of September; in the case of old *Q. ilex* L., the sampling values at the end of August (57.4%) and end of September (58.1%) were very similar. For *M. communis* L., the LFMC minimum value was at the end of August.

For 2012 we observed two minima of LFMC. Spring minimum: sampling at the end of April, except for the LFMC of *A. unedo* L. that occurred in May, (slight difference with the April value). Summer minimum: sampling at half July; except for the LFMC of *Phillyrea angustifolia* L. that occurred at the beginning of October.

A possible explanation of the different LFMC values in the two years is due to both the rainfall trends and the cumulative of rainy events. Comparing the late winter and spring months, we observed that a rainier March in 2011 (67.2 mm against 17.4 mm) was followed by a drier April and May (13.2 mm and 22.6 mm versus 53.6 mm and 66.8 mm respectively). Dry June in both years (6.0 mm and 8.6 mm). In the 30 days before the July 2012 sampling there were any rainfalls (in 2011 29.6 mm). The opposite situation for August: no significant rainfall in 2011 compared to a cumulative of 24.2 mm in 2012. September 2012 was rainier than in 2011 (84 mm against 17.8 mm). The same for October: 76 mm (2012) vs 34 mm (2011).

Trends of drought indices in Follonica site

In 2011, from the beginning of spring, the KBDI value increases until it reaches its maximum between the end of September and the beginning of October (the second part of the summer and the beginning of autumn are poor in rainy events). It is observed that this index has a strong negative correlation with LFMC of young *Quercus ilex* L., *Fraxinus ornus* L. and *Rhamnus alaternus* L. The cor-

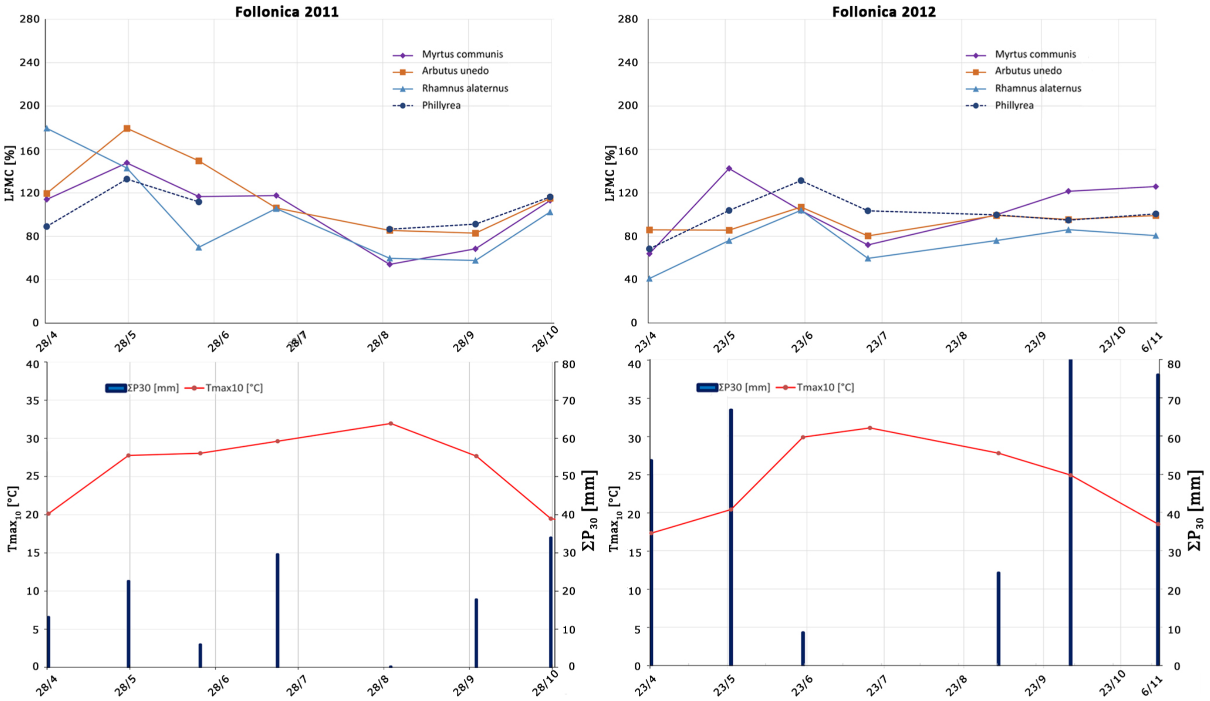

Fig. 2. Follonica (coastal area of Tuscany, Italy). On the top: LFMC trends for four shrub species during the period spring-autumn 2011 and 2012. On the bottom: rainfall cumulated in 30 days before sampling data (ΣP_{30}) and mean of daily maximum air temperatures in the ten days before sampling (Tmax$_{10}$).

relation between KBDI and LFMC of *Myrtus communis* L. and *A. unedo* L. is lower, while the one with LFMC of *P. angustifolia* L. is almost absent. In general, in 2011, the trend of the KBDI and the LFMC of the various species is quite equivalent (Fig. 3).

In 2012, the highest KBDI values were recorded in correspondence with the September sampling (the absolute maximum is September 18, before two rainy events) in fact, September 2012 was rainier than September 2011 (84.0 mm against 17.8 mm). The only correlation (even if positive and weaker, in absolute value, than in 2011) is observed between KBDI and LFMC of young *Q. ilex* L.; the correlations between KBDI and LFMC of the other species are very weak or absent (Table 1).

In the two years of the experiment, KBDI did not generally assume values above 150, which are associated with dry conditions that can lead to an increase in hazard of wildfire occurrence. Only at the end of the summer were the KBDI values typical of this period where the lower litter layers could actively contribute to the fire intensity by actively burning (Copernicus 2019) (Fig. 3).

DC has a very similar trend to the KBDI, as is also evidenced by the correlation values between the two indices in both years: 0.920. In 2011 the maximum value of DC was obtained with the sampling of the end of September, while in 2012 the maximum value was reached in correspondence with the sampling of the beginning of October. In 2011 DC shows a highly significant negative correlation with LFMC *F. ornus* L., *R. alaternus* L., young *Q. ilex* L., *M. communis* L. and *A. unedo* L., while the negative correlation with the LFMC of the other two species is weak (Table 1). In 2012 the correlation between DC and LFMC of the sampled species was generally weaker if not negligible (*M. communis* L. and *P. angustifolia* L.) or almost absent (*F. ornus* L.) (Fig. 3; Table 1).

In the two years of sampling, the DMC (Duff Moinsture Code) index did not show a very significant correlation with LFMC for sampled species, as we will see in the next lines and in Table 1; considering this evidence, this index cannot be considered the most appropriate to assess drought in Mediterranean broadleaves forest (Steinfeld et al. 2022). The differences between the recorded performances are significant given that indices are fitted for a local meteorological stations grid with high-resolution and it is especially true in areas with a complex and diverse topography and spatial variability. In fact, the DMC index assumed in 2011 a relative maximum in the sampling at the end of June, (with a cumulative rainfall of 6 mm in period before the sampling), where there is a relative minimum of LFMC for *M. communis* L., *P. angustifolia* L., *R. alaternus* L., *F. ornus* L. and young *Q. ilex* L. and an absolute maximum for old *Q. ilex* L. In the sampling of 20th July DMC has a relative minimum corresponding to a relative maximum of LFMC of *M. communis* L. The DMC absolute maximum is recorded in the sampling at August's end, where there is the absolute minimum of LFMC for *M. communis* L., *P. angustifolia* L. and old *Q. ilex* L. As previously mentioned, DMC is weakly negatively correlated with the LFMC of *F. ornus* L., *R. alaternus* L. and *M. communis* L.:

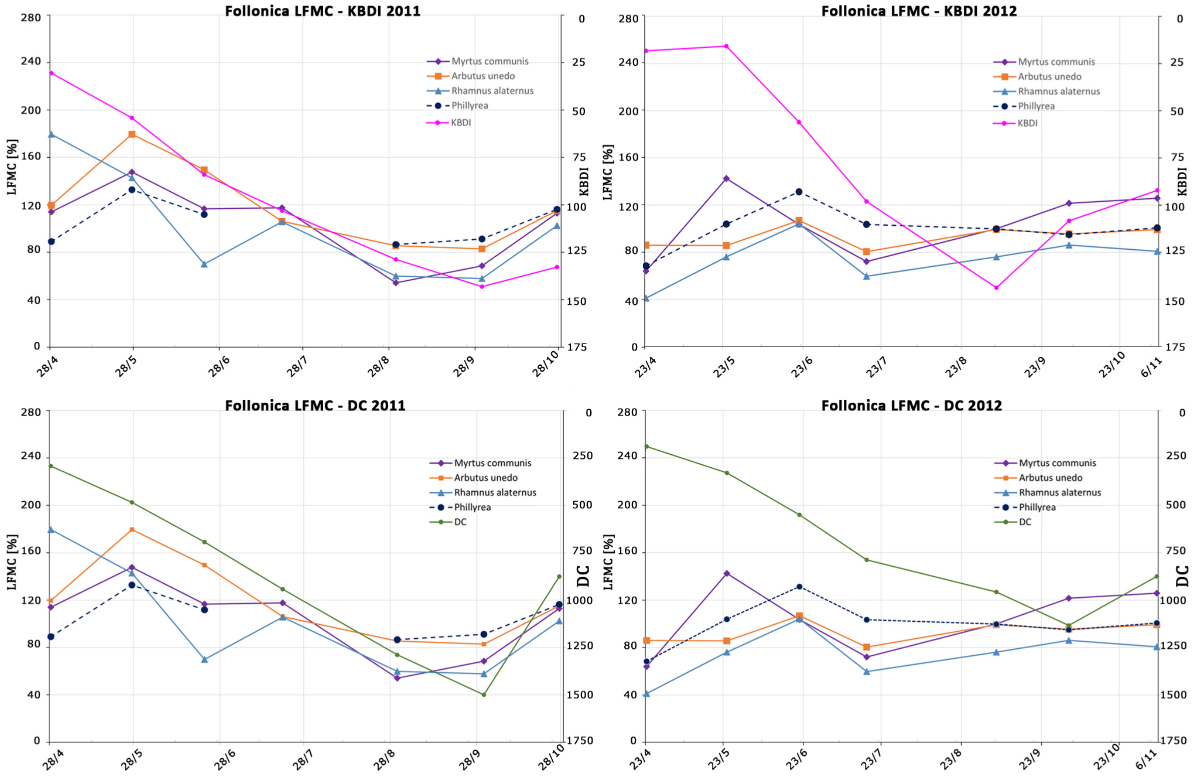

Fig. 3. Follonica (coastal area of Tuscany, Italy); seasonal trends of most significant drought indices KBDI (in the top) and DC (in the bottom) compared with LFMC values for the four shrub species monitored during the period spring-autumn 2011and 2012.

the relative maxima (minima) of DMC correspond to the minima (maxima) of LFMC; any correlation with the LFMC of other species. In 2012, the DMC reached the maximum value in mid-July, where the minimum LFMC of all species (except *P. angustifolia* L.) was recorded. DMC is weakly correlated negatively with the LFMC of *M. communis* L. and positively with that of *P. angustifolia* L.; no or negligible correlation with LFMC of other species (Table 1).

The two "meteorological" indices $Tmax_{10}$ and ΣP_{30} showed, from a statistical point of view, little significant correlation with LFMC of the considered species. In fact, $Tmax_{10}$ was weakly negatively correlated in 2011 with LFMC of *F. ornus* L. and *R. alaternus* L. while in 2012 it was positively correlated with LFMC of young *Q. ilex* L. and *P. angustifolia* L. In 2011 ΣP_{30} has a weak positive correlation with LFMC of *M. communis* L. and *P. angustifolia* L.; while in 2012 it has a positive correlation with LFMC of *M. communis* L. and a weak negative correlation with LFMC of *P. angustifolia* L. (Table 1).

3.2. Lecceto (mid-hill site)

In the hilly area of Lecceto, compared to the average cumulative rainfall of the last 23 years, 2011 was poor in precipitations (about 30% less); while 2012 was slightly rainier than average (about 11% more). The comparison of the spring-autumn period in the two years underlined that:

1) the average of the maximum daily temperatures in the 10 days before the sampling is higher in 2011 (26.4 °C) than in 2012 (23.5 °C);
2) the cumulated rainfall in the 30 days before the sampling results on average higher in 2012 (89.1 mm against 33.9 mm). In particular, in 2012, ΣP_{30} val-

Table 1. Follonica (coastal area of Tuscany): correlation between drought meteorological indices and LFMC of the species sampled during the measurement campaigns carried out in the periods April–November 2011 and April–November 2012. In **bold** the significant correlations.

	Young *Q. ilex* L.		*Arbutus unedo* L.		Old *Q. ilex* L.		*Fraxinus ornus* L.		*Myrtus communis* L.		*Rhamnus alaternus* L.		*Phillyrea*	
Year	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
KBDI	**–0.834**	0.520	–0.674	0.331	–0.437	0.291	**–0.885**	0.056	–0.673	–0.007	**–0.845**	0.262	–0.239	0.166
DC	**–0.845**	0.486	–0.754	0.354	–0.516	0.433	**–0.906**	0.163	–0.817	0.234	**–0.859**	0.419	–0.440	0.216
DMC	–0.135	0.226	–0.027	–0.224	0.298	–0.146	–0.487	–0.287	–0.410	–0.489	–0.580	0.003	–0.231	0.410
Tmax–10	–0.120	0.660	–0.119	0.181	0.115	0.077	–0.575	0.013	–0.354	–0.229	–0.591	0.401	–0.109	0.642
PC –Σ30	0.127	–0.388	0.119	–0.001	–0.081	0.192	0.196	0.275	0.510	0.587	0.303	–0.010	0.561	–0.444

Note: (p = 0.05)

ues are higher in April and May and from August to November.

Analyzing the LFMC trend of *Viburnum tinus* L., it is observed that the mean value is very similar in the two years with a higher variance in 2011. The mean value of LFMC of *Arbutus unedo* L. is slightly higher in 2011 (5.5%) but the variance is almost double. In the case of *Erica arborea* L. the average LFMC value is higher in 2011 (about 20%) with greater variability. In the case of young and old *Quercus ilex* L. and *Ligustrum vulgare* L., the average LFMC value is higher in 2012 (40%, 15% and 10% respectively) while the variance is higher in 2011.

In 2011 the LFMC for per *A. unedo* L., old *Q. ilex* L., *E. arborea* L. assumes the minimum value in the sampling at the end of July. The LFMC values of *L. vulgare* L. are almost constant in the summer period, close to the absolute minimum. The minimum LFMC value for *V. tinus* L. is reached at the end of August. The LFMC trend of young *Q. ilex* L. shows two low values at the end of June and at the end of September, with the values of the other summer samples well below the average value.

For 2012, two LFMC minima are observed: one in spring, sampling at the end of April, one in summer, sampling in mid-July. After July sampling, the LFMC trend for *A. unedo* L. is a plateau. Small fluctuations are noted in the late summer-autumn period for the LFMC of *Q. ilex* L.

As in the case of Follonica, the significantly different pluviometric trends between 2011 and 2012, both temporally and in terms of cumulative, are a plausible explanation for the different LFMC trends between the two years in Lecceto (Fig. 4). Comparing the months of late winter and spring, it is observed that in 2011 the January–March period was rainier than in 2012 (196.4 mm versus 36.8 mm), followed by drier April and May (17.8 mm and 14.8 mm respectively against 109.2 mm and 93.2 mm, recorded in 2012). For the summer months in 2011 June was rainier (86.8 mm compared to 22.8 mm in 2012) while in the 30 days before the July sampling, few rainy events were recorded in both years (20.8 mm and 7.6 mm). For August no significant rainfall was recorded in 2011 compared to a cumulative of 127.8 mm in 2012. September 2012 was rainier than in 2011 (105.4 mm against 16.0 mm); the same occurred for October: 167.6 mm (2012) versus 81.4 mm (2011) (Fig. 4).

Trends of drought indices in Lecceto site

In Lecceto, as well as in Follonica, the value of KBDI increased in 2011 from the beginning of spring until it reached its maximum between the end of September and the beginning of October (the second part of the summer period and the beginning of autumn were poor in rainy events). It is observed that KBDI has a strong negative correlation with the LFMC of *V. tinus* L. while its negative correlation with the LFMC of the old *Q. ilex* L. and *A. unedo* L. is less strong (Table 2). The correlations of

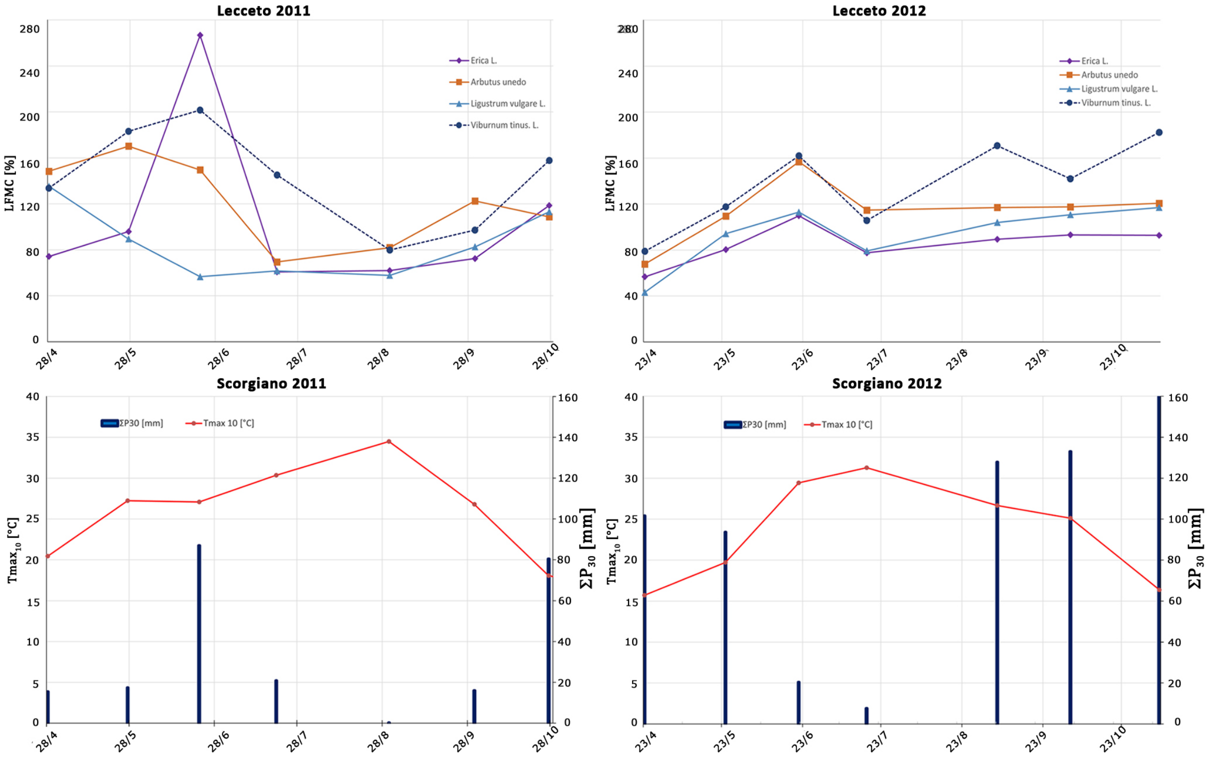

Fig. 4. Lecceto (mid-hill site of Tuscany). LFMC seasonal trends (in the top) for the four shrub species during the period spring-autumn 2011 and 2012. On the bottom: rainfall cumulated in 30 days before sampling data (ΣP_{30}) and mean of daily maximum air temperatures in the ten days before sampling ($Tmax_{10}$) – meteorological data from Scorgiano weather station.

Table 2. Lecceto (mid-hill site of Tuscany): correlation between drought meteorological indices and LFMC of the species sampled during the measurement campaigns carried out in the periods April–November 2011 and April–November 2012. In **bold** the significant correlations.

	Young *Q. ilex* L.		*Arbutus unedo* L.		Old *Q. ilex* L.		*Erica* L.		*Ligustrum vulgare* L.		*Viburnum tinus* L.	
Year	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
KBDI	–0.253	–0.108	–0.585	0.365	–0.602	0.156	–0.455	0.189	–0.328	0.046	**–0.732**	0.015
DC	–0.509	0.042	–0.596	0.424	–0.733	0.330	–0.373	0.379	–0.566	0.360	**–0.756**	0.348
DMC	–0.302	–0.261	–0.383	0.311	–0.435	0.054	–0.372	0.068	–0.575	–0.113	–0.661	–0.238
Tmax–10	–0.446	0.155	–0.415	0.621	–0.504	0.343	–0.148	0.483	**–0.855**	0.296	–0.352	0.157
PC –Σ30	0.037	0.109	0.205	–0.327	0.453	0.045	**0.823**	–0.098	0.010	0.193	0.685	0.385

Note: (p = 0.05)

KBDI with LFMC of the other sampled species are weak (*Erica arborea* L.) or negligible (Table 2). In 2011, the summer minimum of LFMC for (young and old) *Q. ilex* L. was reached corresponding to the lowest values of KBDI (sampling at the end of September). In this period the LFMC values for old *Q. ilex* L. are very low, while for the other four species the LFMC values, after reaching the minimum in the sampling at the end of August, had a slight increase. In 2012, the highest values of KBDI were recorded between the end of July and August (the absolute maximum occurs on 25th August, before two rainy events), in other words in correspondence with the summer minimum of LFMC. The correlation between KBDI and LFMC of the sampled species was very weak (*A. unedo* L.) or negligible (all other species) (Fig. 5; Table 2).

In 2011 ΣP_{30} showed a significant positive correlation with *Erica arborea*'s LFMC; the correlation was slightly less significant with the LFMC of *V. tinus* L., while that with LFMC of old *Q. ilex* L. was weak; finally, those with LFMC of the other species were negligible (Table 2). In 2012 ΣP_{30} showed a very weak positive correlation, while the correlations with the LFMC of the other species were almost negligible (*V. tinus* L.) or even absent or negligible (Table 2).

4. Discussion

Analyzing the results obtained in the two sites and considering operative applications, the KBDI and DC drought indices have a good correlation when they indicate, for a given period, a good correspondence in the trend of the meteorological parameters considered. The results obtained by the indices comparison demonstrate the

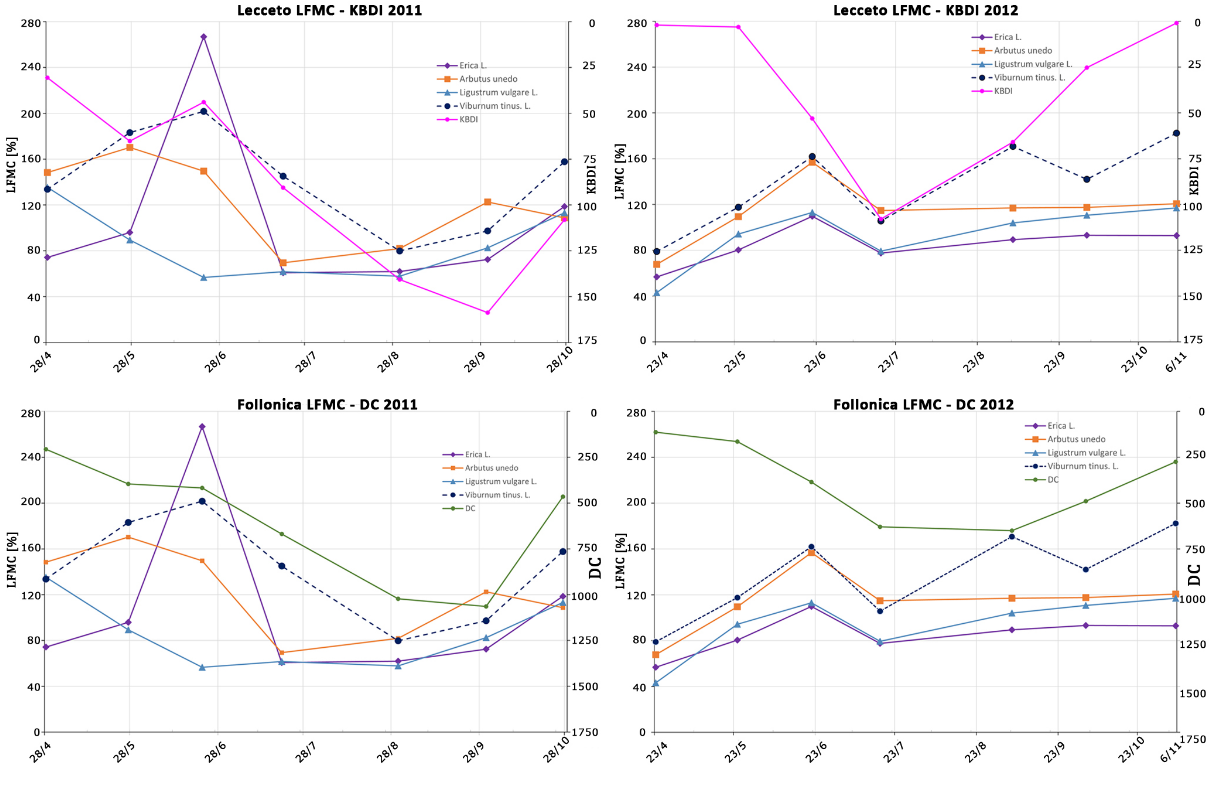

Fig. 5. Lecceto (mid-hill site of Tuscany): seasonal trends of most significant drought indices KBDI (in the top) and DC (in the bottom) compared with LFMC values for the four shrub species monitored during the period spring-autumn 2011and 2012.

effectiveness in comparing indices correlation with LFMC to discriminate their strength of agreement/disagreement with the meteorological parameters trends. In general, the drought indices better describe the state of hazard of dry years (as was 2011 in the areas considered), in fact they are applied to evaluate severity and duration (in space and time) of drought period, combining information on anomalies of precipitation, soil moisture and vegetation drought (Rodrigues et al. 2023).

For agro-forestry meteorological evaluation it is important to notice that, in the two test-sites the rain-Evapotranspiration potential deficit is lower in 2012 than 2011. Furthermore, KBDI, DMC and DC are lower in 2012. Finally, a negative correlation is observed between $Tmax_{10}$ and ΣP_{30} in 2012 (–0.779 in Follonica and –0.734 in Lecceto) and, although weaker, in 2011 (–0.449 in Follonica and –0.504 in Lecceto). This highlights that a very negative precipitation-evapotranspiration balance plays an important role in explaining fire-risk areas even in late spring and autumn, suggesting a potential lengthening of the fire season.

Analysis of the results suggests that a rapid and effective evaluation of drought dynamics in vegetation status is therefore crucial to improve the performance of the forest fire hazard indexes. This is particularly relevant for the planning of the prescribed burning, the issue of public notifications and the allocation of firefighting resources (Torres et al. 2018).

As shown, in this study, three drought indices that model vegetation water content have been compared, with the aim of evaluating their performance in capturing the seasonal trends of different species in relation to meteorological parameters.

To comprehensively investigate the effectiveness of the indices, we focused on the high fire risk seasons of two consecutive years characterized by different meteorological trends in relation to seasonal averages calculated over 15 years: 2011 classified as a drought year and 2012 as an average year. This comparative approach allowed us to identify meteorological variables most closely linked to the physiological responses of different species. The results demonstrated that analyzing consecutive years provided insights into the environmental parameters that most strongly influence vegetation drought status.

Our approach showed promising results in modeling drought effects on vegetation, taking into consideration the difficulty of setting and standardizing meteorological data. Unlike previous studies, our research focused on restricted areas, enabling the fine-tuning of index performance for potential future operational applications. Although this comparative analysis was not designed for immediate operational use, it serves as an initial investigation to assess drought conditions that correlate with fire ignition and potential spread.

A major limitation identified in this study is the scarcity of accurate meteorological measurements and the limited understanding of drought-fire relationships in various Mediterranean forest ecosystems. Bridging this gap is essential for translating drought research into practical fire management strategies.

Drought played a crucial role in determining fire-risk zones, even in late spring and autumn, due to alterations in the rainfall-evapotranspiration balance. This suggests a possible extension of the fire season in response to projected future drought trends.

Modeling drought levels in heterogeneous landscapes remains an uncertain process. Accurate estimation of Live Fuel Moisture Content (LFMC) is essential for understanding water catchment balance, yet it remains elusive due to fluctuating precipitation patterns and vegetation complexity. Our results provide insights into the sensitivity and accuracy of drought models (KBDI, DC, and DMC) in capturing meteorological trends and LFMC variations in Mediterranean ecosystems.

The methodology developed in this study offers a reliable framework for predicting forest fire risk year-round. By comparing two years with distinct meteorological conditions, we identified fire indices that better align with actual fire occurrences. This integrated approach demonstrated its potential for assessing seasonal variability in LFMC across fire-prone Mediterranean ecosystems.

The capability of these models to simulate vegetation drought dynamics can be further enhanced by integrating field-based measurements of moisture content across different forest structures and types.

5. Conclusions

The indications obtained from this study confirm that the used method is effective for fuel management planning, by accounting for the connectivity of wildfire spread across diverse land cover types. Understanding LFMC trends is particularly relevant for silvicultural interventions, as it provides guidance for managing fuel loads based on climatic and seasonal variations in specific regions. These insights contribute to wildfire management within complex landscapes, addressing uncertainties related to fire behavior under changing climatic conditions (Keyes 2006). In Italy, the practice of prescribed burning remains underutilized compared to other Mediterranean countries. This is due to landscape complexity, socio-cultural resistance, legislative fragmentation, and limited financial and educational investments. Moreover, forest fire control strategies in Italy are predominantly reactive, focusing on suppression rather than prevention. The availability of real-time and easily updatable LFMC data during the early and late high-risk months (April–May and October) could facilitate an extended prescribed burning window. This period coincides with the availability of firefighting resources, which are deployed for summer fire suppression (Ascoli & Bovio 2013).

Future research should focus on assessing the fine-scale impacts of climate changes on drought-fire dynamics, refining drought indices for operational use, and integrating remote sensing and field data to improve predictive capabilities. Addressing these gaps will enhance the strategic management of fire-prone Mediterranean ecosystems, ultimately contributing to more effective wildfire prevention and mitigation strategies.

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