Live fuel moisture content time series in Catalonia since 1998

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Abstract

Key message We present a structured and curated database covering 21 years of LFMC measurements in the Catalan region, along with an associated R package to manage updates and facilitate quality processing and visualisation. The data set provides valuable information to study plant responses to drought and improve fire danger prediction. Dataset access is at https://doi.org/10.5281/zenodo.4675335, and associated metadata are available at https://metadata-afs.nancy.inra.fr/geonetwork/srv/fre/catalog.search#/metadata/583fdbae-3200-4fa7-877c-54df0e6c5542.

Keywords Mediterranean shrublands · Fire danger · Fuel moisture database

1 Background

Live fuel moisture content (LFMC), the ratio of water mass over the dry mass of living shoots, is a critical parameter related with flammability and wildfire behaviour (Chandler et al. 1983; Chuvieco et al. 2009; Fares et al. 2017; Resco de Dios 2020). In 1994, the Catalan Forest Fire Prevention Service (SPIF), in collaboration with Catalan Forest Rangers, initiated a LFMC monitoring program to provide operational fire danger evaluation with ground information regarding plant water status. Only four sites were monitored during 1994–1996, following Countryman and Dean (1979) and Norum and Miller (1984). With the aim to increase the size and representativeness of LFMC samples, in 1997 researchers of the Ecological and Forestry Applications Research Centre (CREAF) were requested to suggest a broader set of sampling areas and species representative of Mediterranean shrub habitats, as well as to standardize field and laboratory protocols (Piñol and Ogaya 1997). With this information in hand, in 1998 SPIF initiated the systematic monitoring of LFMC in

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Contribution of the co-authors Eva Gabriel and Ruth Delgado-Dávila are co-first authors.
EG and RDD designed the database and conducted the data quality controls.
RDD programmed the associated R package.
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Table 1  Climate, habitat, geological characteristics, and year of last fire (if any) of the nine localities included in the LFMC monitoring (see Fig. 1). The coordinates of the sampling sites and sampling periods are given in Table 2. MAP: mean annual precipitation (mm·year\(^{-1}\)); MSP: mean summer precipitation (mm·year\(^{-1}\)) (source: Digital Climatic Atlas of Catalonia 1961–1990); fire: year of last wildfire impacting the area. AWS code: nearest Automatic Weather Station Code (www.meteo.cat/wpweb/serveis/cataleg-de-serveis/dades-meteorologiques/#xema).

| Locality          | Code | MAP  | MSP  | Fire  | Habitat                                                                 | Lithology                                      | AWS code |
|-------------------|------|------|------|-------|--------------------------------------------------------------------------|-----------------------------------------------|----------|
| Port de la Selva  | 1    | 550–600 | 80–100 |       | Silicicolous *Cistus monspeliensis* formations of maritime zones          | Palaeozoic metamorphic lithologies (schists and slates) | D4       |
| Montmell          | 2    | 600–650 | 120–140 | 1976  | Kermes oak garrigues with little or no thermo-Mediterranean plants       | Mesozoic sedimentary rocks (limestones and dolomites) | UH       |
| Tivissa           | 3    | 600–650 | 60–80  | 1994  | Caliciphile *Erica multiflora* formations of maritime zones              | Mesozoic sedimentary rocks (limestones and dolomites) | VB       |
| Torà              | 4    | 500–550 | 100–120 |       | Lowland rosemary scrubs and kermes oak garrigues                         | Cenozoic sedimentary rocks (marls and sandstones) | VP       |
| El Bruc           | 5    | 650–700 | 100–120 | 1986  | Low land rosemary scrubs and caliciphile *Erica multiflora* formations of maritime zones | Cenozoic sedimentary rocks (conglomerates) | CL       |
| Caldes de Malavella | 6   | 700–750 | 120–140 |       | Mixed woodland of cork-oak and pines with *Erica arborea* heaths         | Palaeozoic intrusive igneous rocks (granodiorites) | CL       |
| Begues            | 7    | 600–650 | 100–120 | 1982  | Thermo-Mediterranean garrigues dominated by *Chamaerops humilis* and invaded by the high tussocks of *Ampelodesmos mauritanica* | Mesozoic sedimentary rocks (limestones and dolomites) | UF       |
| Camarasa          | 8    | 550–600 | 100–120 |       | Kermes oak garrigues with little or no thermo-Mediterranean plants       | Mesozoic sedimentary rocks (limestones) | WX       |
| Badalona          | 9    | 600–650 | 100–120 | 2003  | Silicicolous *Cistus monspeliensis* formations of maritime zones          | Palaeozoic intrusive igneous rocks (granodiorites) | WU       |

Fig. 1  Geographical distribution of sampling sites (table 2) in the nine localities (table 1) in forest areas of Catalonia. Number of samples and last sampling year are indicated.
Table 2  Geographic coordinates (WGS84), period of years, number of samples (n), means, and 5% and 95% quantiles of available LFMC data, per plant species and sampling site within the nine localities

| Locality                  | Sampling site (code) | Lon. (°) | Lat. (°) | Period | Salvia rosmarinus (L.) Scheleid. | Quercus coccifera | Cistus monspeliensis L. | Pinus halepensis Mill. | Arbutus unedo L. |
|---------------------------|----------------------|----------|----------|--------|----------------------------------|-------------------|------------------------|-----------------------|-------------------|
|                           |                      |          |          |        | n Mean Q0.05 Q0.95               | n Mean Q0.05 Q0.95| n Mean Q0.05 Q0.95    | n Mean Q0.05 Q0.95    | n Mean Q0.05 Q0.95 |
| Port de la Selva           | Els Llaures (1)      | 3.2304   | 42.3418  | 2001–2019 | 412 105.7 49.3 150.0            | 411 126.7 52.3 191.4 | 39 105.6 47.9 141.6 | 412 110.6 98.4 124.1 |
|                           | Montperdut (10)      | 3.1010   | 42.3476  | 1998–2000 | 39 104.4 61.4 140.3            |                   |                        |                       |                   |
| Montmell                  | Puig Cabriel (2)      | 1.4910   | 41.3351  | 2002–2019 | 396 104.2 53.9 145.3            | 396 104.2 53.9 145.3 | 58 76.0 64.2 93.9    | 59 107.2 98.2 118.7 |
|                           | Vallflor (20)        | 1.4842   | 41.3373  | 1998–2001 | 60 91.4 42.2 132.9            |                       |                        |                       |                   |
| Tivissa                   | Bosc de Biscorn (3)  | 0.6752   | 41.0137  | 2017–2019 | 66 89.7 49.0 132.7            | 66 99.7 91.1 107.7  | 38 109.8 98.1 119.0  |                       |                   |
|                           | Coll de Mafla (34)   | 0.7959   | 41.0515  | 2016–2019 | 38 104.3 54.5 152.3            | 38 104.3 54.5 152.3 | 38 104.3 54.5 152.3  |                       |                   |
|                           | Barranc de les Anyeres (33) | 0.7974 | 41.0434 | 2011–2016 | 107 113.2 67.8 157.6          | 107 113.2 67.8 157.6 | 107 113.2 67.8 157.6 |                       |                   |
|                           | Mafla (32)           | 0.8018   | 41.0511  | 2004–2011 | 171 115.5 72.7 151.7          | 171 115.5 72.7 151.7 | 171 115.5 72.7 151.7 | 171 115.5 72.7 151.7 |                   |
|                           | Corral de Mafla (31) | 0.7984   | 41.0531  | 2001–2004 | 51 122.3 76.6 175.5          | 51 131.5 75.2 173.5 | 51 131.5 75.2 173.5 | 51 131.5 75.2 173.5 |                   |
|                           | Mas d’en Gil (30)    | 0.7867   | 41.0361  | 1998–2001 | 47 116.3 60.9 149.0          | 47 116.3 60.9 149.0 | 47 116.3 60.9 149.0 | 47 116.3 60.9 149.0 |                   |
|                           | L’Aguda (39)         | 1.3959   | 41.1996  | 2018–2019 | 434 94.1 54.2 138.3          | 434 94.1 54.2 138.3 | 434 94.1 54.2 138.3 | 434 94.1 54.2 138.3 |                   |
|                           | Bruc (50)            | 1.7586   | 41.6166  | 2001–2016 | 397 93.3 55.2 134.2          | 397 93.3 55.2 134.2 | 397 93.3 55.2 134.2 | 397 93.3 55.2 134.2 |                   |
|                           | La Pinassa Plana (5) | 1.7292   | 41.5258  | 1998–2001 | 37 110.0 58.3 151.0          | 37 110.0 58.3 151.0 | 37 110.0 58.3 151.0 | 37 110.0 58.3 151.0 |                   |
|                           | Flandes de la Venta (50) | 2.8468 | 41.8161  | 1998–2019 | 476 112.1 50.7 154.6         | 476 112.1 50.7 154.6 | 476 112.1 50.7 154.6 | 476 112.1 50.7 154.6 |                   |
|                           | Caldes (6)           | 1.9240   | 41.3185  | 2001–2019 | 404 99.2 58.0 132.1          | 404 99.2 58.0 132.1 | 404 99.2 58.0 132.1 | 404 99.2 58.0 132.1 |                   |
|                           | Begues (7)           | 2.2223   | 41.4785  | 2013–2019 | 156 81.1 66.8 108.0          | 156 81.1 66.8 108.0 | 156 81.1 66.8 108.0 | 156 81.1 66.8 108.0 |                   |
|                           | Camarasa (8)         | 0.8813   | 41.9777  | 2001–2019 | 391 87.9 50.1 127.0          | 391 87.9 50.1 127.0 | 391 87.9 50.1 127.0 | 391 87.9 50.1 127.0 |                   |
|                           | Badalona (9)         | 2.1429   | 41.4666  | 2002–2013 | 14 79.1 65.1 105.7          | 14 79.1 65.1 105.7 | 14 79.1 65.1 105.7 | 14 79.1 65.1 105.7 |                   |
four localities and five additional ones were included in 2001, achieving nine localities representative of Mediterranean shrublands within Catalonia. LFMC measurements were initially performed every two weeks from May to September and monthly during the rest of the year, but since 2004 LFMC samples are taken every two weeks the whole year round.

Fig. 2 Relational data model of the LFMC database, showing the entities along with their corresponding attributes, entity integrity constraints (primary and foreign keys), and the cardinality correspondence among entities.
2 Methods

2.1 Site description

Sampling sites are distributed in nine localities within the Mediterranean climate area of Catalonia, five of them between 0 and 300 m.a.s.l., and four of them between 500 and 700 m.a.s.l. The mean annual temperature range across sampling localities is 13 to 16 °C, and mean annual precipitation goes from 500 to 750 mm (Table 1).

Sampling sites are in places with less than 30% slope, a southern aspect, tree canopy cover of less than 10%, homogeneous vegetation age (four of them in previously burnt areas), and sufficient abundance of target species to sample. The representative area ranges from 2 to 7 ha across sampling sites. During the 25 years of LFMC monitoring, some sampling sites have been relocated due to wildfires, fuel treatments, or access difficulties. This explains why some localities include different sampling sites, as shown in Table 2.

2.2 Species description

The five sampled species (Arbutus unedo L., Cistus monspeliensis L., Pinus halepensis Mill., Quercus coccifera L., and Salvia rosmarinus (L.) Schleid) are characteristics of Mediterranean shrublands and widely distributed in the Mediterranean basin. Despite that all five species are well adapted to summer drought, they present different morphological traits to cope with drought intensity and extension. A. unedo and Q. coccifera are evergreen broad-leaved shrubs or small trees and resprout after fire from belowground organs. P. halepensis is an evergreen needle-leaved tree that usually regenerates densely after fire from seeds stored in serotinous cones. Among the five species, A. unedo has the highest leaf size, specific leaf area, and mean diameter of xylem vessels, and lowest wood density, suggesting a lower tolerance to severe drought (Castro-Díez 1996). Low specific leaf area and mean vessel diameter in Q. coccifera and P. halepensis suggest a higher tolerance to drought of both species. C. monspeliensis and S. rosmarinus regenerate from seed bank after fire. Despite their high mean vessel diameter, tolerance to drought of these species relies on their low specific leaf area and leaf marcescent phenology, some of them falling during severe summer drought and the rest rehydrating after rain.

2.3 Vegetation sampling and LFMC estimation

Vegetation sampling and laboratory protocols follow Piñol and Ogaya (1997). LFMC samples are currently collected in the field by Catalan Forest Rangers at 12:00 UT every 2 weeks all year round (Gabriel et al. 2021). Two or three species are sampled in each locality (Table 2). For each species to be sampled in each site, 20 shoots of 5-mm-diameter live branches, exposed to the sun and corresponding to different individuals, are selected, clipped, and put together into a 5-l hermetic plastic container. Soil and temperature data are also recorded in three localities (Begues, El Bruc, and Camarasa) using time-domain reflectometry (TDR) sensors.

Once at the laboratory, samples are weighted fresh (Fw), oven dried at 100 °C for 48 h and weighted dry (Dw) with a balance (0.1 g precision). After that, fuel moisture content, as percent on a dry mass basis, is calculated using

\[
\text{LFMC} \% = \frac{(Fw-Dw)}{Dw} \times 100
\]

After weighting dry samples, leaf and stem fractions are separated, obtaining the dry weight of leaves (Lw) and stems (Sw), from which the leaf-to-stem (LSR) percent ratio is obtained:

\[
\text{LSR} \% = \frac{Lw}{Sw} \times 100
\]

LSR is measured and stored to inform about the dynamics of fuel load or the level of branch defoliation. The mean and 5% and 95% quantiles of LFMC series per plant species and sampling site within the nine localities are shown in Table 2.

| Name          | Functionality                    | Description                                                                 |
|---------------|----------------------------------|-----------------------------------------------------------------------------|
| InitDB        | Database management              | Creates a database, defining the entities with their corresponding attributes |
| populateLFMC  | Database management              | Fills LFMC entity                                                            |
| outlierSearch | Database management and data     | Detects and flags outliers in LFMC data                                      |
| heatmapLFMC   | Data visualization               | Plots temporal patterns of biweekly or monthly LFMC values by year            |
| seasonalPlot  | Data visualization               | Plots quantiles of biweekly or monthly LFMC values                           |
2.4 Manual filtering

LFMC raw data tables were manually processed to detect inconsistencies and anomalous values related to sample processing, wrong species, or site coding. Missing database records were filled when physical paper backups were available; otherwise, they were excluded. Anomalous LFMC values were identified if being outside a species-specific range.

2.5 Automated outlier detection

Data quality from each species in each site was assessed using univariate time series analyses. These analyses require complete series; therefore, a previous imputation process was carried out. For each series, the unsampled fortnights were identified as missing LFMC values and replaced by a linearly weighted moving average, with a four-value window size. For automatic outlier detection, we used an approach based on fitting an autoregressive integrated moving average (ARIMA) model to each time series. We only considered those series with more than 15 years of data. The ARIMA model selection was carried out using the auto.arima function from forecast package (Hyndman et al. 2020). The order of non-seasonal differencing was set to zero for all series, after evaluating stationarity using augmented Dickey-Fuller t-statistic tests. Parameter values of the selected model by series are available as ancillary dataset in the LFMC package. Two types of outliers were determined: (1) Additive Outliers (AO), single anomalous observations that do not affect subsequent observations in the series, and (2) Temporary Changes (TC), an anomalous event with a decreasing exponential effect. We did not consider a third type called Level Shifts (LS), because an abrupt change in LFMC values is not expected to permanently change the average of LFMC time series. The automatic procedure to detect outliers was implemented using the ‘tso’ function from tsoutliers package in R (López-de-Lacalle 2019). Outliers were iteratively detected in the ARIMA model residuals by calculating two different test statistics, according to each outlier type. All outliers detected were manually verified by species.

3 Access to the data and metadata description

3.1 Database structure and design

A relational database was designed to store LFMC data in a format ensuring long-term integrity. Additionally, this approach allows a flexible access to data, while maintaining the database in a consistent state. The relational model for LFMC database is shown in Fig. 2, which includes seven tables:

| Locality       | Sampling site | Species          | Samples | Total AO | Total TC |
|----------------|---------------|------------------|---------|----------|----------|
| Port de la Selva | Els Llaures    | *Cistus monspeliensis* | 412     | 5        | 0        |
|                |                | *Pinus halepensis*  | 410     | 9        | 1        |
|                |                | *Salvia rosmarinus* | 412     | 3        | 0        |
| Montmell       | Puig Cabirol   | *Pinus halepensis*  | 395     | 2        | 0        |
|                |                | *Quercus coccifera* | 396     | 8        | 7        |
|                |                | *Salvia rosmarinus* | 395     | 2        | 0        |
| Tivissa        | Tivissa        | *Pinus halepensis*  | 367     | 6        | 1        |
|                |                | *Quercus coccifera* | 367     | 6        | 11       |
|                |                | *Salvia rosmarinus* | 366     | 2        | 0        |
| Tora           | L’Aguda        | *Pinus halepensis*  | 433     | 5        | 0        |
|                |                | *Quercus coccifera* | 431     | 7        | 6        |
|                |                | *Salvia rosmarinus* | 433     | 4        | 0        |
| Bruc           | La Pinassa Plana | *Pinus halepensis* | 395     | 6        | 0        |
|                |                | *Quercus coccifera* | 393     | 5        | 7        |
|                |                | *Salvia rosmarinus* | 396     | 3        | 1        |
| Caldes         | Can Caldes     | *Arbutus unedo*    | 478     | 1        | 0        |
| Begues         | Serra de la Guardia | *Quercus coccifera* | 405     | 5        | 8        |
|                |                | *Salvia rosmarinus* | 404     | 3        | 0        |
| Camarasa       | Penyalta       | *Quercus coccifera* | 391     | 9        | 7        |
|                |                | *Salvia rosmarinus* | 391     | 3        | 0        |
The LFMC table contains both LFMC and LSR estimates, along with their components. Each record corresponds to the pooled sample of 20 shoots by species (Sect. 2.3). Each sample is identified with a unique sample code. The table includes two logical variables (flags) to indicate the results of manual and automatic outlier detection procedures (Sects. 2.4 and 2.5).

For those records in the LFMC table including reproductive and leaf phenology data, the information specifying phenology system and phenology values are stored in table PHENOLOGY.

The SPECIES table contains a unique identifier per species (SpeciesCode), and the scientific and vernacular species names.

Fig. 3 Live fuel moisture content (LFMC) and Standardized precipitation index (SPI) series at “Penyalta” sampling site for the period 2002–2011: LFMC original data series (grey line), adjusted series (colour), and outliers detected (red points) for *Salvia rosmarinus* (a) and *Quercus coccifera* (d). Trend component of LFMC time series for *S. rosmarinus* and (b) *Q. coccifera* (e). SPI series for 3-month accumulation period (C), and 12-month accumulation period (F).
• SITES table contains information about sampling sites, including a unique identifier of the locality-sampling site (SamplingSiteCode), locality and sites codes and names, site coordinates, and the starting and ending sampling years.

• For records in the SITES table including data of soil temperature and time-domain reflectometry (TDR) moisture sensor, the information associated is stored in tables SOIL_MEASUREMENTS, and TDRSENSOR.

• Table SITES_SPECIES corresponds to a transitive table that allows the referential integrity in the database. This table contains a unique identifier for each species sampled in each sampling site (SiteSpCode).

3.2 Database management

The LFMC database was implemented using the SQLite database management systems. An associated R package was written to facilitate database update and maintenance, as well as data processing and visualization. The main functions included in the package are shown in Table 3.

3.3 Data accessibility

A public version of the database and associated R package is available through Zenodo (Gabriel et al. 2021, https://doi.org/10.5281/zenodo.4675335) and includes data for attributes FreshMass, DryMass, LFMC, and quality flags. Associated metadata are available at https://metadata-afs.nancy.inra.fr/geonetwork/srv/fre/catalog_search#/metadata/583f9dbae-3200-4fa7-877c-54df0e6c5542. Development versions of the package are available in a GitHub repository (https://github.com/spif-ctfc/LFMC). Access to PhenologyCode, DryStem, DryLeaf, and LeafStemRatio attributes of the LFMC data table, as well as data from tables PHENOLOGY, SOIL_MEASUREMENTS, and TDRSENSOR, will be made publicly available in a near future.

4 Technical validation

A total of 94 Additive Outliers and 49 Temporary Changes were automatically detected for LFMC values (Table 4). Both types of outliers were most often found for LFMC series of Quercus coccifera. For this species, the delta parameter determining the exponential decay improved the AO estimations when set to $\delta = 0.5$. For the remaining species, $\delta = 0.5$ did not increase the number of TC found nor improved the AO estimations, so the default value ($\delta = 0.7$) was kept. The high incidence of TC values in Tivissa might be explained because the locality includes different sampling sites. For all LFMC series, while AO values did not show a seasonal tendency, most of the TC found occurred during spring.

Figure 3 shows two examples of LFMC series in the database, corresponding to Salvia rosmarinus and Quercus coccifera in the same sampling site (Camarasa). AO and TC detected by the time series analysis are indicated, as well as the long-term trend obtained from the same analysis. To assess the correspondence between LFMC trends and weather indices, we used the Standardized Precipitation Index (SPI) time series (McKee et al. 1993) from weather data of nearby automated stations of the Catalan Meteorological Service. Time series of the SPI for 3-month and 12-month accumulation period are also shown in Fig. 3.

Trend component series for both Salvia rosmarinus and Quercus coccifera are broadly related with SPI series, the lowest values of SPI coinciding with the lowest trend values, although the trend for Salvia rosmarinus seems to be more sensitive to drought periods than that of Quercus coccifera. TC and AO values found for Q. coccifera, and the corresponding increase in the LFMC trend, occurred in periods 2002–2003 and 2009–2010, which were relatively moist compared to the dry years between 2005 and 2008.

5 Reuse potential and limits

We expect the LFMC database to be useful for research on LFMC behaviour, prediction, and how it relates to meteorological, physiological, or remote sensing data (e.g. Ruffault et al. 2018a). In particular, we expect it to be useful for research related with the evaluation of wildfire risk, such as the study of the relationships between drought or climate drivers with the LFMC of different species (Viegas et al. 2001; Castro et al. 2003; Pellizaro et al. 2007), the calibration and validation of remote sensing products (Yebra et al. 2013; Marino et al. 2018), the study and prediction of plant flammability (Saura-Mas et al. 2010; Madrigal et al. 2013; Fares et al. 2017) and fire spread rate (Rossa et al. 2016; Pimont et al. 2019), or the study of the LFMC role in wildfire events and regimes (Ruffault et al. 2018b). In addition, the database can be used to study the eco-physiological traits and processes driving LFMC dynamics (De Cáceres et al. 2015; Nolan et al. 2018; Pivovaroff et al. 2019). Importantly, pooling this LFMC database with the French Reseau Hydrique (Martin-StPaul et al. 2018; Duché et al. 2017) would yield a great robust and long-term LFMC dataset covering the north-western Mediterranean area for more than 20 years. The presented database also contributes to increase the amount of LFMC data available worldwide (Yebra et al. 2019).

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13595-021-01057-0.
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Declarations

Conflict of interest The authors declare no competing interests.

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