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DATA PAPER

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, RDD, MDC, PC and XC designed the study.
EG and RDD designed the database and conducted the data quality controls.
RDD and MCA programmed the associated R package.
EG and RDD led the manuscript writing, with inputs from all co-authors.

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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	Calciphile *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 calciphile *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

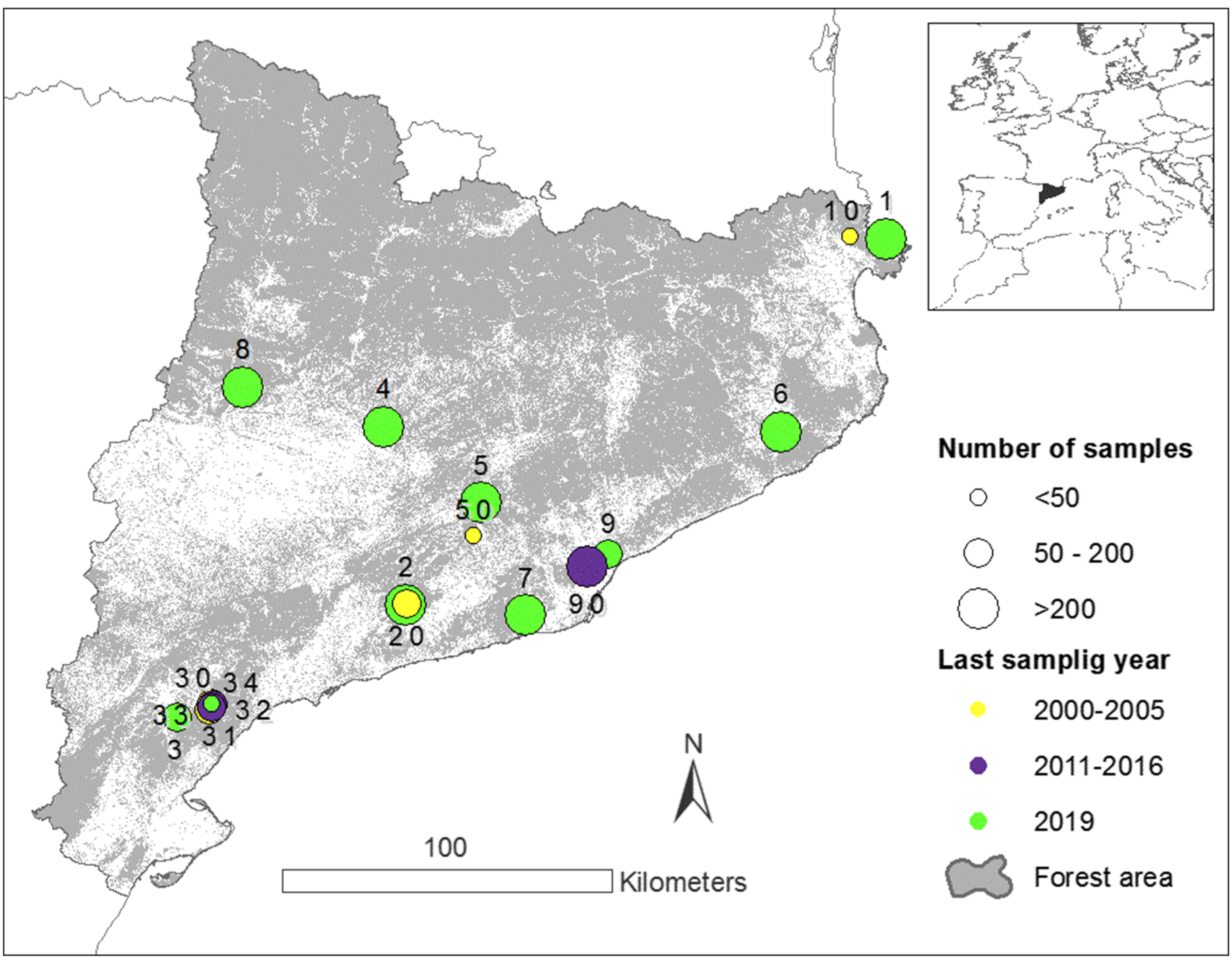

Fig. 1 Geographical distribution of sampling sites (table 2) in the nine localities (table 1) in forest areas of Catalonia. Number of samples and last sampling year are indicated

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	412	110.6	98.4	124.1				
	Montperdut (10)	3.1010	42.3476	1998–2000	39	104.4	61.4	140.3					39	105.6	47.9	141.6	38	107.7	101.5	121.2				
Montmell	Puig Cabirol (2)	1.4910	41.3351	2002–2019	396	104.2	53.9	145.3	396	76.5	65.9	93.9					396	105.6	94.8	116.7				
	Vallflor (20)	1.4842	41.3373	1998–2001	60	91.4	42.2	132.9	58	76.0	64.2	93.9					59	107.2	98.2	118.7				
Tivissa	Bosc de Biscorn (3)	0.6752	41.0137	2017–2019	66	89.7	49.0	132.7	66	73.7	63.3	95.8					66	99.7	91.1	107.7				
	Coll de Mafla (34)	0.7959	41.0515	2016–2019	38	104.3	54.5	152.3	38	74.9	64.3	93.3					38	109.8	98.1	119.0				
	Barranc de les Anyeres (33)	0.7974	41.0434	2011–2016	107	113.2	67.8	157.6	107	75.3	63.7	103.1					107	111.0	101.6	119.7				
	Mafla (32)	0.8018	41.0511	2004–2011	171	115.5	72.7	157.1	171	73.7	62.9	96.7					171	112.6	102.5	124.7				
	Corral de Mafla (31)	0.7984	41.0531	2001–2004	51	122.3	76.6	175.5	52	84.2	70.9	117.5					52	110.2	103.8	120.5				
	Mas d'en Gil (30)	0.7867	41.0361	1998–2001	47	116.3	60.9	149.0	49	76.0	65.3	94.7					50	107.2	99.7	119.2				
Tora	L'Aguda	1.3959	41.8196	1998–2019	434	94.1	54.2	138.3	432	74.2	64.3	93.2					435	97.1	87.6	107.6				
Bruc	La Pinassa Plana (5)	1.7586	41.6166	2001–2019	397	93.3	55.2	134.2	394	76.2	65.5	95.9					396	110.8	102.1	120.6				
	Flandes de la Venta (50)	1.7292	41.5258	1998–2001	37	110.0	58.3	151.0					24	139.9	121.2	159.2	38	110.6	100.2	119.5				
Caldes	Can Caldes (6)	2.8468	41.8161	1998–2019									476	112.1	50.7	154.6					478	117.1	89.5	156.0
Begues	Serra de la Guardia (7)	1.9240	41.3118	2001–2019	404	99.2	58.0	132.1	405	72.0	61.6	91.7												
Camarasa	Penyalta (8)	0.8813	41.9177	2001–2019	391	87.9	50.1	127.0	393	73.6	61.4	96.7												
Badalona	La Vallensana (9)	2.2223	41.4785	2013–2019					156	81.1	66.8	108.0	156	121.5	49.9	175.4								
	Pontell Valldaura (90)	2.1429	41.4466	2002–2013	14				259	79.1	65.1	105.7	244	117.7	55.3	175.0								

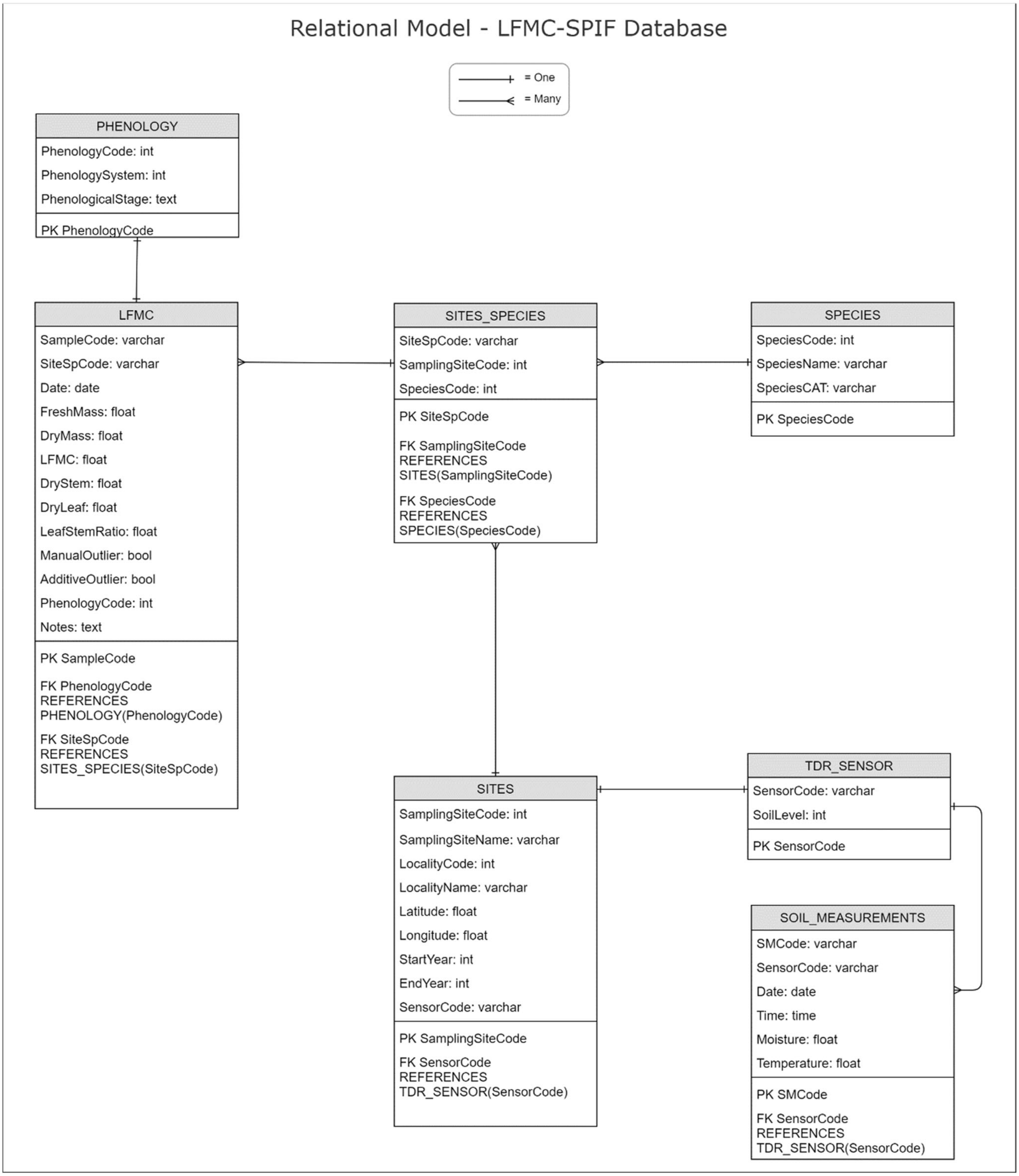

Fig. 2 Relational data model of the LFMC database, showing the entities along with their corresponding attributes, entity integrity constraints (primary and foreign keys), and the cardinality correspondence among entities

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.

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%, homogenous 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

$$\mathrm{LFMC}\ (\%) = \frac{(Fw - Dw)}{Dw} * 100$$

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:

$$\mathrm{LSR}\ (\%) = \frac{Lw}{Sw} * 100$$

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.

Table 3 Main functions of the LFMC package

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 processing	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

Table 4 Total number of LFMC samples, total of additive outliers (AO) and temporary change (TC) detected for each species by sampling site

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

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:

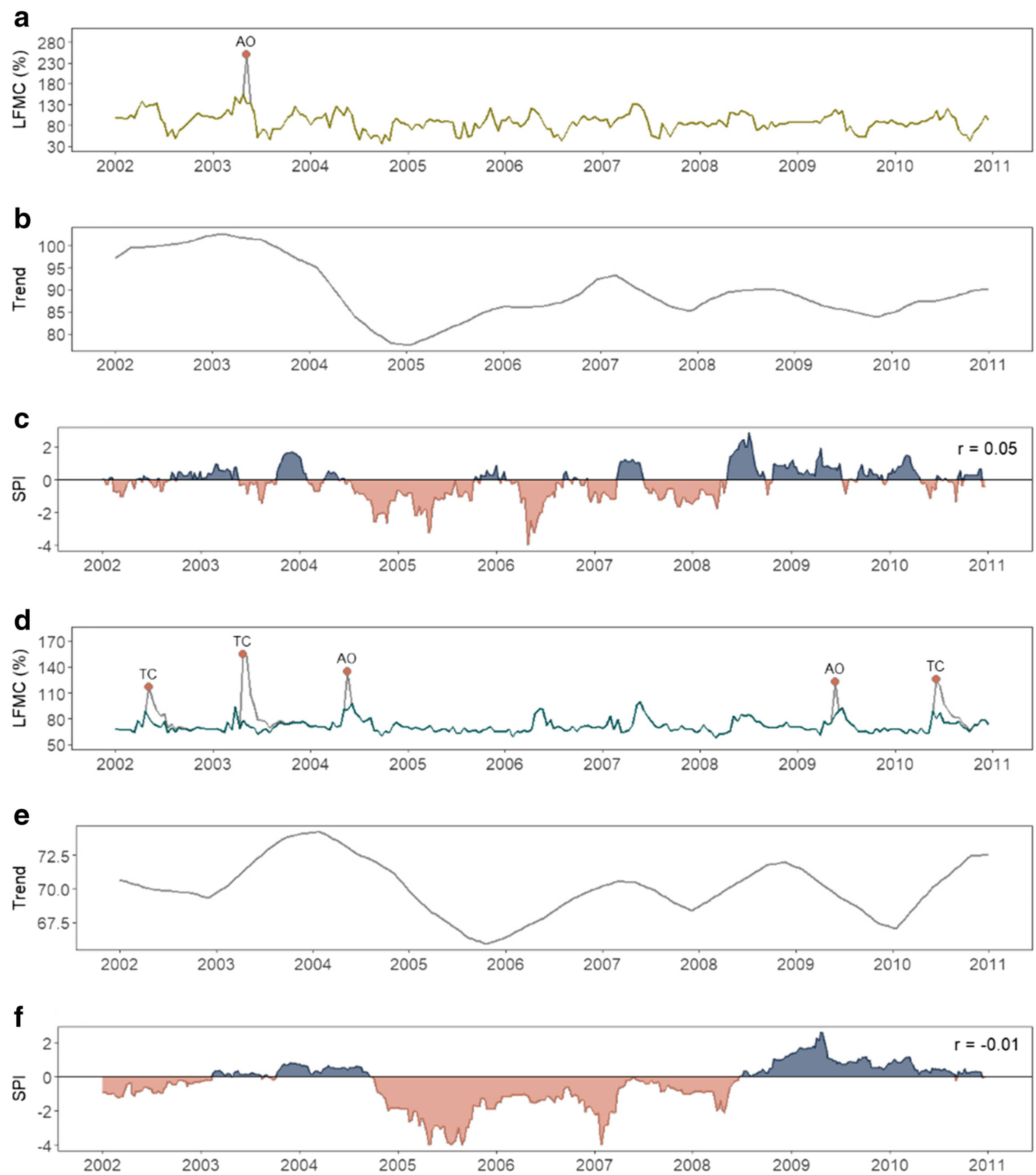

Fig. 3 Live fuel moisture content (LFMC) and Standardized precipitation index (SPI) series at "Penyalta" sampling site for the period 2002–2011: LFMC original data series (grey line), adjusted series (colour), and outliers detected (red points) for *Salvia rosmarinus* (**a**) and *Quercus coccifera* (**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)

- 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.

- 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 TDR_SENSOR.
- 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/583fdbae-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 TDR_SENSOR, 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 *Q. 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 *S. rosmarinus* and *Q. 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 ecophysiological 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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