XV WORLD FORESTRY CONGRESS
Building a Green, Healthy and Resilient Future with Forests
2–6 May 2022 | Coex, Seoul, Republic of Korea

Ecohydrology-based management as a tool for preventing wildfires in the Mediterranean urban interface area

A.J. Molina, M. Patiño, M. González-Sanchis, J. Pérez-Romero, L. Blanco, A.D. Del Campo

Departamento de Ingeniería Hidráulica y Medio Ambiente, Universidad Politécnica de Valencia, España

Abstract

The adaptation to climate change of forest areas with intense anthropic pressure requires innovative management models characterized by an increasingly efficient use of available resources. In Mediterranean areas, the most intense and persistent droughts alter the water relations in the soil-plant-atmosphere (SPA) continuum and therefore the flammability of the vegetation and the risk of wildfires. The main aim of this work is to present the potential of using detailed information characterizing the SPA for estimating key variables used for forest fire prevention. To this end, physiological, ecohydrological and meteorological measurements (water potential, soil/plant water content, sap flow, etc.) are carried out to model the response of live fuel moisture content (LFMC) to environmental conditions in representative Aleppo pine plots located in a forested area close to Valencia city (Spain). In addition, spectral indexes estimated from Sentinel bands (NDVI, EVI, NDMI, MSI, RGR, BSI and NDWI) are also tested for obtaining the spatio-temporal dynamics of LFMC at the forest scale. The results show the importance of assessing LFMC along the entire hydrological year due to its variation with phenology: minimum values are obtained at the beginning of spring (81.3%, 64mm of soil water content in the profile and 0.2Kpa of VPD) vs. 90.1% during the driest environmental (summer) conditions (18mm of soil water content and 1.9Kpa of VPD). Combining physiological and environmental predictors provides good estimations of LFMC (R^2 >0.70-0.84 in several cases). In addition, RGR, BSI and NDWI indexes are found to be promising predictors of LFMC (R2= 0.7). Efforts such as the one presented here to link a detailed SPA characterization with fire prevention are innovative and emerging, but also necessary when realistic estimations of LFMC dynamics are required. Particularly, our results will serve to improve the forest management of Mediterranean forests, allowing for the precise prediction and identification of forest wildfire behavior and risk thresholds (from surface fire to crown fire), but also the design of optimum irrigation schemes to decrease the risk of crown fires as those with the highest negative impacts.

Keywords: live fuel moisture content; ecohydrology; fire weather index; wildland-urban interface; sapflow

1.Introduction, scope and main objectives

Droughts and wildfires are the most important disturbances which are expected to increase their future negative impacts on the structure and function of forests growing under Mediterranean conditions (Moriondo et al., 2006; Vilà-Cabrera et al., 2018). Recent extended tree mortality processes in water-limited regions, higher frequency of forest fires and greater affected burned area are examples showing this reality which is already happening (de la Serrana et al., 2015; Doblas-Miranda et al., 2017).

In Spain, like in other Mediterranean regions with similar socio-economic contexts, land use changes during the last 50 years have promoted increased forested area but also an increase in the Wildland-Urban interfaces (WUI) (Vacca et al., 2020). WUI are characterized by residential areas (normally second home areas) where recreational uses are common, and the forest fire ignition is more likely to appear as compared to remote forested areas

(Vacca et al. 2020). In addition, negative impacts of forest fires normally involve higher infrastructure and human risks (Vacca et al. 2020), so special attention should be taken to these areas when planning forest prevention actions at regional scales.

Forest fire prevention services normally use real time monitoring data for estimating forest fire risk at a daily scale. The Fire Weather Index (FWI) is the most common used, as it is directly calculated from climatic observations in common meteorological stations (de Dios, 2020). However, several authors have observed that FWI does not correctly predict forest fire danger due to a poor characterization of the water content dynamics of forest fuels, especially under Mediterranean conditions (Dimitrakopoulos et al., 2011; Ruffault et al., 2018). Apart from other estimations based on climatic data required to calculate FWI, the Live fuel moisture content (LFMC) corresponds to that water which is part of the green plant tissues with diameters lower than 3mm (Nolan et al., 2018). It is related not only to surface fires but also to crown fires, so its correct estimation is not only important for estimating risk indexes but also for predicting forest fire behavior and the likely impacts (Ruffault et al., 2018).

Contrasted results have been observed when intending to explain LFMC with only information regarding climatic conditions (de Dios, 2020; Nolan et al., 2018) or climatic-derived indexes for simple water balance such as the Keetch-Byram Drought Index (KBDI) (Xanthopoulos et al., 2006). This aspect is especially challenging in water-limited conditions, where plants develop sophisticated physiological mechanisms to avoid water loss through stomata, especially those with iso-hydric strategies. A particular case is *Pinus halepensis* stands growing under Mediterranean conditions and low soil water holding capacity. Therefore, it seems that data describing the water relations within the soil-plant-atmosphere continuum are required for a proper LFMC estimation under these circumstances (de Dios, 2020).

This work is part of the European project entitled "Green Urban Actions for Resilient fire Defence of the Interface-Guardian (https://proyectoguardian.com/en/), where several innovative actions are proposed for improving forest resilience against climate change in a Mediterranean site characterized by several WUI areas. One of these actions is related to improve our knowledge about water relations in Aleppo pine forests in order to further irrigate them automatically and hence improving LFMC in the WUI strip. The main aim of this work was to analyse the temporal dynamics of several environmental and eco-hydrological variables, and then using them as predictors in order to obtain reliable estimates of LFMC. In addition, spectral information from satellite images was also tested for this objective.

2. Methodology/approach

2.1. Study site, experimental design and measurements

The study site is located at approximately 20 km from the Valencia city (Eastern Spain) in the "Vallesa" forested area (39º 32´N, 0º 30´W, 90 m a.s.l) within the Natural Park of Turia River. Climate is Mediterranean with mean cumulated rainfall and evapotranspiration of 396 mm and 1135 mm respectively. The site shows high anthropogenic pressure mainly related to recreational uses due to the proximity to urban areas, and it is characterized by several wildland-urban interfaces. As a result, two important forest fires have affected the area during the last 15 years.

Two plots of 50x50 m^2 (R and NR) were stablished in a representative *Pinus halepensis* stand previously selected based on processed information obtained from a Lidar flight of high resolution. Table 1 shows the main metrics characterizing the forest and tree structure within the experimental plots.

Table 1: Mean values for forest structure metrics characterizing the experimental plots. D: tree density, FC: forest cover, DBH: diameter at breast height, BA: basal area, Th: Total tree height, Ch: crown depth

Plot	D (trees/ha)	FC (%)	DBH (cm)	BA (m2/ha)	Th (m)	Ch (m)
R	376.0	73.1	22.8	16.2	10.0	4.1
NR	388.0	76.6	21.2	16.0	10.5	4.3

Automatic monitoring was carried out for obtaining environmental and eco-physiological variables. A total of 12 climatic variables were continuously measured at 2 m above the forest canopy with a compact meteorological station. For each sample tree (n=6-12 trees depending on the variable considered), several soil water content and soil matric potential sensors were buried at 15 and 30 cm depth in three pits surrounding each tree trunk (Figure 1). Sap flow and tree water content sensors were installed at two heights for each sample tree (at 1.3 m height and at the height corresponding to the beginning of crown). The sensors were connected to a CR1000x CSI logger programmed to collect data every 10 minutes, and solar panels and 75Ah battery were on charge of providing energy to the entire system.

Manual measurements were carried out approximately every two weeks and at two times during each sampling date (predawn and midday). At each field campaign, water potential (Scholander´s chamber) was measured in twigs of two branches per tree (north and south orientation), and these samples were after used for measuring live fuel moisture content (LFMC, % of water over dry weight). To this end, fresh weights were obtained at the field with a 0.001 g scale and dry weights after heating them at 65 ºC during two days in laboratory. LFMC was obtained for the total sample but also after its subsampling it into the current year needles, the one-year-old needles and the woody part of the twig.

In order to study the relationships between LFMC and the variables measured to characterize the soil-tree-atmosphere continuum, we calculated several basic statistics descriptors for two time windows characterizing the antecedent environment and plant water status conditions (1 -day and 4-days windows, respectively). Then, multiple linear regressions were used in order to obtain the best set of predictors. The day of the year (DOY) was also considered as potential predictor given the expected LFMC variation related to phenology (Balaguer-Romano et al., 2020).

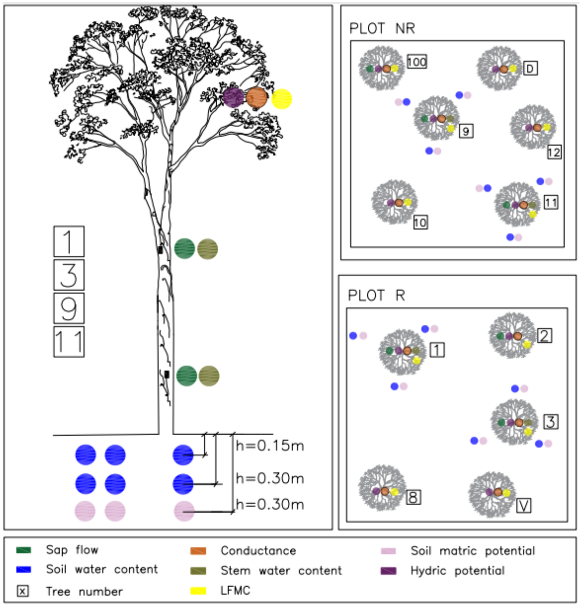

Fig. 1: Schematic representation of the monitoring system, showing the different measures taken at the sample trees. Both type of measurements (automatic and manual) are shown.

2.2. Spectral information from satellite images

Satellite images were obtained from Sentinel bands (10-20m resolution) for the entire study period. They were after used to derive several indexes related to vegetation status, soil and water availability such as NDVI, NDWI, SAVI, etc. (see for example https://www.indexdatabase.de/db/ias.php for a further description of indexes). The estimated indexes were later aggregated at the plot scale and related to the mean LFMC from the two experimental plots. To this end, multiple linear regressions were used in order to obtain the best set of indexes predicting LFMC.

3. Results

3.1. Seasonal changes in environmental conditions, fire risk and forest ecohydrology

The temporal dynamics of environmental conditions and variables describing plant water status clearly showed how the semiarid conditions affected the tree-water relations in our study site (Figure 2). In this respect, as FWI is estimated from climatic information, this fire danger index was also indicative of lower water content within the system during the drought periods, and therefore of higher wildfire risk. However, FWI showed similar values during several periods of winter probably due to they had several days without effective rainfall but also the higher wind velocities observed in our study site. Leaf water potential showed its minimum value (-3.2 KPa at midday) during the lowest soil water content conditions observed during the first drought period (about 0.1 cm^3/cm^3), and its temporal variation was clearly related to soil water dynamics during the study period (Figure 2b). In contrast, LFMC dynamics was affected by soil water content to a lesser extent, especially when considering those for the current-year needles but also for the global one (Figure 2c). It is interesting to highlight that, contrary to expected, the lowest values for the later were obtained at the spring season (Figure 2c)

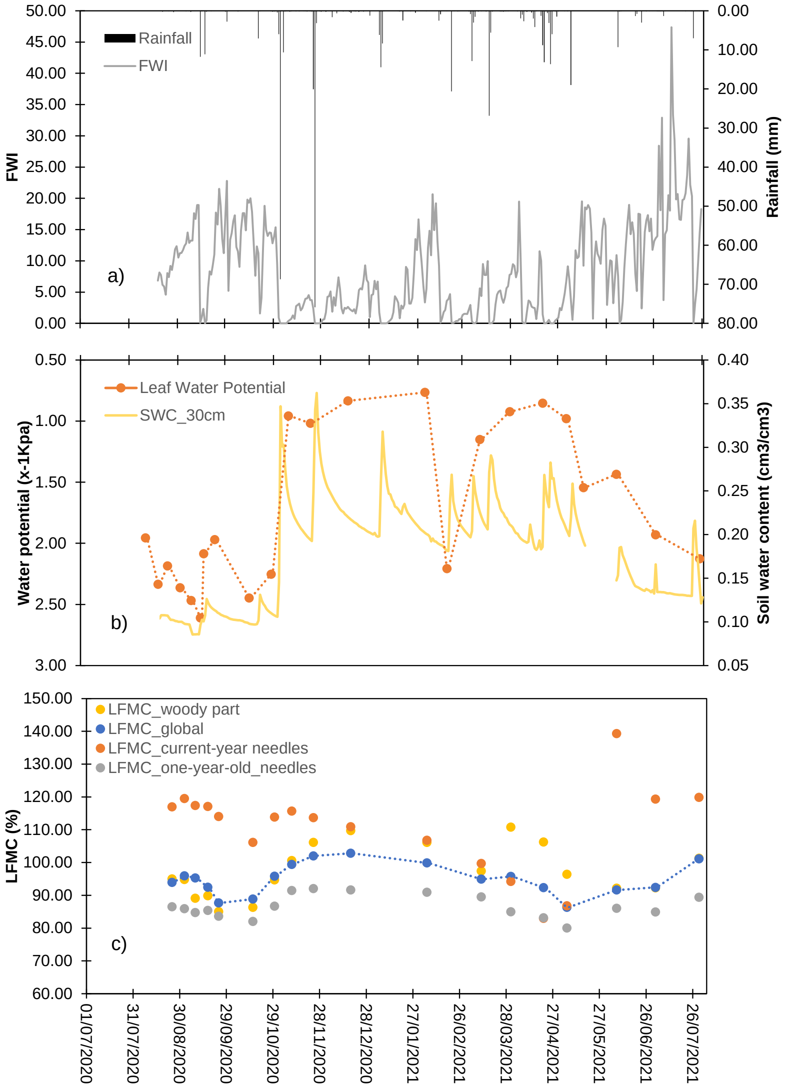

Fig. 2: Temporal dynamics of rainfall (cumulated daily value, mm), soil water content (SWC) at 30 cm soil depth (cm^3/cm^3), Live Fuel Moisture Content (LFMC, %) and leaf water potential (Kpa) during the study period (samples taken at predawn). Note that LFMC is presented for the different components (current-year needles, 1-year-old needles, woody part) and as the global one integrating all of them.

3.2. Predicting the LFMC variation

The LFMC values obtained at predawn and midday showed poor relationships with both the Fire Weather Index and the Drought Code (Figure 3). In contrast, LFMC showed a high number of significant correlations with those variables measured to characterize water relations within the soil-tree-atmosphere continuum, and also with several indexes derived from Sentinel images (Figure 4, Table 2).

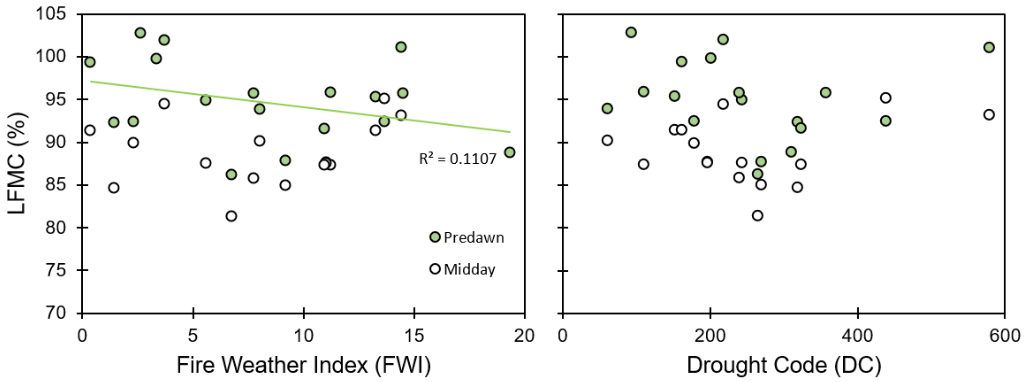

Fig. 3: Live Fuel Moisture Content (LFMC, %) as a function of FWI (left) and DC (right).

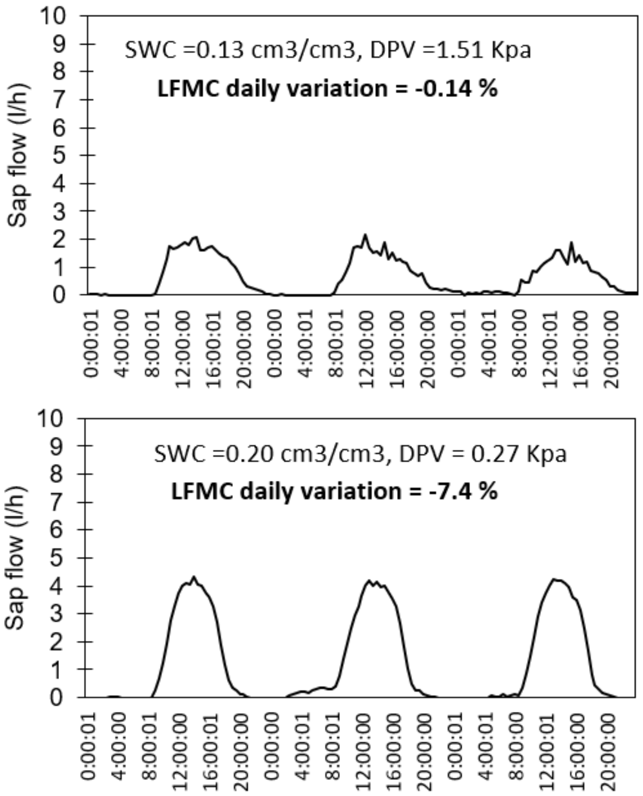

Fig. 4: Hourly dynamics of sap flow (l/h) for two 3-days-length periods showing the effects of contrasting environmental conditions and the related daily changes of LFMC. Note the highest LFMC decrease during the better environmental conditions and higher tree transpiration.

In the first case, the results for the multiple linear regressions (MLR) showed variable performance depending on the LFMC variable and the sets of predictors selected (Table 3). The best results were obtained for the MLR estimating LFMC_current-year needles obtained at midday (R^2 = 0.94) as a function of mean values of sap flow velocity and soil water potential during the antecedent 4-days to the LFMC measurements. In contrast, LFMC_woody part was poorly explained by the tested MLR for the both time periods considered (R^2 = 0.37 *vs.*

0.40). On its part, LFMC_global showed acceptable goodness of fits when considering measures taken at both predawn and midday (R^2 =0.64 *vs.* 0.71).

Table 2: Spearman's rank correlation coefficient for the relationships between LFMC (%) and different indexes derived from Sentinel bands. See https://www.indexdatabase.de/db/ias.php for a further description of indexes.

Index	R correlation (Spearman)
NDVI	0.51
NDII	0.71
RGR	-0.67
MSI	-0.71
SAVI	0.09
BSI	0.34
NBR	0.73
ARVI	0.64
GCI	0.22
EVI	0.45
SIPI	-0.81
EVI2	-0.14
NDWI	-0.12
RVI	0.5

The MLR tested for the indexes obtained from Sentinel images also showed different results depending on the LFMC variable considered (R^2 ranging from 0.4 to 0.8). As example, the best MLR model for predicting LFMC_global was as follows: 148.94-50.49· RGR +316.78· BSI + 107.39· NDWI (R^2= 0.71).

Table 3: Results of the Multiple Linear Models for estimating LFMC as a function of environmental and ecohydrological variables. DPV: Vapor pressure deficit (KPa), SF: sap flow (l/h), SWP: soil water potential (KPa), TWC: Trunk water content (cm^3/cm^3), vs: sap flow velocity (cm/h), HR: relative humidity (%), T: temperature (ºC). 1: time period of 1 day-length, 4: time period of 1 day-length. BH: measured at 1.3m, CH: measured at the beginning of the crown. Intercept values are not showed for simplicity. Significance (Sig): *** 0.001, *** 0.01, **0.05, ·0.1

Independent Variable	Explicative variables	Coefficient	Sig.	R^2
	DPV_max_4	-3.980	**	
	meanSF_4CH_lh	-4.386	**	
Global LFMC_predawn	SWP_4_mean	0.004		0.642
	meanSF_1BH_lh	-4.703	**	
	SWP_1_mean	3.688	**	
Global LFMC_midday	TWC_1_C_mean	2.076		0.7079
	vs_mean_1CH_cmh	-4.262	***	
	SWP_1_mean	0.009	**	
	HR_._mean_1	-0.175	*	
Current-year LFMC_predawn	TWC_1_C_mean	233.273	*	0.849
	vs_mean_4BH_cmh	-6.489	***	
Current-year LFMC_midday	SWP_4_min	0.006	**	0.927
	T_ºC_max_1	-0.885	***	
	HR_._max_1	0.237	*	
Wood part_LFCM_predawn	meanSF_1BH_lh	2.253	.	0.722
Wood part_LFCM_midday	T_ºC_max_1	-1.009	**	0.4083

4.Discussion

A proper assessment of wildfire risk and fire behavior requires realistic measurements of water status of forest fuel, not only of dead fraction but also the living one. In this sense, this work is consistent with others that have shown how FWI and DC indexes, but also single climatic data, are insufficient for a proper estimation of water content of tree canopy cover under limited environmental conditions (Xanthopoulos et al., 2006). In this sense, our results highlight the complexity when trying to understand the LFMC dynamics in *Pinus halepensis* stands characterized by water-limited conditions (low rainfall input and deficient soil water holding capacity) and a markedly isohydric strategy with a strong control of leaf stomatal closure to avoid water loss. As stated by other authors (Nolan et al., 2018; Ruffault et al., 2018), the estimation of LFMC based on climatic information is not enough for obtaining reliable predictions. In this sense, Nolan et al. (2018) obtained the best general linear model based on the water potential as the unique predictor for a variety of species within a Mediterranean forest. This effort, however, did not allow estimating LFMC in a continuous way. In our case, as we measured several variables characterizing the soil-plant-atmosphere continuum with automatic sensors, we were able to combine this detailed information for selecting the best linear models, allowing the estimation of LFMC at a daily scale as required for the FWI index. Most of our selected linear models combined information from climate, plant water status and soil water content availability, and they were able to predict LFMC in a reasonable way in most cases. The unexplained variation in some predictions maybe related to leaf phenology (Balaguer-Romano et al., 2020), affecting both components of the LFMC (fresh and dry weights) but also how the different temporal dynamics of the constituent parts (especially the current-year needles) affect the general LFMC. This is especially noticeable in our study, where the lowest LFMC values are not obtained during the summer period but during the spring one.

In addition, the first analyses carried out with several indexes estimated from Sentinel bands seem to be a promising way for the LFMC scaling-up from particular forest plots to the entire forest area with similar structure. In this respect, our fits are in the range of other studies using this type of predictors (Yebra et al., 2013). In this respect, further combination of indexes trying to control phenology effects are expected to improve the prediction (Yebra et al., 2013).

Conclusions/ wider implications of findings

This study has showed the potential of using high-resolution measurements in order to improve our capacity for preventing forest fires. Efforts such as the one presented here to link a detailed SPA characterization with fire prevention are innovative and emerging, but also necessary when realistic estimations of water status dynamics are required. Particularly, our results will serve to improve the forest management of Mediterranean forests, allowing for the precise prediction and identification of forest wildfire behavior and risk thresholds (from surface fire to crown fire), but also the design of optimum irrigation schemes to decrease the risk of crown fires as those with the highest negative impacts. In this sense, a further characterization of shrubland layer is desirable for a more complete description of the live fuel moisture content presented in this type of forests.

Acknowledgements

This work is funded by the Urban Innovation (UIA) Actions of the European Union through the Guardian project (UIA03-338). A.J. Molina is beneficiary of an “APOSTD’ fellowship (APOSTD/2019/111) funded by the Generalitat Valenciana.

References

- Balaguer-Romano, R., Díaz-Sierra, R., Madrigal, J., Voltas, J., Resco de Dios, V. (2020). Needle senescence affects fire behavior in aleppo pine (Pinus halepensis Mill.) stands: A simulation study. Forests, 11(10), 1054.
- de Dios, V. R. (2021). Plant-Fire Interactions Applying Ecophysiology to Wildfire Management. Elsevier, 208 pp.
- de la Serrana, R. G.; Vilagrosa, A.; Alloza, J. A. (2015). Pine mortality in southeast Spain after an extreme dry and warm year: interactions among drought stress, carbohydrates and bark beetle attack. Trees 29, 1791-1804. 10.1007/s00468-015-1261-9
- Dimitrakopoulos, A. P., Bemmerzouk, A. M., & Mitsopoulos, I. D. (2011). Evaluation of the Canadian fire weather index system in an eastern Mediterranean environment. Meteorological Applications, 18(1), 83-93.
- Doblas-Miranda, E.; Alonso, R.; Arnan, X.; Bermejo, V.; Brotons, L.; De las Heras, J.; ... López-Serrano, F. R. (2017). A review of the combination among global change factors in forests, shrublands and pastures of the Mediterranean Region: Beyond drought effects. Global and Planetary Change, 148, 42-54. http://dx.doi.org/10.1016/j.gloplacha
- Moriondo, M.; Good, P., Durao, R.; Bindi, M., Giannakopoulos, C., Corte-Real, J. (2006). Potential impact of climate change on fire risk in the Mediterranean area. Climate Research, 31, 85-95.
- Nolan, R. H., Hedo, J., Arteaga, C., Sugai, T., & de Dios, V. R. (2018). Physiological drought responses improve predictions of live fuel moisture dynamics in a Mediterranean forest. Agricultural and Forest Meteorology, 263, 417-427.
- Yebra, M., Dennison, P. E., Chuvieco, E., Riano, D., Zylstra, P., Hunt Jr, E. R., ... & Jurdao, S. (2013). A global review of remote sensing of live fuel moisture content for fire danger assessment: Moving towards operational products. Remote Sensing of Environment, 136, 455-468.

- Ruffault, J., Martin-StPaul, N., Pimont, F., & Dupuy, J. L. (2018). How well do meteorological drought indexes predict live fuel moisture content (LFMC)? An assessment for wildfire research and operations in Mediterranean ecosystems. Agricultural and Forest Meteorology, 262, 391-401.
- Vacca, P., Caballero, D., Pastor, E., & Planas, E. (2020). WUI fire risk mitigation in Europe: A performance-based design approach at home-owner level. Journal of Safety Science and Resilience, 1(2), 97-105.
- Vilà-Cabrera, A.; Coll, L.; Martínez-Vilalta, J.; Retana, J. (2018). Forest management for adaptation to climate change in the Mediterranean basin: A synthesis of evidence. Forest Ecology and Management, 407, 16-22.
- Xanthopoulos, G., Maheras, G., Gouma, V., & Gouvas, M. (2006). Is the Keetch-Byram drought index (KBDI) directly related to plant water stress?. Forest Ecology and Management, 234(1), S27.