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Electrical Responses of *Pinus halepensis* Mill. as an Indicator of Wildfire Risk in Mediterranean Forests by Complementing Live Fuel Moisture

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Abstract: *Pinus halepensis* forests, as Mediterranean-type ecosystems, are subject to high levels of wildfire risk in times of drought, with meteorological conditions of water stress and very high temperatures, mainly in summer. Considering the difficulty of knowing the phenological state of this species, the objective of this research was to evaluate the possibility of implementing the electrical responses (voltage and short-circuit current) as a variable in fire risk management models, compared to live fuel moisture. On the one hand, the obtained results demonstrate non-significant differences between the moisture content of the different fractions of the living branches (base and half of the branch and live fuel), even in times of drought with hydric stress and very high temperatures. Live fuel moisture of *Pinus halepensis* does not show significant seasonal variations under the influence of extreme fire risk factors. For this reason, it should be complemented with other variables for fire risk management models. On the other hand, the differences registered in the electrical signal show oscillations with significant variations, which are strongly correlated with the periods of extremely favourable meteorological conditions for wildfires. So, the voltages measured show ranges that correspond with great accuracy to the FWI. Voltage variation is dependent on the hydraulic dynamic plant behaviour and a result of the physiological response of pine trees to abiotic stress of drought. It is an easy-to-measure electrical parameter as well as a very reliable indicator with a high correlation with wildfire risk. Thus, electrical responses could add more knowledge about the phenological state of the trees in dependence on stress climatic conditions, allowing integration of these variables in the preventive wildfire modelling and management.

Keywords: wildfire risk; plant electrophysiology; *Pinus halepensis*; phenological state; live fuel moisture; climatic conditions; Mediterranean forests

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1. Introduction

Wildfires have been present in the Mediterranean climatic regions around the world, as a natural phenomenon long before man existed [1,2]. Wildfire is a powerful ecological and evolutionary force that regulates organismal traits, population sizes, species interactions, community composition, carbon and nutrient cycling and ecosystem functions [3,4]. Mediterranean climates are characterized by a drought season, but their length and severity can be highly variable across regions [5]. Mediterranean-type ecosystems (MTEs), with their unique climatic regime [6], support the growth of trees during the rain of spring and autumn, while the long summer drought together with the elevated temperatures produce strong biomass desiccation [7], creating highly flammable conditions [8]. Additionally, MTEs are biodiversity hotspots located between temperate mesic climates and semi-deserts and deserts, strongly affected by climate change [9].

In all these regions, wildfires present a major disturbance to natural ecosystems, resulting in significant economic and ecological losses [4,10]. Therefore, fire risk assessment becomes a critical component of land management because it is very advantageous to anticipate the probability and magnitude of a wildfire [10]. McLauchlan et al. [4] described the diversity of ways in which fire operates as a fundamental ecological and evolutionary process and identified three emergent research challenges: the need to study fire across temporal scales, to assess the mechanisms underlying a variety of ecological feedbacks involving fire and to improve representation of fire in a range of modelling contexts. On this background, the relationship between meteorological extreme conditions and live fuel moisture is a key research topic in the complex field of fire ecology [11–21], always supported by the development of innovative technologies, especially remote sensing [22–31] and machine learning [32–34].

Forest management administrations and firefighting agencies and services are often confronted with the task of establishing proactive fire management in dependence on vulnerability and risk in different MTEs [35,36]. Many of the forecast systems are based, mainly, on meteorological data that are collected by weather stations [37], as the Canadian Forest Fire Weather Index System, which is in widespread usage globally [38]. Nevertheless, fire risk is the sum of other multiple factors [39], referring to the probability of fire ignition [37]. Globally, there is a close relationship between wildfires and anthropogenic activities, i.e., wildfires understood as human events due to negligence (e.g., agricultural burning escapes), and deliberate actions (e.g., pyromania, revenge, land use change attempts) [40], but also lightings are more and more frequent natural causes [41], especially in large unmanaged forestlands [42].

Three major influencing factors with their respective variables intervene in the behaviour of an extreme wildfire: meteorology (wind regime, temperature, and relative humidity), topography (terrain configuration in terms of slope, accessibility, and vegetative structure) and the state of the forest fuel (moisture and flammability characteristics) [43]. All factors are closely related and jointly influence the vulnerability of forest fuel to igniting, but several authors point out the mechanisms through which plant responses to drought and, consequently, to forest flammability, specifically live fuel moisture, but also physiological reactions to water stress in the ecosystem (soil water content and plant traits, including rooting patterns and leaf traits such as the turgor loss point, osmotic potential, sap flow, elasticity and leaf mass ratio of dead to live fuels, etc.) [44,45].

In fact, the relationships between drought and wildfires are well documented for MTEs, especially in Europe [46,47], Australia [48,49] and North America [50], with wildfire occurrence and area clearly increasing in response to drought [51,52]. There is also evidence that drought interacts with other controls (wind regimes, topography, forest management activities) to affect fire intensity, severity, extent, and frequency [50,53]. Due to drought directly influences vegetation dryness in trees and shrubs [21], live fuel moisture has been identified as a key factor of significance in biomass combustibility [54–58]. In this context, it should be considered that the large plant diversity that characterizes MTEs is associated with the success of coexisting species in avoiding competition for soil resources (water and nutrients) by differential exploitation in space (soil layers) and light time (year and daily) [59]. So, live fuel moisture content is influenced by meteorological and soil variables, but mainly by the plant species and its phenological state, and hydraulic behaviour [58]. Therefore, given this influence, it is considered necessary to expand the knowledge regarding the phenological state of the different species present in the ecosystem, to know its magnitude and its seasonal variation, and to understand and predict fire behaviour [58], by testing several innovative technologies of terrestrial [60,61] and remote sensing [62].

Rothermel [63] proposed a classification of the humidity of live fuel; this classification was based on the stage of development of the vegetation. However, the data obtained in studies carried out in some MTEs differ from this classification [19,64,65], since they find a differentiated behaviour of live fuel moisture according to each species and strongly depending on seasonality [23,66]. Several authors have studied the phenological state of the vegetation by directly measuring the live fuel moisture content by taking physical samples in the field [58,67]. Through these works, it was able to relate the phenological state of the plants with their fuel moisture content, at least in a large part of the species that inhabit the MTEs [58]. Nevertheless, for one of the most important tree species in the Mediterranean basin, such as *Pinus halepensis* [51,68–72], the results on the variation in seasonal moisture were not conclusive [58]. Since *Pinus halepensis* hardly show variation in moisture content throughout the vegetative cycle; neither show moisture variations in the face of extreme heat and drought episodes that are usually recorded in the Western European Mediterranean area [58].

Moreover, for a better understanding the phenological state of the plants in MTEs in dependence on severe drought conditions, different plant hydraulic traits have been analysed, such as the measurement of the sap flow, which was proposed for the evaluation of transpiration rates [73]. However, some authors claim that sap flow measurements only provide information on the water movement within plants and are not directly related to the rapid responses to environment or climatic stress [74]. Other authors have analysed other plant hydraulic traits, such as saturated moisture content, cell wall rigidity or turgor loss point, cell solute potential, symplastic water fraction and tissue capacitance [75].

Furthermore, some authors have been proposed the measurement of electric potential as a valid method to evaluate the phenological state and stress responses of trees and shrubs [76]. The existence of a continuous electric potential between the electrodes inserted in the tree phloem and the surrounding soil was discovered and described many years ago [77–80]. This electric potential is associated with electrochemical effects that include membrane diffusion potentials and active transport of ions [81]. In addition, more recent works documented that some environmental stimuli also produce changes in electrical signals of trees [82]. More specifically on *Pinus halepensis*, a high correlation between meteorological variables and variations in electrical signals could be demonstrated [61]. According to some authors [83–85], electrical properties (as plant physiological reaction) seem to be related to rapid responses to water stress. Unfortunately, these responses are sometimes not evident or do not produce consistent visual indicators, such as wilting and changes in leaf colour [86].

Considering these characteristics of electrical signal measured on trees, the increasing importance of *Pinus halepensis* in European Mediterranean forests [51,58,68–72], and the difficulty of knowing the phenological state of this species [58], the objective of this research was to preliminarily evaluate the possibility of implementing the electrical signals responses of *Pinus halepensis* as an indicator to complement live fuel moisture assessment, as a method to monitor the phenological state and the drought stress level. Finally, the research aims to analyse the relationship between the obtained results for electrical signals and the wildfire risk rating, normally used by firefighting agencies.

2. Materials and Methods

2.1. Research Design

This main objective of the research is to study the relationship between the electrical signals as a result of phenological state of *Pinus halepensis*, live fuel moisture content and wildfire risk. Therefore, the main parameters to be measured will be the components of the electrical signal: voltage and short-circuit current [87], together with measurements of the moisture content of the live fuel, as well as also with the main meteorological conditions (temperature, relative humidity, and rainfall) and wildfire risk index published by local meteorological or emergency agencies.

To do this, the research has been divided in two phases:

1. In a first stage, the measurements were carried out during the main wildfire season (24 weeks in the hottest and driest months, from end of spring to beginning of autumn) in a representative area of the Mediterranean basin.
2. The results of this first phase were complemented with a second survey, in which the values of the electrical signals collected in previous three years were retrospectively analysed.

2.2. Selection of Sample Stand

Pinus halepensis Mill. (Aleppo pine) and *Pinus brutia* Ten. (Turkish or Calabrian pine) are two systematically close tree species dominating MTEs in the European basin [24], which can naturally hybridize where they co-occur [88]. So, both are drought-tolerant and fast growing native coniferous species [24], well adapted to dry summer conditions [70]. *Pinus halepensis* widely covers the western side of the basin, while *Pinus brutia* is located mainly on the eastern side, both mainly at coastal zones [89]. They are among the species most affected by wildfires in Europe [90], although they are fire resilient trees due to the high production of serotinous cones that favour a quick post-fire regeneration [91]. These species have been widely planted between 1930 and 1980 in Mediterranean areas for soil protection and windbreaks near the coasts [92]. Specifically, *Pinus halepensis* is the most widely distributed and abundant pine in MTEs, covering nearly 7 million ha in this region [93], being present in all regions on both shores of the Mediterranean Sea and extending from the Western Mediterranean (Spain, Morocco), where it is most abundant, to Lebanon through Southern France, Italy, Greece and Turkey in South Europe and Algeria, Tunisia, Libya in North Africa. Bioclimatic envelope models predict that the suitable climatic area of *Pinus halepensis* is clearly in expansion [94–96]. Thus, we have selected *Pinus Halepensis* because of its increasing importance and representativeness in the MTEs [97]. Actually, it is the most influential tree species in the total availability of biofuel in the Mediterranean forests [58]. Furthermore, Soriano [58] describes that *Pinus halepensis* is not showing strong variations in its moisture content in the face of seasonal variations, so that possible variations of electrical responses could add more knowledge about the phenological state of the trees in dependence on severe drought conditions, allowing for the integration of these variables in the preventive wildfire management.

As in previously published works [61,98], we decided to use as a study area a representative young forest composed of 93% of *Pinus halepensis* from a post-fire natural regeneration, located within the protected area of the Sierra Calderona Natural Park in Gátova, Valencia (Spain). The selected stand is located at latitude 39°45′28.80″ N and longitude 0°30′36.36″ W. The forest stand has a population density of 484 trees/ha, with an average DBH of 12.10 cm, a tree height of 5.16 m, and an age of 27 years (Figure 1).

Figure 1. View of the sample stand (August 2021).

This sample stand was selected because it is an even-aged forest with enough homogeneous trees, within an area not affected by significant natural disturbances, such as recent wildfires, pests, or damage due to hurricanes or heavy snowfall. It was sought that the stand had these conditions of even-age (natural regeneration after a previous wildfire occurred in summer of year 1994), to reduce the differences between the individuals that are part of the study since, as we have seen in previous works, age is an influencing factor in the amplitude of the electrical signal [98]. The selected stand meets all the characteristics above described, with constant site conditions (soil and water, orientation, and slope).

A soil analysis based on edaphic profiles was carried out to obtain the main soil variables that can influence on the electrical behaviour of the sample trees (Table 1).

Table 1. Soil properties in pilot stand.

		Texture (%)				
Sand	Silt	Clay	USDA Classification			
20.1	43.6	12.3	Loam			
Moisture Factor	Ph	Electric Conductivity [ds/cm]	Wp [%]	Field Capacity [%]	Pore Space [%]	Depth [cm]
0.92	8.2	1.869	3.7	11.8	45.66	30

2.3. Selection of Sample Trees

The first phase of this study was carried out on a total of 240 trees, selected following the method described by Hapla and Saborowski [99] and used by other authors [100,101] for sampling representative trees in a forest stand for analysing physical wood characteristics.

Although the electrical measurement process is non-destructive (see Section 2.4.1 (a)), obtaining the moisture content (see Section 2.4.1 (b)) requires cutting plant material (living branches) from the standing trees in different testing times. This is obviously not possible without seriously injuring the trees. To avoid this impact, the total set of 240 trees has been subdivided into 24 groups, i.e., one group of 10 trees per evaluation week. Each weekly sample group was formed by the 10 trees closest to the centre placed ground electrode.

In the second phase of this work, the electrical signal values obtained in previous works [61,98] were measured in fifteen representative trees of the same stand over three years. These trees were also selected using the representative tree selection method described [61,98,99].

2.4. Measurement Procedures

In each of the 24 weeks of the first phase, the values of the two components of the electrical signal (voltage V and short-circuit current ISC) were recorded and the moisture content of ten trees was measured each week.

These measurements were carried out in the 24 hottest and driest weeks of the year, from one month before the start of the official wildfire season in the Region of Valencia/Spain (May 2021) until one month after the end of it (October 2021). All weekly measurements were taken on Saturdays at 12:00 p.m. CET, since this is the time for which wildfire risk predictions are made according to the Fire Weather Index (FWI) system of the Spanish Meteorological Agency (AEMET) [102]. In addition to that, as could be demonstrated in previous works, the central hours of the day, close to the zenith, are the moments in which the tree presents the minimum value of electrical signal [61].

For the second phase, the voltage (V) and short-circuit current (ISC) values used in our previous work [61], were retrospectively evaluated. These electric signal values were collected weekly, using the same data acquisition protocol as used in the present study, since May 2018.

2.4.1. Measurement of Electrical Signal

The values of voltage (V) and short-circuit current (ISC) of the trees were measured between the electrodes inserted in the trunk and the electrode buried in the ground. To carry out this work, electrodes with the same characteristics as those of our previous works [61,98] as well as those used by other authors [61,76,81,98,103,104] were used.

Two electrode types were used according to their function.

(a) The electrode used in the tree, made of stainless steel, was inserted directly into the trunk at 1.5 m above the ground at a depth sufficient to ensure contact with the phloem tissue. A screw shape was chosen due to its greater ease of insertion and removal from the trees, causing only a minor wound. In addition, thanks to the screw spiral, these electrodes have a larger contact surface with the vegetative tissue compared to smooth cylindrical electrodes. So, these electrodes were inserted into the trunk ensuring contact with the phloem tissue, by inserting them with a torque wrench, which allowed us to detect the change in tissue hardness. This last action we consider fundamental, since electrical signals are more easily transmitted throughout this tissue, given its lower resistance to electrical flow, compared to other plant tissues [82].

(b) The second type was a non-polarized platinum electrode [105], which was used as ground reference. These electrodes were buried in the mineral soil at a depth of between 20–25 cm once the top layer of topsoil had been removed. It should be noted that given the natural conditions in which the experiments were carried out, we could not install the reference electrode in a greater depth due to the soil hardness and the presence of rocks.

Both electrodes were connected to the measuring equipment through electrical connectors and a 0.5 mm copper conductor cable insulated with a flexible plastic sheath (CE 0123) (see Figure 2).

(**A**) (**B**) (**C**)

Figure 2. Tree electrode (**A**), ground electrode placement (**B**), arrangement of measuring equipment (**C**).

The equipment used for the voltage (V) and short-circuit current (ISC) measurement was a multimeter UT71D UNIT with an input impedance of 2.5 GΩ and a precision of 0.1% ± 2 mV.

2.4.2. Measurement of Moisture Content

Physical samples were taken to the laboratory, following the methodological recommendations of the National Forest Research Institute of Spain [106,107].

1. Field work: The following samples were taken from the first live and healthy branch from the bottom of the tree-crown: Fraction 1 (BB): samples were taken from the base of the branch on a weekly frequency, with diameters of 20–30 mm and 5–10 cm length, without needles, in order to compare it with the non-destructive moisture content methodology. Fraction 2 (BM): samples were taken from the middle of the branch on a monthly frequency, with diameters of 10–20 mm and 5–10 cm length, without needles. Fraction 3 (LF): samples were taken from end part of the branch on a monthly

frequency, with diameters <10 mm, with twigs and needles, without cones. Samples were taken always on Saturdays between 12:05 and 2:00 pm CEST. Each sample was placed in a hermetically sealed plastic container, identified with the reference data and transported immediately to the laboratory.

2. Laboratory work: The samples were weighed on a precision balance in the green state. After being dried in an oven at 105 °C for 24 h until constant weight was obtained, they were weighed in anhydrous state. The moisture content (MC%) is calculated with the formula:

$$\text{MC\%} = \frac{\text{wet weight} - \text{weight after drying}}{\text{weight after drying}} * 100$$

2.5. Meteorological Time-Series

The meteorological data for the area was provided by a professional meteorological station installed at 39°46′10.12″ N, 00°31′14.19″ W. The meteorological station is a Davis Vantage VUE model owned by the Valencian Meteorological Association (AVAMET) [108].

2.6. Wildfire Risk Assessment

The Spanish State Meteorological Agency (AEMET) publishes the official FWI daily [104]. The data is open and available online through its web services. We have used the data recorded to the region of Valencia, defined as Zone 3, where our pilot stand is located. The FWI levels are coloured from green (low risk) to red (extreme risk).

3. Results and Discussions

3.1. Comparison between Moisture Content in Different Live Branch Fractions

Figure 3 shows the obtained laboratory data for the moisture content in the three branch fractions during the six months of measurement. For all measurements taken during this period, the mean value obtained for the moisture content measured at the branch base (BBMC%) is 91.92%, with a standard deviation of std ± 9.12%, very similar to the mean value for the moisture content measured at the middle of the branch (BMMC% = 91.18%, std ± 12.06%) and slightly under the mean value obtained for the fine live fuel moisture content (LFMC% = 98.17%, std ± 10.27%). Other authors reported very similar LFMC% measured in needles and twigs for Mediterranean pines [18,58,109].

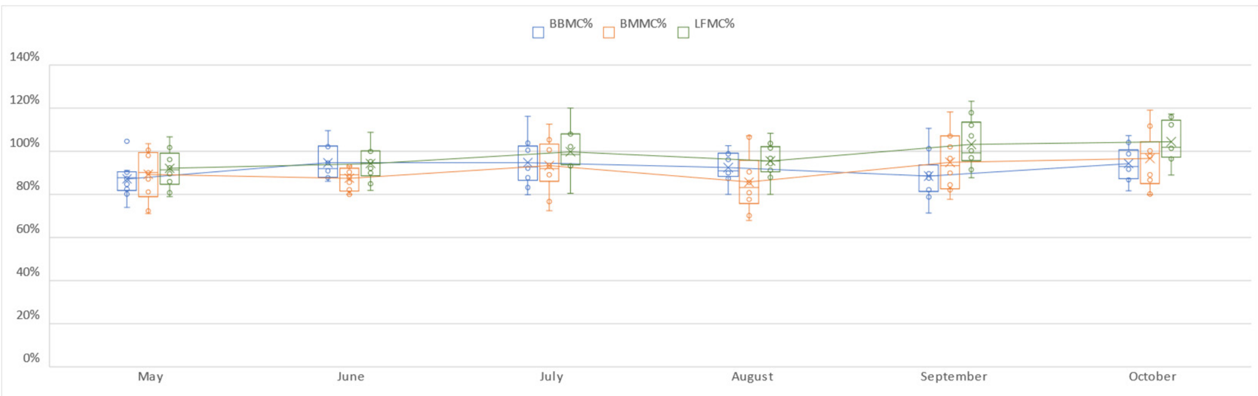


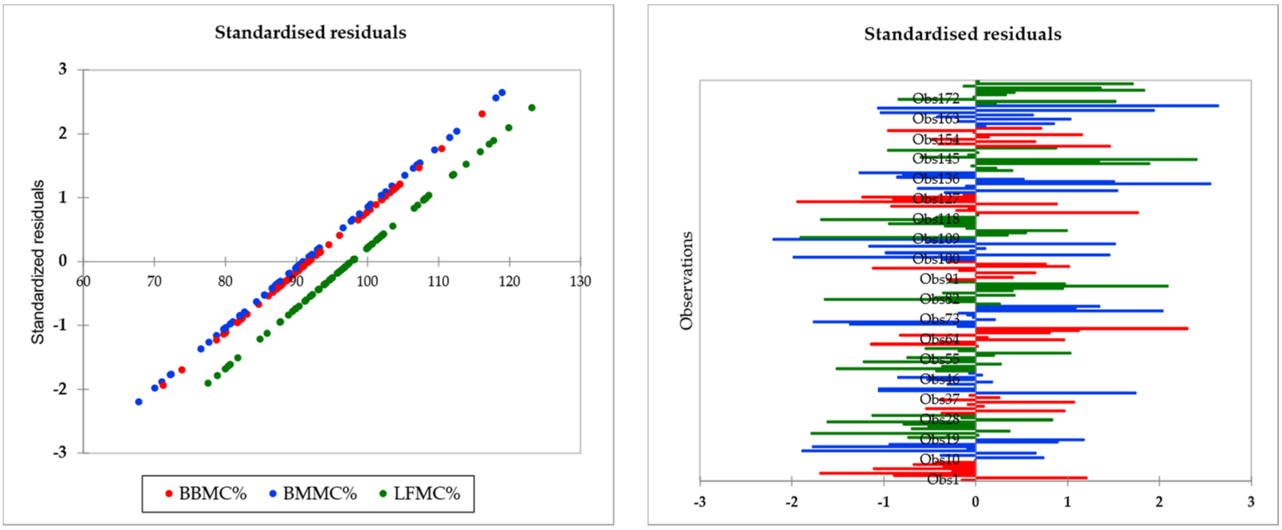
Figure 3. Comparison between moisture content in different branch fractions of *Pinus halepensis* from May to October 2021: branch base (BBMC%, middle of the branch (BMMC%) and fine live fuel (LFMC%).

In order to analyse possible significance differences among BBMC%, BMMC% and FMC%, several ANOVA tests are performed for the total sampling period and for each month among the three fractions. Table 2 shows the results.

Table 2. Results of the analysis of variance (ANOVA) among BBMC%, BMMC% and LFMC%.

Sample	F	Pr > F	*p*-Value	α	Result
May	0.714	0.499	0.381	0.05	non-significant differences
June	1.278	0.295	0.837	0.05	non-significant differences
July	1.211	0.314	0.863	0.05	non-significant differences
August	1.461	0.250	0.295	0.05	non-significant differences
September	3.793	0.035	0.646	0.05	non-significant differences
October	2.516	0.100	0.389	0.05	non-significant differences
Total Period	7.367	0.001	0.208	0.05	non-significant differences

Although the values obtained for LFMC% are slightly higher than BBMC% and BMMC% for the total sample, as well as for the individual months (between 5 and 10%), the variance analysis demonstrate that these differences are non-significant, neither for the individual samples in each month nor for the total sample. The standardised residual analyses shown in Figure 4 also demonstrate this result.



(**a**) (**b**)

Figure 4. Standardised residual analyses among BBMC%, BMMC% and LFMC% for the total period (**a**) and standardised residual vs total observations (**b**).

The results obtained demonstrate that there are non-significant differences among the moisture content among the three branch fractions (BBMC%, BMMC% and LFMC%). In this sense, samples of live branches bases can be representative for the moisture content for entire live fuel. Following Mitsopoulos and Dimitrakopoulos [110], the live aerial fuels that are consumed during crown fires in *Pinus halepensis* forests are composed of needles (16.7%), twigs with 0.0–0.63 cm diameter (12.6%), branches with 0.64–7.5-cm diameter (62.7%), and branches >7.5-cm diameter (3.7%). Taking BBMC% as a reference measurement at the base of the first living branch in standing trees opens an opportunity to monitoring through sensorised moisture meters, e.g., by electrical resistance or capacitive devices.

3.2. Seasonal Variability of Live Fuel Moisture Content

Figure 5 visually shows the values obtained for the moisture content of the three fractions (BBMC%, BMMC% and LFMC%) of the first living branch during the 24 weeks measurement in the critical wildfire risk season, i.e., from late spring to early autumn 2021.

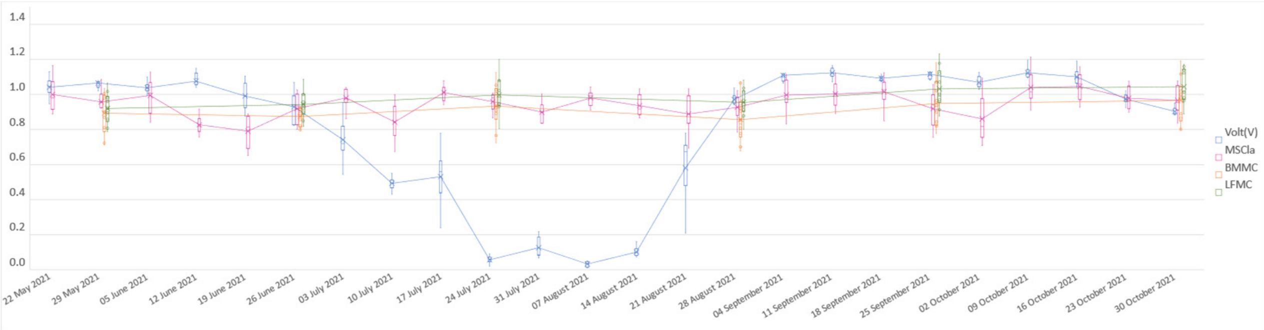


Figure 5. Seasonal variability of moisture content of the first living branch (BBMC%, BMMC% and LFMC%) in comparison with voltage during the 24 weeks from late spring to early autumn 2021.

The first visual analysis indicates that *Pinus halepensis* does not present clear seasonal variations of moisture content, neither in the woody fractions of the branches (BBMC% and BMMC%) nor in the fine live material (LFMC%), even during the water stress conditions of the hot and dry summer weeks. An ANOVA test among the 24 mean values of the weekly measurements for BBMC% shows also non-significant differences (F = 1.38, $p < 0.001$). Furthermore, non-significant differences can be demonstrated among the monthly measurements of BBMC% (F = 1.34, $p < 0.001$) as well as LFMC% (F = 2.75, $p < 0.001$). Finally, Figure 5 also shows through the Box and Whiskers plots that the variation among the 10 measured trees in each measurement trial is very low. Additional individual ANOVA tests demonstrate the non-significant differences of moisture content for the three variables (BBMC%, BMMC% and FLMC%) among trees ($p < 0.001$). Other authors reported very similar behaviour of LFMC% of Mediterranean pines [18,58,109], also not being able to demonstrate representative and significance seasonal variations.

3.3. Seasonal Variability of Electrical Signals in the Trees

Table 3 present the total results obtained for the electric signal measurements: voltage (V) and short-circuit current (ISC). Both V and ISC present much higher variations than the moisture measurements. So, V has an average value of V = 0.808 V with very high standard deviation (std = ±0.381 V) and variance. The same heterogeneous behaviour present ISC with an average value of ISC = 1.998 mA and std = ±2.531 mA.

Table 3. Descriptive statistics for the results of voltage (V) and short-circuit current (ISC) from 240 samples measured in 24 weeks from late spring to early autumn 2021.

	Electrical Signals	
	Voltage (V) [V]	**Short-Circuit Current (ISC) [μA]**
Mean	0.808	1.998
Median	0.990	1.100
Minimum	0.032	0.000
Maximum	1.124	15.690
Standard deviation (n − 1)	0.381	2.531
1st Quartile	0.569	0.238
3rd Quartile	1.081	2.735
Variance (n − 1)	0.145	6.408

These heterogeneous values can be explained by the analysis of the seasonal variations. So, Figure 5 also shows the results obtained for the voltage (V) measured in the trees during the 24 weeks of higher wildfire risk from late spring to early autumn 2021.

The results obtained clearly show that the electrical signals measured in the trees coincide with the two growth seasons of *Pinus halepensis*, specifically spring and autumn [111,112]. Therefore, with this, we can associate the moments in which the environmental conditions are favourable for the growth of the trees with the highest values of the electrical signal. On the contrary, the periods in which the environmental conditions become more difficult for the survival of the pines, specifically during heavy drought conditions of continuous lack of rain and very high temperatures, the tree gives us a clear reduction in the electrical signal, which is observed more clearly in the case of voltage (V), with reductions of up to 90% and, in any case, of more than 50%.

Hence, the seasonal variations of voltage in *Pinus halepensis* observed can be interpreted as a direct result of a loss of conductivity during the strong climatic conditions in the driest summer days. In this sense, Fotelli et al. [113] demonstrate that during xerothermic periods, *Pinus halepensis* has typical isohydric behaviour: maximum photosynthesis, sap flow and stomatal conductance declined through stomatal control to limit water potential reduction and loss of conductivity. This loss of sap flow and conductivity has been also observed in several studies [114]. Electrical responses such as voltage seem to be directly related with sap flow conductivity, so that further research activity to analyse in detail this relationship should be carried out.

3.4. Relationship between Life Fuel Moisture and Electrical Signals

As shown in the previous chapters, the live fuel moisture content of *Pinus halepensis* do not present significant variations throughout the warmest and driest part of the year, without showing a significant decrease in the hot summer months, on the contrary that the electrical signals do, especially the voltage. So, the detailed analysis shows that the voltage curves remain more or less constant during the months of May and June, as well as from the beginning of September to the end of October. However, as soon as extreme summer conditions with high temperatures and very low rainfall dominate the central summer months (July and August), the voltage values drop very clearly and significantly. The more or less constant voltage of around 1 V decreases clearly under <0.5 V under the nine weeks between beginning July and End of August, and even dramatically during the central weeks of end of July and beginning of August with <0.1 V. In fact, the moisture content and voltage curves are closely aligned during May and June, decoupling very clearly during the central part of the summer in July and August, and re-coupling from the beginning of September.

Moreover, Figures 6 and 7 show that precipitation, temperature, and relative air humidity do not exert a direct influence on live fuel moisture content of *Pinus halepensis*. Not even noticeable changes in BBMC%, BMMC% or LFMC% can be observed on the central summer weeks of end of July and beginning of August, with the hottest and driest days, especially the 24 July and 7 August 2021, which were classified as an extreme risk by the weather and firefighting agencies, following the FWI criteria [102].

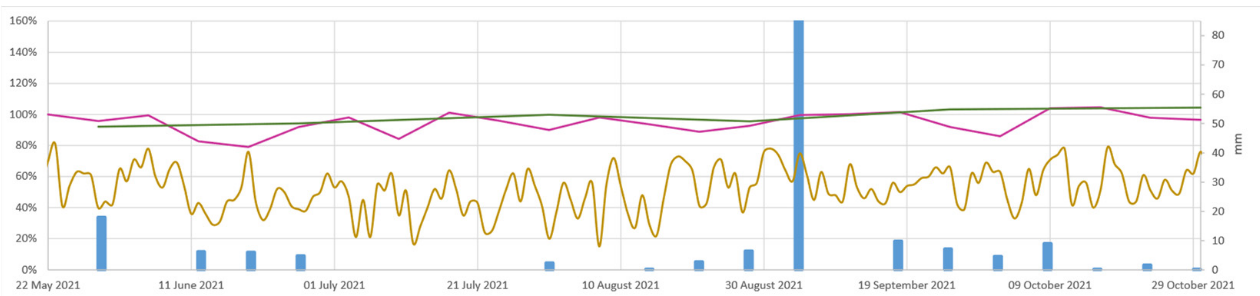


Figure 6. Moisture content (BBMC%, purple line and LFMC%, green line) vs. weekly-accumulated precipitation (blue column) and relative humidity (light brown line) during the 24 weeks study.

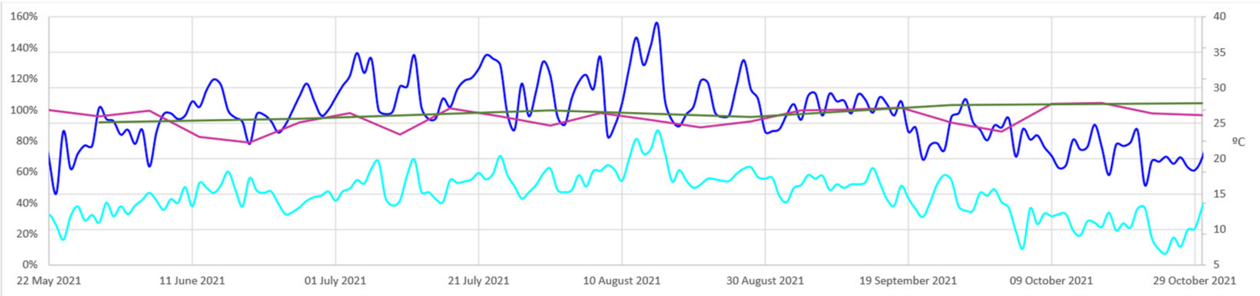


Figure 7. Moisture content (BBMC%, purple line and LFMC%, green line) vs. maximum (dark blue line) and minimum (light blue line) daily temperatures.

The results obtained demonstrate that the moisture content (BBMC% or even LFMC%) do not present representative seasonal variations in *Pinus halepensis* and is not able to react directly or quickly to extreme drought conditions. Characterization of the fuel structure and its relevance for fire behaviour has been the topic of much research in MTEs [115]. Thus, variations in LFMC% are often taken into account, although some discussions are still active on its role in fire propagation [116]. Some studies have addressed the role of FMC on fire behaviour [117]. Others have addressed how canopy drying, following bark beetle attacks, for instance, impacts fire behaviour [118–120].

In our research, the moisture content measured at the living branches of *Pinus halepensis* (including LFMC%) shows no representative seasonal variations, with values between 80 and 100%, which is consistent with other studies with this species [109]. Although LFMC% is considered as an important determinant of forest flammability under Mediterranean conditions [45], other authors demonstrate that even other Mediterranean pines show also very limited LFMC% seasonal variations: Pinus pinaster 90%–100% [121] and Pinus nigra: 95%–115% [122]. These pines exhibit isohydric behaviour [113], i.e., little variation in midday leaf water potential, and relatively tight regulation of stomata in response to soil drying [122]. Mediterranean pines are adapted to the xerothermic conditions (high temperatures and droughts) of summertime, due to its drought avoidance strategy of reducing stomatal conductance under water shortage [123]. *Pinus halepensis* displayed a water-saving, drought avoidance (isohydric) strategy via stomatal control in response to summer drought [124,125]. The species benefited from periods of high available soil water (normally autumn to spring) [126,127]. These drought episodes do no influence directly moisture content at branches and leaf level [58,128], so that direct measurement of LFMC% of Mediterranean pines should not be considered as the only appropriate indicator to monitor wildfire risk. Moreover, strong drought conditions and consequently high evapotranspiration carries physiological responses in branches and needles of *Pinus halepensis*. Thus, Fotelli et al. [113] demonstrate that during xerothermic periods, typical isohydric behaviour was exhibited by *Pinus halepensis*: maximum photosynthesis, sap flow and stomatal conductance declined through stomatal control to limit water potential reduction and loss of conductivity. This loss of sap flow and conductivity has been also observed in several studies [114]. However, in periods when water availability was not a limiting factor, this species was able to maximize its carbon gain if other controlling parameters, such as air temperature and net radiation, simultaneously ensured a favourable environmental regime [113].

On the contrary, LFMC% does present representative seasonal variations in some Mediterranean shrub species. Thus, compared to the results obtained for *Pinus halepensis* (and those observed for other Mediterranean pines), the main shrubs that are part of MTEs behave significantly differently [129]. Especially relevant is the seasonal variation in LFMC% of Rosmarinus officinalis, with minimum values of 40% in summer and maximum values of 140% in autumn, winter, and spring [19,109,112]. Also, other species, e.g., Ulex parviflorus (60%–120%), Erica multiflora (50%–90%) or Juniperus oxycedrus (65%–100%)

shows very clear seasonal variations [58,111]. This undoubtedly explains the importance that the summer drop in the LFCM% has on the vulnerability of wildfire in shrublands [130]. Undoubtedly, for future research, it would be very interesting to relate the variation in the LFMC% and its relationship with the voltage in these shrubs, as they have shown very similar behaviour patterns.

Following our results, it seems to be very difficult to assess and monitor vulnerability of Mediterranean pine forests to wildfire risk only in dependence on LFMC% of pine trees. Additionally, other physiological plant traits seem to better explain the high wildfire risk in times of drought, especially osmotic potential, sap flow, wilting and needle senescence or dead fuel presence and evolution. Fuel dynamics, as a result of the physiological response of the pine trees to drought conditions, have to be analysed integrating variables resulting from water stress (soil water content and plant traits, including rooting patterns, and leaf traits such as the turgor loss point, osmotic potential, sap flow, elasticity and leaf mass per area), but also the ratio of dead to live fuels [131,132]. In this sense, needle cavitation and subsequent shedding is of particular relevance for pines, transforming green live fuel into dead fuel, which are totally dry, and thus easier to ignite [45]. Therefore, it is necessary to investigate the seasonal fuel dynamics from a more integral perspective, complementing the measurement of LFMC%. All variables resulting from physiological responses that can influence fire risk and that can be easily measured and monitored, including electrical signals, should be integrated into the risk models.

3.5. Relationship between Electric Signals and Wildfire Risk

(a) Assessment for the 24 weeks study in year 2021

A first analysis of the relationship between the electrical signals and the wildfire risk has been carried out, by comparing the mean values of both V and the ISC for each week (always measured on Saturdays) with the wildfire risk following the FWI criteria of those same days, considering for this daily maximum temperature, minimum relative humidity, maximum wind speed and rainfall. The results obtained are shown graphically in Figures 8 and 9.

The results obtained cannot demonstrate a representative correlation between moisture content and FWI. The highest FWI values, and consequently the brunt of the fire season in the Western Mediterranean Basin occurs normally during July [132], while the observed moisture content values do not show any reduction, as also observed by Qi et al. [131]. Soler Martin et al. [121] demonstrate that no seasonal changes of LFMC were recorded during summer in needles and small branches in Pinus pinaster stands, contrary to predictions from the FWI, which fully matches with the results obtained in our study for *Pinus halepensis*.

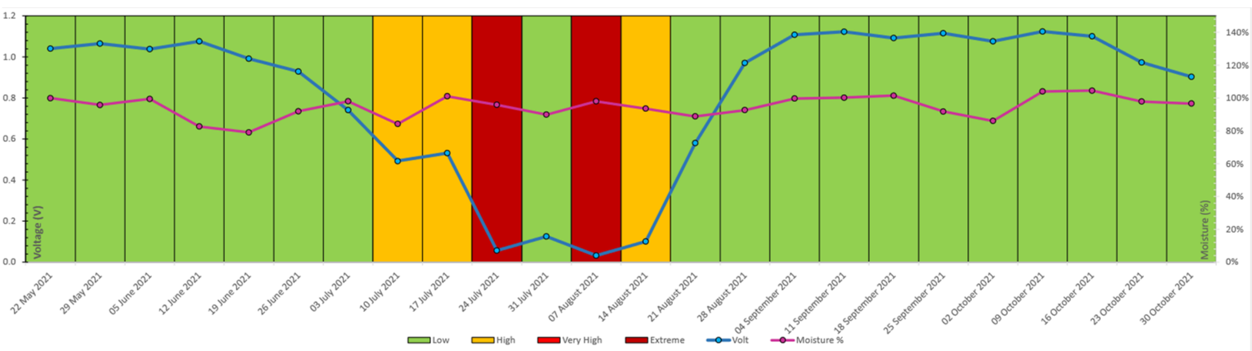


Figure 8. Mean values of V (blue line) and BBMC% (pink line) vs. FWI classification of the measurements according to FWI criteria during the 24 weeks study (background colour).

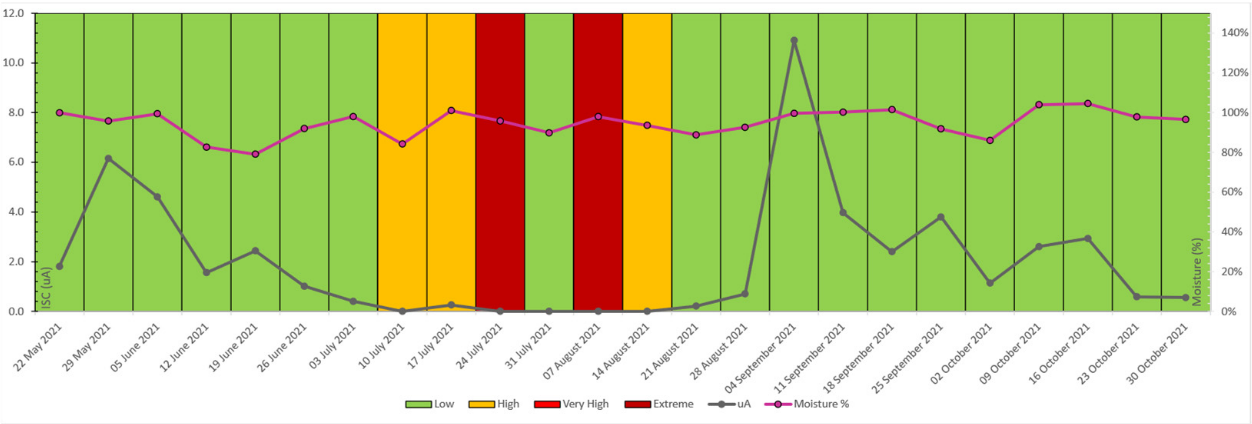


Figure 9. Mean values of ISC (tagged uA in the figure with a dark grey line) and BBMC% (pink line) vs. FWI classification of the measurements according to FWI criteria during the 24 weeks study (background colour).

These results demonstrate that both electrical signals measured (V and ISC) show a noticeable reduction during the summer period, reaching the minimum values on the days in which the FWI in the pilot stand was classified as extreme [102]. However, the results for V are much clearer and more significant related to FWI than the results obtained for ISC.

(b) Assessment for three years survey (2018–2021)

Measurements for electrical signals, specifically voltage, have been performed in the pilot stand since May 2018 until October 2021, so that we can make a long-term evaluation of the relationship between V and FWI. Figure 10 shows in Box and Whiskers plots the average, standard deviation and minimum-maximum for all days during the three years classified by wildfire risk categories (low, high, very high, extreme) following FWI criteria.

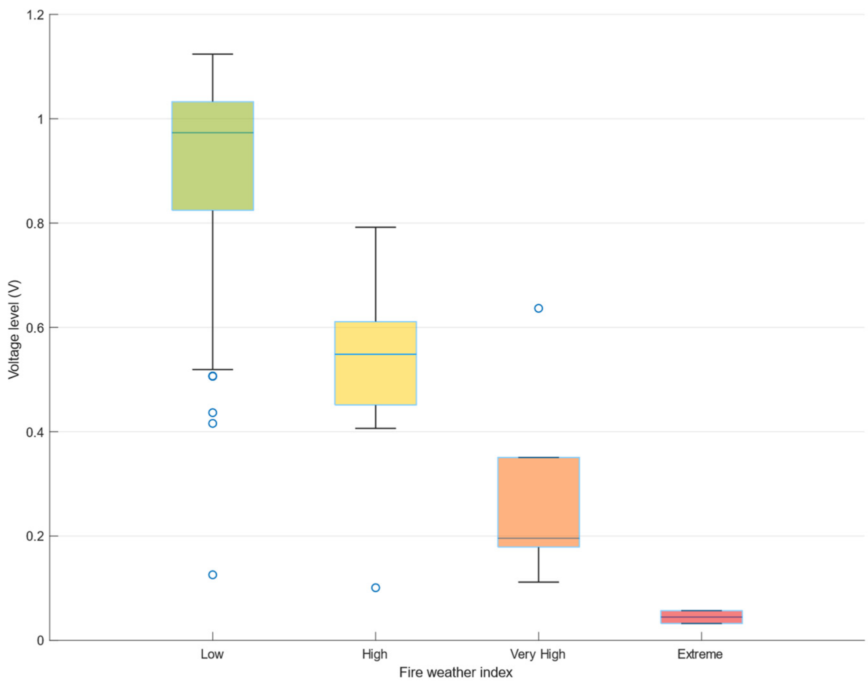


Figure 10. Voltage values for all measured days from May 2018 to October 2021 classified by FWI categories (low, high, very high and extreme wildfire risk).

The first interpretation of the results allows us to observe that the mean values obtained for V in the four FWI categories are significantly different, clearly reducing the voltage as the risk increases. An ANOVA test also corroborates the observed differences as statistically highly significant (F = 39.138, $p < 0.001$). Thus, while FWI low presents an average of 0.90 V, the FWI high class decreases to 0.53 V and the FWI very high class to 0.28 V, with the FWI extreme class reaching a mean of only 0.04 V.

Finally, this analysis also shows that on days with low fire risk (FWI low) practically all the values (96%) greatly exceed >0.5 V. Even 81% exceed the threshold of >0.8 V. On the other side, on the days classified as very high risk (FWI very high) and extreme risk (FWI extreme), only one of all values (88%) exceed >0.4 V, even 100% of the extreme risk does not exceeds even >0.1 V.

The voltage level is a result of the physiological response of *Pinus halepensis* to the abiotic stress of drought in summer. It is an easy-to-measure electrical parameter as well as a very reliable indicator with a high correlation [133] with wildfire risk. Having obtained a Spearman's Rank correlation coefficient of 0.6816 (p-value < 0.001) between the FWI index and the raw voltage values for the 24-week study in 2021, the same test for the period 2018–2021 increases to 0.7816 (p-value < 0.001). We have to notice, that our research is a pioneer study to link electrical signals with plant physiology in a context of wildfire risk management, and our findings demonstrate the potential of incorporating electrical responses as one of the ecophysiological plant traits to investigating seasonal changes in wildfire ignition risk and flammability.

4. Conclusions

The most important conclusions that we can draw from the research are the following:

- No significant differences have been observed between the moisture content of the different fractions of the branches of *Pinus halepensis* (base of the branch, half of the branch and twigs and needles as live fuel), even in times of drought with hydric stress and very high temperatures.
- Live fuel moisture content has not shown significant variations under the influence of extreme fire risk factors in the summer time. For this reason, it should be complemented by other reliable variables for fire risk assessment and monitoring in MTEs dominated by *Pinus halepensis*. Thus, other plant physiological traits have to be integrated in the assessment and modelling of the high risk of wildfires in *Pinus halepensis* stands in times of water stress and high temperatures, related both to hydraulic dynamics (osmotic potential, sap flow) and dead fuel (wilting and needle senescence, dead fuel presence and evolution). However, as LFMC% responds better to fire risk conditions in some shrub species in MTEs, we propose to analyse in-depth the relationship between LFMC% and electrical responses in these shrubs.
- The variations registered in the electrical signal generated in *Pinus halepensis* show oscillations with significant variations, which are strongly correlated with the periods of extremely favourable meteorological conditions for wildfires (Spearman rho of 0.78).
- The voltages measured show ranges that correspond with great accuracy to the official fire risk levels based on the FWI system.
- The electrical signals, specifically voltage, are a result of the physiological response of the Mediterranean pine trees to the abiotic stress of drought in summer. It is an easy-to-measure electrical parameter as well as a very reliable indicator with a high correlation with wildfire risk.
- Electrical responses could add more knowledge about the phenological state of the trees in dependence on stress climatic conditions, allowing for the integration of these variables in the preventive wildfire management. Although for this we also consider that a more in-depth investigation is necessary.
- Finally, the results obtained and the knowledge gained allows for the exploration of new possibilities for the development of wireless terrestrial sensors based on voltage measurement, which allow online monitoring of the risk of wildfire ignition and propagation with potentially maximum spatial and temporal resolution.

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