Understanding the impact of thinning on holm oak water-use through simultaneous and continuous monitoring of twig water potential, transpiration and soil moisture.

Laura Blanco Cano[1], Antonio D. Del Campo García[1], María González-Sanchis[1], Antonio J. Molina[1], Javier Pérez Romero[1], Lyda Milena Patiño Guío[1]

[1] Universitat Politecnica de Valencia, Valencia, Comunitat Valenciana, Spain.

Abstract

Adaptive silviculture in semiarid climates must focus on enhancing eco-physiogical traits that provide functional advantages to water scarcity. Intraspecific plasticity in such traits is especially important to correctly address silvicultural prescriptions. Studying changes in avoidance (tightly closure of stomata when water potential drops, or atmospheric demand rises) or tolerance (weak stomatal control of transpiration) mechanisms to water stress after forest treatments could improve the understanding of their eco-physiological impact to cope with increasing aridity in forests. Water potential (Ψ), transpiration (T) and other ecohydrological variables are important in this sense and can be simultaneously assessed, although measuring Ψ in forests with traditional pressure chamber is cumbersome and not continuous in time. The aim of this work is to use continuous measures of Ψ, T and soil moisture (SM) to test the ecohydrological behavior of oaks 10 years after thinning. This study was carried out in a holm oak forest in southwestern Spain, where one plot was thinned 10 years ago, and another plot was a control (without treatment). Three trees in each plot were continuously (every hour) monitored for Ψ, T and soil moisture (SM) besides meteorological variables. The continuous measurement of Ψ was obtained by using psychrometers and validated with pressure chamber. Our results show that the average Ψ of the thinned trees, -0.487 ± 0.639 MPa, reflects a more favorable water status than that of the control plot, -0.604 ± 0.698 MPa, despite the lower tree-water use in the latter plot. Also, it was observed a more positive relationship between T and Ψ in the control than in thinning plot. On the other hand, the relationship between Ψ and SM was not affected by the treatment. In addition to this physiological benefit, it could be an advantage against climate change, since by favoring these flows, the trees' CO2 uptake will increase.

Keywords: Adaptive and integrated management, Monitoring and data collection, Sustainable forest management, Knowledge management, Climate change.

Introduction, scope and main objectives

Forests worldwide are suffering the effects of global change at an unprecedented rate (Dale et al., 2001; Pecl et al., 2017). Specially in the case of Mediterranean forests which are already suffering from increased mortality (Doblas-Miranda et al., 2017). This requires forest management based on adaptive forestry (Lindner et al., 2014), which aims to adapt forests or improve their resilience to new environmental conditions (Seidl et al., 2016). This management can improve the water status of the system. Holm oak (*Q. ilex* L.) is a widely distributed tree in the Mediterranean basin and is closely linked to the precipitation gradient. At the northern limit of its range, the species has been observed to be colonising new areas (Delzon et al., 2013). However, in the southwest of Spain conditions are drier, so its populations are found in high and scattered areas (Terradas & Savé, 1992; Hampe y Petit, 2005). Populations are therefore subjected to a different degree of water stress, which may result in changes in eco-physiological response (Gratani et al., 2003). This makes them particularly interesting for the study of physiological water use strategies, most relevantly stomatal control (Martínez-Vilalta et al. 2014).

Previous studies on this physiological response of holm oak to water stress have shown both avoidance (Barbeta & Peñuelas, 2016) and tolerance mechanisms (Ugolini et all., 2012). Avoidance consists in the reduction of stomatal conductance to avoid conductivity losses at less negative water potentials and, consequently, trees have a lower risk of xylem embolism (Ogaya el all., 2014), although this leads to a decrease in transpiration and photosynthesis. Tolerance consists of adjusting water potential in drought situations, maintaining stomatal conductance and transpiration, thus showing less stomatal control and increasing the risk of cavitation (Franks et al., 2007). Hence the importance of understanding how a forestry treatment can change these strategies and thus the water uses of the tree is essential.

In this study, a plot of holm oak thinned in 2012 and a control plot (not thinned) were used. This treatment generated an early decrease in competition for water and consequently a decrease in water stress (del Campo et al., 2019). To check if there was a physiological change in the mid-term (9 years later), simultaneous and continuous measurements of water potential and transpiration were taken together with other eco-physiological variables, such as soil moisture in 2021. The most interesting measure shown is the continuous water potential, as traditionally only one-time measurements are taken isolated through pressure chambers. The objective is to study the mid-term effect of thinning on the eco-hydrological variables of the oaks (water potential, transpiration and soil moisture). For this purpose, the time series of the treated and untreated plots will be analyzed and compared on the basis of these three variables, both on a daily basis and differentiating between day and night.

Methodology

1- Study area and experimental plots.

The study area was carried out in a marginal oak forest located in the southwestern region of the province of Valencia in Spain (39°04'-N, 1°14'-W elevation 1.080-1.100 m a.s.l.). The climate is typically Mediterranean with continental influence. The accumulated rainfall is in the range of 466 mm and the average temperature is 12.8 ºC according to a nearby weather station. These averages are strongly affected by seasonality and can therefore vary widely. The soil is relatively shallow (10–40 cm), sandy-silty-loam textured and basic pH (8.0 ± 0.1). Additional properties of soils are described in di *Prima et al. (2017)*. Parent rock is a karstified limestone resulting in a high stoniness but at the same time, it gives a high degree of fissuring, which generating water reservoirs. The dominant species in this site Holm oak (*Quercus ilex* subsp.*ballota* (Desf.) Samp.) and accompanying species are *Q. faginea* Lam., *Pinus halepensis* Mill., *Juniperus phoenicea* L. and *J. oxycedrus* L. This coppice oak forest had a traditional fuelwood use until 1970, so its abandonment has led to high stem densities and therefore to high intraspecific competition from holm oaks.

In May 2012, two experimental rectangular plots were established, one control (C) and one treatment (Tr) plot of approximately 1.800 m^2 with a slope of 31% and a NW aspect, these are located adjacent to each other. The treatment consisted of an experimental thinning (and shrub clearance), which was conducted and supervised by the Forest Service of Valencia. Thinning reduced the number of initial trees by approximately one third and it focus on to achieve a relatively homogeneous tree distribution (based on forest cover). Further information on the study plots can be found in del Campo et al. (2018, 2019).

2- Study variables and field instrumentation

This study spans the period from March 20, 2021 to April 08, 2021. Measurements were taken continuously and simultaneously, at soil-plant level, being: soil moisture at 15 cm (SM), transpiration (T) and water potential (Ψ). In addition, they were taken separately for each plot.

Soil moisture (SM, m3/m3) was measured continuously throughout the period every 10 min using FDR probes (EC-5, Decagon Devices Inc., Pullman, WA, USA) connected to the CR1000 data logger. The sensors were installed by digging 9 pits per plot (18 in total) which were homogeneously distributed at a depth of 15 cm. After installation, the pits were backfilled with the excavated soils and lightly compacted to a condition similar to undisturbed soil. This allows a reading to be obtained that includes stoniness (as rocks do not retain moisture).

Transpiration was represented by sap flow velocity (T, cm h-1), measured hourly using the heat ratio method, HRM (Burgess et al., 2001) by means of 14 sensors, 7 per plot, powered by a 12 V battery connected to a solar panel and a data-logger (Smart Logger, ICT International, Armidale, NSW, Australia). These sensors provide an output every hour. The sensors were installed on the ascending side of the trunk at a variable height depending on the trunk shape (between 0.3 and 1.0 m high). In addition, the sensors were distributed considering the different diameter classes of the oaks. This sample size is within the range normally considered in studies of tree water relations (Martínez-Vilalta et al., 2003; Klein et al., 2013).

Water potential was measured continuously every half hour using a thermocouple hygrometer or psychrometer (PSY1 Stem Psychrometer, ICT International, Armidale, NSW, Australia). Sensors were powered by a 12 V battery connected to a solar panel. The distribution was 3 sensors per plot and the six selected trees also had an HRM sensor installed. These were installed on branches of the crown, trying to ensure that they were all in the same orientation and with a similar branch thickness. Once installed, the wounds and the sensor contour were sealed with neutral resin, avoiding increased water loss and errors in the readings due to temperature changes or wind.

3- Data analysis

The analyses were carried out considering both the general daily behavior and the change of the physiological variables in the presence or absence of sunlight. Therefore, three scenarios were studied: i) only in the presence of sunlight (Day, to 7:00 from 20:00), ii) only in the absence of sunlight (Night, from 21:00 to 6:00) and ii) daily cycle (Daily, from 00:00 to 23:00). The different datasets of the study variables were processed to obtain a reading every hour (transpiration marks this frequency limit).

Basic statistics (mean, standard deviation, minimum and maximum) were calculated in order to compare differences between control/treatment plots and between day/night/daily scenarios. We studied the relative contribution of the treatment, soil moisture and transpiration on water potential. To this end, relationships were investigated through Pearson correlations, cross-correlation and linear regression models. Cross-correlation was used to study whether there was a lag in the relationship between water potential and transpiration. This was maintaining the time series of water potential at time 0 (Lag 0) and the correlation was calculated for different forward lags in transpiration: 1h, 2h, 3h and 4h (Lag 1, Lag 2, Lag 3 and Lag 4). The regression models are not intended for predictive purposes but for quantifying the relative importance of the different independent variables (treatment, soil moisture and transpiration) in explaining the variance of water potential (dependent variables). The criterion for selecting a significantly positive variable was p-value < 0.05.

Results

Time series of the three study variables without considering a time lag (Lag 0) are presented in Figure 1. It can be observed how Ψ and T have an opposite daily behavior, meaning that when Ψ becomes more negative, T increases and conversely, when Ψ becomes positive, T decreases. On the other hand, it is shown how plot C in comparison to plot Tr uses less water through transpiration and the Ψ of plot C generally reaches more negative Ψ values than plot Tr. Soil moisture showed a decreasing trend along the studied days (Fig. 1).

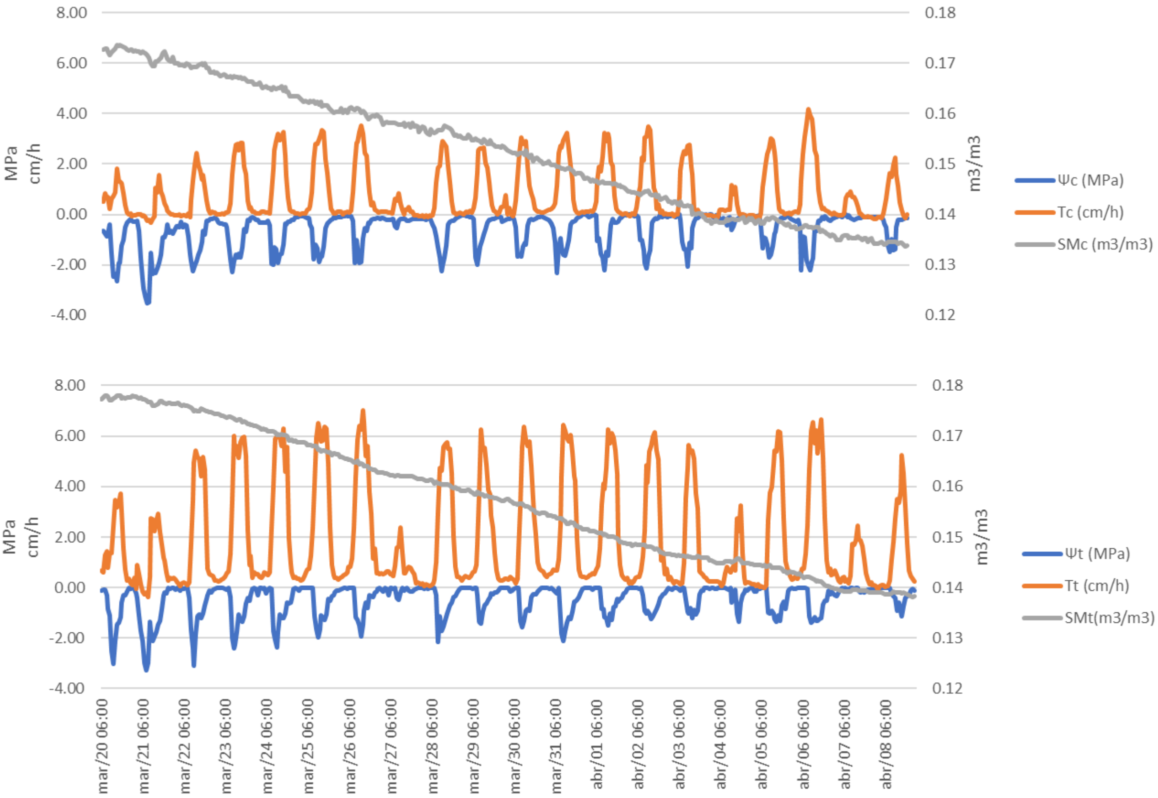

Fig. 1: Time series of the study variables for plot C (control, upper graph) and plot Tr (thinned, lower graph). Series shown are in real time, that is, without time lag (Lag 0) and at daily level. Water potential (Ψ), transpiration (T) and soil moisture (SM) are represented.

The basic statistics (Table 1) show that by day, both the mean and minimum Ψ are more negative in the control (Ψ_C,-0.885 ± 0.750 and -3.510) than in the treatment (Ψ_{Tr}, -0.760 ± 0.690 and -3.280), however the mean and maximum T are higher in the treatment (T_{Tr}, 3.030 ± 2.164 and 7.010) than in control (1.306 ± 1.140 and 4.168). In addition, the thinned plot has a slightly higher SM (0.157 ± 0.013) than the control (0.153 ± 0.012). During the night this difference in Ψ and T between control and treatment continues being seen, however a generalized reduction in T is seen, accompanied by a more positive Ψ. In all three scenarios, the standard deviations are higher in plot Tr than in plot C. (Table 1).

Water potential, Ψ, correlates negatively to T and SM during the day and similarly in both plots. The correlation is higher between Ψ and T, especially to T one hour later. During the night, the correlation becomes practically absent between Ψ and T in both plots (C: 0.07; Tr: -0.02), increasing a little in the case of the control with T one hour later (0.11) and the treatment with T two hours later (0.24). However, the correlation between Ψ and SM remains negative especially in the control (C: -0.41; Tr: -0.18) (Table 2).

Table 1. Basic statistics (mean, standard deviation (sd) minimum (min) and maximum (max)) of the studied variables: water potential (Ψ), transpiration (T) and soil moisture (SM) of both control (C) and treatment (T) in the three-time scenarios (daylight, night and daily).

Daylight						
	Ψ_C	T_C	SM_C	Ψ_{Tr}	T_{Tr}	SM_{Tr}
mean	-0.885	1.306	0.153	-0.760	3.030	0.157
sd	0.750	1.140	0.012	0.690	2.164	0.013
min	-3.510	-0.325	0.134	-3.280	-0.390	0.139
max	0.000	4.168	0.174	0.000	7.010	0.178
Night						
	Ψ_C	T_C	SM_C	Ψ_{Tr}	T_{Tr}	SM_{Tr}
mean	-0.198	0.049	0.152	-0.094	0.383	0.157
sd	0.316	0.114	0.012	0.221	0.231	0.013
min	-2.925	-0.175	0.134	-2.105	-0.143	0.138
max	0.000	0.765	0.173	0.000	1.563	0.178
Daily						
	Ψ_C	T_C	SM_C	Ψ_{Tr}	T_{Tr}	SM_{Tr}
mean	-0.604	0.792	0.153	-0.487	1.946	0.157
sd	0.698	1.075	0.012	0.639	2.117	0.013
min	-3.510	-0.325	0.134	-3.280	-0.390	0.138
max	0.000	4.168	0.174	0.000	7.010	0.178

Table 2. Correlation between Ψ and T and SM without considering any time lag (Lag 0). They also include the correlations between Ψ and T, subjecting T to 4-time lags: 1 hour later (Lag 1), 2 hour later (Lag 2), 3 hour later (Lag 3) and 4 hour later (Lag 4). All correlations differentiate between C and Tr and between daylight, night or daily.

			Lag 0	**Lag 1**	**Lag 2**	**Lag 3**	**Lag 4**
Daylight	**Control**	Ψ_C | T_C	-0.54	-0.63	-0.58	-0.46	-0.31
		Ψ_C | SM_C	-0.36				
	Treatment	Ψ_{Tr} | T_{Tr}	-0.58	-0.61	-0.50	-0.36	-0.24
		Ψ_{Tr} | SM_{Tr}	-0.36				
Night	**Control**	Ψ_C | T_C	0.07	0.11	0.17	0.14	0.10
		Ψ_C | SM_C	-0.41				
	Treatment	Ψ_{Tr} | T_{Tr}	-0.02	0.20	0.24	0.21	0.13
		Ψ_{Tr} | SM_{Tr}	-0.18				
Daily	**Control**	Ψ_C | T_C	-0.64	-0.70	-0.67	-0.57	-0.42
		Ψ_C | SM_C	-0.31				
	Treatment	Ψ_{Tr} | T_{Tr}	-0.69	-0.71	-0.64	-0.54	-0.41
		Ψ_{Tr} | SM_{Tr}	-0.26				

During the daylight, the linear models fitted indicate that T explains almost 30% of the Ψ (C: 29% and Tr: 33%). Although in the case of plot C, T one hour later increases the explanation to 39%. On the other hand, SM explains 13 % of the Ψ in both plots during the day. During the night, T is not significant in any plot. On the other hand, the relationship between the SM and the Ψ in plot C stands out, since it reaches 17% of explanation. On a daily basis, the explanatory power of T seems to increase both with the T at time 0 (C: 41% and Tr: 48%) and the T one hour later (C: 49% and Tr: 51%) (Table 3).

Table 3. Explanatory power of T and SM on Ψ in both plots and in the three temporal scenarios (Lag 0). The explanatory power of T was also seen with a time lag of one hour later with respect to Ψ (Lag 1).

			Lag 0		Lag 1	
			R^2	p-valor	R^2	p-valor
Day-light	Control	$\Psi_C \mid T_C$	0.29	0.00	0.39	0.00
		$\Psi_C \mid SM_C$	0.13	0.00		
	Treatment	$\Psi_T \mid T_T$	0.33	0.00	0.33	0.00
		$\Psi_T \mid SM_T$	0.13	0.00		
Night	Control	$\Psi_C \mid T_C$	0.00	0.34	0.01	0.13
		$\Psi_C \mid SM_C$	0.17	0.00		
	Treatment	$\Psi_T \mid T_T$	0.00	0.83	0.04	0.01
		$\Psi_T \mid SM_T$	0.03	0.01		
Daily	Control	$\Psi_C \mid T_C$	0.41	0.00	0.49	0.00
		$\Psi_C \mid SM_C$	0.10	0.00		
	Treatment	$\Psi_T \mid T_T$	0.48	0.00	0.51	0.00
		$\Psi_T \mid SM_T$	0.07	0.00	0.07	0.00

Discussion

Control plot shows more negative potentials and lower transpiration than the thinned plot. This implies that the control trees subject the xylem vessels to higher pressure, thus showing higher water stress than thinning. However, in spite of such hydraulic forcing, they were not able to use the same amount of water that the treatment trees use. Increase in transpiration after tinning has been seen in other works (Reyes-Acosta & Lubczynski, 2013; del Campo et al., 2019). In our case, the more favorable conditions of thinned trees in the early post-treatment years (del Campo et al., 2019) would have allowed for a more developed and advantageous root system of treated trees with consequences in their water access and water status nine years later as compared to the control. This would explain why the thinned plot has a comparatively more favorable water status than the control under similar soil water conditions. Other work has also linked the depth of the root system to improved water status (David et al., 2007). Another indication of the eco-hydraulic improvement of the system is that the treatment has larger deviations, which may be an indication of the ability of its mechanisms to adapt to the environment and therefore the plasticity to cope with different climatic situations.

In addition to the improvement of the water status of the trees, a slightly higher amount of water is observed in the treatment. This effect will be related to the lower number of trees, both in terms of competition for water and canopy interception, which increases net precipitation. This reduction in interception can be significant in prolonged dry spells as it is estimated that the canopy can retain an average of 22.2% (Díaz, 2013).

High correlations between water potential and transpiration one hour later may be due to two phenomena: i) a decoupling between stomata closure and sap flow or ii) that this decoupling is due to the location of the sensors in the tree, as the water potential sensor is located on the top branches whilst the transpiration sensor on the trunk (about 1-2 meters lower). Also noteworthy is the negative correlation between soil moisture and water potential, possibly due to the positive relationship between soil moisture and transpiration.

Degree of explanation provided by transpiration for the potential was to be expected since both are processes that are stimulated by the same mechanisms. On the other hand, it is noteworthy that soil moisture explains a higher percentage in the control plot, suggesting a greater water limitation in the control (Pallardy, 2010).

Conclusions/ wider implications of findings

Thinning carried out 9 years ago still shows a different behavior of the functional responses of the holm oak. In spite soil moisture is quite similar between control and tinning (assuming net precipitation has approached in both plots) the physiological response of thinned oaks remains improved in the mid-term. As a consequence, the treated plot is in a more favorable water status under the same environmental conditions proving the added value thinned had in this marginal oak stand. In addition, the continuous monitoring of the three selected ecohydrological variables (water potential, transpiration and soil moisture) was key to understand the system.

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