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Ecohydrological turnover in overstocked Aleppo pine plantations: Does the effect of thinning, in relation to water, persist at the mid-term?

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ABSTRACT

In Mediterranean pine plantations forest dieback and tree mortality are not only related to increased drought, but also to a lack of management, which intensifies inter-tree competition for available soil water. In this complex context simple but also difficult questions such as why, how and when manage forests should be directly responded and quantified by applied science. In this study we specifically analysed the forest-water relationships of an Aleppo pine plantation where experimental thinning was carried out ten years ago at three different intensities (H: high-, M: moderate- and L: low-thinning plots plus a control one, C). To this end, we again measured tree sap flow, soil water content and meteorological conditions. In addition, the relative importance (RI) of thinning intensity and environmental drivers when explaining tree/stand-water at the short-term were compared with those obtained in this study in order to elucidate how the role of thinning intensity may change on time. The impact of thinning on soil water content showed that significant differences were maintained after ten years (H > M > L > C), but that values between the different thinning intensities were closer than those observed at the short-term. In contrast, tree transpiration from the high-thinning plot was very similar to that from the moderate-thinning one (means of 13 and 14.7 l·day^{-1}, respectively). These results support the idea that an excessive forest opening makes the understorey compete more strongly for water, thus counterbalancing the higher tree transpiration observed in the short-term. The combined analyses of thinning intensity and environmental drivers highlight how the role of thinning intensity in controlling tree and stand transpiration in the short-term was clearly replaced by soil water availability ten years after the thinning intervention (RI means from 13.1 to 39.5% for soil water availability and from 26.8 to 19.0% for thinning intensity). Our results support the need to study how the transpiration-soil water relationships progressively change over the distance in time from thinning in order to assess the impact of understorey properly and thus systematically calculate the ecohydrological turnover at every thinning intensity tested.

1. Introduction

Application of the most recent knowledge from disciplines such as forest ecology or forest ecohydrology to managing forests is still far from complete (Jackson et al., 2017). This is seen clearly when academic results are not framed and translated into technical guidelines, leaving foresters unaccompanied in their decision-making processes, which are especially tough in a context of climate change. It is here where simple, but also difficult questions such as why, where and how manage forests should be directly responded and quantified by applied science. This is particularly important in Mediterranean areas where the negative effects of climate change on forest structure and function are already noticeable (Martínez-Vilalta and Pinol, 2002; McDowell and Allen, 2015) and are predicted to increase in the future through more intense droughts (Lindner et al., 2014; Soteriades et al., 2017) and the subsequent changes in forest-water relationships (Tague et al., 2019). A clear example is the Aleppo pine plantations growing in Eastern Spain, where silviculture is called to play a significant role in adapting them to the new ecological conditions.

The role of forest density reduction in hydrology has become steadily more important, especially in regions where reductions in streamflow are significantly affected by forest encroachment at headwaters, which

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then affects water resources downstream (Lorenzo-Lacruz et al., 2012; Hidalgo-Muñoz et al., 2015; Buendia et al., 2016). Several studies have highlighted the strong inter-dependence between water intercepted and transpired by vegetation (green water) and available water (blue water), from paired catchment experiments designed to isolate the effects of forest cover manipulation on outlet flows (Bosch and Hewlett, 1982; Brown et al., 2005; Coble et al., 2020) to those carried out at the stand scale for analysing the effects of thinning on stand-water relations (Dung et al., 2012; del Campo et al., 2019; Gavinet et al., 2019). The impact of thinning on increasing soil water content availability is seen very clearly in overstocked plantations at the stand scale (Ganatsios et al., 2010; del Campo et al., 2014, 2018). In this context, concepts such as "hydrology-based silviculture" (Molina and del Campo, 2012), "eco-hydrology-based forest management" (del Campo and González-Sanchis, 2017), "adaptive water-saving silviculture" (David et al., 2011) or "watering the forest for the trees" (Grant et al., 2013) are proposed. These concepts emphasise the key message that forest management should be strongly biased towards forest-water relationships in critical areas by watering the remaining trees after intervention, which improves forest resilience (Grant et al., 2013; Tsamir et al., 2019).

Although the question of why forests should be managed in terms of forest-water relations is already well supported, in the authors' opinion, there are others that remain unclear and need further hydrological studies. Tree density reduction (optimum thinning intensity) and when to thin out again (how long the effects last) are the second and third questions that need to be tackled. Raz-Yaseef et al. (2010), when proposing an optimum canopy cover for maintaining forest productivity, based their view on hydrological flux components in a pine forest growing under semi-arid conditions. In contrast to this approach, assessing hydrologic impacts of thinning is normally achieved by comparing a plot treated by common timber procedures with another plot acting as a control (Simonin et al., 2007; Grant et al., 2013; del Campo et al., 2018). Furthermore, most of the available studies on the topic are focused in the short-term effects (Raz-Yaseef et al., 2010; Gebhardt et al., 2014; del Campo et al., 2019), so the longer temporal dynamics of forest canopy and understorey are rarely considered. This aspect is especially important when steady changes in water evaporation from soil surface and/or in understorey rainfall interception and transpiration may counterbalance the positive thinning impact for the remaining trees of increased net rainfall in the short- term (Raz-Yaseef et al., 2010; Gebhardt et al., 2014; del Campo and González-Sanchis, 2017). Different forest density reductions coupled with long-term monitoring schemes would show for instance when a thinned stand has similar evapotranspiration to the untreated one. The result would support whether to thin out again or define a new silviculture strategy for that specific thinning intensity. This water-oriented approach can complement and technically support current frameworks for adaptive silviculture to climate change, such as the framework of Millar et al. (2007) who defined resistance, resilience, transition and inaction treatments. Thus, measurement of the temporal dynamics in forest-water relationships may help to evaluate properly these four treatment categories at a particular site, since it can complement more common information regarding growth and forest structure.

The present study revisits an Aleppo pine experimental deployment where positive thinning effects were demonstrated in several aspects in the short-term, such as rainfall partitioning (Molina and del Campo, 2012), tree growth (Fernandes et al., 2016) and water balance at the stand scale (del Campo et al., 2014). This study has the general objective of assessing the impact of thinning intensity on these relationships ten years after the forest intervention. Specific objectives are to (i) analyse the single role of thinning intensity on soil water content and tree transpiration variables; (ii) assess the changes in relative importance of thinning intensity and environmental conditions when comparing tree- and stand-water relationships between the short- and the mid-term. By addressing these objectives, we provide new insights to better define the ecohydrological turnover as a function of thinning intensity when managing Mediterranean pine plantations characterized by excessive tree density.

2. Materials and methods

2.1. Study site

The study was conducted at a planted *P. halepensis* area located in the public forest "La Hunde y Palomeras" in eastern Spain (39°05′N, 1°12′W; 950 m a.s.l). Like many Mediterranean areas in Spain, the site is characterized by large pine plantations, dating from the national reforestation programmes of the 1950s and 1960s, which had a clear soil–water conservation objective. Mean annual values for temperature, Penman-Monteith reference evapotranspiration and rainfall are 13.7 °C, 749 and 466 mm, respectively. The soils, leptosols according to the World Reference Base for Soil Resources (WRB, 2015), display a basic pH of 7.6, are relatively shallow (50–60 cm) and have a sandy–silty loam texture. The slope in the planted area is less than 5%. There are three main understorey woody species in the plantation, *Quercus ilex* sbsp. *ballota* (Desf.) Samp. (sapling density of 1206.9 ± 566.8), *Juniperus oxycedrus* L. (sapling density of 2066.5 ± 1346.2) and *J. phoenicea* L. (sapling density of 4391.8 ± 416.4). The forest has not been managed since its establishment except for the usual linear-strip thinning to prevent forest fire propagation and for the experiments described below.

2.2. Experimental design

In February 2008, an experiment including four thinning intensities (see below) was carried out in three replicates or blocks, each with four square 30 m-side experimental units. One unit was not thinned (control, C, 83% of forest cover, 1,289 trees·ha^{-1}); and the other units were thinned at three different intensities: high (H, 16% of forest cover, 178 trees·ha^{-1}), moderate (M, 46% of forest cover, 478 trees·ha^{-1}) and low (L, 64% of forest cover, 689 trees·ha^{-1}) (more details in Molina and del Campo, 2012). Thinning removed the less developed trees and achieved a relatively homogeneous tree distribution (based on forest cover). All the biomass removed was piled outside the plots.

From 2008 to 2012, forest structure, growth and hydrologic variables such as rainfall interception or tree sap flow were continuously measured in order to clarify how thinning affected various ecohydrological processes in the short-term (t_1 period). This study revisits experimental units (hereafter plots) 10 years after the forest management intervention and measures again sap flow and soil water content in the same trees and locations than in the t_1 period (block I) in order to test the effect of thinning in the mid-term (t_{10} period).

2.3. Forest structure monitoring

Forest inventories in 2018 obtained the following information: diameter at breast height (cm), tree height (m), basal area (m^2 ha^{-1}), forest cover (%) and leaf area index (LAI – unitless). All measurements were made in areas at least 2 m away from the plot limits to avoid edge effects. The diameters and heights were measured by tapes and clinometers, respectively. Forest cover was measured with a vertical densitometer (GRS, USA) with 50 readings per experimental unit in a 4 × 4 m grid. LAI was calculated with a LAI-2000 sensor following Molina and del Campo (2011), in order to take the measurements under direct solar radiation, with a single sensor. Briefly, 6 "B'' type measurements were carried out per experimental plot along 2 perpendicular axes, 3 per axis. 4 "A'' type measurements were made in nearby clearings, 2 for each axis. LAI estimation was performed by taking into account only the fourth ring by means of C-2000 software. Table 1 shows the measured forest structure variables one (t_1) and ten years (t_{10}) after the thinning intervention.

Table 1
Mean values in the experimental plots for the stands' metrics one (t_1) and ten years (t_{10}) after thinning intervention. t_1 data is taken from Molina and del Campo (2011). Thinning resulted in tree densities of 1289, 688, 478 and 177 trees·ha^{-1} for control (C), low-thinned plot (L), moderate-thinned plot (M) and high-thinned plot (H), respectively. BA: basal area, Cover: forest cover, LAI: leaf area index, DBH: diameter at breast height, Height: total tree height.

	BA ($m^2 \cdot ha^{-1}$)		Cover (%)		LAI ($m^2 \cdot m^{-2}$)		DBH (cm)		Height (m)	
Plot	t_1	t_{10}	t_1	t_{10}	t_1	t_{10}	t_1	t_{10}	t_1	t_{10}
C	40.1	37.7	83.3	88.9	2.6	2.9	17.9	21.2	11.5	11.2
L	27.2	34.5	46.0	91.5	1.7	2.3	20.2	25.0	12.2	12.3
M	18.2	30.3	50.0	80.8	1.7	1.9	23.2	29.0	11.3	12.4
H	9.4	16.9	22.0	41.4	0.5	0.9	23.4	28.3	12.2	11.5

2.4. Sap flow measurements and determinations

Sap flow was measured following the same methodology as in the previous study (del Campo et al., 2014) from June 2018 to October 2019. Heat pulse velocity was measured through the HRM method (HRM sensor, ICT International, Australia) by installing one sensor per sample tree on the north side and at a height of 1.3 m. A heater emits the heat pulse, and the temperature increase is then measured by two thermocouples located at 27.5 and 12.5 mm from their bases (outer and inner). Each pair of measurements is then used to calculate the heat pulse velocity at the two depths, which is converted to sap flow velocity, vs (Burgess et al., 2001). The sensors were powered by a voltage regulator connected to a 12-V battery and several solar panels.

Sapwood area was obtained by subtracting heartwood area from the inner-bark area (Giuggiola et al., 2013) from two cores per sample tree. The sapwood area was divided into four different sections with different vs values assigned, in order to calculate daily values of tree transpiration (Tr_{tree}, l day^{-1}) (del Campo et al., 2014; Delzon et al., 2004): (1) the vs from the outer thermocouple was assigned to the sapwood area from the cambium to the middle point located between the outer and inner thermocouples (i.e. 20-mm depth); (2) the vs from the inner thermocouple was assigned to the sapwood area from the middle point to the inner depth of the sensor (27.5-mm depth from the cambium); and (3) the remaining area from the inner depth to the beginning of the heartwood (or to the pith, if there was no heartwood) was divided into two halves. Then, the vs value from the inner thermocouple was multiplied by 0.75 and 0.25, respectively. Stand transpiration (Tr_{stand}, mm) was obtained by multiplying mean tree transpiration by the tree density of each experimental plot. Finally, normalized tree transpiration (Tr_{norm}) was obtained by dividing tree transpiration by the sapwood area of each sample tree (l day^{-1} cm^{-2}).

2.5. Environmental measurements

Daily rainfall (Gr, mm) at the study site was obtained from a rain gauge located 2 km away from the experimental plots ("Ayora-La Hunde" station, belonging to the Spanish SAIH network). Air temperature (°C) and relative humidity (%) were measured by a single sensor (RH/T sensor, Decagon Devices, Pullman, USA) placed 2 m high in an open area located 400 m from the experimental plots. These data were subsequently used to obtain values for vapour pressure deficit on a daily scale (VPD, KPa). Gaps in data were filled by linearly regressing our measurements with those taken at a nearby research site (del Campo et al., 2019).

Soil water content (SWC, m^3 m^{-3}) during the study period was continuously measured in all experimental plots every 20 min by means of FDR sensors (EC-TM, Decagon Devices Inc., Pullman, WA) connected to EM-50 (Decagon) dataloggers. As between 6 and 9 sensors were already installed at 30 cm depth in each plot (criteria explained in del Campo et al., 2014), those not working were replaced by new FDR sensors. Given the wide soil variability among the plots (different water holding capacities), SWC was normalized by field capacity (SWC/FC) for each sampling point to assist comparisons between the plots. Field capacity was calculated from the average of the SWC readings for the dates after rainfall with depth higher than 30 mm. The SWC value when the drainage slopes changed in the time series was taken into account.

2.6. Data treatment and statistical analyses

To test the single effect of thinning intensity on tree-water relationships while being consistent with previously reported results (del Campo et al., 2014), days were again classified in 4 types according to daily precipitation and daily mean temperature. First, days were grouped into dry or wet spells (D, W). A dry spell began when none of the previous 14 consecutive days recorded daily precipitation greater than 5 mm. Secondly, in either period, each single day was classified as cool or warm (C, W) if its mean temperature was, respectively, lower or higher than the overall mean. The DC, DW, WC and WW codes were used for each day-type.

Univariate ANOVA was used for testing for differences in tree transpiration, normalized transpiration and SWC/FC between the plots (treatment as fixed factor) when grouping by day-type. When ANOVA indicated significant differences, the Tukey post-hoc test was selected for the comparison of multiple means. In every case, the data were examined to ensure normality with the Kolmogorov–Smirnoff test; and homogeneity of variance, with the Levene test. When these assumptions were violated, the variables were transformed to achieve homoscedasticity or, alternatively, the non-parametric Kruskal–Wallis test or the Tamhane T2 tests for comparing multiple means were used.

Multivariate analyses studied the combined effects of thinning intensity, environmental factors and time elapsed from thinning (t_1 vs. t_{10}) on SWC and the different transpiration variables considered (normalized transpiration, tree and stand transpiration). The machine learning technique of boosted regression tree models (BRT) was used to assess the relative importance (RI) of the predictors set on the response variables (Elith et al., 2008). This was performed in R software (RStudio Team, 2015) by using the "gbm" package (Elith and Leathwick, 2017; Ridgeway, 2017). Gaussian distribution was selected for our independent variables. The train function in the "caret" package calculated the optimal values for the most important parameters in the BRT analyses (Gu et al., 2019). The function tries a number of different parameters, compares the error rates and then suggests the smallest parameter that generates an appreciable decrease in the error rate, following some rules of thumb described in previous studies of BRT procedures (Elith et al., 2008; Elith and Leathwick, 2017). As a result, we used shrinkage (learning rates) of 0.1, tree complexity of 5 and bag fraction of 0.5. The minimum number of trees was in all cases above 1600. RI measures the number of times a predictor variable is selected for splitting, weighted by the squared improvement in the model as a result of each split, averaged over all trees and calculated so that it adds up to 100 (Elith et al., 2008). The higher the RI, the stronger the influence of a certain predictor. In addition, partial dependency plots (PDP) were produced in order to further study the effect of thinning intensity in the fitted functions for the tested dependent variables. See, for instance, del Campo et al. (2019) to see more details about applying this methodology to test thinning effects on forest hydrology.

3. Results

3.1. Meteorological conditions

Both studied years (2018 and 2019) had intense water deficits, with accumulated reference evapotranspiration more than double the rainfall (1,272 and 1,311 mm for ETo vs. 491 and 566 mm for rainfall) and with long rainless periods in the spring and summer seasons (91 and 108 days in 2018 and 2019 with daily rainfalls lower than 5 mm). Temporal dynamics of vapour pressure deficit and temperature were quite similar in both the studied years, while rainfall and water deficit differed slightly, especially in the January-May period (Fig. 1): 2018 had more homogenous rainfall events, while these were more intense and of greater magnitude in 2019. Worthy of note was a total of 181.6 mm fallen during 4 days in April 2019 (90.2 mm in one day alone). These aspects were clearly reflected in the climatic water deficit: about −100 mm at the beginning of June and a quite similar decreasing slope from this moment until mid-August in both study years (Fig. 1).

3.2. Univariate analyses: Effects of thinning intensity on vegetation-water relations ten years after the forest intervention

The ratio of SWC over field capacity varied significantly between experimental plots (Fig. 2 and Table 2). H and M plots showed the highest values during the study (Table 2), except for the period of slow SWC drainage (at about SWC/FC < 0.5) after the highest soil water recharge (SWC/FC > 1) (total rainfall of 177 mm from 18th to 24th April 2019) (Fig. 2). During this time period and until the next intense showers, the L plot had a dynamic that contrasted with the other plots, characterized by higher and more persistent SWC availability. In contrast, the C plot showed the lowest values during most of the study period. In addition, a Kruskall-Wallis test revealed non-significant differences between the experimental plots when the relative SWC/FC increments for rainfall events higher than 5 mm were compared (inlet in Fig. 2).

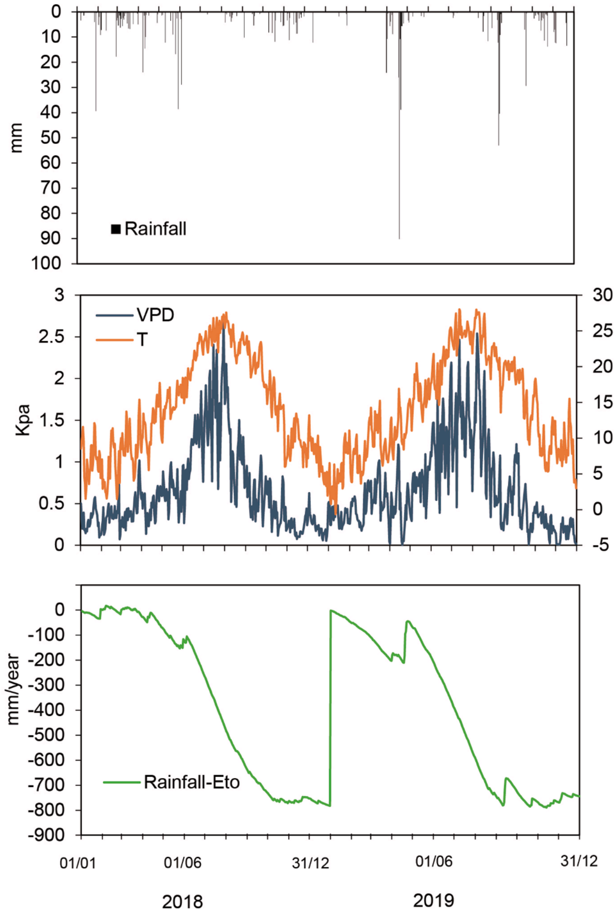

Fig. 1. Daily time series of rainfall (mm), mean vapour pressure deficit (VPD, KPa), mean temperature (T, °C), and daily accumulated difference between rainfall and reference evapotranspiration (mm) for each study year.

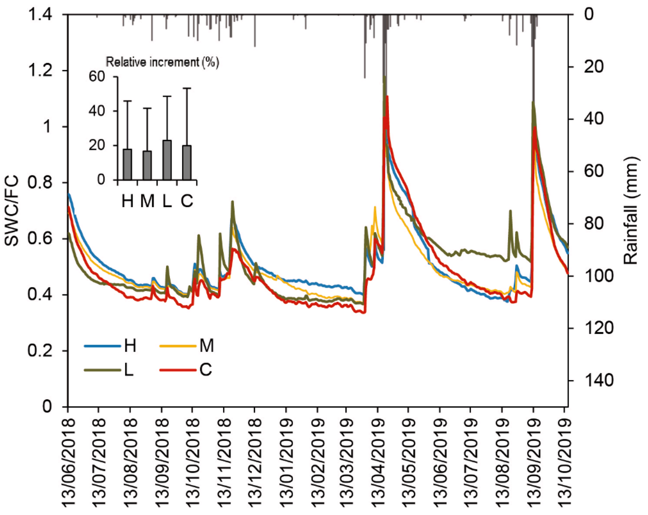

Fig. 2. Mean daily values of soil water content over field capacity (SWC/FC) for each experimental unit. Bars in the inlet figure are the mean (standard deviations also shown) increments of SWC/FC calculated for rainfall events >5 mm as the relative differences between the initial and final values, divided by the initial ones and multiplied by 100. H: high-thinned plot, M: moderate-thinned plot, L: low-moderate thinned plot, C: control plot.

Table 2
Mean values of daily transpiration normalized by sapwood area (Trnorm, l/cm^2 day), tree transpiration (l/day) and soil water content over field capacity (SWC/FC). Different letters indicated significant differences in the post-hoc analyses after a significant effect of thinning was indicated by ANOVA or Kruskall-Wallis test. Results are grouped by day-type according first to rainfall and then to temperature as explained in the text: DC: dry and cool; DW: dry and warm; WC: wet and cool; WW: wet and warm. C: control plot, L: low-thinned plot, M: moderate-thinned plot, H: high-thinned plot.

	C	L	M	H
Trnorm (l/cm^2 day)				
DC	0.008a	0.006a	0.025b	0.030b
DW	0.033a	0.023b	0.064b	0.066b
WC	0.01a	0.009b	0.025b	0.028b
WW	0.003a	0.005a	0.024b	0.027b
Tree transpiration (l/day)				
DC	1.93a	1.19a	12.33b	8.97b
DW	7.16a	4.56b	23.4c	23.56c
WC	2.43a	1.56b	12.07c	9.21c
WW	0.63a	0.93b	11.21c	10.26d
SWC/FC				
DC	0.42a	0.39b	0.43a	0.47c
DW	0.48a	0.48a	0.47a	0.53b
WC	0.52a	0.52a	0.61b	0.55a
WW	0.51a	0.53ab	0.58b	0.54b

Significant differences between the experimental plots were observed in the 4 day-types considered in normalized tree transpiration (Tr_{norm}, $l\ day^{-1}\ cm^{-2}$) and tree transpiration ($l\ day^{-1}$) (Table 2). Results for Tr_{norm} clearly ranked thinning intensities as L < C < M < H (except for WW, with L > C) and two contrasting groups appeared (C with L vs. M with H) (Fig. 3 and Table 2), while this ranking changed to L < C < H < M in the case of tree transpiration, with two or three different groups

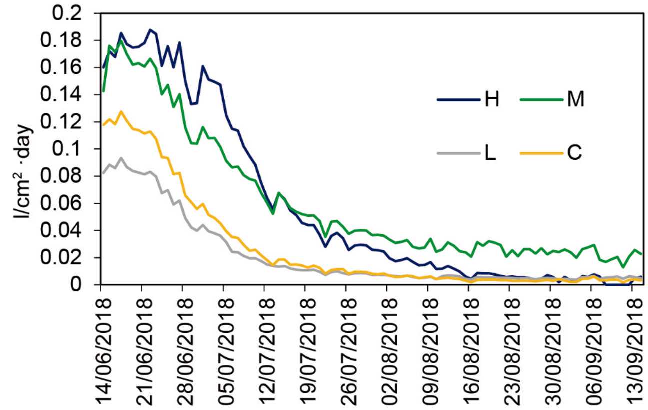

Fig. 3. Time series of mean transpiration normalized by sapwood area (l/cm^2·day) for each experimental plot during the 2018 summer. H: high-thinned plot, M: moderate-thinned plot, L: low-moderate thinned plot, C: control plot.

(Fig. 4 and Table 2).

3.3. Multivariate analyses: The combined effects of thinning intensity, environmental factors and the time elapsed since forest intervention

Boosted regression tree (BRT) models were fitted to compare the contribution of environmental conditions and thinning intensity to green and blue waters in the short- and the mid-term (eight different models). All models gave high cross-validation (CV) correlations ranging from 0.76 to 0.98 (Table 3) and were clearly lower than those correlations obtained for the training data. The former correlations are indicative of the predictive ability of the models, while the latter indicate the explanatory performance of the predictors set. In any case, all transpiration variables were better explained/predicted than the SWC one (Table 3).

The relative importance (RI) for every predictor in all the variables relating to green water was calculated at different spatial scales (Tr_{norm}, tree transpiration and stand transpiration), whilst only the stand scale was considered for blue water, through the mean SWC/FC values (Fig. 5). It is interesting to see how RI changes for a particular predictor when moving from one period to another (t_1 vs. t_{10}) and also when comparing among the variables to be explained. The RI of thinning intensity was lower, despite the time period for blue water, than that of reference evapotranspiration, with RI of about 70% for both t_1 and t_{10} periods (Fig. 5). The influence of SWC on the three transpiration variables showed marked increases when moving from t_1 to t_{10} (RI values from 8.4 to 17.9% in t_1 to 38.1–41.0% in t_{10}), whilst the thinning intensity itself showed an opposite trend (mean decrease of 36.5%). This suggests that SWC regains its influence on green water once it has become a limiting factor over time, regardless of the plot. In fact, vapour pressure deficit showed the opposite pattern, with a marked decrease from t_1 to t_{10} but of lower magnitude (demand and offer aspects of transpiration). Therefore, the SWC effect increased when taking into account the time from thinning intervention for all variables; and the opposite was observed for the effect of thinning.

Partial dependence plots (PDP) indicated that the thinning intensity effects on transpiration variables contrasted between t_1 and t_{10} periods. In the cases of Tr_{norm} and tree transpiration, the most interesting result was the clear change when looking at the temporal effect in the H plot, from a strong positive impact at t_1 to being very close to the other plots at t_{10} (Fig. 6). Regarding stand transpiration, the H plot behaved very differently at t_1 than the other plots by clearly reducing the mean stand transpiration, while for the t_{10} period, the C plot had a significantly higher mean than the other plots (Fig. 6).

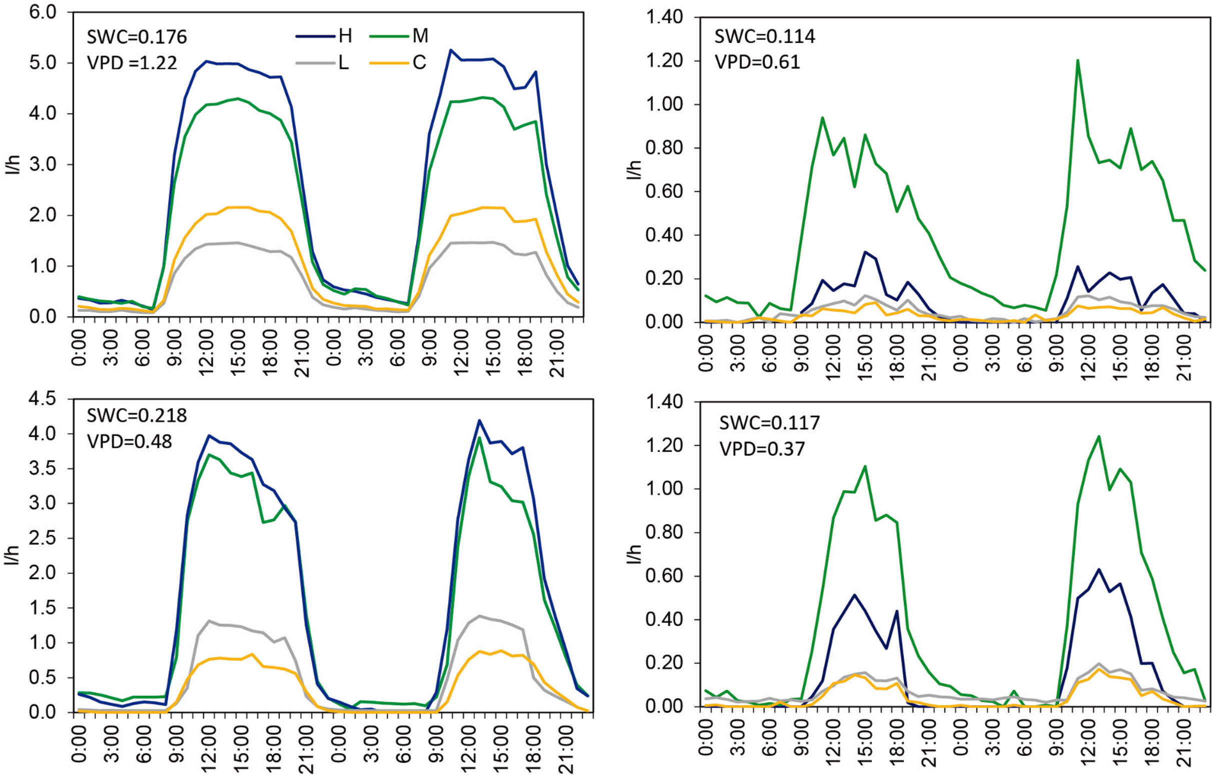

Fig. 4. Hourly dynamics of tree transpiration (l/h) for each experimental plot (means from four sampled trees) in two-day periods. SWC is the mean soil water content (cm^3 cm^{-3}) from all the experimental plots, while VPD is the mean vapour pressure deficit (KPa). Note the differences in the ranges of Y axes. H: high-thinned plot, M: moderate-thinned plot, L: low-moderate thinned plot, C: control plot.

Table 3
Summary of the BRT models fitted for explaining normalized transpiration (Tr_{norm}), tree transpiration and SWC/FC in the two time periods considered: one (t_1) and ten (t_{10}) years after thinning intervention. The predictors were selected after studying Spearman correlations and selecting those higher correlated with the dependent variable when they were linearly related. In parenthesis are presented the standard errors of the coefficients.

Time period	Variable	No. trees	Mean total deviance	Mean residual deviance	Estimated CV deviance	Training data correlation	CV correlation
t1	Tr_{norm}	3350	0.001	<0.001	<0.001 (<0.001)	0.998	0.976 (<0.001)
	Tree transpiration	3000	96.545	0.368	4.777 (0.466)	0.998	0.976 (0.001)
	Stand transpiration	3250	0.195	0.001	0.014 (0.001)	0.996	0.963 (0.004)
	SWC/FC	5600	0.063	0.008	0.024 (0.001)	0.939	0.786 (0.011)
t10	Tnorm	2300	0.001	<0.001	<0.001 (<0.001)	0.999	0.974 (0.0004)
	Tree transpiration	1600	168.051	0.589	7.25 (0.515)	0.998	0.979 (0.001)
	Stand transpiration	3000	0.656	0.002	0.043 (0.004)	0.999	0.968 (0.002)
	SWC/FC	2900	0.014	0.002	0.006 (0.001)	0.932	0.759 (0.027)

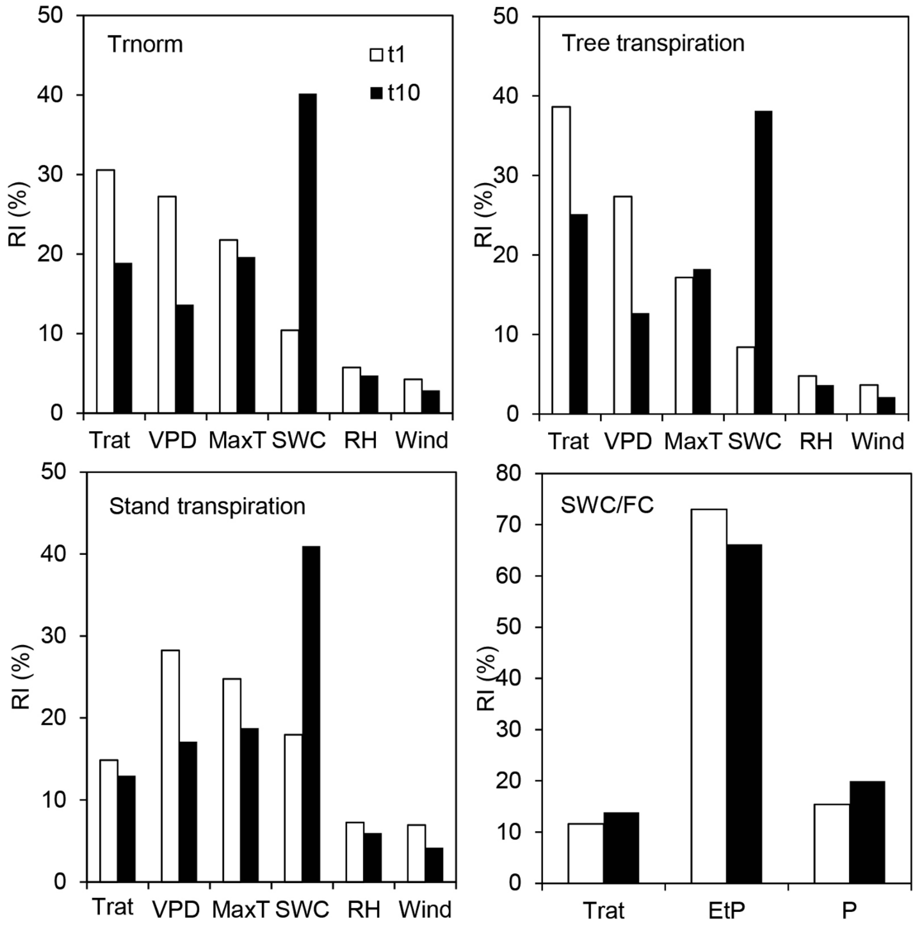

Fig. 5. Relative importance (RI, %) obtained from the BRT models whose coefficients are given in Table 3. The predictors for each variable were selected after studying Spearman correlations and selecting the higher ones correlated with the dependent variable when two predictors were linearly related. Trat: application of thinning; VPD: vapour pressure deficit; MaxT: maximum daily temperature; SWC: mean daily soil water content; RH: mean daily relative humidity; Wind: mean daily wind velocity; EtP: daily accumulated reference evapotranspiration; P: daily accumulated rainfall.

4. Discussion

The results presented in this study allow for a quantitative assessment of the hydrological impacts of thinning intensity in mature Aleppo pine plantations characterised by excessive forest density. In this section, we firstly discuss about the changes in soil water content and transpiration ten years after the forest thinning intervention. Then, the quantification of the environmental and thinning impacts on these water cycle components at both the short- and the mid- term is used for assessing how the role of thinning change with time in this type of forests.

4.1. Vegetation-water relationships ten years after thinning

This study also observed differences in the FC values between experimental units (data not shown) as in the previous study that analysed the water balance at the study site (del Campo et al., 2014). SWC/FC dynamics are thus expected to be better explained than of SWC by above-ground hydrological processes (including forest-floor processes), plant-soil–water dynamics in the 0–30 cm soil profile and, to a lesser extent, soil structure in the soil volume explored by the probes. The results given in Fig. 2 regarding relative increments (inlet) focused on studying how vegetation structure (canopy plus understorey) may affect rainfall partitioning. This is based on the assumption that soil infiltration among the experimental plots is behaving in a similar way as a consequence of the time elapsed from thinning (Di Prima et al., 2017; Lull et al., 2020). Our results revealed non-significant differences in the experimental plots for rainfall events higher than 5 mm. The C and L plots had similar forest cover, basal area and LAI in 2018 (Table 1). While L, M and H plots had significant increases from 2008 to 2018, they

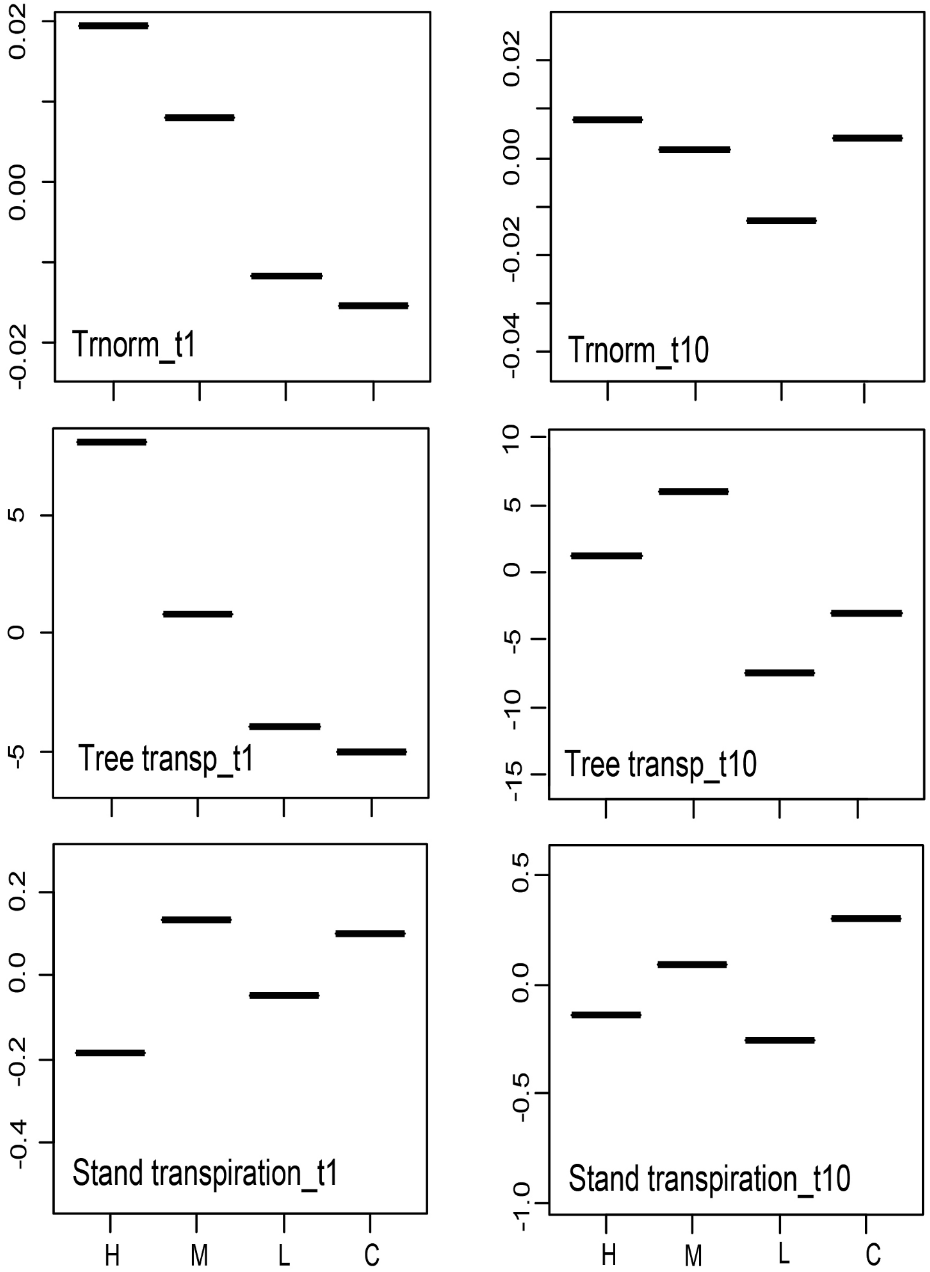

Fig. 6. Partial dependence plots (PDP) of the BRT models, showing the fitted functions for the predictor thinning intensity (H, M, L, C) in transpiration variables (normalized transpiration, tree transpiration and stand transpiration) at both the time scales considered, t_1 and t_{10}. The Y-axes are centred to have zero mean over the data distribution and spans in units of standard deviation from the mean predicted response value. H: high-thinned plot, M: moderate-thinned plot, L: low-moderate thinned plot, C: control plot.

were not observed in the C plots. Depending on the metric considered, values in 2018 were close for L and M plots, and H had the lowest values in all the stand variables. Given this canopy structure, our data suggest that the highest rainfall interception by understorey (here considered as shrubs and tree saplings) in the H plot (and in the M plot to a lesser extent) is counterbalancing the forest cover effect in the other plots. On the other hand, the comparisons of SWC/FC values among the experimental plots indicated differences that depended on the day-type, with H and M plots showing the highest values, while L and C plots had very similar ones. These results show a quite similar pattern to the pattern observed two years after thinning (del Campo et al., 2014), although in the previous study the differences between experimental plots were greater, especially between H and the remaining plots. While the understorey plays an important role by differently affecting rainfall partitioning, it does not seem to follow the same pattern in its impact on SWC/FC. Shrubs and young oak and pine trees (field observations) in H and M plots reduced soil water content, but these reductions were not enough to counterbalance the effects of tree transpiration in the L and C plots. Changes following thinning are related to the intensity of disturbance not only in overstorey but also in understorey vegetation and forest floor (Ares et al., 2010). In general, thinning intensity increases understorey vegetation cover (Ares et al., 2010; Bataineh et al., 2014). Trentini et al. (2017), for instance, found higher increases in understorey cover in the severe-thinning plots than in the moderate-thinning ones in loblolly pine plantations, although the results are limited to the two years after thinning. In our case, field observations in 2012 (Lacovelli, 2013) indicated understorey vegetation cover of 17.8, 11.9, 10.5 and 29.9% for C, L, M and H, respectively. Although these observations were limited to the 4 years after thinning, they support the ideas presented here dealing with the differential effects of understorey depending on thinning intensity.

For sap flow, we looked again at the arguments given in del Campo et al. (2014) for the validity of our calculations of the role of thinning intensity when using the heat pulse method. It is well documented that the trees remaining after thinning enjoy greater availability of limited resources such as soil water, PAR and nutrients, and they subsequently increase their transpiration rates, at least in the short-term (Medhurst et al., 2002; Grant et al., 2013; del Campo et al., 2019). Two complementary variables (Tr_{norm} and tree transpiration) were employed in this study for understanding the role of thinning intensity ten years later its application. Our Tr_{norm} results clearly indicate trees behaving very similarly in L and C and in M and H (Fig. 4 and Table 2), while these patterns were less consistent when looking at tree transpiration (Fig. 3 and Table 2), given the distinct tree size increment induced by thinning intensity (Table 1). On examining dates when soil water availability was not a limiting factor in any of the plots, higher Tr_{norm} values in M and H indicate higher hydraulic sapwood conductivity due to tracheids being more functional. In fact, when comparing outer and inner measurements (at 12.5 and 27.5 mm from cambium, respectively) for these days, i.e. the radial variation in sap flow velocity, the mean relative ratios of inner over outer are linearly related to thinning intensity: 133.8, 116.8, 73.5 and 46.9% for H, M, L and C plots, respectively. This result is quite surprising given that radial profile is normally characterized by the outermost part giving low sap flow velocity, the maximum at about 1 cm sapwood depth and declining sap flow velocity with sapwood depth from the maximum on (Ford et al., 2004; del Campo et al., 2014; Berdanier et al., 2016). We hypothesized that the better sapwood hydraulic conductivity induced by thinning in the short-term (inner tracheid with higher lumens) (Medhurst et al., 2002; del Campo et al., 2014) was steadily reduced over time (outer tracheid with lower lumens), but still persisted ten years after thinning when at least 60% of tree density is harvested (M plot). On the other hand, when looking at tree transpiration, the most remarkable result was that the M plot showed the highest values (Table 2), in contrast to the results of del Campo et al. (2014) with those for the H plot. Dendrochronological measurements taken at the site during 2019 (results not published) indicate that the significant differences in basal area increment between the H and M plots disappear three years after thinning. Thus, these results also support that the highest understorey development observed in the H plot greatly affected tree-water relations, making trees from the H and M plots to have very similar sapwood areas despite their differences in forest structure.

4.2. *Short-term versus mid-term effects of thinning intensity and environmental conditions on green and blue water*

BRT models were used to clarify how the relevant factors driving SWC and transpiration change their relative importance (RI) when the time periods elapsed from thinning are at 2 years (t_1 period) and 10 years (t_{10} period) (this study). For the former, the RI of predictors did not substantially change between periods. Thinning, regardless of its intensity and timing, showed a slight effect on soil water dynamics on a daily scale (very similar to that of rainfall), while meteorological variables related to the water demand by atmosphere exercised great and persistent control (expressed as reference evapotranspiration). These results contradict findings that showed rainfall characteristics playing a significant role in SWC dynamics (Bachmair et al., 2012; del Campo et al., 2019; Molina et al., 2019), but also other studies indicating that the thinning effect was higher than the other factors studied (Bréda et al., 1995; del Campo et al., 2019). Despite this, it is important to note that thinning had a significant effect on SWC/FC at both time scales (Table 2) and that there were greater differences between the experimental plots in the short-term (mean differences of 24.0% and 9.3% in C and H plots in the short- and the mid-term, respectively). The BRT results for the transpiration variables may help understand these results. Water demand (meteorological conditions and thinning) is shown to clearly control transpiration in the short-term. However, when moving from the t_1- to t_{10}-period, the thinning impact becomes reduced, while there is an important shift in the role of SWC, with RI increases higher than 50% in all cases. Therefore, ten years after thinning the dependency of transpiration on SWC is clear. In fact, the greater homogenisation between the treated plots as observed in the PDP for stand transpiration (reducing the values when compared to the C plot) and the increased variability of tree transpiration during the t_{10} period (Fig. 6) indicate that more detailed information is required at the tree scale (soil characteristics, understorey and SWC) to deepen our understanding of vegetation-water interactions at the plot scale. We can thus affirm that the short-term benefits caused by thinning on transpiration diminish, and the local ecosystems dynamics observed in the experimental plots are playing the highest control by affecting soil water content ten years after the intervention. Therefore, addressing how the relationships between transpiration and SWC progressively change over time can be a systematic way to evaluate whether repeat thinning (ecohydrological turnover) or to adopt new silvicultural strategies depending on initial density reduction.

5. Conclusions

Our study focused on the mid-term effects of thinning intensity on vegetation-water relationships with a view to improving criteria for managing Mediterranean pine plantations. To the authorś knowledge, this type of information is lacking and the time elapsed from thinning together with the optimum tree density are not questions normally addressed when the impacts of silviculture on water cycle components are studied. When analysing the single impact of thinning intensity ten years after intervention, the most remarkable result was that the highest tree transpiration was observed in the moderate-thinned plot ($M > H > C > L$). The excessive tree opening in the high-thinned plot led to the highest ground cover and sapling density, thus greatly affecting tree water use and growth. In addition, the decreasing role of thinning intensity and the increase of that for soil water content highlight that short-term effects of thinning do not persist ten years after intervention (increasing role of soil water availability vs. decreasing role of water demand). Therefore, studying how transpiration-soil water relationships progressively change over time may be a systematic way to estimate the ecohydrological turnover at every thinning intensity tested, especially when reductions on tree transpiration are expected due to understorey competition. On the other hand, the results for the non-thinned plot, with better physiological performance than the low-thinned one, show that a strategy of non-intervention could be pertinent under proper environmental conditions (no tree mortality observed), while the low-thinning intervention would require intense forest management (ecohydrological turnover $<$ 10 years) to maintain a stable state. In any case, in a context characterized by increased aridity in semi-arid areas, time elapsed from thinning intervention should be further evaluated in different forest types in order to improve our understanding of thinning intensity impacts on forest-water relations, and thus providing useful information to forest managers.

CRediT authorship contribution statement

Antonio J. Molina: Conceptualization, Methodology, Investigation, Writing - original draft, Funding acquisition. **María González-Sanchis:** Writing - review & editing. **Carme Biel:** Writing - review & editing. **Antonio D. del Campo:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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