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The effects of experimental thinning on throughfall and stemflow: a contribution towards hydrology-oriented silviculture in Aleppo pine plantations

Antonio J. Molina[1, 2], Antonio D. del Campo[1, *]

[1] Research group in Forest Science and Technology (Re-ForeST), D.I.H.M.A.
E.T.S.I. Agronómica y del Medio Natural
Universitat Politècnica de València, Camí de Vera s/n, 46022 VALENCIA (SPAIN)
* Corresponding author: ancamga@dihma.upv.es
Phone: (+34) 963877966
Fax: (+34) 963877618
[2] Presently with the Surface Hydrology and Erosion group, Geosciences Department, Institute of Environmental assessment and Water Research (IDAEA), CSIC, Jordi Girona, 18-26, 08034 BARCELONA (SPAIN)

Abstract

Rainfall interception by the forest cover causes an important reduction in bulk rainfall in semiarid climates, such as the Mediterranean. Unmanaged, dense pine stands in this area are expected to have an important impact on water resources. This paper studies the effect of forest management on the partitioning of rainfall into throughfall and stemflow in an Aleppo pine plantation in eastern Spain. Three thinning-intensity treatments were compared with unmanaged stands that served as the control. The results revealed a very low throughfall in the control treatments during the study period of 55.9 %, whereas throughfall increased significantly after thinning to 83.8, 67.7 and 61.3 % of the bulk rainfall for high-, moderate- and low-intensity treatments, respectively. Total throughfall was negatively and linearly related to the tree density, forest cover, basal area and leaf area index. In contrast, weekly throughfall was modelled by considering these variables together with bulk rainfall in a multiple exponential expression; the weekly throughfall R^2 values (corrected Pearson coefficient) were above 0.9. These models would facilitate the implementation of hydrology-oriented silviculture via a more accurate prediction of the impacts of thinning on throughfall in this type of forest.

Keywords: *Pinus halepensis* Mill., forest management, rainfall partitioning, interception, hydrology

1. Introduction

Interception is one of the major components of the water cycle in forest ecosystems and has been the central topic of several studies and reviews in forest hydrology in recent decades (Bosch and Hewlett, 1982; Brown et al., 2005; Llorens and Domingo, 2007). Interception losses may account for, on average, 8 % to 60 % of bulk rainfall depending on the forest type and structure and on climatic conditions (David et al., 2011). In

Mediterranean climates, a mean interception value of approximately 20 % has been determined in an extensive review of the topic (Llorens and Domingo, 2007), although values of approximately 30 % were reported in the most semiarid conditions. In these drier areas, annual water consumption in forests can be nearly equal to the total annual rainfall (Schiller and Cohen, 1998), with transpiration leading interception in total forest evapotranspiration (David et al., 2011).

Special attention needs to be paid to the forest-water relationships in the Mediterranean due to the natural scarcity of water, on one hand, and the important values associated with forests in a region where physiographic, climatic, geological and historical land-use factors have caused soil erosion and degradation, on the other hand. In this context, Aleppo pine (*Pinus halepensis* Mill.) forests provide landscape quality, soil protection and hydrological cycle stabilisation over approximately 3.5×10^5 ha in the Mediterranean basin (Fady et al., 2003; Zavala et al., 2000), being one of the tree species best adapted to the most arid habitat in the region. The suitability of Aleppo pine trees to these climates has encouraged reforestation efforts utilising this species since the nineteenth century, accounting for approximately 5×10^5 ha of reforested land in Spain (Pemán García and Vadell Guiral, 2009). However, most of the Aleppo pine stands growing as part of these reforestation programmes suffer from a lack of management, which is a result of the absence of sufficient economic incentives from their conventional forest products. This management vacuum leads to high-density forest stands that can exacerbate rainfall interception losses and contribute to a substantial decrease of river flows in forested watersheds (Gallart and Llorens, 2003).

The balance between blue and green water (the total water in liquid state and the water used by vegetation in a particular ecosystem) in forest ecosystems is receiving increased attention as a consequence of expected changes in the global climate (Birot et al., 2011) and the subsequent mitigation/adaptation measures that need to be implemented (Ganatsios et al., 2010; Planisek et al., 2011). Studying the effects of vegetation management on the water cycle should, thus, become a priority for policy makers because adaptive forest management policies in Mediterranean ecosystems should have a strong hydrological foundation. Therefore, it is necessary to develop appropriate quantitative tools.

The quantification of hydrological processes in forests is an important component of studies aiming to increase water yields (Bosch and Hewlett, 1982; Stednick, 1996) because a reduction in forest cover increases water yield due to the subsequent reduction in evapotranspiration (Brooks et al., 2003; Hibbert, 1983; Zhang et al., 2001). This general rule, however, may have exceptions depending on the specific conditions of the forested watershed in question (Andreassian, 2004; Brooks et al., 2003; Cosandey et al., 2005; Lewis et al., 2000). Forests growing in dry areas have been considered less suitable for water-yield silviculture (Hibbert, 1985, in Brooks et al., 2003); with examples showing that the water increase is after used by residual trees and understory plants or easily evaporated from soil surface (Andreassian, 2004). However, there is a widely recognised need for an adaptive water-saving silviculture in these forests (Birot et al., 2011; Breda 2008). Several studies have been conducted at the stand level in the Mediterranean basin of Europe, although very few have focused on the effects of thinning on rainfall partitioning (Ganatsios et al., 2010; Limousin et al., 2008; Llorens and Domingo, 2007), with a specific lack of knowledge in *Pinus halepensis* Mill and in poorly managed plantations.

As an alternative to directly measuring the components of the water cycle and using empirical models based on these measurements, interception can be estimated from conceptual physically based models. The Rutter and Gash models, in both their original and improved versions, are the most widely used for the purpose of estimating interception (see the review by Muzylo et al., 2009). One of the main practical drawbacks of using these models is the lack of data with sufficient temporal definition and the need for a large number of parameters to apply the models. These limitations are even greater when the models are applied for practical purposes, such as those related to forest management.

Thus, two types of information are needed to develop and apply a hydrology-based silviculture aimed at the manipulation and quantification of the water cycle in forests. Additional studies at the stand scale (management unit) are required to clarify the hydrological behaviour of Mediterranean forest structures and their possible modification after vegetation treatments are applied (Ganatsios et al., 2010; Grünzweig et al., 2003, in Shachnovich et al., 2008). These studies should be applicable beyond their specific locations through the fitting of their empirically derived results with physical models and the consideration of easily measured forest structure variables and parameters.

The aim of this study is to investigate the relationships between rainfall partitioning into throughfall and stemflow and the management of a typical Mediterranean *Pinus halepensis* plantation with high tree density and low management input. This led us to establish the following objectives: a) to quantify the effects of forest thinning at different intensities on the partitioning of rainfall and b) to develop and contrast simple modelling tools for addressing rainfall partitioning as a function of forest management to facilitate the implementation of hydrology-based silviculture.

2. Materials and methods

2.1. The study site

The study area, *Monte de La Hunde y Palomeras* (39º 05' 30" N, 1º 12' 30" W), is located in the southwest of Valencia Province, Spain, at 950 m a.s.l. The climate is Mediterranean with a mean annual rainfall of 466 mm and a mean annual temperature of 13.7°C (1960-2007). The annual potential evapotranspiration is 749 mm. Soils have a high concentration of carbonate (26-38 %, pH 7.7-8.2), are approximately 50-60 cm deep and have a sandy-silty loam texture. The study site, like many Mediterranean areas in eastern Spain, is characterised by large areas of *Pinus halepensis* originating from the national reforestation program developed during the 1950s and 1960s. Presently, several of these forests are almost monospecific ecosystems with scant presence of other tree species either in forest gaps or as understory species (e.g., *Quercus ilex* sbsp. *ballota*).

2.2. Experimental design and thinning treatments

The experimental design was randomised and included 3 blocks with the same orientation (I, II and III) and area (0.36 ha) that were less than 200 m apart. All of the blocks were on a slope of less than 5 % and were laid out in a homogeneous Aleppo pine plantation established during the late 1940s. No significant evidence of silvicultural intervention has been observed since the 1940s, corroborated by the personnel at the nearby forest nursery. Each block was divided into four experimental plots with equal areas of 30 × 30 m. One plot in each block was not thinned (control, C) and the other plots were thinned at three different intensities: high (H), moderate (M) and low (L) (Figure 1). Thinning was conducted in February 2008 following two criteria: to eliminate the less developed trees and to achieve a relatively homogeneous tree distribution (based on forest cover) in the plots. Thinning was conducted and supervised by the province of Valencia’s publically owned forest service; timber and debris were removed and piled outside the plots.

Most of the trees from the moderately thinned plot (M) in Block I were felled by sustained 140 km/h winds of the January 2009 Klaus cyclone; this plot was not considered further.

2.3. Forest structure characterisation

Plots were inventoried in March 2009 to determine the following forest structure variables: Leaf Area Index (LAI, $m^2\ m^{-2}$), forest cover (FC, %), basal area (BA, $m^2\ ha^{-1}$) and tree density (D, trees per ha) (Table 1). All measurements were made within areas at least 2 m away from the plot limits to avoid edge effects.

LAI was estimated with a LAI-2000 sensor (Li-Cor, 1991) that recorded 6 “B” type measurements per plot along 2 perpendicular axes, 3 per axis. 4 “A” type measurements were made in nearby clearings, 2 for each axis. Readings were taken under direct solar radiation (Molina and Del Campo, 2011) with a 270^o view cap and with the sensor always shaded to avoid light dispersions affecting sensor readings (Li-Cor, 1991). LAI estimation was performed by taking into account only the fourth ring by means of C-2000 software, following the protocols of Leblanc and Chen (2001). Forest cover was measured in all of the plots with a vertical densitometer (GRS, USA) with 50 readings per plot in a 4 × 4 m grid. Basal area and tree density were estimated by measuring tree diameters and counting all trees in the plots (Molina and Del Campo, 2011).

2.4. Rainfall and rainfall partitioning

Bulk rainfall (R) was measured in an open area 150 m away from the experimental plots by means of a tipping-bucket rain gauge (Davis, USA) programmed to measure at 1-minute intervals. Throughfall was measured at 6- to 12-day intervals (considered as “weekly” periods in further analyses) from April 2008 to June 2008 (4 weekly intervals) and from March 2009 to February 2010 (14 weekly intervals).12 throughfall devices per treatment (4 per block) were systematically arranged along both diagonals of the square plot and maintained in the same positions throughout the study. The devices used were PVC gutters 400 cm long × 13.17 cm wide, set at 50 cm above the soil and sloping at 5º towards a 25-L plastic container, providing a total collecting area per treatment of 6.3 m^2, considered to be a suitable area to obtain an estimate of the mean with a 95 % probability (Rodrigo and Avila, 2001).

Stemflow was also measured at 6- to 12-day intervals from March 2009 to September 2010. In this case, we decided to keep measuring until September 2010 in order to study stemflow in the treatments during a period with similar accumulated rainfall than that of throughfall. Thus, interception was assessed from March 2009 to February 2010. In each treatment (Block I; Block II for the moderate-intensity treatment), 4 diameter classes were defined after thinning, and a representative sample tree with a diameter close to mean was selected for each (n = 4, N = 16). The bark on each sample tree was scraped off to smooth the surface in preparation for the fitting of a plastic collar with silicon at a height of 1.3 m. After the plastic collars were attached, plastic tubes were inserted into small holes located in the lowest part of the collars to collect the water in 15-L containers. Extrapolation to the entire treatment (mm) was conducted according to the tree density for each treatment.

2.5. Statistical analysis

Differences in the accumulated values of throughfall and stemflow among the treatments were analysed with ANOVA (Steel and Torrie, 1988) with treatment and block considered as fixed factors (no block in the case of stemflow) and the throughfall data or stemflow data as dependent variables. In every case, the data were examined to ensure normality using the Kolmogorov-Smirnoff test and the homogeneity of variance using the Levene test. When these assumptions were violated, the variables were transformed with power functions to achieve homoscedasticity. When ANOVA indicated significant differences between treatments, the Tukey post-hoc test was selected for the comparison of multiple means.

Differences in mean weekly values of throughfall and stemflow (n =18 and 25, respectively) among treatments were tested by ANOVA or by the Kruskal–Wallis test based on the chi-squared statistic when ANOVA assumptions were violated. Tamhane's T2 test was used to compare multiple means for the Kruskal–Wallis results.

Relationships between throughfall (dependent) and forest structure (independent) were investigated through linear and exponential regression models. In the first case, simple models were used (with forest structure as the single independent variable), whereas in the second case, bulk rainfall was added as an independent variable (a multiple regression of two independent variables) to achieve a greater fit. In all of the models, the residuals were examined for normality and independence (Steel and Torrie, 1988). A significance level of $P \leq 0.05$ was used for all analyses. Data were analysed with SPSS© 16.0.

3. Results

3.1. Rainfall partitioning in the different treatments

The bulk rainfall during the 18 weekly intervals of throughfall measurements was 310.4 mm whereas it reached a total of 340 mm during the 25 intervals of stemflow. The average depth of gross rainfall per weekly period during throughfall measurements was 18.2 mm (±11.4), with a maximum of 46 mm and a minimum of 1 mm. In the case of stemflow, the average was 13.4 mm (±8.2), with maximum and minimum values of 36.8 and 0.4 mm respectively.

Thinning had a clear effect on the rainfall partitioning in the stands studied here. The total accumulated values of throughfall increased gradually with thinning intensity (Table 2). The control treatment was found to be significantly different from both the high- and moderate-intensity treatments and exhibited higher throughfall values of 28 % and 12 %, respectively. In contrast, the low-intensity treatment was not significantly different from the control, indicating that a mean reduction in basal area of 9.3 m^2 ha^{-1} (0.76 m^{-2} m^{-2} in terms of LAI; Table 1) was insufficient to increase the rainfall reaching the soil surface via throughfall. The differences between the moderate- and low-intensity thinning treatments were not significant (Table 2). In the case of the total accumulated values for stemflow, the most remarkable result was the relatively low value found in comparison to throughfall (Table 2). In contrast to throughfall, there was a progressive increase of stemflow with tree density, accounting for a mean difference of 1.4 %, or 4.7 mm, between the unmanaged forest and the high-intensity thinning treatment. Subsequent statistical analyses identified all of the thinning treatments as being different from the control.

The throughfall differences among the treatments during each of the different weekly periods paralleled the pattern described for the accumulated values during the entire study period, with the ranking H>L>M>C maintained in most of the cases (Figure 2). The throughfall in the high-intensity treatment (H) was found to be the highest in all the periods analysed. In contrast, control treatments had the lowest values in most of the periods, except for 2 weekly periods when values in the low-intensity thinning treatment (L) were slightly lower. In 15 out of the 18 weekly periods, throughfall values were found to be different between the control and the high-intensity thinning treatments. In contrast, control and low-intensity thinning treatments were not found to be different during any weekly period, indicating that specific rainfall characteristics and environmental conditions did not allow this treatment to be differentiated. The throughfall in the control treatment was significantly lower than in the moderate-intensity treatment in 5 of the weekly periods. In summary, the means of the C, L, M and H treatments, with their corresponding standard deviations, expressed as percents of bulk rainfall, were 56.0 ± 16.7 %, 61.5 ± 19 %, 69.8 ± 18.01 % and 86.2 ± 18.5 %, respectively. The significant differences between the control and the thinning intensity treatments for stemflow measured during the weekly periods were related to thinning intensity (Figure 3). The control and the high-intensity thinning treatments were found to be different in 10 out of the 25 weekly periods, whereas moderate- and low-intensity thinning treatments were differentiated in 9 and 6 weekly periods, respectively. In summary, all of the thinned treatment values were different than the control values during 5 weekly periods.

Finally, the means and the standard deviation values of interception during the 14 weekly periods in 2009 (bulk rainfall = 179 mm) were 47.4 ± 13.9 % for the control and decreased with increasing intensity of thinning to 37.4 ±13.8 %, 40.6 ± 13.2 % and 16.8 ± 12.9 % for L, M and H, respectively.

3.2. Throughfall as a function of forest structure and bulk rainfall

Linear regressions between the data for accumulated throughfall (%) for the entire study period in the plots and the four forest-structure variables considered (Leaf Area Index, LAI; forest cover, FC; tree density, D; and basal area, BA) were significant ($p<0.001$) in all cases. The basal area was found to be the best variable to explain throughfall, with a total explained variance of 79 % and a standard error of 5.53 %. The other variables had R values of between 76 and 62 % (Figure 4).

Linear regressions between the weekly values of throughfall (% of bulk rainfall) and the forest structural variables were statistically significant. These regressions maintained very similar slopes and intercept values to those observed in the throughfall for the entire study period for all the forest-structure variables considered. However, these expressions were determined not to be suitable to estimate weekly throughfall values because of their more unexplained variation (R^2 values between 25 % and 20 % and standard errors > 14 % in all cases). We also examined throughfall depth (mm) for this time scale. First, we observed that the relationship between throughfall and bulk rainfall (mm) was significantly linear in all the treatments (explained variation from 87 to 94 %), with most of the linear regressions differing from one another except for the control and the low-intensity treatments, in which intercepts and slope were not significantly different. Second, after testing different mathematical forms, we found that the function that achieved the best fit in all cases was an exponential expression in the form of $T=R*e^{aX}$, where T is the value of weekly throughfall (mm), R is the bulk rainfall (mm), a is the exponential decay constant (negative) and X is the value of the considered forest-structure variable. Table 3 depicts the a value adjusted for the different forest-structure variables considered. LAI, FC and BA had very similar results with negligible differences in the root mean square error (RMSE). The tree density was not suitable for predicting throughfall as a result of the near-zero value in the exponential decay constant. Figure 5 provides a comparison between modelled and measured throughfall values for FC (chosen because it had the best results in terms of error estimate), with a close fit to the 1:1 line and a relatively low RMSE. The total cumulative FC values (11 experimental plots for 18 weekly periods) observed and modelled for weekly throughfall were 2,428.2 and 2,564.1 mm, respectively, indicating a general overestimation of 5.6 %.

4. Discussion

This work examined the effect of differential thinning intensities on rainfall interception in a dense, growth-depressed stand of *Pinus halepensis*.

The results reveal high interception losses in the untreated control plots, accounting for approximately 43 % of the bulk rainfall. This interception value is in the upper range presented in the review by Llorens and Domingo (2007) for Mediterranean conditions in Europe and higher than when their results are filtered by applying certain quality criteria (such as minimum total collection area for a good estimate of throughfall). In contrast, the value presented in this study (1.5 %) for stemflow is close to the mean for Mediterranean conifer stands (1.74 %) found in the review by Llorens and Domingo (2007). The principal characteristic of our control plots is reduced throughfall when compared to either the mean for Mediterranean conifers (77 %) or with previous values reported for this species (Llorens and Domingo, 2007; Shachnovich et al., 2008). Rainfall interception by forests is a well-known and documented process that depends on several factors related to the forest structure and climate (Crockford and Richardson, 2000). The minimal management of forests in reforested Aleppo pine stands is typical as a result of their lack of profitability and because of protection objectives, which have resulted in tree growth slowdown and stand stagnation (Montero et al., 2001). Minimal forest management has resulted in a simple tree structure where excessive competition does not allow for other vegetation strata and results in an excessive tree density, leading to a reduced and degraded hydrological performance. Aleppo pine density in 50-60-year-old reforested stands depends on site quality; however, it is expected to be in the range of 736-653 trees ha^{-1} for site quality Q14 (Montero et al., 2001), values that represent approximately 55% of the density found in our control plots (1,289 ± 174 tree ha^{-1}). This may be the case in many plantations established in the Mediterranean areas of Spain during the second half of the last century. This structure may have a direct impact on the canopy storage capacity of water, with a value of 3.6 ± 2.3 mm for our unmanaged control treatments (estimated using the method of Rutter, 1963). This high storage value is probably caused by the low leaf/wood ratio in the control stand (Llorens and Gallart, 2000), another consequence of an excessive competition among individual trees. Other studies on rainfall partitioning in *Pinus halepensis* at the stand scale reported a lower interception value and lower stand densities, i.e., 360-660 trees ha^{-1} (Rapp and Romane, 1968, in Llorens and Domingo, 2007; Shachnovich et al., 2008). Thus, minimal management could be part of the explanation for our low throughfall results, indicating that these stands are capable of holding high amounts of rainfall once saturating rainfall ends. Climate may also be a determinant factor in our results, as the mean annual potential evapotranspiration (749 mm, Thornthwaite) and reference evapotranspiration (1,200 mm, Hargreaves) values for the site (Pérez-Cueva, 1994) are considerable and in the higher range of previously reported values (Llorens and Domingo, 2007). This implies that evaporation, either during or after rainfall, plays a very important role in the hydrologic cycle of our unmanaged stands, which is an important factor in semiarid climates (Dunkerley, 2000; Llorens et al., 1997).

Forest management can be an important tool to modify the forest water cycle (Bosch and Hewlett, 1982; Stednick, 1996). In the present study, thinning treatments caused throughfall to increase and stemflow to decrease for the entire period of the study and for most of the weekly periods considered. These results support the hypothesis that thinning reduces interception in the short term (see Aboal et al., 2000 for a review of studies), although the opposite trend has also been found in *Pinus canariensis* forests because of increased fog entrapment (Aboal et al., 2000). However, the differences found in our work stand out in their magnitude with respect to the control. Thus, considering the moderate-intensity treatment (the removal of 41 % of the basal area, an amount in the range of that found in other studies), throughfall has been enhanced to 12 % of the bulk rainfall, which is higher than the increases achieved in other studies

(Aussenac and Granier, 1988; Breda et al., 1995; Crockford and Richardson, 1990; Ganatsios et al., 2010; Limousin et al., 2008; Teklehaimanot et al., 1991), who reported increases of generally less than 10% after the removal of 50% of the basal area. Therefore, a reduction of forest structure in a dense forest could produce a greater effect than a comparable reduction in a less dense stand. However, the absence of significant differences found between low-intensity treatments and the control indicates that a minor silvicultural intervention (in our case, a reduction of 26.2 % in basal area) is not enough to increase the water reaching the soil surface via throughfall. This implies that there is an optimum value of forest structure reduction of between 41 and 26.2 % of basal area (from moderate- to low-intensity treatments) to attain a significant increase in throughfall.

The lack of appreciable differences in throughfall found between the control and the low-intensity treatments may be the result of the increase in the ventilation of the residual trees and the higher evaporation rates during rainfall (Teklehaimanot et al., 1991). Thus, the reduction of the storage capacity of the control stand through low-intensity thinning does not appear to be enough to compensate for the increase in the evaporation rate when trees grow farther apart (Dunkerley, 2000). However, a drastic reduction in basal area (77% in our high-intensity thinned plots), which frequently occurs in forest-fire preventive silviculture or shelterwood systems, would enhance throughfall to 25-30% of the bulk rainfall.

In the case of stemflow, results for the entire study period indicate that stemflow in the control was different than in the treatments. This means that even the lowest reduction of forest biomass (from control to low-intensity treatment) reduced this water cycle component during the entire study period. The results at the tree level (this variable was scaled up according to the plot density) showed higher stemflow volume per tree in the control treatment as well (60 to 40% higher according to thinning intensity, data not shown). Because all of the trees belong to the same initial population, this difference could arise from differences in the evaporation rate rather than in tree structure. A number of tree structure parameters (tree crown projected surface, tree volume, competition index, height, etc.) were not significantly correlated with stemflow (not shown), supporting the hypothesis that more closely spaced trees evaporate less water than identical trees that are farther apart (Dunkerley, 2000). The study by Dunkerley (2000) proposes that a higher canopy roughness is expected in the wetted surfaces of the thinned trees in response to an improved efficiency of water vapour transfer from the wet vegetation to the atmosphere. This effect can be important in dryland plant communities and reinforce the abovementioned effect of canopy evaporation in the context of our experiment.

Previous attempts to relate interception and/or throughfall to forest structure have mainly focused on the canopy storage capacity as a key variable, and most rainfall partitioning models take this variable into account together with climate (approaches of Gash and Rutter, see the review by Muzylo et al., 2009). However, despite the profound hydrological implication of this variable, it is of limited applicability for a forest technician wanting to manage and implement hydrology-based silviculture. In addition, the requirement of complementary instrumentation to estimate the evaporation ratio during the rainfall events (largely based on the Penman equation) makes typical hydrological models difficult to implement in practice, although several of them have been satisfactorily tested under Mediterranean conditions (Limousin et al., 2008; Llorens, 1997). Therefore, the use of stand-structure variables, common in forest inventories, would be much more familiar to a forester (Gash et al., 1995; van Dijk and Bruinzeeel, 2001). In our case, the good fit found between the throughfall and certain typical forest structure variables has led to simple linear equations for the entire study period. These simple equations would be suitable for predicting the possible effects of thinning in reforested Aleppo pine stands under similar climatic conditions. These simple models are not, however, suitable when a more detailed temporal analysis is to be taken into account because a decrease in the temporal scale involves high variability. Consequently, additional factors should be considered to explain the hydrological processes in these cases (Llorens et al., 1997). The exponential models incorporating both the influence of bulk rainfall and one of the variables of forest structure have been developed in this study for predicting the effect of thinning on the throughfall process. These models are very close in form to the model proposed by Misson (2004) for the estimate of direct throughfall based on the Gash model for disperse vegetation (Gash et al., 1995). Thus, our empirical models are similar to more physical models, thereby giving them additional support in addition to their goodness of fit and low measured error. From the point of view of forest management, these models are easy to use (involving the measurement of a certain forest stand variable such as FC, LAI or G). Consequently, the hydrological effects of silvicultural interventions can be easily studied.

5. Conclusions

Excessive water loss via the process of interception has been identified in the unmanaged pine plantation studied as a result of both a high tree density and the severity of the semiarid climate in the region.

In the global and regional scope of climate change predictions, these stands should be managed to reduce their density and to increase throughfall, thereby facilitating a balance between green and blue water. However, forest management should be conducted in consideration of other site limitations such as slope, soil type and extreme rain events. This work provides useful information for foresters in charge of such forest management. With the results and empirical models obtained in this study, these foresters can judge the level of intervention needed and quantify its impact on throughfall. No similar tool was previously available for foresters intending to apply an adaptive approach to silviculture in *Pinus halepensis* plantations in the Mediterranean. Our results represent the first effort to develop a hydrology-based silviculture in this type of forest. Complementary studies are needed to validate our models in other *Pinus halepensis* plantations. In addition, other studies considering the impact of other important water cycle elements (soil water variation, transpiration, etc.) are also needed to address the impact on the whole water cycle and to improve the implementation of hydrology-oriented silviculture in conjunction with fire-preventive silviculture. Also, the temporal duration of the efficiency of these intervention methods remains to be resolved (Aussenac and Granier, 1988).

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Table headings:

Table 1. The means ± standard deviations for the forest-structure variables in the treatments (from Molina and del Campo, 2011). LAI = Leaf Area Index, FC = Forest Cover, BA = Basal Area, D = Tree Density. Letters indicate significant differences at p-level<0.5.

Table 2. The cumulative values (with standard deviations) of throughfall and stemflow expressed as depth (mm) and the percentage of bulk rainfall (%) in the different treatments. Letters indicate the results of the post-hoc analysis at p-level ≤0.05.

Table 3. The parameters of the generic throughfall (T) regression T=R*e^ (a*X) for the different forest-structure variables (X): LAI = Leaf Area Index, FC = Forest Cover, BA = Basal Area. Tree Density (D) was not considered because its exponential decay parameter "a" was found to be null. R is the corrected Pearson coefficient, and RMSE is the root mean squared error.

Figure captions:

Figure 1: a) control, b) thinning intervention c) high-intensity thinning treatment depicting the throughfall devices.

Figure 2. The means and standard deviations of weekly throughfall in the treatments together with the bulk rainfall (mm). Asterisks indicate a significant difference in the ANOVA test: * = p≤ 0.05, ** = p≤ 0.01, *** = p≤ 0.001. Numbers summarise the homogeneous groups from the post-hoc tests: 1: C(a) H(b) M(b) L(a); 2: C(a) H(b) M(bc) L(ac); 3: C(a) H(b) M(c) L(ac); 4: C(a) H(b) M(a) L(a); 5: C(a) H(b) M(ab) L(a). C: control, L: low-intensity treatment, M: moderate-intensity treatment and H: high-intensity treatment.

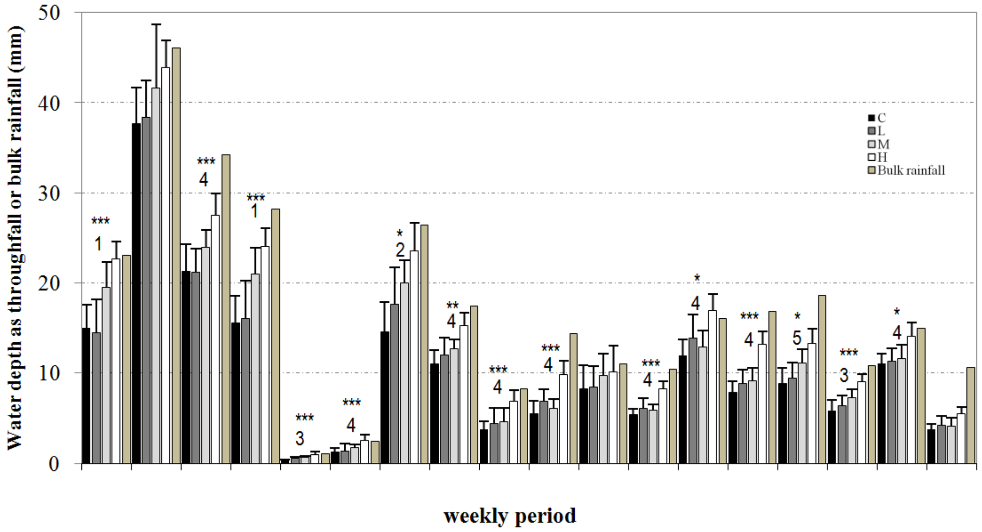
Figure 3. The accumulated values of weekly stemflow (mm) in the treatments. C: control, L: low-intensity treatment, M: moderate-intensity treatment and H: high-intensity treatment.

Figure 4. Linear regressions between throughfall (%) and the four forest-structure variables (LAI, FC, D and BA) for the accumulated values of throughfall. All regressions were statistically significant (p<0.001).

Figure 5. Plots of modelled (Y axis) versus measured (X axis) throughfall with independent variables of bulk rainfall and forest cover. Also presented is the 1:1 line.

Figure

Figure


Water depth as throughfall or bulk rainfall (mm)
50
40
30
20
10
0
weekly period
C
L
M
H
Bulk rainfall
***
1
***
4
***
1
***
3
***
4
*
2
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4
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4
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4
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4
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4
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4
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3
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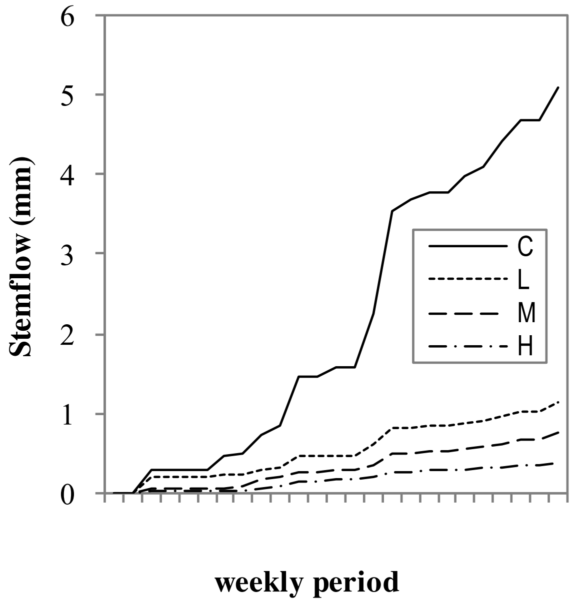
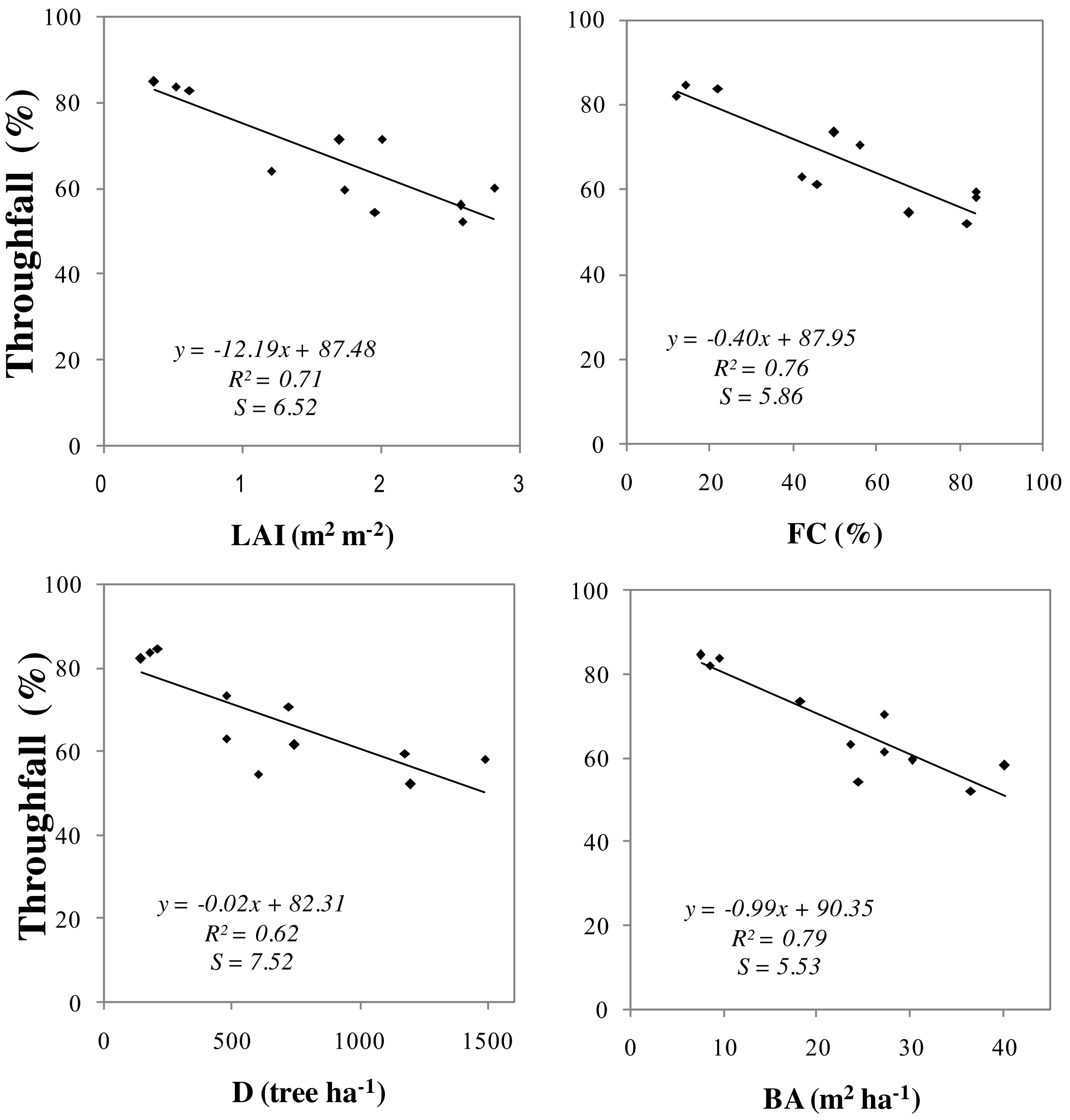
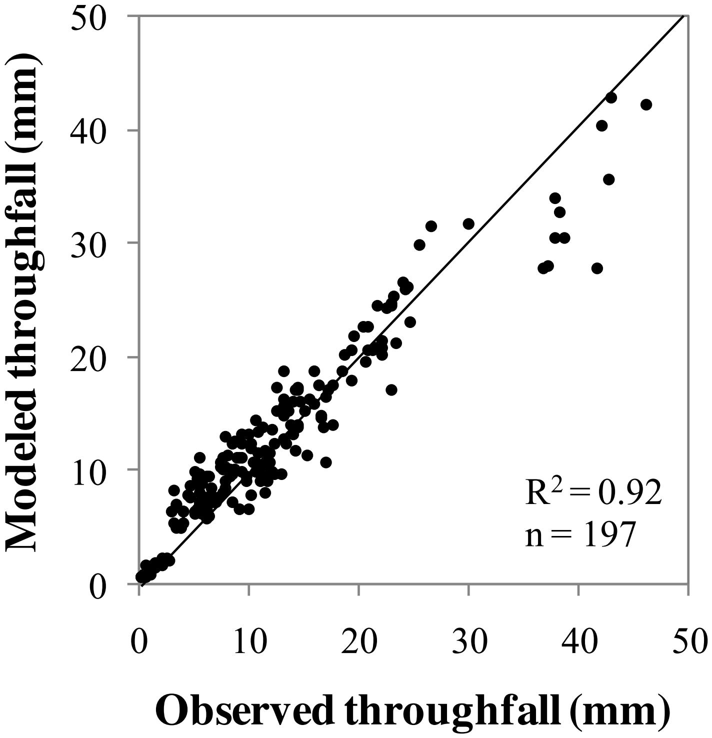
Figure



Figure


Throughfall (%)
100
80
60
40
20
0
0
1
2
3
LAI (m² m⁻²)
y = -12.19x + 87.48
R² = 0.71
S = 6.52
100
80
60
40
20
0
0
20
40
60
80
100
FC (%)
y = -0.40x + 87.95
R² = 0.76
S = 5.86
Throughfall (%)
100
80
60
40
20
0
0
500
1000
1500
D (tree ha⁻¹)
y = -0.02x + 82.31
R² = 0.62
S = 7.52
100
80
60
40
20
0
0
10
20
30
40
BA (m² ha⁻¹)
y = -0.99x + 90.35
R² = 0.79
S = 5.53

Figure


50
40
30
20
10
0
Modeled throughfall (mm)
R² = 0.92
n = 197
0
10
20
30
40
50
Observed throughfall (mm)

Table

Treatment	**LAI (m^2 m^{-2})**	**FC (%)**	**BA (m^2 ha^{-1})**	**D (trees ha^{-1})**
Control (C)	2.6±0.1a	83.3±1.1a	35.6±5.1a	1289±173.6a
Low (L)	1.9 ± 0.1b	64 ± 6.9b	26.3±1.6b	688.7± 77.6b
Moderate (M)	1.5 ± 0.3b	46 ± 5.6b	20.9±3.8b	478±15b
High (H)	0.5 ± 0.1c	16 ± 5.3c	8.3 ± 1.0c	177.7±33.5c

Table

	Throughfall		**Stemflow**	
Treatment	**mm**	**%**	**mm**	**%**
Control (C)	173.4 (21.9)a	55.9 (7.0)a	5.04(1.3)a	1.5(0.3)a
Low (L)	190.1(30.0)ab	61.3(9.7)ab	0.98(0.3)b	0.30(0.1)b
Moderate (M)	210.3(18.7)b	67.7(6.0)b	0.66(0.3)b	0.21(0.1)b
High (H)	260.1(15.7)c	83.8(5.1)c	0.34(0.05)b	0.10(0.01)b

Table

Forest structure variable (X)	**a**	**R^2**	**RMSE**
LAI	-0.179	0.91	1.58
FC	-0.006	0.91	1.52
BA	-0.013	0.91	1.54