The influence of thinning on rainfall interception by Pinus pinea L. in Mediterranean coastal stands (Castel Fusano–Rome)

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ORIGINAL PAPER

The influence of thinning on rainfall interception by *Pinus pinea* L. in Mediterranean coastal stands (Castel Fusano—Rome)

Gianluigi Mazza · Emilio Amorini · Andrea Cutini · Maria Chiara Manetti

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Abstract
• ***Context*** This research was conducted in a 62-year-old stone pine (*Pinus pinea* L.) forest within the National Natural Reserve of the Roman Coast, Italy. Net under-canopy precipitation was measured between September 2004 and December 2008 in a unthinned and a thinned area of about 1 ha each.
• ***Aims*** The goals were to document and compare net under-canopy rainfall (throughfall and stemflow) in thinned and unthinned stands, and evaluate how the re-growth of tree crowns following thinning influences canopy interception.
• ***Methods*** Thinning was carried out during the winter of 2002 and reduced the number of trees by 56% and leaf area index (LAI) by 63%. Rainfall, throughfall, and stemflow were measured and analysed.
• ***Results*** Interception loss averaged 23% and 40% in the thinned and unthinned areas respectively, but difference decreased during larger rainfall events. Net under-canopy precipitation was always higher ($P<0.001$) in the thinned area, and showed a significant ($P=0.041$) relationship with LAI. Stemflow was very low.
• ***Conclusion*** These results highlight the positive effect of thinning, which reduces water loss from precipitation caused by interception of rainfall in Mediterranean forests that have never been thinned. Thinning guarantees a greater flow of water under the canopy, particularly in the driest months and for lower amounts of rainfall, and improves stand growth rates.

Keywords Thinning · Rainfall interception · Throughfall · Mediterranean pinewood · Stone pine

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Contribution of the co-authors All authors contributed equally to this research

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1 Introduction

The importance of the amount of precipitation reaching the soil, and the recognition of its role as the main input of water to a forest stand has been highlighted and reported by many studies in several countries, for different species, and at various sites and in a variety of stand structures (Crockford and Richardson 2000; Iovino et al. 2009; Llorens and Domingo 2007). Rainfall interception by vegetation canopies affects precipitation inputs. Canopy interception represents the volume of water lost by evaporation from the wet canopy during rainfall as well as afterwards (Crockford and Richardson 2000; Dunkerley 2000; Llorens et al. 1997). Interception loss can be estimated by measuring the difference between gross rainfall and the sum of throughfall and stemflow (Aussenac 1968; Cape et al. 1991; Loustau et al. 1992; Rutter 1975). The amount of canopy interception, throughfall and stemflow depends on the characteristics of precipitation and the structure of the vegetation, such as tree species composition, stand age and density, horizontal and vertical structure, canopy cover, crown architecture and phenology.

Several models have been developed to estimate interception loss and canopy water balance to improve the agreement between simulated and measured interception loss, which has important implications for water resource management (Gash and Morton 1978; Calder 1986; Hall 2003; Lankreijer et al. 1993; Whitehead and Kelliher 1991). However, verification of the models used to estimate any significant changes in interception loss under climate change in different forests and locations still requires additional parameters to create more realistic simulations.

Other studies have shown high rates of interception loss for low volume rainfall events and low rainfall intensity in dry atmospheric conditions (Callegari et al. 2001; Llorens et al. 1997). The effects of structural characteristics on canopy interception have been investigated widely by thinning experiments (Llorens and Domingo 2007), which show an increase in the proportion of water reaching the soil after thinning (Aussenac and Granier 1988; Iovino et al. 2001; Simonin et al. 2007; Stogsdill et al. 1989). Few researchers have studied stone pine (*Pinus pinea* L.) pinewoods even though the species is distributed widely in coastal environments of the Mediterranean basin. Climatic scenarios based on the Global Circulation Model (GCM) and particularly local regional models predict a decrease in the annual precipitation amount (5% per century) and a trend towards drier conditions (Brunetti et al. 2006; Cubasch et al. 1996; Dunkeloh and Jacobeit 2003; Gibelin and Déqué 2002; IPCC 2001; IPCC, WG I 2007). Longer and more severe dry seasons and associated water shortages could seriously affect tree growth and reduce the net primary productivity of stands, and could modify transpiration efficiency (Osborne et al. 2000).

Stone pine is one of the most important Mediterranean pine species characteristic of the Italian coastline; it has been cultivated traditionally for the production of both wood and pine nuts, and in the last few decades has acquired a high ecological, recreational and landscape value. In most cases, stone pine stands have not had regular silvicultural management and have become densely overgrown with a notable accumulation of deadwood, making them highly susceptibility to fire. Despite the lack of past thinning, even if thinning is carried out later rather than at the right time, thinning can lead to better formation of individual stems and crowns. Also, silvicultural treatments can guarantee a greater flow of under-canopy water and reduce the competition for water, light and nutrients, encouraging growth in residual trees and improving stand stability (Cutini et al. 2002; Martín-Benito et al. 2010; Stogsdill et al. 1989).

Our goal is to improve our knowledge of the relationships between stand density and net under-canopy precipitation following late and heavy thinning, and evaluate whether silvicultural practices play a positive role in water availability within planted pinewoods of stone pine. The aim of this study was to: (1) quantify and compare the amount and the trend of net under-canopy rainfall (throughfall and stemflow) in thinned and unthinned stands; (2) assess the relationship between net under-canopy precipitation and event magnitude; and (3) evaluate how the regrowth of tree crowns following thinning influences canopy interception.

2 Materials and methods

2.1 Stand characteristics and climate conditions

The study area is located in the Castel Fusano pinewood, inside the National Natural Reserve of the Roman Coast, 20 km southwest of Rome, Italy (41°43′N; 12°19′E), at about 14 m above sea level and with a south-westerly aspect. This stone pine pinewood covers about 1,100 ha creating a wide, dominant crop layer. Holm oak (*Quercus ilex* L.) and other typical broadleaf maquis shrubs (*Phillirea sp*., *Pistacia lentiscus* L., *Arbutus unedo* L., *Rhamnus alaternus* L.) dominate the subcanopy.

Research was carried out within a 62-year-old pine forest, created by seeding, in two areas of about 1 ha each, separated by wire fencing and with a mean height and crown depth of about 18 m and 6.7 m, respectively. Only one area was thinned in the winter of 2002, reducing the number of trees by 56% to balance crown morphology and to improve the stand structural diversity and resilience, favouring the growth of the maquis shrubs and Holm oak.

Structural measurements were recorded after thinning, in April 2003 and later in February 2008. The measurements of crown projection to estimate canopy cover were carried out within two subplots (80×20 m) located in each area, with the goal of evaluating the tree growth redistribution, stand structure regulation and stability improvement after five growing seasons.

Two properties of plant communities were also analysed, (1) leaf area index and (2) growth efficiency (GE), expressed in grams of biomass produced and in cubic metres of wood per square metre of projected leaf surface area (Waring 1983) to estimate forest growth after thinning. Leaf area index (LAI) was measured monthly during the growing season from 2003 to 2008 with two LAI 2000 Plant Canopy Analyzers (PCA, Li-Cor, Lincoln, NE) using fixed points based on a defined sampling procedure (Cutini et al. 1998). The GE has been evaluated using the stem volume and the total epigeous biomass estimated using the allometric equations for this pinewood (Cutini et al. 2009).

Fifty years of meteorological data, registered by the Meteorological Station Roma Collegio Romano (U.C.E.A.—41°53′54″N and 12°28′46″E) was collected and analysed to define the climatic characteristics of the study site. The climatic analysis showed a typically Mediterranean trend, with a total annual rainfall of 700 mm and an average annual temperature of 16.5°C. Most rainfall was concentrated in late autumn and the 3-month dry period extending from June to August with July being the driest month (Fig. 1).

2.2 Data collection and experimental design

The effects of thinning were studied in relationship to canopy rainfall interception in pine stands by measuring the net under-canopy precipitation (throughfall and stemflow) during four consecutive years (September 2004–December 2008) and by monitoring 129 rainfall events, ranging from 1 to 82 mm. Measurements were recorded after each storm by staff of the Centro di Educazione Ambientale (CEA; Centre for Environmental Education) located within the Reserve.

Rainfall amounts outside the pine stands were collected using three fixed 33.5-cm diameter plastic gauges connected to funnels mounted 1 m above the ground. These collectors were placed in the nearest pinewood clearing, about 800 m from the study areas and were at least twice the height of the nearest trees at the pinewood edge.

Throughfall was collected by 25 of the same type of rain gauges used to measure rainfall: 15 gauges in the thinned area and 10 in the unthinned area. These gauges were spaced evenly in the two areas and positioned at fixed locations throughout the study period, and were at least 1 m from tree stems and at the vertices of a regular grid 20 × 25 m (Fig. 2). This placement was designed because of the homogeneity of canopy cover (LAI estimates) and so the measurements of throughfall of each collector were not influenced by nearby collectors. Also the gauges were placed in both open spaces and beneath tree canopies to capture both the rainfall component that reached the ground directly through canopy gaps and from water dripping from tree crowns. Gauges were also placed at least 15 m from the edges of the area to avoid outside influences. The total collecting surface of throughfall was 1.32 m^2 in the thinned area and 0.88 m^2 in the unthinned area. Data for each gauge were recorded separately and expressed as millimetres of precipitation.

Stemflow was collected from six representative trees in each area using lead strips moulded into U-shaped troughs and twisted into a spiral around each trunk to catch the stemflow, which was then channelled into individual containers. Similar devices have been used in most reported studies of stemflow (Aussenac 1968; Crockford and Richardson 2000; Loustau et al. 1992; Scarascia Mugnozza et al. 1988). Stemflow amounts were calculated as millimetres of precipitation from the volume collected and the number of trees per hectare in each of the two areas.

2.3 Statistical analysis

The data collected were analysed statistically to study the influence of thinning on the rainfall redistribution process

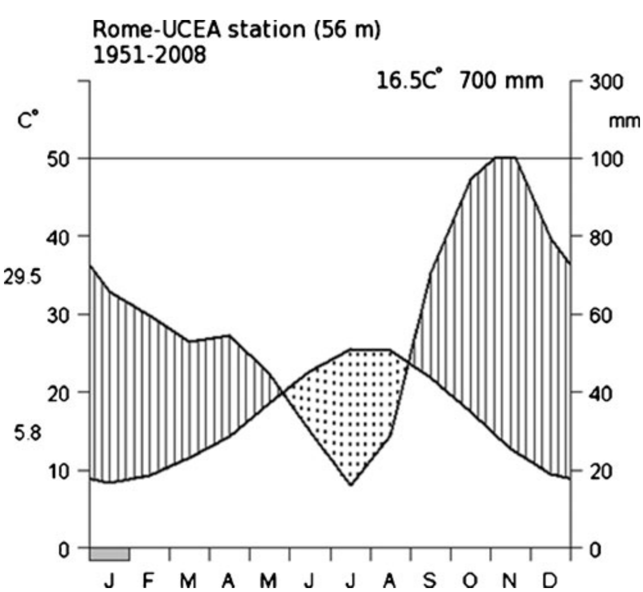

Fig. 1 Plot of the Walter and Lieth climatic diagram of the Meteorological Station Roma Collegio Romano (U.C.E.A.)—41°53″ 54″N , 12°28′46″E. The *dotted area* indicates the season with water deficit

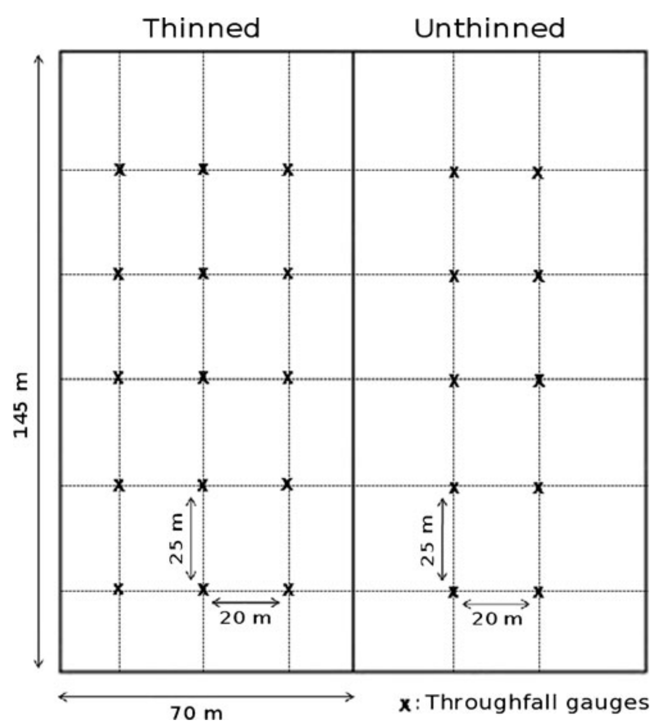

Fig. 2 Spatial distribution of the throughfall gauges in the two areas

within the two areas. The spatial independence of the throughfall measurements was computed evaluating their spatial autocorrelation for five representative storms in each area.

The canopy interception of rainfall and the net under-canopy precipitation in the thinned plot were compared to those of the unthinned plot. The Wilcoxon-Mann-Whitney (W) non-parametric test for independent samples was used, because the data samples were not distributed normally. The test was applied on two different temporal scales: event scale (each rainfall event) and monthly scale, to account for the accumulated monthly rainfall. A comparison between gross rainfall and net under-canopy precipitation in both the thinned and unthinned areas was also made using the analysis of variance (ANOVA) and the Tukey HSD test for multiple comparisons of averages, applied to the individual rainfall events and transformed into logarithms to satisfy the conditions of a normal distribution.

All the storms were grouped into three classes of precipitation to assess possible correlations between the canopy interception of the tree crowns in the two areas and the amount of rainfall (expressed in mm): Class I, rain showers ≤10.00 mm; Class II, rainfall from 11.00 – 20.00 mm; and Class III, rain showers >20.00 mm. The relationships between these classes of gross rainfall (independent variable) and the differences of the net under-canopy precipitation in the two areas, were analysed using the Kendall tau (τ) and Spearman rho (ρ) non-parametric correlation coefficients and regression analysis. The regression analysis was performed supposing a stochastic process and using a simple linear model: $yi = \alpha + \beta xi + \varepsilon i$, applied to the three classes of rainfall and assuming the residuals were independent and normally distributed (0, σ^2). For this aim, the model was estimated by applying the ANOVA to the regression coefficients, and a residuals analysis was done to verify, together with the statistical specification test for the regression model, the conformity of the observed data to the theoretical model (goodness-of-fit). In the graphic analysis, the simple linear regression was compared with the Loess non-parametric regression model.

Within the three classes of rainfall, a trend analysis of the net under-canopy precipitation was performed using the Man-Kendall test (Camuffo and Pagan 2003; Dunkeloh and Jacobeit 2003; Hamed 2008; Mariani 2006), to evaluate the effect that tree canopy recovery had on the quantity of rainfall reaching the ground during the 4 years of observation in relation to the events magnitude. To estimate this trend, a linear regression model was constructed by using the trigonometric functions of sine and cosine. This model expresses the trend as a function of time, and seasonality as the sum of the sine and cosine (Masarotto 2005; Ricci 2005). The linear dependence between the variables of the model was evaluated in relation to the significance of the regression coefficients and the ANOVA applied to the model. All the data analysis was carried out using the free software environment R (R Development Core Team, 2008. http://cran.r-project.org/).

3 Results

3.1 Stand characteristics

Table 1 shows the main structural and ecological parameters of the study areas. Immediately after thinning, tree density and basal area were reduced by 56 % and 45%, respectively. The percentage of incremental increase in basal area after five growing seasons was higher in thinned stands (9.97 vs 6.69).

After five growing seasons the canopy cover in the thinned area increased from 54 to 72%—an 18% increase compared to a 3% increase in the unthinned area (Table 1).

Table 1 Main structural measurements taken following thinning and after five growing seasons. *LAI* Leaf area index

Parameter		Species	Unthinned		Thinned	
			2003	2008	2003	2008
Tree density (n ha^{-1})		*Pinus pinea*	307	307	146	145
		Quercus ilex	176	253	67	130
		Total	483	560	213	275
Basal area (m^2 ha^{-1})		*P. pinea*	36.9	39.2	20.3	22.4
		Q. ilex	1.4	1.6	0.9	0.9
		Total	38.3	40.8	21.2	23.3
Basal Area Increment (%)			6.69		9.97	
Canopy cover (%)		Total	84.0	87.0	54.0	72.0
LAI		Total	5.07	5.42	1.90	2.95
Growth efficiency	Volume (m^3 ha^{-1} $year^{-1}$)	*P. pinea*	4.10		8.09	
	Biomass (Mg ha^{-1} $year^{-1}$)		3.47		6.92	

The LAI also increased in the thinned area by 1.05 compared to 0.35 in the unthinned area. Growth efficiency (GE), using the stem volume, doubled from 4.10 (m^3 ha^{-1} $year^{-1}$) in the unthinned area to 8.09 in the thinned area. A similar result of GE, 6.93 vs. 3.47 (Mg ha^{-1} $year^{-1}$), was obtained using total epigeous biomass (Table 1).

3.2 Net under-canopy precipitation

The measurements of throughfall for each collector were assumed to be independent of each other, as no spatial autocorrelation was found for the selected storms. The spatial variability of throughfall was higher for light storms, and the coefficient of variation decreased almost asymptotically with the increase in gross rainfall, especially for events of more than 20 mm (Fig. 3). The net under-canopy precipitation (throughfall and stemflow) was 14.5% higher in the thinned area then the unthinned (control) area. This difference was also found for the seasonal amounts, in which the difference between the net under-canopy precipitation in the two areas decreased in going from seasons with less rainfall to those with more rainfall. In fact, in the unthinned area, less than 23% and 19% of the net under-canopy precipitation was found, respectively, during the summer and spring periods, while 9% less was found during the autumn (Table 2). Analysis of variance, when applied to the temporal scale of individual rainfall events, indicated a significant difference of 99% between the net under-canopy precipitation in the thinned area, the net under-canopy precipitation in the unthinned one and the gross rainfall (F=10.09, 2 df with P<0.001). The results of the Tukey HSD test (Fig. 4) showed a significant difference between the net under-canopy precipitation in the unthinned area and the gross rainfall (P<0.001). Also, no significant difference existed between the net under-canopy precipitation in the thinned area and the gross rainfall.

Table 2 Total annual and seasonal rainfall, net under-canopy precipitation (throughfall+stemflow) expressed as measurements (mm) and as a percentage of rainfall and a coefficient of variation

Year/season	Rainfall amount	Throughfall + stemflow			
		Thinned		Unthinned	
	mm	mm	% rain	mm	% rain
2005	1,030	951	92.3	842	81.8
2006	446	390	87.3	341	76.3
2007	433	361	83.3	291	67.3
2008	855	709	82.9	628	73.5
Spring	88	51	76.3	37	57.0
Summer	13	11	83.5	8	60.0
Autumn	208	174	83.6	156	75.0
Winter	190	158	83.3	135	71.0

The stemflow measurements were very low, comprising only 0.20% of the gross rainfall in the thinned area and 0.27% in the unthinned. These figures are much lower than data relating to broadleaf trees, and lower than data reported in other studies performed on other species of pine trees.

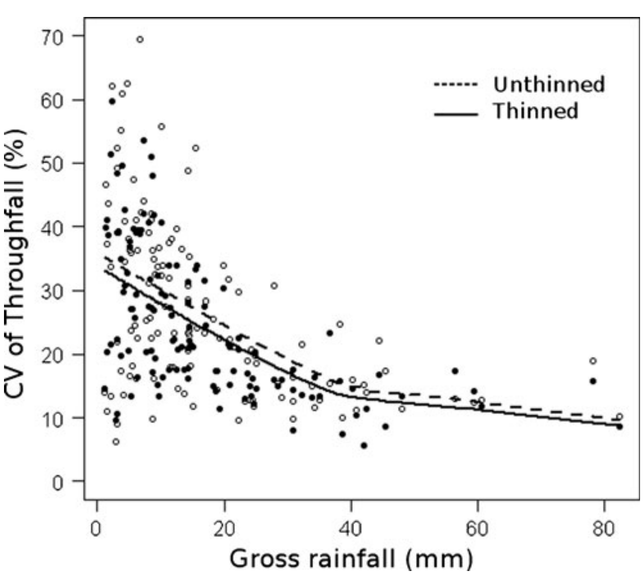

Fig. 3 Relationship between the variation coefficient of throughfall (as a percentage) and rainfall depth (mm)

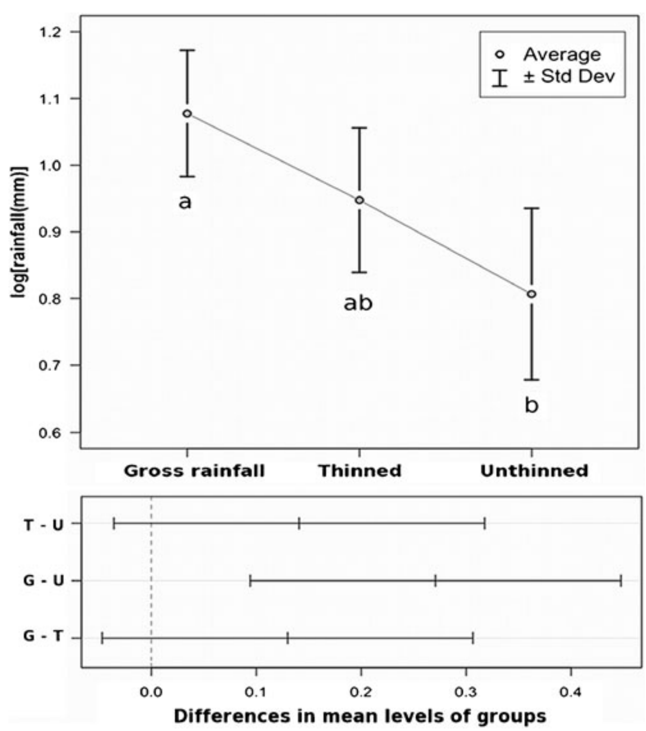

Fig. 4 Group means plot with 99% of confidence intervals of gross rainfall (G) and net-under-canopy precipitation in two areas, thinned (T) and unthinned (U), transformed to logarithms, and Tukey HSD test results

Table 3 Number of storms by precipitation class (CI–CIII) during the study period

Class	Rainfall amount (mm)	Number of storms					Total (%)
		2004	2005	2006	2007	2008	
I	0.00–10.00	4	10	13	16	14	44.2
II	11.00–20.00	2	9	7	7	7	24.8
III	21.00–30.00	2	5	2	5	6	15.5
	31.00–40.00	1	4	-	1	3	7.0
	41.00–50.00	-	2	1	-	3	4.6
	> 50.00	1	2	1	1	-	3.9

3.2.1 Net under-canopy precipitation related to rainfall depth

The rainfall events yielded typically up to 10 or 10–20 mm precipitation (44% or 25% of rainfall events, respectively), while rainfall events over 50 mm were rare (Table 3).

As the depth of gross rainfall increased, the difference between the net under-canopy precipitation in the two areas decreased: from 34.2% in class CI rainfall events, to 23.0% in CII and 8.6% in CIII.

The non-parametric correlations between gross rainfall and the differences of the net under-canopy precipitation in the two areas showed a statistical significance up to approximately 20 mm (tau=0.51 and rho=0.67 with $P<0.001$). The significance of these differences decreases as the amount of rainfall increases within the classes of rainfall. In class CIII there was no significant correlation.

The linear dependence between the variables of the model was assessed in relation to the significance of the regression coefficients and the ANOVA applied to the model. Considering all the rainfall events, the coefficients of linear regression were highly significant, $F(1,127)=21.48$ with $P<0.001$, and this relationship was found in rainfall events up to 20 mm, $F(1,87)=52.96$ with $P<0.001$. Within the three classes of rainfall depth the linear dependence between the variables was statistically significant only for CI (Table 4), and the function of linear regression and the Loess function with the two different degrees of smoothing are more similar in this class (Fig. 5).

The differences of the net under-canopy precipitation between the two areas showed a negative trend with up to 10 mm of rainfall (Fig. 6). The application of the Mann-Kendall test confirmed the presence of the trend for rainfall events with up to 10 mm of rain with a level of significance of 95% (tau=−0.22 with P-value=0.016). Also, after estimating the linear regression model using trigonometric functions, from the valuation of the regression coefficients, a negative trend with statistical significance (P-value= 0.019) was also found for events up to 10 mm.

3.2.2 Net under-canopy precipitation related to canopy cover

The increase in canopy cover from 54% to 72% over 5 years in the thinned area (Table 1) tended to diminish the flow of under-canopy rain. The annual canopy interception from 2005 to 2008 nearly doubled, increasing from 79 mm to 146 mm. The differences of under-canopy precipitation in the thinned area decreased from 108 mm to 81 mm during the 4 years of monitoring. As the canopy reformed during the 5 years after

Table 4 Linear regression model for the difference of net under-canopy precipitation between the two areas as a function of rainfall depth during the monitoring period. *SE* Standard error

Independent variable	Estimate	Standard error	*t* value	R^2	R^2 adjusted	*F*	Residual SE
Gross rainfall—total	−0.387	0.117	−3.30**	0.15	0.14	df 127	0.928
Intercept	0.021	0.004	4.64***			21.48***	
Gross rainfall ≤20 mm	−1.099	0.173	−6.34***	0.38	0.37	df 87	0.794
Intercept	0.120	0.016	7.28***			52.96***	
Gross rainfall—CI	−1.563	0.211	−7.39***	0.55	0.54	df 55	0.672
Intercept	0.266	0.033	8.14***			66.25***	
Gross rainfall—CII	−0.708	1.104	−0.64	0.01	−0.02	df 30	1.011
Intercept	0.048	0.074	0.65			0.42	
Gross rainfall—CIII	−0.613	0.462	−1.33	0.05	0.03	df 38	1.002
Intercept	0.018	0.013	1.48			2.18	

** Significant at $P<0.01$; *** significant at $P<0.001$

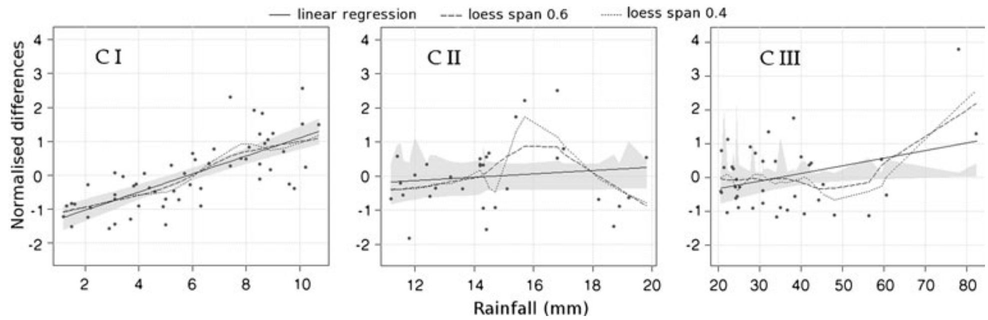

Fig. 5 Linear regression (*solid line*) and Loess non-parametric functions (*dotted lines*: with span=0.4 and 0.6) between gross rainfall, and the differences of the net under-canopy precipitation in the two areas, in the three classes of rainfall depth. *Shaded area* Confidence interval

thinning, the reduction in the net under-canopy precipitation reaching the ground was statistically significant (*P*-value= 0.019) only for rainfall events up to 10 mm.

The LAI in the two areas showed significant differences at the 99% level, and a positive trend (from 2003 to 2008) with statistical significance (*P*-value<0.01) was found only for the increase of LAI in the thinned area. Also, within this area, there was a statistically significant correlation at the level of 95% and 99% (for tau and rho rank correlations, respectively), between the mean annual measurements of LAI and relative throughfall (expressed as percentage of gross rainfall), and the linear regression showed a negative relationship [R^2 adjusted=0.99; F(1,1)=243; *P*=0.0408; residual standard error: 0.408]. No relationships between LAI and relative stemflow were found.

3.3 Rainfall interception

Mean canopy interception (as a percentage of rainfall) was higher in the unthinned area (41.3%) than in the thinned area (23.3%) during the entire period of observation, and for each rainfall event. There were highly significant differences in canopy interception between two areas, taking into consideration both the individual rainfall events and the cumulated monthly data (W=3,813.5 and W=188 with *P*<0.001). Figure 7 shows that interception amounts between 0 and 20% were found more frequently in the thinned area (51% of showers vs 16% in the unthinned) while amounts of over 40% were more frequent in the unthinned area (48% of showers in the unthinned area vs 13% in the thinned). This result confirms that less rainwater is lost by interception following thinning.

Canopy interception was higher in the unthinned area, both for individual rainfall events (especially for events between 0 and 20 mm) and for monthly totals, and remained constant for greater events. Also, with the increase in the amount of rainfall, the differences in canopy interception between the two areas decreased (Fig. 8). The decrease of the difference in canopy interception between the two areas was confirmed by the Mann-Kendall test, with a level of significance of 99%

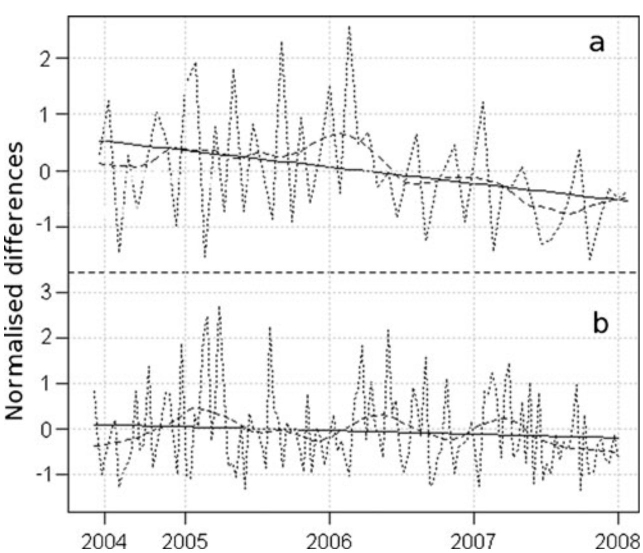

Fig. 6 Differences normalised between the under-canopy precipitation in the two areas during the entire study period, for **a** lower levels of rainfall depth, and **b** total precipitation for all class of rainfall events

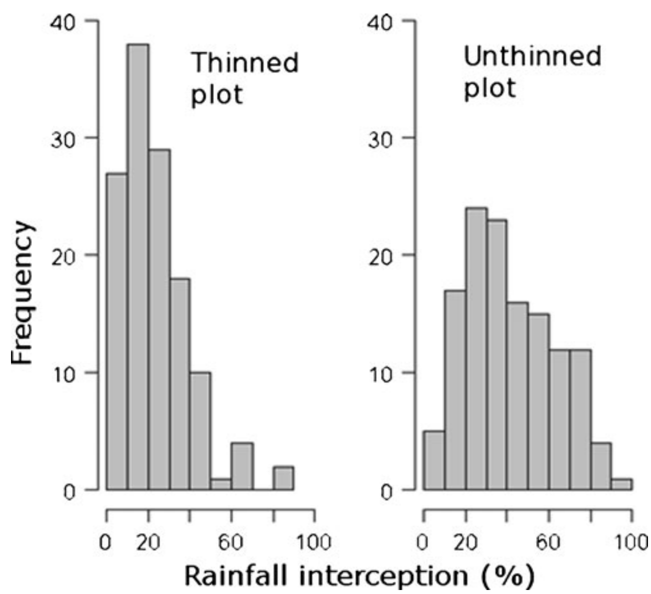

Fig. 7 Frequency distribution of canopy interception expressed as a percentage of rainfall

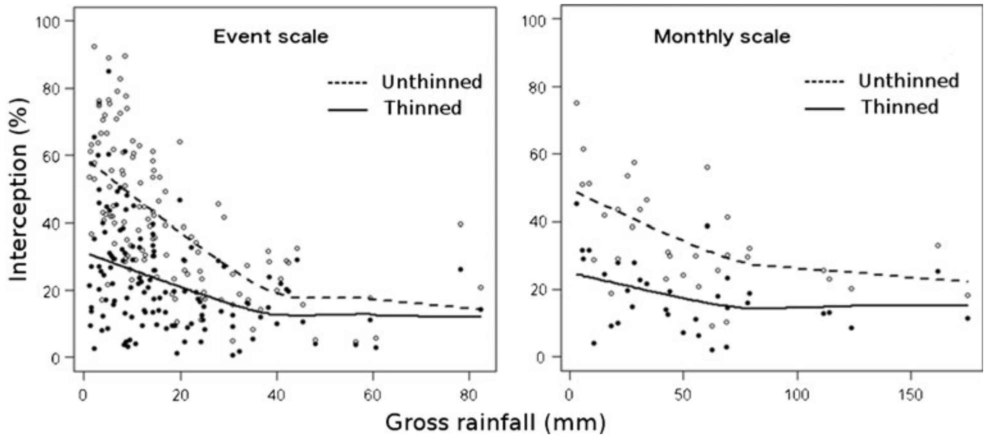

Fig. 8 Relationship between interception (%) and gross rainfall in two areas, for different temporal scale of analysis: event scale and monthly scale

both for single rainfall events and for the total monthly amounts (tau=−0.46 and −0.51 with $P<0.001$, respectively).

The analysis of the differences between the percentages of rain intercepted on an annual scale also showed the same tendency, and in fact there were major differences in years with less rainfall, 2006 and 2007 (Fig. 9). In particular, in these latter years, during which the rainfall was 50% less than in the other two years, the differences in interception in the two areas increased by approximately 25.6%, increasing from 16 to 21.5%.

4 Discussion

The widespread stone pine pinewoods of the Italian coast often lose their resilience following disturbance. Over time, the lack of silvicultural activities has reduced their stability, leaving these environments more susceptible to drought damage.

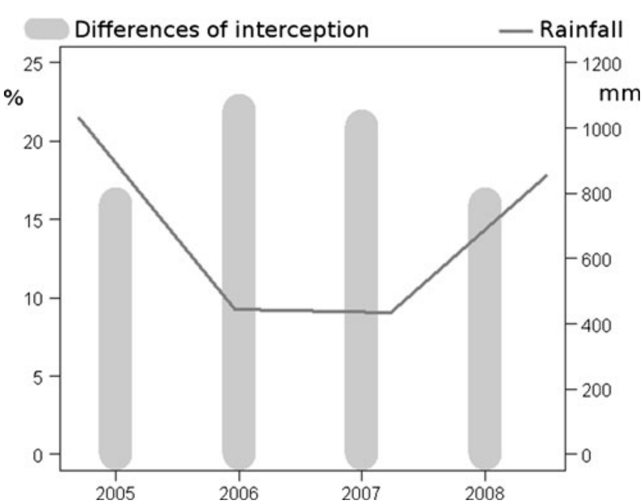

Fig. 9 Percentage differences of rainfall interception by canopy cover between the two areas on an annual scale

Late and heavy thinning of a pinewood that has never been thinned proved to be justifiable as a sustainable management strategy. No mortality caused by uprooting, stem-breakage or other stand damage was recorded after 5 years. Also, thinning promoted an increase in under-canopy water. Removing 45% of basal area and reducing LAI by 63% increased the total throughfall by an average of 14.5%. The spatial variability of throughfall also decreased with the increase in rainfall, as observed previously by other authors at other sites (Llorens et al. 1997; Loustau et al. 1992), and showed no significant differences between the two areas studied here.

The influence of thinning on rainfall redistribution was confirmed by the statistically significant difference between the net under-canopy precipitation and gross rainfall in the unthinned area. The net under-canopy precipitation was always greater in the thinned area than in the unthinned one, highlighting the greater flow of under-canopy water following thinning and confirming similar results in stands of other conifers (Aussenac and Granier 1988; Iovino et al. 2001, 2009; Llorens and Domingo 2007). This was particularly true for light rainfall events (between 0.00–10.00 and 11.00–20.00 mm) because of the greater interception of rainfall by the tree canopy. This trend was also observed during years with less annual rainfall, and especially during the dry summer months, when the net under-canopy precipitation in the unthinned area decreased by nearly 23%.

The difference in the net under-canopy precipitation between the two areas following thinning decreased with the increase in gross rainfall, indicating that canopy interception is notably reduced during heavy rainfalls. Other authors have shown there is a decreased capacity in interception in mountain stands of *Pinus laricio* Poiret spp. *calabrica* for rainfall events over 30 mm (Callegari et al. 2001), and in a forest patch of *Pinus sylvestris* for events greater than 20 mm (Llorens et al. 1997). Crockford and Richardson (2000) observed that, 1 year after the removal of 50% of the basal area, the decrease in interception for small showers was

50%, while for showers over 15 mm it was 30%. For light showers (< 10 mm) the influence of thinning on water reaching the ground was highly significant, becoming negligible with the increase in the amount of rainfall, as shown by correlations analysis and the linear relationship between the variables. The difference in the net under-canopy precipitation between the two areas showed a negative trend only up to 10 mm and 20 mm of rain. This could be explained by the fact that, following heavy thinning, such as the type done for this study, the re-growth of the tree crowns had not yet completely closed the gaps that had been created. The trend that larger rainfall events have similar interception in the thinned and unthinned area may be explained partly by the canopy storage capacity being reached as the rainfall event progresses.

Stemflow ranged from 0.02 to 1.12% of total rainfall and averaged 0.05% higher in the unthinned area. These percentages were lower than measurements taken in other studies involving other species of pine trees. In a *Pinus sylvestris* forest patch with an average annual rainfall of 850 mm, Llorens and others (1997) reported stem-flows of 1.3%. In a plantation of *Pinus laricio* spp. *calabrica*, with an average annual rainfall of 915 mm, Callegari et al. (2001) reported stemflows of 0.64% of rainfall in an unthinned plot with 1,533 trees per hectare and 0.51% in a plot that had been thinned by 50%. Gash and Morton (1978) reported stem-flows of 2% in a mature stand of *P. sylvestris* in the Thetford Forest. The low stemflow measurements found in this study can be attributed to the typical umbrella-shaped crown architecture of an adult stand of stone pine, which is characterised by almost horizontal branches.

The increased flow of water reaching the ground, and the related increase in light availability following thinning has encouraged the growth of residual trees, as shown by the higher GE found in the thinned area at the conclusion of the study period. In fact, in the thinned area, this index doubled both with volume and epigeous biomass.

5 Conclusion

In the Mediterranean region, increased evapotranspiration caused by increased air temperature and a reduction in precipitation could diminish soil water availability, and so induce increased water stress. An analysis of meteorological characteristics of the study site from 1951 to 2008 confirmed this climatic trend and documented a highly significant ($P < 0.001$) increase in the average temperature during the dry, summer period especially since the start of the 1980s, and a corresponding decrease in the amount of rainfall from June to August and from December to February.

The results of this study emphasize the positive effects of thinning, even thinning carried out after the passage of half a century, in Mediterranean pinewoods that have never been thinned. Thinning the canopy cover reduces water loss due to interception and guarantees greater net under-canopy water, particularly during dry periods with lower amounts of rainfall. This could also provide an advantage to other plants, especially Holm Oak and the Mediterranean maquis shrubs that are often present in the midstory of pinewoods, favouring an increase in stand growth rate and efficiency, and biodiversity. This also guarantees good soil coverage during any heavy rainfall events and/or extreme storms, underlining the important role of thinning in the mitigation of the effects of climatic changes in the Mediterranean basin.

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