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Forest Ecology and Management 206 (2005) 179–190
Forest Ecology and Management
www.elsevier.com/locate/foreco

Litter fall in Mediterranean *Pinus pinaster* Ait. stands under different thinning regimes

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Received 25 March 2004; received in revised form 9 August 2004; accepted 16 October 2004

Abstract

Litter quantity and composition and its fall pattern throughout the year in Mediterranean pine afforestation of *Pinus pinaster* in Fuencaliente (Central Spain) were studied in relation to thinning treatments. The experiment lasted 10 years (1986–1995) and tested two low thinning regimes with a control one and with a stand that had never been thinned. Mean litter production for all years and treatments was 3284 kg ha^{-1} year^{-1} although it varies between 1520 kg ha^{-1} year^{-1} for the heavy thinning in 1994 and 5700 kg ha^{-1} year^{-1} for moderate thinning in 1989. Litter fall had two relative maximums throughout the year, the largest during the months of July, August and September, and the second one during January and February. The temperature of the previous month and moisture deficit resulted to be the most correlated climatic variables with monthly litter fall. Both time and treatments, and also their interaction, had a significant effect on litter fall, decreasing the quantity of litter fall with thinning intensity. Five years after thinning, this effect on the litter fall disappeared.

Keywords: Litter fall pattern; Thinning treatments; Pines; Nutrient cycle; Nutrient composition

1. Introduction

The organic layer of the forest floor regulates most of the functional processes occurring throughout the forest ecosystem: it acts as an insulating layer which protects the soil from extreme changes in moisture and temperature; it protects the soil from erosion and frost and it improves water infiltration. Litter fall is a particularly key process in nutrient cycling of forest ecosystems as it provides the main above-ground contribution of carbon and nutrients to the forest floor through the formation of humus that is characteristic of each ecosystem (Gallardo et al., 1998) and represents a provisional accumulation of elements which are released gradually, thereby guaranteeing a permanent contribution of nutrients to the soil (Palma et al., 1998).

The process of decomposition is mainly controlled by climate (Florence and Lamb, 1975; Hart et al., 1992), litter quality (Berg, 1984) and soil organisms (Pausas, 1997), among others. Litter decomposition rates also determine soil organic matter accumulation

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0378-1127/$ – see front matter
doi:10.1016/j.foreco.2004.10.068

rates on the forest floor. The balance between litter production and its decomposition controls the size of the carbon reservoir within the soil. A good knowledge of these processes in field conditions and without experimental artefacts is essential in order to predict the fate of this carbon reservoir in response to climate changes (Kurz et al., 2000). The accumulation of litter on the forest floor is regarded in different ways: it can be a threat to site productivity, as nutrients are immobilized in the litter, organic acids are released and moisture penetration is altered (Dames et al., 1998).

Several studies have reported litter fall nutrient content and mineral return on Mediterranean forest ecosystems, which show important interspecific differences (Kruger et al., 1983; Specht, 1988; Kavvadias et al., 2001). In the Mediterranean geographic area, these facts have been investigated most often in perennial oak forests (*Quercus ilex*, *Q. suber*, *Q. coccifera*) and in deciduous oak forests (*Q. pyrenaica*, *Q. faginea*) (Rapp, 1971; Loissaint and Rapp, 1978; Escarré et al., 1984; Santa Regina and Gallardo, 1995; Cañellas et al., 1996; Caritat et al., 1996; Robert et al., 1996; Cañellas and San Miguel, 1998; Gallardo et al., 1998), but comparatively little is known about litter fall in Mediterranean pinewoods (Rapp, 1984; Kurz et al., 2000; Kavvadias et al., 2001), and even less in reforestation areas. The role of litter decomposition in nutrient cycling becomes still more important when considering the degradation of forest vegetation and soils by wild fires, long destructive cultivation and overgrazing.

To adapt to water deficit conditions, trees tend to shed old leaves in order to reduce the transpiration surface. This adaptative mechanism leads to a rapid substitution of old leaves by new shoots, which exert a high photosynthetic capacity and are more efficient in water regulation (Kummerow, 1983). In the Mediterranean area, water deficit is higher in summer, but a marked variability in water supply during the growing season leads tree species to show a certain plasticity in litter fall. In this aspect thinning is one of the most important silvicultural treatments of forest stands. It is carried out to reduce inter tree competition and results in increased growth of the remaining trees; moreover, thinning has various ecological effects on the ecosystem (heat radiation reaches the forest floor, higher temperatures for root growth), which accelerate decomposition and mineralization processes in the soil, increasing the amount of nutrients available to plants. The typical thinning applied in pine reforestation, normally with high density and deep accumulations of litter, modifies not only the amount of litter fall produced in the stands, but also decomposition rates and processes and critically affects the performance of understory herbs.

The objectives of this research were: (a) to increase knowledge regarding the dynamics of plantation pines, through the quantity and composition of the litter and its fall pattern throughout the year in Mediterranean pine forests of *Pinus pinaster* Ait., a coniferous tree common in warm Atlantic and Mediterranean climates, on acid parent material in the Iberian Peninsula, especially in Central, Eastern and Southern Spain; (b) to analyze the effect of thinning treatments in the amount and pattern of litter fall in these pine woods.

2. Materials and methods

2.1. Site description

The study was carried out in a *P. pinaster* Ait. stand in Fuencaliente, located at 4°21′W longitude and 38°28″N latitude. Its aspect is north-east, the altitude is 900 m a.s.l. and the mean slope is 15–20%. Annual rainfall is 790 mm with a mean temperature of 15 °C (Fig. 1); soil type is Xerochrept. Potential vegetation corresponds to *Pyro bourgaenae—Quercetum rotundifoliae* association and the present vegetation is a pinewood of *P. pinaster* with some isolated trees of *Q. ilex* L. subsp *ballota*, *Q. faginea* Lamk. and *Arbutus unedo* L. The pinewood was established in 1951 following artificial seedling. Precommercial thinning was carried out when the stand was 18 years old with the exception of a small area (initial density 3600 trees ha^{-1}). At the beginning of the experiment the stand was 33 years old with an average density of 1400 trees ha^{-1}.

2.2. Design

The thinning experiment was carried out in 1984 according to a random complete blocks design with three treatments and three blocks. Treatments applied

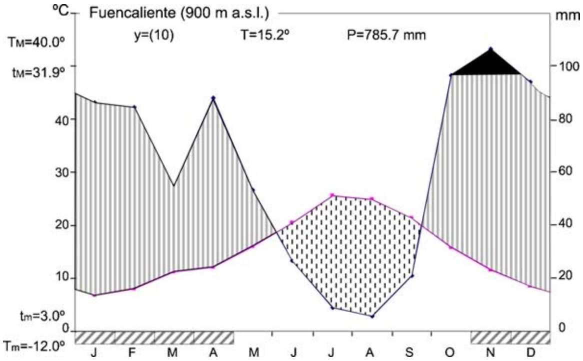

Fig. 1. Climatic diagram (Walter, 1963) of the experimental site during the studied period of time. *y*: number of years considered; *T*: mean annual temperature (°C); *P*: mean annual amount of precipitation (mm); T_M: absolute maximum temperature (°C); t_M: mean daily maximum temperature of the hottest month (°C); t_m: mean daily minimum temperature of the coldest month (°C); T_m: absolute minimum temperature (°C). Obliqued striped area shows months with an absolute minimum below 0 °C.

consisted of comparing two low thinning regimes with a control one, with no thinning (C); moderate thinning (T_1) – 30% and 21% basal area removed in the first and second thinning, respectively; and heavy thinning (T_2) – 40% and 25% basal area removed in the first and second thinning, respectively. In both treatments, thinning rotation was 8 years (stand thinned in 1984 and 1992). All trees in the nine plots were identified by a number and diameter was measured at breast height. Total height was recorded in a sample of 40 trees per plot covering all diameter classes to estimate top and mean heights. Inventories were carried out every 4 years from 1984 until 1996. Plot size was 40 m × 25 m (1000 m^2) and buffers were 10 m wide. Besides the thinning experiment, a plot of the same size was installed in the area that had never been thinned in order to follow up the litter fall in a never thinned stand (NT). The mean stand variables per treatment are presented in Table 1. In non-thinned plots the removed stand corresponds to natural mortality.

In each plot five 0.5 m × 0.5 m (0.25 m^2) plastic litter traps, with a height of 0.15 m, were installed in 1986; one was installed in the centre of the plot and the other four in the middle of each semi-diagonal. The total litter fall was collected monthly for 10 years (1986–1995) and dried to constant weight at 102 °C. Litter fall contained mainly needles. Cones, bark and branches were excluded due to the scarce proportion of these fractions in litter fall, their high variation coefficients (Pausas, 1997) and the sampling method, that makes it difficult to register the largest components of litter fall.

Nutrient content in litter fall (needles) was analyzed monthly during the first 3-year period. At each sample, the content in N, P, K, Ca and Mg was determined as a percentage of total dry weight. Samples were dried at 75 °C for 24 h and weighted to the nearest 0.1 g. N was determined by semimicro-distillation following a Kjeldahl digestion. After triturating them, 2 g of each was burned at 490 °C for 12 h and the ashes were prepared with chloric acid. Ca and Mg were determined by atomic absorption (lanthanum chloride was used to control interference of other elements in the Ca and Mg analyses); K was determined by emission spectrophotometry. P was determined colorimetrically, after reduction of phospho-molibdate by stannous chloride to molybdenum blue.

2.3. Statistical analysis

The measured annual litter fall has been referred to the hectare and transformed through logarithm to achieve normality. Differences in nutrient content of litter between months were analyzed using ANOVA techniques for each element.

The potential relation between the amount of litter and climate was explored using Pearson's correlation. Climatic variables analyzed were monthly precipitation and monthly mean temperature for each month and, with the same climatic variables, from the month before, 2 months before, etc. to the data for the previous year. Litter amount was also compared with an edapho-climatic parameter – the monthly moisture deficit – (Thornthwaite and Mather, 1957), again, using Pearson's correlation. The climatic and edapho-climatic variables with higher correlations with the amount of litter fall (dependant variable) were used as independent variables in a multiple linear regression. All variables were log-transformed before statistical analysis. Climatic diagrams for the mean year of the period of time studied and for each year were calculated and drawn.

Since two thinning has been applied (1984 and 1992), the measured series of litter fall (years 1986–

Table 1
Evolution of the stands in relation to time and thinning intensity

Treatment	Date	Stand before thinning						Removed stand[a]					Total stand			
		N	D_g (cm)	H_g (m)	H_o (m)	G (m^2/ha)	V (m^3/ha)	N	D_g (cm)	H_g (m)	G (m^2/ha)	V (m^3/ha)	GT (m^2/ha)	VT (m^3/ha)	MIV (m^3/ha)	CIV (m^3/ha)
NT	1984	3600	15.0	12.1	13.4	63.8	354	–	–	–	–	–	63.8	354	10.7	–
	1988	3540	16.0	12.7	14.0	72.2	422	60	11.3	11.8	0.6	3.1	72.2	422	11.4	17.1
	1992	2770	16.5	13.2	14.5	75.8	459	770	10.9	12.0	7.1	37.6	76.4	463	11.3	10.0
	1996	2350	18.2	13.8	14.9	71.7	452	420	12.8	13.0	5.4	30.7	79.4	493	11.0	7.6
C	1984	1193	22.9	13.4	14.5	49.0	309	–	–	–	–	–	49.0	309	9.4	–
	1988	1187	24.2	14.5	15.6	54.6	371	13	11.3	11.1	0.1	0.6	54.7	372	10.1	15.7
	1992	1173	25.2	15.4	16.4	58.2	417	10	11.4	12.3	0.1	0.7	58.4	418	10.2	11.5
	1996	1163	25.8	16.1	17.1	60.8	454	63	14.3	14.0	1.0	6.2	61.2	456	10.1	9.5
T_1	1984	1420	21.2	13.5	15.1	49.6	316	667	17.0	12.5	15	87.7	49.6	316	9.6	–
	1988	753	26.4	15.5	16.2	41.0	291	17	20.1	14.5	0.5	3.2	56.0	379	10.2	15.8
	1992	736	28.2	16.4	17.0	45.6	343	193	25.3	16.0	9.8	71.7	61.1	434	10.6	13.7
	1996	543	30.3	17.2	17.7	38.9	306	13	26.9	16.9	0.7	5.6	62.2	469	10.4	8.9
T_2	1984	1570	20.4	12.9	15.7	51.4	317	883	17.3	12.1	20.8	120.2	51.4	317	9.6	–
	1988	687	26.0	15.1	15.8	36.4	254	20	21.2	14.5	0.7	4.2	57.2	374	10.1	14.4
	1992	667	28.0	16.1	16.7	40.8	302	207	24.8	15.8	10.0	72.0	62.2	426	10.4	13.0
	1996	460	30.9	17.0	17.4	34.8	268	3	20.7	15.3	0.1	0.8	65.8	465	10.3	9.6

NT: never thinned; C: control; T_1: moderate thinning regime; T_2: heavy thinning regime. N: number of trees; D_g: quadratic mean diameter; H_g: mean height; H_o: dominant height; G: basal area; V: volume; GT: total basal area; VT: total volume; MIV: mean increment in volume; CIV: current increment in volume.

[a] Removed stand includes natural mortality.

1995) have been divided into two periods to study the effect of the time elapsed after the thinning: between first and second thinning (1986–1991) and after the second thinning (1993–1995). The effect of thinning and the effect of the time since the thinning on annual litter fall were analyzed by repeated measurement analysis of variance (RMANOVA). The general expression of the model for a complete random block design is:

$$Y_{ijkl} = \mu + B_j + T_k + \gamma_l + B\gamma_{jl} + T\gamma_{kl} + \varepsilon_{ijkl} \qquad (1)$$

where Y_{ijkl} is the observed value for the response variable Y on the ith sample in block j, under treatment k and in year l; μ the mean overall value of the response variable; B the block effect; T the treatment effect, thinning intensity; γ the time effect, year; $B\gamma$ the block–time interaction effect; $T\gamma$ the treatment–time interaction effect; and $\varepsilon_{ijkl} \sim N(0, \sigma)$ the random error terms, with variance–covariance matrix σ. Mauchly's criterion test for the compound symmetry of the variance–covariance matrix was obtained for each analysis. The block and treatment effect was evaluated by means of a null hypothesis test for between subjects, since it does not require sphericity. To assess significance of time, time × block and time - × treatment effects, the univariate approach was selected when hypothesis of sphericity was accepted because of its greater robustness (Moser et al., 1990). If sphericity was rejected, the multivariate approach following Roy's Greatest Root test was selected (SAS, 1988; Moser et al., 1990). Duncan's multiple range test was used to analyze the differences among treatments per year for the litter fall amount (95% of significance level).

In the same way the RMANOVA analysis was used to analyze differences in litter fall between seasons of the year in the following order: spring (April–June), summer (July–September), autumn (October–December) and winter (January–March). For each season the same post-hoc test procedure was performed.

3. Results

3.1. Litter fall pattern and composition

The evolution of annual litter fall of all tested treatments during the decade studied is shown in

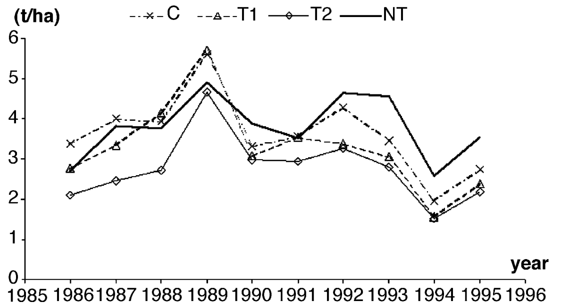

Fig. 2. Evolution of total annual litter fall along the decade of study per treatments. C: control; T_1: moderate thinning regime; T_2: heavy thinning regime; NT: never thinned.

Fig. 2. The mean litter production for all years and treatments is 3284 kg ha^{-1} year^{-1} (Table 2), although it varies between 1520 kg ha^{-1} year^{-1} for T_2 treatment in 1994 and 5700 kg ha^{-1} year^{-1} for T_1 treatment in 1989. The years 1989 and 1994 should be highlighted for producing the maximum annual litter fall for all treatments, in the case of the former, and minimum, in the case of the latter.

Litter fall has two maximums throughout the year; the largest maximum is in summer, during the months of July–September, especially in August (Fig. 3). Most years then present another relative maximum during the months of January and February (Fig. 4). Only the years 1990–1992 do not show this second maximum peak in winter. Minimums occur in late winter and spring from February–March to June every year. All treatments share the same annual pattern although the amount of resulting litter can be quite different.

For all treatments, the mean litter fall amount for spring is 13% of the total, 59% for summer, 17% for autumn and 12% in winter. At every season the above-mentioned maximum of 1989 can be recognized (more noteworthy in autumn and winter), as can the

Table 2
Mean value, standard deviation (S.D.), lower (Lc_i) and upper (Uc_i) confidence interval limits ($P = 0.05$) for annual litterfall (kg ha^{-1} of dry matter) and nutrient content (% of dry matter)

	kg ha^{-1}	N	P	K	Ca	Mg
Mean	3284.92	0.400	0.034	0.171	0.542	0.122
S.D.	1153.76	0.096	0.017	0.078	0.146	0.023
Lc_i	3183.54	0.367	0.029	0.144	0.492	0.114
Uc_i	3386.29	0.433	0.040	0.198	0.592	0.130

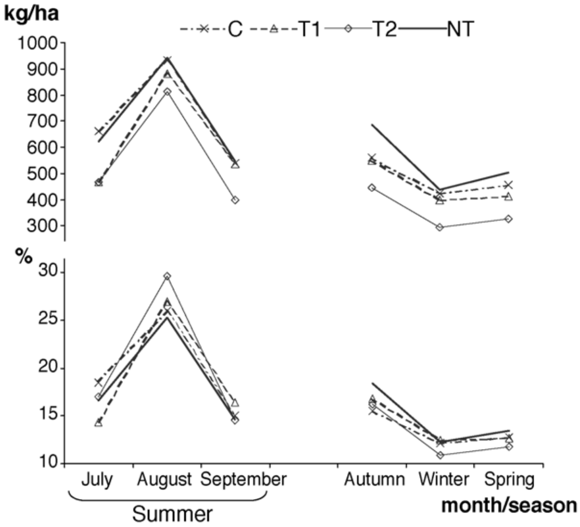

Fig. 3. Absolute (Kg ha^{-1} of dry matter) and relative (%) mean values of litter fall per treatment and seasons of the year (relative values in relation to total annual litter fall). Summer has been divided into the 3 months considered.

relative maximum of 1992–1993, while the minimum of 1994 is not so clear among seasons (Fig. 4).

Table 3 shows litter fall content in N, P, K, Ca and Mg for each month and the existence of significant differences between months (Table 4). As a general rule, litter fall has lower N and K content during winter and autumn months and higher content in spring and summer.

3.2. Relationship with climate

Transformed climatic variables from the temperature and the precipitation of previous months turned out to be the most significantly correlated with monthly litter fall (mean value for all treatments), with r values (Pearson's correlation coefficient) of −0.4371 for precipitation and 0.6799 for mean temperature; the relationship with monthly moisture deficit also turned out to be significant with 0.5218 as the Pearson correlation coefficient (Fig. 4). A multiple regression analysis was used to determine the relationship between litter fall and these variables that explained 51% of total variability (adjusted $R^2 = 0.5034$) where the only significant coefficients were temperature ($\beta = 0.197$) and moisture deficit ($\beta = 0.563$). The resulting equation was (standard errors of parameters in brackets):

$$\log L = 1.982(0.451) + 0.0944(0.043)\log M + 1.1598(0.187)\log T \quad (2)$$

where L is the monthly litter fall (kg ha^{-1} year^{-1}), M is the monthly moisture deficit (mm) and T is the mean temperature of the previous month (°C).

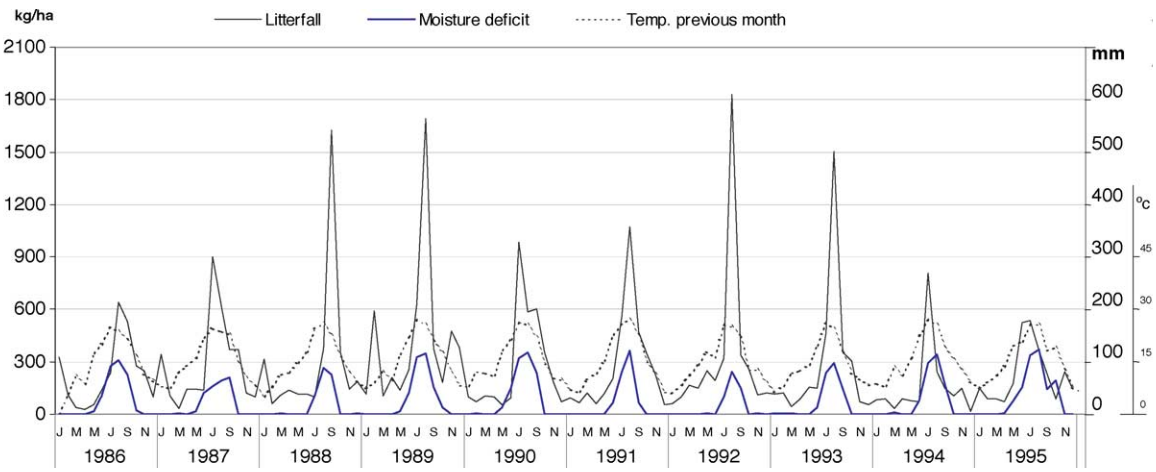

Fig. 4. Evolution of monthly litter fall (kg ha^{-1} of dry matter, mean of all treatments), mean monthly temperature (°C) and moisture deficit (mm) during the period of time studied.

Table 3
Result of the analysis of variance on monthly nutrient content in litter fall (% of dry matter)

Nutrient	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	$P < F$
N	0.365	0.420	0.443	0.493	0.547	0.467	0.423	0.320	0.300	0.307	0.330	0.377	0.0022
P	0.020	0.033	0.040	0.043	0.047	0.047	0.050	0.033	0.027	0.020	0.020	0.027	n.s.
K	0.090	0.130	0.133	0.260	0.267	0.167	0.187	0.250	0.183	0.137	0.107	0.113	0.0078[a]
Ca	0.605	0.643	0.597	0.490	0.347	0.437	0.517	0.550	0.553	0.507	0.640	0.640	n.s.
Mg	0.115	0.107	0.113	0.110	0.110	0.120	0.133	0.160	0.140	0.130	0.107	0.113	n.s.

[a] Logarithm transformation of the variable.

Table 4
Differences between months in N and K (log-transformed) content in litter fall (Duncan's test, significance at 5%)

N												log(K)											
My	A	Jn	M	Jl	F	D	J	N	Ag	O	S	A	My	Ag	Jl	S	Jn	M	O	F	N	D	J
a	a	a	a	a	a							a	a	a	a	a	a						
	b	b	b	b	b	b	b						b	b	b	b	b	b	b				
			c	c	c	c	c	c	c						c	c	c	c	c	c	c	c	
				d	d	d	d	d	d	d	d							d	d	d	d	d	d

3.3. Influence of thinning regime

Fig. 3 shows the distribution of litter fall by seasons per treatment, in absolute and relative values. T_2 stands show more concentrated litter fall in summer, with 61% of the total annual litter fall, while the other seasons have lower percentages than the average values and than those of the rest of the treatments. On the other hand, NT treatment has a much more widespread distribution throughout the year than other treatments, with the lowest percentage in summer and the highest values in other seasons, while absolute values are always the largest at every season.

A repeated measures analysis of variance was used to evaluate significant differences through time and those due to treatment (control, moderate and heavy thinning) for the two periods of time considered (Table 5). The average litter biomass for stands with different treatments and the differences found in the ANOVA analysis are displayed in Table 6. Both time and treatments had a significant effect ($P < 0.05$) for the periods before the second thinning of 1992 and after it. An interaction between treatment and time was also found to be significant for the 1986–1991 interval. After the first thinning in 1984 and before the second one, there are mainly differences between the group formed by control and T_1 treatments and the T_2 stands, the latter with lower litter fall values. In the same period and due to the significant interaction (time $\times$ treatment), differences among treatments are reduced as time goes by. In the same way, after the second thinning of 1992 the main differences are found between the control and the thinned stands (T_1 and T_2 group).

In the study by seasons, time and treatment continue to have a significant effect in every season during the two periods of time considered (before and after the thinning of 1992). Results for interaction of time $\times$ treatment, treatment $\times$ block or even the effect of block are variable according to the studied season. Treatment $\times$ time always has a significant effect during the first period of time (from 1986 to 1991)

Table 5
Result of the repeated measurement analysis of variance on log-transformed annual litter fall in the univariate approach of RMANOVA

Source	1986–1991		1993–1995	
	d.f.	$P > F$	d.f.	$P > F$
Within subject				
Time	5	0.0001*	2	0.0001
Time $\times$ block	10	n.s.	4	n.s.
Time $\times$ treatment	10	0.0027*	4	n.s.
Between subject				
Block	2	n.s.	2	n.s.
Treatment	2	0.0001	2	0.0022

C: control; T_1: moderate thinning regime; T_2: heavy thinning regime.
* Multivariate approach by Roy' Greatest Root MANOVA.

Table 6
Differences between treatments per year in annual litter fall (Duncan's test, significance at 5%)

Treatment	log[annual litter fall (kg ha^{-1})]									
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
C	8.11 a	8.28 a	8.27 a	8.62 a	8.09 a	8.17 a	8.35 a	8.13 a	7.56 a	7.90 a
T_1	7.90 b	8.09 a	8.32 a	8.64 a	8.01 a	8.15 a	8.11 b	8.02 ab	7.33 b	7.76 ab
T_2	7.61 *c*	7.77 b	7.90 b	8.43 b	7.97 a	7.96 b	8.06 b	7.93 b	7.31 b	7.66 b

C: control; T_1: moderate thinning regime; T_2: heavy thinning regime.

Table 7
Result of the repeated measurement analysis of variance on log-transformed summer litter fall in the univariate approach of RMANOVA

Source	1986–1991		1993–1995	
	d.f.	$P > F$	d.f.	$P > F$
Within subject				
Time	5	0.0001[a]	2	0.0001
Time × block	10	n.s.	4	0.0463
Time × treatment	10	0.0030[a]	4	n.s.
Between subject				
Block	2	n.s.	2	n.s.
Treatment	2	0.0001	2	0.0300

C: control; T_1: moderate thinning regime; T_2: heavy thinning regime.

[a] Multivariate approach by Roy' Greatest Root MANOVA.

and never during the second period. The trend of similarities during the first and second periods is maintained: treatments C and T_1 are similar during the 1986–1991 period while during the 1993–1995 interval T_1 and T_2 are grouped. A detailed analysis of the summer season is presented in Tables 7 and 8 as a sample of the evolution of litter fall during the most important season in the litter fall process.

4. Discussion and concluding remarks

Neddle fall observed for *P. pinaster* in Fuencaliente reforestation was quite different from that reported for the same species in other situations: Hernández et al. (1992) estimated annual litter fall of 1800 kg ha^{-1} year^{-1} for the same subspecies in Central Spain. Kavvadias et al. (2001) compared the evolution of litter fall in reforestation stands of *P. pinaster* in Greece with different density and site quality. The annual amount of litter was close to 1500 kg ha^{-1} year^{-1}, quite similar in both quality and density sites. On the other hand, Kurz et al. (2000), measured 3675 kg ha^{-1} year^{-1} of needle fall (4640 kg ha^{-1} year^{-1} of total litter fall) in Southern France for the Mediterranean subspecies. The figure that we found at Fuencaliente (3284 kg ha^{-1} year^{-1}) is intermediate when compared with the previous ones due to its relatively dense afforestation (basal area of 35–65 m^2 ha^{-1}). Other authors studied litter fall in some other conifer species and cited quite variable figures in a wide range of sites, i.e. for *Pinus sylvestris:* 1800–2000 kg ha^{-1} year^{-1} (Albera, 1980); 4100 kg ha^{-1} year^{-1} (Santa Regina and Gallardo, 1995); or 1760 kg ha^{-1} year^{-1} (Pausas, 1997).

In relation with the common rhythm of litter fall for all treatments, similar seasonal trends have been obtained in other Mediterranean species. In general, needle litter fall increases in summer with a unique maximum in the annual distribution from August to October although the annual litter fall pattern can vary slightly from year to year (Cañellas et al., 1996; Caritat et al., 1996; Pausas, 1997; Kurz et al., 2000). We also reported another peak for litter fall in winter

Table 8
Differences between treatments per year in summer litter fall (Duncan's test, significance at 5%)

Treatment	log[summer litter fall (kg ha^{-1})]									
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
C	7.42 a	7.73 a	7.75 a	7.99 ab	7.67 a	7.72 a	7.90 a	7.77 a	7.07 a	7.00 a
T_1	7.22 b	7.47 b	7.75 a	8.01 a	7.57 a	7.67 a	7.64 b	7.58 b	6.90 a	6.88 ab
T_2	7.03 b	7.24 b	7.35 b	7.86 b	7.50 a	7.48 b	7.63 b	7.58 b	6.95 a	6.80 b

C: control; T_1: moderate thinning regime; T_2: heavy thinning regime (much smaller than the summer one) in most of the years studied. The fact that the maximum summer needle fall peak was different in time over the years seems to be related to the difference in weather conditions over the years sampled in annual climatic characteristics. Comparing curves of litter fall for all treatments with the annual climatic diagram for each year, it seems that the maximum litter fall peak extends throughout the months with physiological drought (rainfall line above temperature line on the climatic diagram). For example, on the litter curve for the year 1988 (Fig. 4), the summer peak starts in August–September and it is very short (2–3 months). On the climatic diagram of 1988, summer drought also starts in August – very late for Mediterranean conditions – and only lasts 3 months. On the contrary, 1995 showed a summer litter fall peak that extended from May to October–November; in the same way summer drought for this year affected the same months. If we enter the moisture deficit and temperature of the previous month as variables (combining climatic and soil variables), the relationship between those independent variables and litter fall turns out to be direct and significant (Fig. 4). Reich and Borchert (1984) also showed how drought constrains different plant phenologies and litter fall in tropical forests. Different studies have reported this relationship between dry conditions during the growth period and the timing of needle fall in different coniferous forests (Cromer et al., 1984; Kumar Das and Ramakrishnan, 1985; Hennessey et al., 1992; Pausas, 1997). Huebschmann et al. (1999) modelled annual litter fall in *Pinus echinata* Mill. stands and found that litter fall at the end of a particular growing season is a function of the average temperature during the spring, when the needles formed, and site index.

Although we found slight differences in some nutrient content (N, K) in litter fall throughout months and seasons of the year, there was no common trend in other studies published about this issue. Ca is the most abundant element in litter fall nutrient content, as the greatest needs for Ca is in the leaves. Similar levels were found in *Pinus halepensis* (Rapp, 1974) and *P. sylvestris* (Santa Regina et al., 1989) in Mediterranean ecosystems. Sometimes low contents of N in soil can promote low levels of the element in leaves, as occurs in our work, even though N is usually quite abundant in these organs (Rodin and Bazilevich, 1967; Volay, 1975). There are few studies concerning foliar nutrient responses of coniferous species to thinning. Wollum and Schubert (1975) found no changes in foliar nutrient concentrations in ponderosa pine; other authors reported large annual and geographical variations in foliar N, P and K concentrations after thinning in diverse species, but only slight differences between thinned and unthinned stands (Möller et al., 1991).

We did not find significant differences in litter fall nutrient content for P, Ca and Mg between months. Since we only measured nutrient contents in litter fall, other ecological processes such as translocation could be hiding the differences between months (Addicott and Lyon, 1973; Escudero and del Arco, 1987). Also, nutrients that are not resorbed at all increase their concentration owing to the weight loss of needles during senescence as a consequence of the reduction in water content, other mobile nutrients and compounds such as carbohydrates (Cañellas and San Miguel, 1998). This kind of studies should be complemented with nutrients content measurements on crown needles to assess those ecological processes, possible differences between months or the effects of human activities.

The effects of thinning on litter fall have been studied in two periods. Firstly the interval of 1986–1991 after thinning in 1984, and secondly the period of 1993–1995, after the second thinning in 1992. We did not report a growing trend in litter fall after thinning as other authors have done (Cousens, 1988); however the effect of thinning on stands has been noted. The untreated stands (control and never thinned) produced, in general, the largest amount of litter fall compared with treated stands, as has been tested in other works (Harrington and Edwards, 1999). Two years after the first thinning, litter fall was significantly different among all treatments (C, T_1 and T_2) but from the third year after the first thinning of 1984 only litter fall from treatment T_2 was different from the control and the light thinning stands. Five years after thinning, the effect on litter fall had disappeared, probably due to the recovery of canopy in thinned plots. The second thinning of 1992 created differences between the control stand and both thinned stands. In the same way, Huebschmann et al. (1999) on *P. echinata* stands found that litter fall weights were significantly and positively correlated with stocking levels. There was often considerable variation in litter fall amounts within and between thinning treatments, as well as between growing seasons.

Both times (1984 and 1992) thinning type was low, eliminating smallest, worst formed and generally dominated trees. Dominated trees do not contribute to litter fall production at stand level too much because of their small crown size (Inagaki et al., 2003). That could be one of the reasons that explains the low difference at litter fall production between thinned and control stands.

To evaluate the sustainability of the thinnings, it is necessary to deeply study their effects on the production and nutrients content of litter fall with regard to thinning rotation. In that sense, at least, the interval between two thinnings must be long enough to allow the forest to recover the extracted biomass and nutrients (Rubio and Escudero, 2003). In Fuencaliente where low, light or moderate thinnings have been applied, there are no differences in litter fall production among treatments 5 years after the fellings (Table 6) which implies the recovery of the canopy at that term. However, after including processes, such as mineralization or decomposition in their studies, different authors (Rolff and Agren, 1999; Rubio and Escudero, 2003) advise lengthening rotation even more and reducing the number of thinnings.

Mediterranean type ecosystems are characterized by hot, dry summers and warm, wet winters. This temporal asynchrony of favourable temperature and moisture conditions could limit rates of litter decomposition (Kimmins, 1987; Hart et al., 1992). Although some authors have found similar decomposition rates in Mediterranean and temperate ecosystems despite their climatic differences, low initial litter quality seems to limit decomposition rates, as happens in *Pinus* forests, whose leaves are rich in resistant components (Moro and Domingo, 2000). Consequently, even when thinning does not seem to accelerate nutrient turnover to soil (Montero et al., 1999), it is an effective tool to avoid litter accumulation on soil.

The silvopastoral aptitude of Mediterranean *Pinus* forests can be enhanced through thinning treatments. Even though these considerations have not been evaluated in this work, it would be interesting to bear them in mind for future experiences. Litter fall amount is related to the abundance of understory species, which can be considered as a limiting factor to regeneration (Oliver and Larson, 1990) or even as an important pastoral resource for livestock in a silvopastoral use (Étienne, 1996). Harrington and Edwards (1999) studied the effect of thinning in dense plantations of longleaf pine at an intensity comparable with this study and the treatment provided increases in light availability and decreases in litter fall sufficient to promote herbaceous species both concerning density and abundance. The combination of thinning, seedling and livestock or game grazing has established its ability to create productive and sustainable agroforestry systems in Mediterranean areas (Papanastasis et al., 1995).

Acknowledgements

The authors would like to thank all who collaborated in field data collection, especially A. Bachiller and R. Ruiz-Peinado. This work was carried out within the framework of the INIA research project OT03-002.

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