

Erratum to: Litterfall, litter decomposition and associated nutrient fluxes in *Pinus halepensis*: influence of tree removal intensity in a Mediterranean forest

Luis Lado-Monserrat¹ · Antonio Lidón¹ · Inmaculada Bautista¹

Received: 17 February 2015 / Revised: 2 June 2015 / Accepted: 17 June 2015 / Published online: 27 November 2015
© Springer-Verlag Berlin Heidelberg 2015

Abstract Our knowledge about the influence of silvicultural treatments on nutrient cycling processes in Mediterranean forests is still limited. Four levels of tree removal were compared in an Aleppo pine forest in eastern Spain to determine the effects on litterfall, litter decomposition and the associated nutrient fluxes after 12 years. Removal treatments included clearfelling, two shelterwood intensities (60 and 75 % of basal area removed) and untreated controls. Twelve years later, the basal area removed still explained 60 % of litterfall mass variance and 60 % of C, 52 % of N, 45 % of P, 17 % of K, 47 % of Ca and 60 % of Mg return variances. Litter decomposed somewhat more slowly in clearfellings compared to controls ($p = 0.049$), accumulated more Ca and released less K compared to the other three treatments. This was explained by contamination with mineral particles due to the poorly developed O horizon in clearfellings. We conclude that the management practices reduced the nutrient

return via litterfall, but the nutrient release through decomposition seems poorly sensitive to canopy disturbance. In order to accurately quantify the harvesting impacts on nutrient cycling in this Mediterranean forest system, it is necessary to measure the litterfall of the understory layer.

Keywords Carbon cycle · Nutrient cycling · Shelterwood · Clearfelling · Eastern Spain

Introduction

In recent years, abandonment has been considered a crucial factor influencing Mediterranean forests (Fabbio et al. 2003). Most of these forested areas are pioneer ecosystems that should be managed to increase their ecological value and their resistance to fire and pests (Scarascia-Mugnozza et al. 2000). In the Mediterranean, silvicultural treatments have been postulated as a way to increase tree species richness (Torras and Saura 2008), to augment water yields (Molina and Del Campo 2012) or to reduce fire intensity (Alvarez et al. 2012). In this scenario, it is important to take into account how these practices influence ecosystem stability and functioning to ensure sustainable forest management.

A good knowledge of the impacts that harvesting practices have on nutrient cycling processes is needed to evaluate the sustainability of forest management systems (Kimmins 2004). Litter production and its subsequent decomposition constitute the main aboveground path of nutrients to soil. Therefore, they are common components of mathematical models used to forecast the implications of management at the ecosystem level (e.g. Kimmins et al. 1999; Blanco et al. 2005; Petritsch et al. 2007). Silvicultural treatments that reduce the forest canopy are expected

Communicated by Jarmo Holopainen.

The online version of the original article can be found under doi:10.1007/s10342-015-0893-z.

Unfortunately there are few errors in the originally published article and those mistakes have been corrected in this erratum.

Electronic supplementary material The online version of this article (doi:10.1007/s10342-015-0923-x) contains supplementary material, which is available to authorized users.

✉ Luis Lado-Monserrat
luilamon@mcm.upv.es

¹ Research Group in Forest Science and Technology (Re-Forest), Departamento de Ingeniería Hidráulica y Medio Ambiente, Universitat Politècnica de València, Camino de Vera, S/N, 46022 Valencia, Spain

to reduce nutrient return to soil through litterfall (Prescott 2002; Blanco et al. 2008). This could lead to reduced soil nutrient availability in the long term, depending on intensity of treatments and rotation period duration (Blanco et al. 2005). Besides, changes in the litter production–decomposition balance can modify forest floor layer size, which has been considered to be either a nutrient reservoir that gradually provides nutrients or a temporal obstacle to tree nutrient availability due to immobilisation processes (Roig et al. 2005; Jonard et al. 2006). Litterfall and litter decomposition fluxes are especially important for nutrient budgets in ecosystems whose environmental conditions limit tree vegetation growth (Caldentey et al. 2001). This highlights the pressing need for experimental data to optimise management practices in order to prevent nutrient overexploitation in Mediterranean forests, which usually develop on nutrient-poor soils and are submitted to strong water limitations (which are expected to increase in the future due to climate change; Christensen et al. 2013). Paradoxically, such information for these ecosystems is comparatively scarce.

Litter production seems to decrease proportionally with the stand basal area (Hennessey et al. 1992; Kunhamu et al. 2009; Navarro et al. 2013; Trofymow et al. 1991). Nonetheless, the mechanisms behind reduced litter production are not straightforward. According to Blanco et al. (2006), the forest response to management practices is controlled by several factors and their interaction (e.g. tree species, climatic conditions). Hence it is difficult to predict changes in litter production. The same conclusion can be applied to litter decomposition rates. Thus the literature presents contradictory responses of litter decomposition to partial or total canopy removal, with decreases (Blanco et al. 2011; Prescott 1997; Blair and Crossley 1988), increases (Caldentey et al. 2001; Bates et al. 2007) or no effect (Lytle and Cronan 1998; Wallace and Freedman 1986) in decay rates. Climate has been proposed to be able to explain these different behaviours (Yin et al. 1989). Thus, clearcutting may stimulate decomposition in cold climates because of an increase in soil temperature, whereas decomposition would be inhibited in warm climates as a result of more intense forest floor drying. Although previous studies conducted under Mediterranean conditions coincide with this hypothesis (Cortina and Vallejo 1994), we should be careful when generalising about this issue (Prescott et al. 2000).

Despite all this being true, the consequences that tree harvesting has on nutrient fluxes can be influenced by other interfering factors beyond litter mass production and the decomposition rates of dry matter. For instance, Guo and Sims (1999) reported that tree density affected P release from decomposing litter, but not N release and mass loss rates. Similarly in a *Pinus densiflora* stand, Kim et al.

(2012) reported that partial cuttings significantly reduced the C, N, P and Ca returns to soil via litterfall, but not K and Mg. Moreover, studies have often focused on N and P fluxes as they are most limiting, which means that less information on other macronutrients is available.

Pinus halepensis is a widely distributed tree species in the western Mediterranean basin, but very little information on the impacts of harvesting treatments on its litter production and decomposition nutrient fluxes is available. In a naturally regenerated forest 5 years after a fire, Sardans et al. (2005) reported how nutrient returns through litterfall were affected by removing competing vegetation in an area covering 1 m² around trees. Recently, Navarro et al. (2013) analysed the effect of thinning intensity on litterfall mass production in a 15-year-old *P. halepensis* afforestation area. In the present study, we offer experimental data regarding the effects of management intensity on litter production, litter decomposition and the associated transfers of nutrients (C, N, P, K, Ca and Mg) in a 55-year-old *P. halepensis* forest in the eastern Iberian Peninsula. Treatments were carried out in experimental plots (30 m × 30 m) and included two shelterwood intensities (60 and 75 % of basal area removed), clearfellings and untreated controls. This study was conducted 12 years after intervention. We hypothesised that: (1) litter production and nutrient returns through litterfall will be proportionally reduced with harvesting intensity given the reduced canopy cover; (2) the litter decomposition rate and concomitant nutrient releases will be inversely related to tree canopy removal as a result of increased water limitations.

Materials and methods

Study area and silvicultural treatments

The study area is located closely to the *Alto de la Montalbana* (39°49'26"N; 1°05'47"W, 980 m a.s.l.) in Tuéjar, the province of Valencia, eastern Spain. The climate is Mediterranean type, with dry summers. According to data from the Titaguas station (832 m a.s.l.) for the 1960–1990 period, mean annual temperature is 12.5 °C and mean annual precipitation is 457 mm, with a minimum in summer of 45 mm (Pérez Cueva 1994). The *P. halepensis* Mill. forest resulted from natural regeneration of abandoned agricultural fields. Mean tree age was 55 years when management treatments were applied (1998). The understorey community is dominated by *Quercus coccifera*, *Juniperus oxycedrus*, *Juniperus phoenicea* and *Brachypodium retusum*, with the scant presence of suppressed *Quercus rotundifolia*. Soils in the area are Rendzic Leptosols that develop on calcareous rock, with outcrops of Albic Luvisols and Calcaric Regosols (GVA 1995).

In the spring of 1998, an experimental study began to compare different silvicultural systems on this *P. halepensis* stand. The main goal of these silvicultural systems was to convert the stand into a mixed forest of *P. halepensis* and *Q. rotundifolia* to increase its biological diversity and resilience. Treatments were carried out following a randomised block design, with four treatments and three blocks. The distance among the three blocks was less than 3 km. They had a similar slope (<5 %), canopy and climatic characteristics, but contrasting soil properties (Table 1). In each block, four experimental square plots (30 m × 30 m) were selected, one per treatment. Treatments were: (1) T0: untreated control reference; (2) T60: moderate shelterwood with 60 % of mean basal area

removed; (3) T75: strong shelterwood with 75 % of mean basal area removed; (4) T100: clearfelling (100 % of mean basal area removed). To avoid edge effects, all the treatments were also applied in a strip of 7.5 m around the plots. In all the treatments, stems were removed, and logging residues (branches, needles, cones, etc.) were left in piles in plots. In the shelterwood treatments, no preparatory cuttings were previously performed. Sheltered trees were selected among diameter classes 20 and 25 (DBH, in cm) and were chosen in an attempt to achieve homogeneous spatial distribution in the whole plot. Thus removed trees were mainly suppressed individuals, but some were also dominant. Table 2 summarises the dendrometric parameters that resulted from the shelterwood cuttings.

Table 1 Soil properties in the three study blocks

Block	Location	Depth (cm) ^a	Clay (%)	Silt (%)	Sand (%)	pH	Corg ^b (mg g ⁻¹)	C ^c (mg g ⁻¹)	N ^c (mg g ⁻¹)	P ^c (mg g ⁻¹)	K ^c (mg g ⁻¹)	Ca ^c (mg g ⁻¹)	Mg ^c (mg g ⁻¹)	C:N
I	Tuéjar Left	0–2*	–	–	–	6.0	367	402.0	16.8	0.44	4.2	18.5	2.29	21.8
		2–6	36.0	39.0	25.0	8.2	60	75.6	3.4	0.22	18.3	36.1	6.01	17.6
		6–10	42.0	39.7	18.3	8.2	41	52.2	2.6	0.23	20.6	30.1	6.45	15.8
II	Tuéjar Right	0–5*	–	–	–	7.8	103	124.0	5.5	0.24	15.3	34.5	5.28	18.7
		5–18	36.0	43.7	20.2	8.3	36	63.1	2.4	0.15	16.0	56.5	5.51	15.0
		18–25	36.0	42.0	22.0	8.3	39	78.1	3.0	0.24	13.2	90.1	4.91	13.0
		25–52	34.0	39.5	26.5	8.4	21	81.0	1.9	0.21	10.5	147.2	4.36	11.0
		>52	28.0	37.7	34.2	8.5	12	94.5	0.9	0.12	6.4	169.5	3.26	13.3
III	Chelva	0–2*	–	–	–	6.4	144	144.0	6.8	0.25	3.6	8.6	1.70	21.2
		2–16	18.0	15.7	66.2	8.0	10	13.7	1.0	0.07	6.3	4.1	2.19	10.0
		16–35	30.0	24.5	45.5	8.5	14	65.9	1.8	0.21	9.3	127.4	3.18	7.7
		>35	18.0	27.2	54.7	8.4	11	111.0	1.2	0.17	2.0	184.6	1.30	9.1

^a Asterisks indicate organic horizons

^b Organic carbon

^c Total content

Table 2 Characterisation of the shelterwood treatments

Block	Plot	Basal area (m ² ha ⁻¹)			Density (stems ha ⁻¹)		Forest cover (%)
		Pre-treatment	1999 ^a	2004 ^b	1999 ^a	2004 ^b	1999 ^a
I	T0	27.7	27.3	30.4	1067	833	87.3
	T60	29.5	11.1	15.2	286	286	37.9
	T75	30.4	7.8	12.0	212	207	17.2
II	T0	36.2	37.9	39.4	1167	756	93.7
	T60	29.8	11.6	15.2	331	311	44.7
	T75	26.8	7.4	10.5	188	178	21.4
III	T0	28.9	29.1	32.7	1000	800	85.4
	T60	25.2	11.9	14.8	331	316	34.1
	T75	27.0	7.4	10.0	212	198	19.8

^a Galiana et al. (2001)

^b González Utrillas et al. (2005)

Microclimate

Soil temperature (5 cm depth) was measured in all the plots with soil temperature probes (RT-1, Decagon Devices), except the T75 plots of blocks II and III. Understory air temperature (1.5 m height) was also measured in the T0, T60 and T100 plots of block I with temperature probes (ECT-S, Decagon Devices). Rainfall was measured in the T100 plot of block II with a rainfall recorder (ECH2O rain, Decagon Devices). All the probes were attached to dataloggers (EM50, Decagon Devices), which recorded data at hourly intervals. The monthly temperature average and accumulated monthly precipitation values were obtained. The microclimatic variables were measured during the period covering October 2009–October 2011.

Litter production

The litterfall traps used in this study were constructed with plastic boxes with an opening of $60 \times 40 \text{ cm}^2$ which were 30 cm high and with a plastic mesh (1.2 mm mesh size) attached to the inside. These shallow boxes, which were deployed directly on the soil surface, were used to ensure also collecting the understory litterfall. Twelve traps were distributed randomly in each plot. Litterfall was collected monthly for 2 years, from November 2009 to October 2011. The material from each litter trap was sorted into six fractions: *needle*, *branch*, *bark*, *cone*, *other organs* and *miscellaneous* (other species than *P. halepensis*). Samples were dried in the laboratory at 65 °C for 72 h and weighed.

Litter decomposition

Litterbags ($15 \times 20 \text{ cm}^2$) were constructed with fibre glass mesh (1.5 mm mesh) and sewn with nylon. The filling material, freshly fallen intact needles, was collected from the top of the OL layer in each block in July 2009 and was left to air dry in the laboratory. Next 180 litterbags were filled with 10 g of this material per block. In each plot, 45 bags were attached to the surface with metal pins at the beginning of October 2009, and three bags per plot were retrieved at 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 22 and 24 months after being installed. On each sampling date, the litterbags were transported to the laboratory in sealed plastic bags. Bag content was cleaned of foreign material with a brush and weighed. Then samples were dried at 65 °C for 72 h and weighed again.

Nutrient content analyses

The monthly dynamics of the litterfall nutrient concentration was obtained for the year 2010. A composite sample was prepared for each month and block for both the *needles*

and *miscellaneous* fractions. Another sample was also prepared for each block and season for the other fractions. Additionally, the effect of silvicultural treatments on the litterfall nutrient concentration was evaluated for the *needle* and *miscellaneous* fractions in the summer peaks of litterfall production. Nutrients were analysed for each plot on both the summer peak sampling dates, which corresponded to August 2010 and July 2011. The nutrient concentration was also analysed for the decomposing needles in each plot when litterbags remained in the field for 6, 12, 18 and 24 months. The nutrient content of the initial material (0 months) was also obtained.

The litterfall and litterbag samples were milled and sieved to 500 μm . Total C and total N were determined by a total analyser (FLASH EA 1112 SERIES-LECO TRUSPEC). The P, K, Ca and Mg contents were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES; ICAP 6500 DUO/IRIS INTREPID II XDL), after acid digestion ($\text{HNO}_3\text{--H}_2\text{O}_2$ 4:1) in a microwave.

Data analyses

The returns of nutrients to soil through litterfall for 2010 were obtained by multiplying the corresponding mass production (kg ha^{-1}) by the nutrient concentration (kg kg^{-1}), and by adding up all months and fractions.

In relation to needle decomposition, Olson's (1963) decay rate coefficients (k) were obtained as:

$$W_t = W_0 e^{-kt}$$

where t is time (year), W_t is dry weight at time t (g), W_0 is the initial dry weight (g) and k the annual decay constant (year^{-1}).

The nutrients release from decomposing needles was also obtained as (Entry et al. 1991):

$$N_t = C_0 - [(1 - W)C_t]$$

where N_t is the amount of nutrient released or absorbed at time t (g/100g), C_0 is the initial nutrient litter concentration (g/100g), W is weight loss at time t (%/100) and C_t is the nutrient litter concentration at time t (g/100g).

The effects of block and silvicultural treatment on litterfall production, nutrient return via litterfall, needle-litter mass loss, decomposing needles moisture, the nutrient concentration of decomposing needles and nutrient release from decomposed needles were tested with repeated-measures ANOVAs, where time was the within-subject factor. In the litter decomposition variables, these differences were also tested for each date separately by two-way ANOVAs, where block and silvicultural treatment were the factors. Differences in the *needle* and *miscellaneous* litterfall nutrient concentrations on the summer production peak

dates were analysed with three-way ANOVAs, with silvicultural treatment, block and year used as the factors. Differences in Olson’s k values were analysed with a two-way ANOVA, where block and silvicultural treatment were the factors. In some cases, $\ln(x + 1)$ transformation was used to achieve homoscedasticity (Levene’s test) and approximate normality. When the ANOVAs indicated significant differences between silvicultural treatments, the Tukey’s HSD post hoc test was used. If Levene’s test indicated unequal variances of transformed data, then Tamhane’s T2 post hoc test was used. All the statistical analyses were performed with SPSS v. 16.

Results and discussion

Microclimate

The precipitation observed during the observation period was 804 mm and 545 mm for year 1 and year 2, respectively (Fig. 1a). The mean annual soil temperature at the 5 cm depth was clearly higher in clearfelling (15.6 °C, Fig. 1b) compared to the other treatments (10.4, 11.3 and 12.0 °C in T75, T60 and T0, respectively). These observations contrast with the understory air temperature data, which obtained similar monthly values in the three plots where data were available (Fig. 1c).

Litter production

Twelve years after the interventions, all the litterfall fractions considered in this study were significantly affected by treatment, whereas block was not a significant factor (Table 3). The *P. halepensis* litterfall production (i.e. total litterfall excluding the *miscellaneous* fraction) decreased compared to the untreated forest by 33.5 % for T60, 59.8 % for T75 and 95.8 % for T100. The reduction effect was observed for all the fractions, except *miscellaneous*. This fraction increased quantitatively with treatment intensity. For total litterfall, we found significant differences among all the silvicultural treatments, but not between the two shelterwood treatments in year 1 (Table 3). Similarly, Navarro et al. (2013) reported a significant drop of *P. halepensis* litterfall production in an intense thinning treatment compared to the control, but no differences among the intermediate thinning intensities tested in their experiment (75, 60 and 48 % of basal area removed) were found. The authors attributed such lack of differences to the broad variability between trees and plots, but only 1 year of litterfall data was analysed (Navarro et al. 2013). In our case, no significant differences were observed between shelterwood intensities, but this was true only for year 1 (Table 3). The different behaviour noted

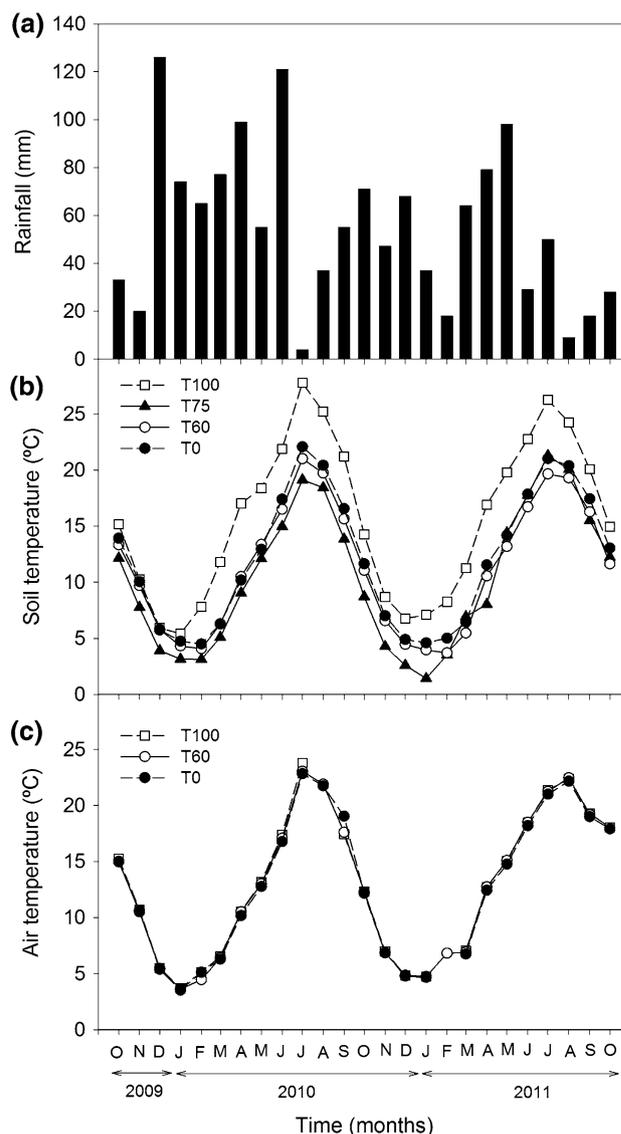


Fig. 1 Monthly precipitation (a), monthly average soil temperature at the 5 cm depth (b) and monthly average understory air temperature at the 1.5 m height (c). Precipitation was measured in the T100 plot of block II. Soil temperature was measured in all the plots, except the T75 plots of blocks II and III. Understory air temperature (1.5 m high) was measured in the T0, T60 and T100 plots of block I

between years can be explained by environmental factors, such as wind or snow, which can modify the year-to-year relationship between stand density and litterfall (Inagaki et al. 2008; Klemmedson et al. 1990). Nevertheless, the analysis of the relationship between basal area removed and the litterfall amount depicted in Fig. 2a proved to be a more appropriate approach to assess this question (Binkley 2008). Thus the similar slope that we found for both years suggests no appreciable differences between years in the litterfall response to cutting intensity.

The litterfall dynamics throughout the year showed a high peak of total litter production in summer (Fig. 2b),

Table 3 Characterisation of litterfall production in the two study years

	Fraction (kg ha ⁻¹ year ⁻¹)						Total
	Needles	Branches	Bark	Cones	Other organs	Miscellaneous	
Year 1							
T0	2080 ± 368a	146 ± 226a	151 ± 81a	122 ± 196a	71 ± 47a	84 ± 61a	2653 ± 612a
T60	1503 ± 558b	30 ± 63b	89 ± 78b	68 ± 174b	42 ± 32b	141 ± 202a	1873 ± 846b
T75	951 ± 498c	24 ± 73b	51 ± 71c	20 ± 73c	29 ± 22b	151 ± 200ab	1226 ± 666b
T100	81 ± 206d	1 ± 2c	2 ± 4d	1 ± 2d	2 ± 2c	265 ± 267b	351 ± 332c
Year 2							
T0	2218 ± 410a	177 ± 224a	278 ± 119a	75 ± 138a	323 ± 102a	99 ± 84a	3170 ± 687a
T60	1399 ± 505b	113 ± 287b	188 ± 143b	48 ± 161b	270 ± 137b	222 ± 293ab	2241 ± 871b
T75	879 ± 454c	15 ± 29b	96 ± 89c	28 ± 64b	170 ± 116c	227 ± 189bc	1416 ± 680c
T100	140 ± 298d	1 ± 3c	4 ± 7d	0 ± 0c	7 ± 15d	425 ± 393c	576 ± 515d

Mean values ± standard deviation. Lower case letters denote post hoc significant differences ($p < 0.05$) for the factor silvicultural treatment. The block factor was not significant in any case

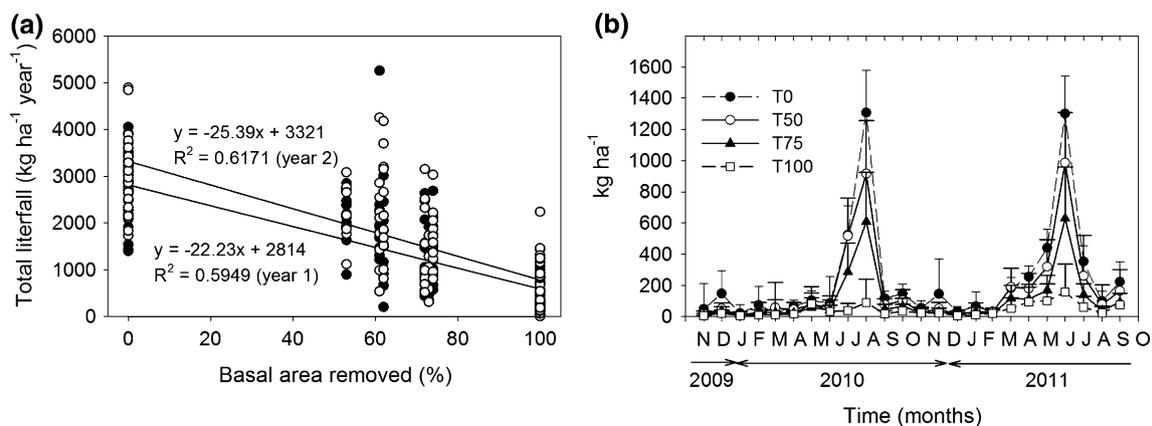


Fig. 2 Relationship between basal area removed and total litterfall (a) and the monthly dynamics of total litterfall in each silvicultural treatment (b). Black circles represent year 1, and white circles represent year 2 in (a)

which is the typical pattern of this species (García-Plé et al. 1995; Navarro et al. 2013). In the clearfelling plots, however, a dramatic change in the distribution of fractions occurred, which smoothed the monthly dynamic pattern (Fig. 2b). The importance of the needle fraction in our T100 plots (23 % of total weight) was not as strong as the 54 % reported by Klemmedson et al. (1990) in clearcuts of Ponderosa pine, probably because of the perimeter trees in our 45 × 45 m² squares (including the buffering zone) having less influence versus their 18-m-wide strips. Interestingly, the modification of the litterfall composition and its monthly pattern attributable to clearfelling was not reflected in deviations in the regression analysis (Fig. 2a). One question that remains unclear is how long this relationship would remain proportional. In clearfelling, we observed the incipient recovering of *P. halepensis*, with some individuals >2 m height, which anticipates major

changes in the amount, composition and dynamics of litterfall in the short term.

Litterfall nutrient content and nutrient return to soil

The nutrient concentrations of senescent *P. halepensis* needles in summer production peaks were more affected by the block factor (i.e. soil type) than by silvicultural treatments (Table 4), and this result coincides with the findings of other authors (Blanco et al. 2008; Inagaki et al. 2008). For N, P and K, lack of differences due to the management practices can be explained by the buffering effect of retranslocation from needles to other plant organs before abscission. Calcium was abundant in our study soils, which developed on calcareous bedrocks (Table 1) and was expected, therefore, to be non-limiting. Mg was the only macronutrient to be significantly affected by the treatment

Table 4 Results of the three-way ANOVA (no replication) with factors silvicultural treatment, block and year on the nutrient concentration of the *needle* and *miscellaneous* litterfall fractions in the summer peaks of production

Factors	Concentration (mg g ⁻¹)											
	Needle						Miscellaneous					
	C	N	P	K	Ca	Mg	C	N	P	K	Ca	Mg
Treatment												
T0	536.6	5.19	0.16	0.95	7.54	1.03a	505.4	8.90	0.39	1.59a	13.10	0.96a
T60	533.9	5.53	0.18	0.91	7.58	0.85b	520.4	7.12	0.27	3.00ab	13.77	1.04ab
T75	540.3	5.84	0.18	0.96	6.37	0.83b	517.1	8.24	0.35	2.89ab	13.17	0.97a
T100	533.8	5.85	0.18	0.99	7.00	0.83b	510.4	7.15	0.28	3.39b	13.72	1.34b
<i>p</i>	N.S.	N.S.	N.S.	N.S.	N.S.	0.002	N.S.	N.S.	N.S.	0.013	N.S.	0.011
Block												
I	535.3	5.40a	0.19a	1.09a	7.93a	0.92ab	522.9a	7.62	0.34	3.56a	14.46	1.20
II	536.8	5.39a	0.17ab	0.83b	7.15ab	0.93a	510.1ab	7.34	0.29	2.43b	14.14	1.09
III	536.5	6.02b	0.16b	0.94ab	6.28b	0.81b	507.0b	8.60	0.33	2.17b	11.71	0.94
<i>p</i>	N.S.	0.048	0.013	0.006	0.003	0.022	0.029	N.S.	N.S.	0.012	N.S.	N.S.
Year												
1	536.3	5.61	0.18	0.87	7.31	0.93	513.5	7.71	0.31	2.32	13.05	1.06
2	536.1	5.59	0.16	1.04	6.93	0.84	513.1	7.99	0.33	3.12	13.82	1.09
<i>p</i>	N.S.	N.S.	N.S.	0.008	N.S.	0.014	N.S.	N.S.	N.S.	0.039	N.S.	N.S.

p < 0.05 is indicated in bold

factor. The Mg concentration in the T0 plots (1.03 mg g⁻¹; Table 4) was significantly higher than the concentration found in the needles of the treated plots (0.83 mg g⁻¹ on average). One possible explanation for this would be an increase in tree nutrient availability as a result of cuttings. For example, magnesium uptake could lower by increased ammonium availability because both cations compete in root uptake (Slovik 1997). Along these lines, Sardans et al. (2005) reported that N and P fertilisation lowered the Mg concentration of litterfall in *P. halepensis* trees. In the light of our Mg results, it is possible that the trees that remained after the shelterwood cuttings, as well as the perimeter trees of the clearfelling plots, were still exposed to fewer nutrient restrictions (lower intraspecific competition) 12 years after implementing the treatments.

Treatments apparently affected the nutrient returns of the year 2010 (shown in Table 5) by controlling litter mass production rather than its nutrient concentration, which coincides with other reports in the bibliography (Blanco et al. 2008; Kim et al. 1996b, Klemmedson et al. 1990). Concomitantly with litter production, no differences between the T60 and the T75 treatments were found in the return of any nutrient for the year 2010 (Table 5). Reductions in nutrient return were also linearly related to treatment intensity (Table 5), which reinforces the first hypothesis of our work. The response to cutting intensity was similar to all the nutrients, and only K showed a remarkably lower sensitivity

to harvest ($r^2 = 0.17$; Table 5). The effect of canopy removal on K supply was buffered by understory contributions: e.g. in treatment T75, the portion of the yearly K return owing to the needle fraction was 51 %, but the portion due to the miscellaneous fraction was as high as 39 % (data not shown). In any case, any conclusions that can be drawn from our nutrient return data should be interpreted with caution as we studied it for a year that was particularly wet. Under Mediterranean conditions, Roig et al. (2005) observed that a longer summer drought was associated with a prolonged duration of the litterfall production peak in *P. pinaster* stands. It is possible that the differences between treatments could be intensified in our plots in dry years, but this remains to be confirmed.

Litter decay rates

In our 2-year study, the decay rate coefficients *k* analyses (Fig. 3a) indicated only lower decomposition in clear-fellings in comparison with the untreated plots, but this difference was barely significant ($p = 0.049$). On the contrary, the repeated-measures ANOVA of litter mass loss indicated no significant effect of silvicultural treatment, although it was on the limit of significance ($p = 0.050$). No differences in mass loss or *k* were attributable to the block. The field litter water content at the time of collection was similar on the majority of the sampling dates for all the

Table 5 Total nutrient return via litterfall in the year 2010 for each silvicultural treatment and the associated regression parameters

	C	N	P	K	Ca	Mg
Return ^a (kg ha ⁻¹)						
T0	1376.8 ± 293.3a	15.62 ± 3.54a	0.54 ± 0.14a	2.90 ± 0.72a	24.30 ± 6.25a	2.96 ± 0.64a
T60	1001.7 ± 410.4b	11.72 ± 5.28b	0.42 ± 0.20ab	2.36 ± 1.50ab	17.93 ± 8.84b	1.96 ± 0.84b
T75	648.3 ± 347.5b	7.92 ± 4.18b	0.28 ± 0.16b	1.80 ± 1.27bc	11.21 ± 7.20b	1.31 ± 0.73b
T100	186.3 ± 178.9c	3.09 ± 2.95c	0.11 ± 0.10c	1.34 ± 1.22c	5.61 ± 4.91c	0.54 ± 0.48c
Regr. parameters ^b						
a	-11.429	-0.1203	-0.004	-0.0151	-0.1838	-0.0236
b	1464.5	16.55	0.57	2.98	25.39	3.06
r ²	0.60	0.52	0.45	0.17	0.47	0.60
p	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^a Mean values (standard deviation). Lower case letters denote post hoc significant differences ($p < 0.05$) for the factor silvicultural treatment in each nutrient. The block factor was not significant in any case

^b The parameters estimated for regression $R = aBA + b$, where R is the total yearly nutrient return (kg ha⁻¹) and BA is the percentage of basal area removed by silvicultural treatments (%)

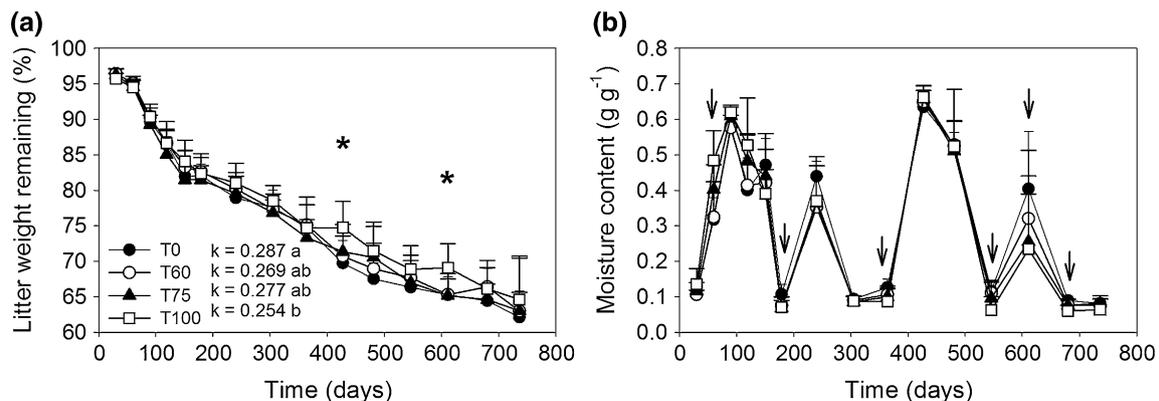


Fig. 3 Percent of the leaf mass remaining in the litterbags (a) and field litter moisture on the sampling dates (b) throughout 2 years for each silvicultural treatment. Asterisks indicate significant differences between clearfelling (T100) and the other treatments. Arrows indicate

significant differences between untreated (T0) and clearfelling (T100). The mean decay constant (k , in year⁻¹) is shown, and different lower case letters indicate significant differences ($p = 0.049$)

silvicultural treatments (Fig. 3b). The main differences were found when litter was obtained at low moisture values, where the highest water contents were encountered in the control plots, and the driest in clearfellings.

The mass loss data of our experiment suggested that clearfelling slowed down the needle decomposition process in comparison with the untreated forest (Fig. 3a), and that litter water content during dry periods was significantly lower in T100 (Fig. 3b). In principle, these results partially support our hypothesis which stated that tree canopy removal would hamper the decomposition process as there would be less moisture on the surface, at least as regards to the T100 treatments. Moreover, the increase in the extremely high soil summer temperatures that we observed (Fig. 1b) has also been suggested as a possible explanation

for lower decomposition rates in clearcuts (Whitford et al. 1981). However, changes in microclimate are not the only explanation for our results, as we discuss later.

Nutrient release through litter decomposition

The shelterwood cuttings did not modify the nutrient concentration dynamics of decomposing needles, although the effect of clearfelling was clearly visible at the end of the study period (Fig. 4). In particular, the needles that decomposed in clearfellings presented a significantly lower C concentration and also considerably higher K and Ca contents. These differences in concentration were expressed as differences in the nutrient release for K and Ca, but not for C (Fig. 5). As a possible explanation, we

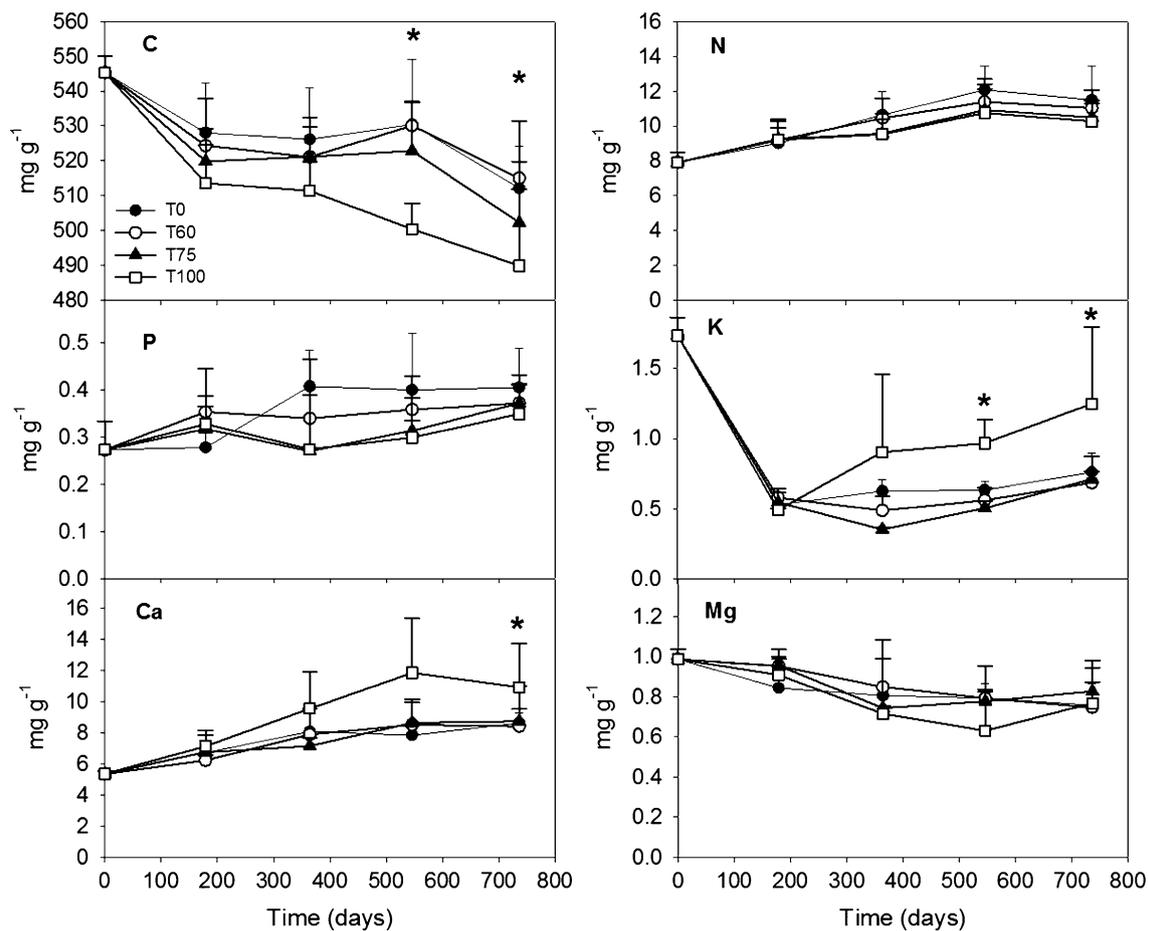


Fig. 4 Nutrient content dynamics in the decomposed litter for each silvicultural treatment. Asterisks indicate significant differences ($p < 0.05$) between clearfelling (T100) and the other treatments. Error bars represent SD

hypothesise a massive mineral particle input into the litterbags of clearfellings, which led to a significant portion of these particles to resist our mechanical brush cleaning. In our T100 plots, a naked-eye examination showed that organic horizon was badly lacking. Litterbags were attached directly to the mineral soil surface in most cases, whereas they were fixed on the O horizon in T0, T60 and T75. Therefore, we expected a higher mineral particle input into T100 due to the wind, splash by raindrops or runoff caused by microtopography. This hypothesis is supported strongly by the higher aluminium concentration of decomposed needles in clearfellings (available online as Supplementary Data Fig. 1a). Al content, considered here as an indicator of the proportion of mineral soil in the sample, explains the lower C concentration, Ca absorption and the poorer K release in the litterbags of the clearfelling plots (Supplementary Data Fig. 1b, 1c and 1d).

The key question that arises here is whether the slightly lower decomposition rates measured in clearfellings are attributable to differences in microclimate (low water availability) or to mineral soil contamination. The

possibility of mineral particles masking an effect prevents us from drawing definitive conclusions about the effects of clearfelling on decomposition mass loss. In fact a slight increase in decomposition is not unconceivable. Almagro and Martínez-Mena (2012) reported a higher decomposition rate of *P. halepensis* litter in an abandoned agricultural field compared with an open forest, with higher plant cover in the latter. They concluded that, due to the recalcitrant chemical composition of Aleppo pine needles, its decomposition was governed mainly by abiotic factors, which were enhanced in the agricultural field. In our study, the T100 treatment increased some abiotic processes associated with higher decomposition rates. We firstly observed a different colour of the needles decomposing in clearfellings (a phenomenon also reported by Kim et al. 1996a), which might be explained by direct exposure to sunlight. In arid and semiarid climates, the role of photodegradation in litter decomposition could be even more important than biological activity (Austin and Vivanco 2006). Secondly, field observations have revealed that frosts were more common and severe in T100. Therefore, frozen litterbags were

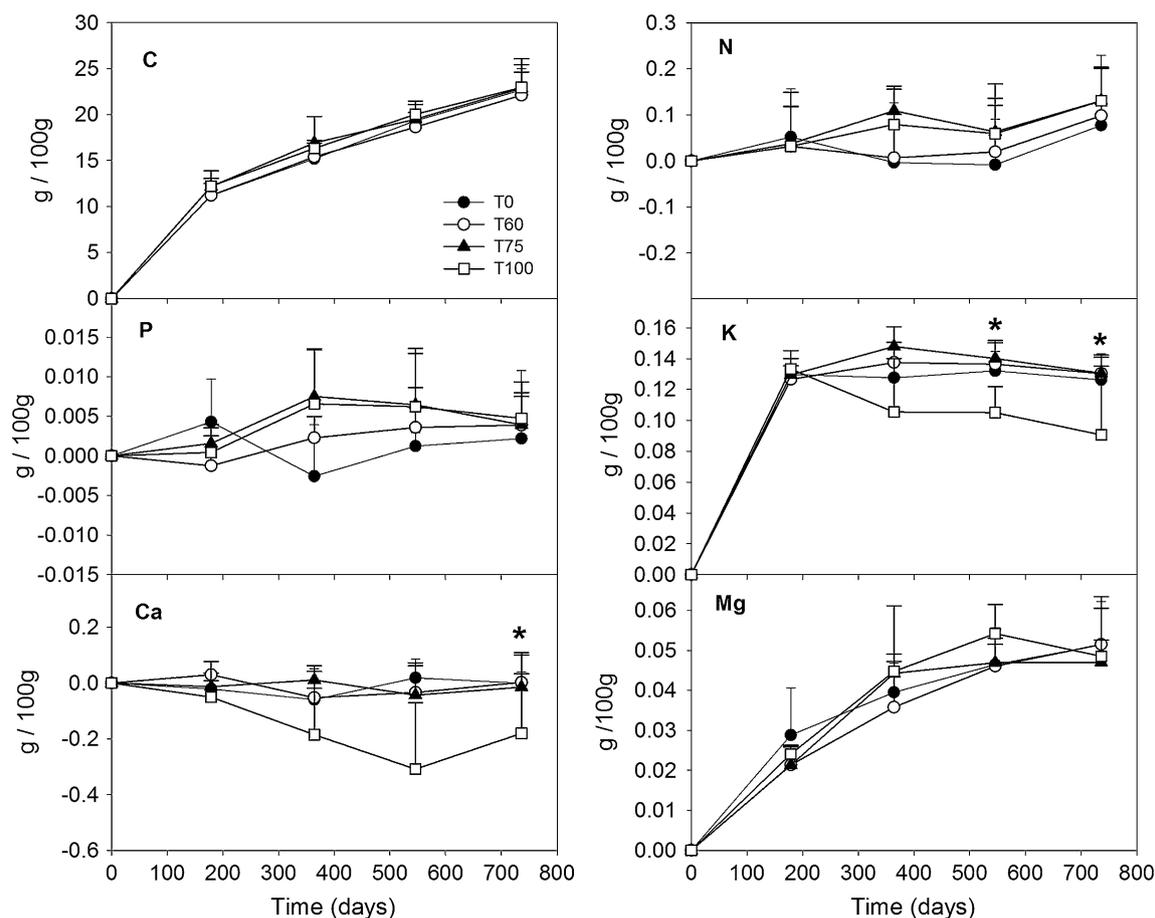


Fig. 5 Nutrients in the decomposing needles released (*positive values*) or absorbed (*negative values*) for each silvicultural treatment. Obtained as (Entry et al. 1991): $N_t = C_0 - [(1 - W) C_t]$, where N_t is the amount of nutrient released or absorbed at time t (g/100g), C_0 is the initial nutrient litter concentration (g/100g), W is weight loss at

time t (%/100) and C_t is the nutrient litter concentration at time t (g/100g). Asterisks indicate significant differences ($p < 0.05$) between clearfelling (T100) and the other treatments. Error bars represent SD

collected more frequently in these plots. This could also stimulate decomposition as freeze–thaw cycles may cause physical damage to litter (Taylor and Parkinson 1988). In any case, the dynamics of N, P and Mg was not significantly affected by either microclimate or mineral particle input, which suggests that the actual effect of clearfelling on needle decomposition was weak in our experiment.

In general, nutrient release through decomposition was not affected by the block factor except in K ($p = 0.008$) and especially for N ($p < 0.001$) (available online as Supplementary Data). These observations are probably related to differences in the chemical composition of the forest floor in the three blocks (Table 1). Nonetheless, the vast differences in N release found herein, associated with the block factor, were not accompanied by a significant block \times treatment interaction ($p = 0.171$). So it can be argued that soil characteristics seem to have very little influence on litter decomposition sensitivity to cuttings. It should be noted that our experimental design allowed us to

evaluate the influence of management on microclimate, but not on litter quality. However, this issue was not apparently important for our study, at least in terms of *P. halepensis* needle nutrient composition as we only found an effect of treatments on its Mg concentration in litterfall (Table 4).

Conclusions

Twelve years after cuttings, the nutrient cycling was modified through reduced nutrient return via litterfall, but the nutrient release through decomposition seems poorly sensitive to management practices. Our results also demonstrate the need to include the shrub layer to obtain an accurate overview of the effects of silvicultural interventions on ecosystem nutrient balances in the long term. In order to optimise nutrient budget management, these observations must be taken into account when making future efforts to analyse and model impacts of harvesting treatments on nutrient cycling in Mediterranean forests.

Acknowledgments This work has been supported by a fellowship from the Generalitat Valenciana, Consellería de Educación, Formación y Empleo awarded to L. Lado-Monserrat (BFPI/2008/041). Silvicultural treatments were carried out by the Mediterranean Centre for Environmental Studies (CEAM) through programme “I + D en relación con la restauración de la cubierta vegetal y otros aspectos de investigación forestal”. Dataloggers and probes were provided by the Generalitat Valenciana through Project “Efecto de diferentes sistemas de aclareo de masa forestal sobre la disponibilidad de agua, nutrientes y la regeneración de la masa arbórea y arbustiva en parcelas de pinar” (GV06/126). We acknowledge Joana Oliver, Ruth M. Tavera and Daniel Fortanet for their help in the laboratory and in the field. The authors wish to thank Francisco Galiana for his assistance, including help in fieldwork and providing information about the experimental design of the silvicultural treatments. Thanks also go to Rafael Herrera from the Centro de Ecología, Instituto Venezolano de Investigaciones Científicas, Caracas, Venezuela and two anonymous reviewers for critically reviewing the manuscript.

References

- Almagro M, Martínez-Mena M (2012) Exploring short-term leaf-litter decomposition dynamics in a Mediterranean ecosystem: dependence on litter type and site conditions. *Plant Soil* 358:323–335
- Alvarez A, Gracia M, Vayreda J, Retana J (2012) Patterns of fuel types and crown fire potential in *Pinus halepensis* forests in the Western Mediterranean Basin. *For Ecol Manage* 270:282–290
- Austin AT, Vivanco L (2006) Plant litter decomposition in a semi-arid ecosystem controlled by photodegradation. *Nature* 442:555–558
- Bates JD, Svejcar TS, Miller RF (2007) Litter decomposition in cut and uncut western juniper woodlands. *J Arid Environ* 70:222–236
- Binkley D (2008) Three key points in the design of forest experiments. *For Ecol Manage* 255:2022–2023
- Blair JM, Crossley DA Jr (1988) Litter decomposition, nitrogen dynamics and litter microarthropods in a southern Appalachian hardwood forest 8 years following clearcutting. *J Appl Ecol* 25:683–698
- Blanco JA, Zavala MA, Imbert JB, Castillo FJ (2005) Sustainability of forest management practices: evaluation through a simulation model of nutrient cycling. *For Ecol Manage* 213:209–228
- Blanco JA, Imbert JB, Castillo FJ (2006) Influence of site characteristics and thinning intensity on litterfall production in two *Pinus sylvestris* L. forests in the western Pyrenees. *For Ecol Manage* 237:342–352
- Blanco JA, Imbert JB, Castillo FJ (2008) Nutrient return via litterfall in two contrasting *Pinus sylvestris* forests in the Pyrenees under different thinning intensities. *For Ecol Manage* 256:1840–1852
- Blanco JA, Imbert JB, Castillo FJ (2011) Thinning affects *Pinus sylvestris* needle decomposition rates and chemistry differently depending on site conditions. *Biogeochemistry* 106:397–414
- Caldentey J, Ibarra M, Hernández J (2001) Litter fluxes and decomposition in *Nothofagus pumilio* stands in the region of Magallanes, Chile. *For Ecol Manage* 148:145–157
- Christensen JH, Krishna Kumar K, et al. (2013) Climate phenomena and their relevance for future regional climate change. In: Stocker TF, Qin D, Plattner G-K et al (Eds.) *Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Cortina J, Vallejo VR (1994) Effects of clearfelling on forest floor accumulation and litter decomposition in a radiata pine plantation. *For Ecol Manage* 70:299–310
- Entry JA, Rose CL, Cromack K Jr (1991) Litter decomposition and nutrient release in ectomycorrhizal mat soils of a Douglas fir ecosystem. *Soil Biol Biochem* 23:285–290
- Fabbio G, Merlo M, Tosi V (2003) Silvicultural management in maintaining biodiversity and resistance of forests in Europe—the Mediterranean region. *J Environ Manage* 67:67–76
- Galiana F, Pérez-Badía R, Camarero E, Estruch V, Currás R (2001) Estimación de la Radiación solar incidente en pinares de *Pinus halepensis* sometidos a tratamientos selvícolas de cortas finales. In: Junta de Andalucía. Consejería de Medio Ambiente (Ed.) *Actas del III Congreso Forestal Español*. Junta de Andalucía. Granada (Original in Spanish)
- García-Plé C, Vanrell P, Morey M (1995) Litter fall and decomposition in a *Pinus halepensis* forest on Mallorca. *J Veg Sci* 6:17–22
- González Utrillas N, González Pérez E, Galiana F (2005) Variación del crecimiento diametral de la masa de pinar de carrasco en cortas finales experimentales, en los montes de Tuejar y Chelva (Valencia). IV Congreso Forestal Español. Zaragoza. Soc. Esp. Cien. For. (Original in Spanish)
- Guo LB, Sims REH (1999) Litter decomposition and nutrient release via litter decomposition in New Zealand eucalypt short rotation forests. *Agric Ecosyst Environ* 75:133–140
- GVA (1995) Mapa de Suelos de la Comunidad Valenciana. Chelva (666). Proyecto LUCDEME (Icona), Centro de Investigaciones sobre Desertificación y Conselleria d’Agricultura i Mig Ambient. Generalitat Valenciana. Valencia, Spain. (Original in Spanish)
- Hennessey TC, Dougherty PM, Cregg BM, Wittwer RF (1992) Annual variation in needle fall of a loblolly pine stand in relation to climate and stand density. *For Ecol Manage* 51:329–338
- Inagaki Y, Kuramoto S, Torii A, Shinomiya Y, Fukata H (2008) Effects of thinning on leaf-fall and leaf-litter nitrogen concentration in hinoki cypress (*Chamaecyparis obtusa* Endlicher) plantation stands in Japan. *For Ecol Manage* 255:1859–1867
- Jonard M, Misson L, Ponette Q (2006) Long-term thinning effects on the forest floor and the foliar nutrient status of Norway spruce stands in the Belgian Ardennes. *Can J For Res* 36:2684–2695
- Kim C, Sharik TL, Jurgensen MF (1996a) Canopy cover effects on mass loss, and nitrogen and phosphorus dynamics from decomposing litter in oak and pine stands in northern Lower Michigan. *For Ecol Manage* 80:13–20
- Kim C, Sharik TL, Jurgensen MF (1996b) Litterfall, nitrogen and phosphorus inputs at various levels of canopy removal in oak and pine stands in northern lower Michigan. *Am Midl Nat* 135:195–204
- Kim C, Son Y, Lee WK, Jeong J, Noh NJ, Kim SR, Yang AR, Ju NG (2012) Influence of forest tending (Soopkakkugi) works on litterfall and nutrient inputs in a *Pinus densiflora* stand. *For Sci Technol* 8:83–88
- Kimmins JP (2004) *Forest ecology, a foundation for sustainable management and environmental ethics in forestry*. Prentice-Hall, New Jersey
- Kimmins JP, Maily D, Seely B (1999) Modelling forest ecosystem net primary production: the hybrid simulation approach used in FORECAST. *Ecol Modell* 122:195–224
- Klemmedson JO, Meier CE, Campbell RE (1990) Litter fall transfers of dry matter and nutrients in ponderosa pine stands. *Can J For Res* 20:1105–1115
- Kunhamu TK, Kumar BM, Viswanath S (2009) Does thinning affect litterfall, litter decomposition, and associated nutrient release in *Acacia mangium* stands of Kerala in peninsular India? *Can J For Res* 39:792–801

- Lytle DE, Cronan CS (1998) Comparative soil CO₂ evolution, litter decay, and root dynamics in clearcut and uncut spruce–fir forest. *For Ecol Manage* 103:121–128
- Molina AJ, Del Campo AD (2012) The effects of experimental thinning on throughfall and stemflow: a contribution towards hydrology-oriented silviculture in Aleppo pine plantations. *For Ecol Manage* 269:206–213
- Navarro FB, Romero-Freire A, Del Castillo T, Foronda A, Jiménez MN, Ripoll MA, Sánchez-Miranda A, Hutsinger L, Fernández-Ondoño E (2013) Effects of thinning on litterfall were found after years in a *Pinus halepensis* afforestation area at tree and stand levels. *For Ecol Manage* 289:354–362
- Olson JS (1963) Energy storage and the balance of producers and decomposers in ecological systems. *Ecology* 44:322–331
- Pérez Cueva AJ (1994) Atlas Climático de la Comunidad Valenciana. Colección Territori n° 4. Generalitat Valenciana. Conselleria d'Obres Publiques, Urbanisme i Transport, Valencia
- Petrtsch R, Hasenauer H, Pietsch SA (2007) Incorporating forest growth response to thinning within biome-BGC. *For Ecol Manage* 242:324–336
- Prescott CE (1997) Effects of clearcutting and alternative silvicultural systems on rates of decomposition and nitrogen mineralization in a coastal montane coniferous forest. *For Ecol Manage* 95:253–260
- Prescott CE (2002) The influence of the forest canopy on nutrient cycling. *Tree Physiol* 22:1193–1200
- Prescott CE, Blevins LL, Staley CL (2000) Effects of clear-cutting on decomposition rates of litter and forest floor in forests of British Columbia. *Can J For Res* 30:1751–1757
- Roig S, Del Río M, Cañellas I, Montero G (2005) Litter fall in Mediterranean *Pinus pinaster* Ait. stands under different thinning regimes. *For Ecol Manage* 206:179–190
- Sardans J, Peñuelas J, Rodà F (2005) Changes in nutrient use efficiency, status and retranslocation in young post-fire regeneration *Pinus halepensis* in response to sudden N and P input, irrigation and removal of competing vegetation. *Trees* 19:233–250
- Scarascia-Mugnozza G, Oswald H, Piussi P, Radoglou K (2000) Forests of the Mediterranean region: gaps in knowledge and research needs. *For Ecol Manage* 132:97–109
- Slovik S (1997) Tree physiology. In: Hüttl RF, Schaaf W (eds) Magnesium deficiency in forest ecosystems. Kluwer Academic Publishers, London, pp 101–214
- Taylor BR, Parkinson D (1988) Does repeated freezing and thawing accelerate decay of leaf litter? *Soil Biol Biochem* 20:657–665
- Torras O, Saura S (2008) Effects of silvicultural treatments on forest biodiversity indicators in the Mediterranean. *For Ecol Manage* 255:3322–3330
- Trofymow JA, Barclay HJ, McCullough KM (1991) Annual rates and elemental concentrations of litter fall in thinned and fertilized Douglas-fir. *Can J For Res* 21:1601–1615
- Wallace ES, Freedman B (1986) Forest floor dynamics in a chronosequence of hardwood stands in central Nova Scotia. *Can J For Res* 16:293–302
- Whitford WG, Meentemeyer V, Seastedt TR, Cromack Jr K, Crossley Jr DA, Santos P, Todd RL, Waide JB (1981) Exceptions to the AET model: deserts and clear-cut forest. *Ecology* 62:275–277
- Yin X, Perry JA, Dixon RK (1989) Influence of canopy removal on oak forest floor decomposition. *Can J For Res* 19:204–214