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The effect of low-intensity prescribed burns in two seasons on litterfall biomass and nutrient content

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Abstract. Litterfall production and composition, fall pattern and nutrient content were studied in a mixed stand of *Pinus nigra* and *Pinus pinaster* (El Pozuelo), as well as in a pure stand of *Pinus nigra* (Beteta) in the Cuenca Mountains in order to determine the effect of two-season prescribed burning treatments. Needles were the most abundant fraction. Pinecone fraction decreased after burning in the mixed stand and the opposite occurred in the pure stand. The inflorescence fraction showed a decrease in the spring-burned plots at El Pozuelo and Beteta. Bark, branch and miscellaneous fractions were affected mainly by meteorological events. Low-intensity prescribed burning was not found to cause significant perturbations. The perturbation was mitigated over the years. An immediate effect of prescribed burning in spring was seen at El Pozuelo and Beteta, although it was more significant for the pure stand. The effect of prescribed burning in autumn at Beteta had a delayed response. As regards nutrient contents, no differences in carbon concentrations were detected. Overall, an increasing trend in N, P, K concentrations in needles after the burning treatment was found. Calcium was not a limiting factor. Magnesium content exhibited no clear trend.

Additional keywords: Cuenca Mountains, defoliation, forest fire, *Pinus nigra*, *Pinus pinaster*, tree crown.

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Introduction

Current climate change projections predict increased temperature and droughts in fire-prone regions such as the Mediterranean (Ferreira *et al.* 2016), which may mean an increase in the area affected by forest fire. Prescribed burning (PB) can be useful to reduce surface fuels, increase height to the live crown, decrease crown density, retain large trees of fire-resistant species (Agee and Skinner 2005) and thus, mitigate high-intensity wildfires (Boer *et al.* 2009).

Pinus nigra Arn. ssp. *salzmannii* (Spanish black pine) and *Pinus pinaster* Ait. (maritime pine) have been suggested to be adapted to fire-prone habitats through several strategies (Fernandes *et al.* 2008). Montane communities of Spanish black pine show adaptations such as thick bark, high crown base height (Pausas *et al.* 2008; Valor *et al.* 2015) and self-pruning ability (Tapias *et al.* 2001; Fulé *et al.* 2008). The same applies to *P. pinaster* (Ryan 1998; Fernandes and Rigolot 2007; Fernandes *et al.* 2008). However, *P. nigra* does not produce serotinous cones (Tapias *et al.* 2001) and it also does not maintain a canopy or soil seed bank (Ordóñez *et al.* 2005). Thus, although PB seems to be a suitable fuel reduction treatment, an adequate prescription must be carefully planned to avoid decreasing resilience in these stands. In addition, the Cuenca Mountains are a typical area where the *P. nigra*–*P. pinaster* ecotone generates stable stands with high ecosystem services and ecological values. It is recognised that interactions between species may reduce the impact of disturbances over time (Thompson *et al.* 2009). Exploring the resilience of mixed and pure stands to perturbations such as PB is therefore essential in order to establish recommendations for management and fire prevention strategies in these stands.

In a preliminary, short-term study carried out in the same study area (Espinosa *et al.* 2018), spring PB appeared to alter litterfall biomass patterns. A trend to stabilisation of the amount of litterfall was also observed 1 year after burning, with some variations in the responses of the different types of stands (mixed or pure). In addition, some slight differences in inflorescences in control and spring-burned plots occurred during the first year. However, the short period of time during which the litterfall was studied raised doubts about the efficacy of the treatment and the duration of the impact. Therefore, a longer-term study is needed to achieve a deeper knowledge of the efficacy and

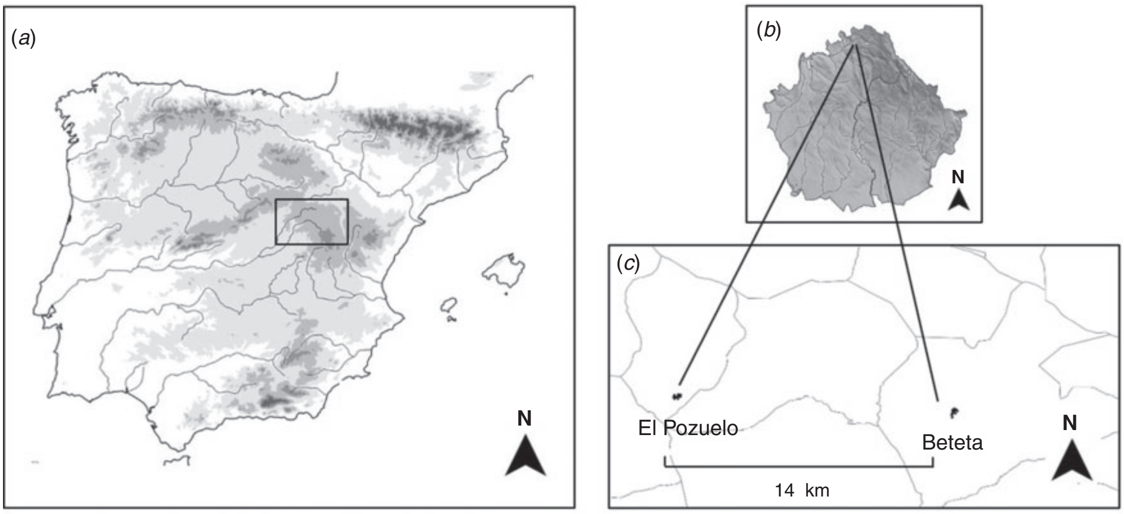

Fig. 1. Location of the study plots in (*a*) the Iberian Peninsula (1 : 1 250 000); and (*b*) the province of Cuenca (1 : 1 200 000); (*c*) locations of El Pozuelo (mixed *Pinus nigra–P. pinaster* stand) and Beteta (pure *P. nigra* stand) (1 : 50 000).

impacts of PB. In this sense, the present study integrates the results of three periods of monitoring in order to analyse the effects of PB in the medium term, adding valuable information to our previous study.

The impact of PB depends greatly on how effective it is in reducing fuel and the extent to which it disturbs the litterfall (Espinosa *et al.* 2019). Indeed, if PB negatively affects the crown, this could lead to an increase in litterfall, which could increase fire risk, thus reducing the effectiveness of the treatment. Regarding the impact of PB, no studies have been conducted to assess the effects on litterfall biomass in pine forests. Thus, the findings reported here expand on existing information about litterfall dynamics after thinning. While some authors observed effects during 1–3 years after thinning (e.g. Ågren and Knecht 2001; Roig *et al.* 2005), another noted alterations in litterfall beyond 5 years (e.g. Navarro *et al.* 2013). These contrasting results suggest that the response of forest stands is determined by multiple factors. Although burning season can be controlled in PB programs, no studies have investigated how burning season affects litterfall patterns in pine forests. The fire season may have different impacts on ecosystems through differences in fire intensity and weather conditions (Hamman *et al.* 2008), phenological status and carbohydrate storage of the trees during burning (Harrington 1993; Thies *et al.* 2005; Knapp *et al.* 2009). Thus, the present study included spring and autumn PBs in order to compare medium-term changes in litterfall in two seasons. This adds an important component relative to our previous research in which only the short-term effects of spring PB were analysed (Espinosa *et al.* 2018). Prescribed burning not only disrupts the amount and distribution of litterfall, but can alter its carbon and macronutrient contents. Litter dynamics are an essential part of nutrient cycling and energy transfer in forest stands (Kavvadias *et al.* 2001). The nutrient pool in soils is crucial for the recovery potential and health status of the ecosystem after fire (regrowth, characteristics and functioning) (Näthe *et al.* 2018). Thus, the nutrient content of the litterfall fractions must be analysed to detect any changes after treatment, adding new information to our previous results. Although some authors have suggested the importance of understanding the effects of silvicultural treatments on litterfall and litter decomposition processes in different forest species and under geoclimatic conditions (Blanco *et al.* 2006; Lado-Monserrat *et al.* 2016), such information is scarce and generally focuses on the effect of different thinning regimes on litterfall. As already mentioned, the effects of PB have not previously been evaluated in pine forests.

The hypothesis proposed in the present study is that PB in a mixed *P. nigra* and *P. pinaster* stand and in a pure *P. nigra* stand will have significant impacts on litterfall dynamics (biomass fractions and nutrient content) and that the PB season will affect litterfall patterns. To test this hypothesis, the specific research objectives of this work were as follows: (1) to analyse the effect of seasonal PB (spring *v.* autumn) on the quantity, patterns and fractions of litterfall in these types of stand; (2) to evaluate the effect of disturbance caused by PB on the carbon and macronutrient content of the litterfall. In addition, as needle fall is used as a sensitive indicator in climate change projections, the present study provides a valuable source of litterfall data relative to mixed *P. nigra* and *P. pinaster* stands and pure *P. nigra* stands.

Material and methods

Study sites

Two sites in the Cuenca Mountains (Iberian System, central-eastern Spain) separated by a straight-line distance of 14 km – El Pozuelo (40°33′36″N 002°15′56″W) and Beteta (40°33′06″N 002°06′32″W) – were selected for study (Fig. 1). In both areas, mean slope varies between 3 and 10%, and elevation ranges between 1015 and 1294 m above sea level (asl). According to data provided by the State Meteorological Agency of Spanish Government (AEMET 2018) obtained from the nearest weather station, located in Cañizares (940 m asl), the mean annual temperature over the last 21 years was 12.1°C (13.2°C during the period from 2016 to 2018) with average precipitation of

Table 1. Main parameters measured in burned and non-burned plots at El Pozuelo and Beteta

Z, zone; PT, plot treatment; Dt, total density; Pn, percentage of *Pinus nigra*; Pp, percentage of *Pinus pinaster*; Ht, total height; H1, height of the first live branch; D60, diameter at 60 cm from the base; D130, diameter at 130 cm from the base; BT, mean bark thickness at 60 cm from the base; G, basal area. Standard deviation in brackets

Z	PT	Dt (trees ha^{-1})	Pn (%)	Pp (%)	Ht (m)	H1 (m)	D60 (cm)	D130 (cm)	BT (cm)	G (m^2 ha^{-1})
El Pozuelo[A]	Non-burned	563 (74)	93 (4)	7 (4)	11.5 (3.2)	5.1 (1.9)	19.7 (3.8)	18.7 (3.7)	1.4 (0.5)	22.5 (7.5)
El Pozuelo[A]	Spring-burned	881 (227)	89 (8)	11 (8)	12.3 (0.8)	7.1 (0.6)	21.3 (1.0)	19.8 (1.0)	1.9 (0.7)	33.7 (9.7)
El Pozuelo	Autumn-burned	437 (110)	85 (20)	15 (20)	12.9 (2.1)	6.9 (2.4)	22.6 (2.9)	21.0 (2.8)	1.8 (0.5)	20.0 (0.7)
Beteta[A]	Non-burned	1456 (507)	100 (0)	0 (0)	10.1 (3.2)	6.1 (3.3)	15.1 (1.7)	13.8 (1.6)	1.3 (0.4)	25.5 (2.1)
Beteta[A]	Spring-burned	1215 (209)	100 (0)	0 (0)	12.7 (0.8)	7.5 (1.3)	20.0 (1.9)	18.2 (2.0)	1.9 (0.7)	39.1 (6.7)
Beteta	Autumn-burned	1274 (335)	100 (0)	0 (0)	14.1 (2.2)	9.4 (1.6)	21.9 (4.9)	20.0 (4.4)	2.0 (0.2)	45.2 (0.9)

[A] Data from Espinosa *et al.* (2018).

Table 2. Main parameters measured during prescribed burns at El Pozuelo and Beteta

Z, zone; PT, plot treatment; T, air temperature; RH, relative humidity; WS, mean wind speed; RS, fire rate of spread; SMx, maximum scorch height; TmMxB, mean maximum bark temperature; TmMxC, mean maximum cambium temperature; TMxB, maximum bark temperature; TMxC, maximum cambium temperature; TRMxB60, percentage of trees in which the maximum temperature in the bark surface (air temperature) was higher than 60°C; TRMxC60, percentage of trees in which the maximum temperature in the cambium was higher than 60°C

Z	PT	T (°C)	RH (%)	WS (m s^{-1})	RS (m min^{-1})	SMx (cm)	TmMxB (°C)	TmMxC (°C)	TMxB (°C)	TMxC (°C)	TRMxB60 (%)	TRMxC60 (%)
El Pozuelo[A]	Spring-burned	21.5	47.7	0.8	0.65	70	209	51	787	521	82	16
El Pozuelo	Autumn-burned	11.9	67.0	0.3	0.59	34	127	49	605	77	60	18
Beteta[A]	Spring-burned	20.4	32.7	0.8	0.76	160	279	41	755	315	96	11
Beteta	Autumn-burned	12.0	43.5	0.1	0.72	59	93	40	702	75	57	5

[A] Data from Espinosa *et al.* (2018).

717 mm (599 mm in the period from 2016 to 2018). During the maximum litterfall season (June–September), the mean annual temperature was 19.7°C and mean annual precipitation 129 mm. There is a high degree of daily and also seasonal oscillation. The soil is calcareous (Lucas-Borja *et al*. 2017; Plaza-Álvarez *et al.* 2017). The mean shrub cover in both zones ranges from 5 to 20% and pine regeneration is irregularly distributed (from 78 to 11 611 seedlings ha^{-1}).

The main characteristics of the stands under study are shown in Table 1.

Experimental design

Data were collected in nine plots (30 × 30 m) per experimental site following a random block design. A total of three treatments per experimental site (non-burned plots, spring-burned plots and autumn-burned plots) with three replicates per block were established. The plots were representative of the study area and homogeneous in terms of structure and composition of stand. To avoid edge effects, a 20-m strip adjacent to each plot was delimited.

All trees in plots were identified and the following measurements were made: total height (Ht, m), height to the first live branch (H1, m), diameter at heights of 0.6 and 1.3 m from the base (D60 and D130, cm), and maximum and minimum bark thickness at 0.6 m from the base (leeward and windward).

Prescribed burning

Spring burns were conducted by the Regional Forest Service in May 2016 (on the same day at each site) whereas autumn burnings were carried out in November 2016 (same day at each of the sites). The strip ignition technique was applied at distances of 1–2 m, downhill and with a head wind. This burning technique is the most widely used in the study area for low–medium-intensity fire behaviour. Precipitation, wind speed, temperature and relative humidity were recorded every 10 min at a meteorological station located adjacent to the study plots. During the burning, the temperature of the bark (outer bark) and at the depth of the cambium (inner bark) of 15 randomly selected trees per plot was monitored at a height of 0.6 m with type K 1-mm-diameter Inconel-sheathed thermocouples (0.3-s response time). The thermocouples were connected to data loggers (DT-USB TCDirect®) that recorded the data at a frequency of 1 s. The threshold value of 60°C in the cambium area corresponds to the commonly accepted lethal temperature for tree cells (Hare 1965). Maximum scorch height was measured after burning. The results are shown in Table 2.

Litterfall

After the prescribed burns had been carried out, a total of eight litterfall collectors per plot ($n = 18$) were installed (the catchment area was 0.38 m^2). In order to ensure representativeness of

Table 3. Annual litterfall collected at El Pozuelo and Beteta per treatment

Z, zone; PT, plot treatment. Standard deviation in brackets

Z	PT	May 2016–April 2017[A] (kg ha^{-1})	May 2017–April 2018 (kg ha^{-1})	May 2018–October 2018 (kg ha^{-1})	November 2016–October 2017 (kg ha^{-1})	November 2017–October 2018 (kg ha^{-1})
El Pozuelo	Non-burned	3171 (649)	3537 (583)	1965 (426)	3532 (585)	2726 (459)
El Pozuelo	Spring-burned	3257 (599)	2991 (191)	1879 (197)	–	–
El Pozuelo	Autumn-burned	–	–	–	2732 (325)	2640 (771)
Beteta	Non-burned	1989 (519)	2585 (762)	1504 (152)	2393 (739)	2376 (472)
Beteta	Spring-burned	3482 (129)	3120 (327)	1762 (415)	–	–
Beteta	Autumn-burned	–	–	–	3629 (527)	3495 (792)

[A] Data from Espinosa *et al.* (2018).

the sample, the collectors were distributed such that they covered the entire working area (in the 30 × 30-m plot). The litterfall collection system was designed in accordance with the recommendations and parameters outlined in the manual of the United Nations Economic Commission for Europe (UNECE) under the project entitled ‘International co-operative program on assessment and monitoring of air pollution effects on forests’ (ICP Forests 2011) (Ukonmaanaho *et al.* 2016) to guarantee the quality and quantity of the sample (see details in Espinosa *et al.* 2018). On each collection day, the samples were taken to the laboratory and oven-dried at 65°C to constant weight. The samples from each plot were weighed and separated into different fractions: needles, cones, inflorescences, branches of diameter <2 cm, bark and miscellaneous (unclassified material, seeds, lichens and leaves of other species).

The study was carried out between May 2016 and October 2018 in the spring-burned and non-burned plots, and from November 2016 to October 2018 in the autumn-burned plots (a total of 4032 samples).

Nutrient content analyses

Needles, cones, inflorescences, branches of diameter <2 cm and bark corresponding to the same period (first period: May 2016 to April 2017 for the non-burned and spring-burned plots and second period: May 2017 to April 2018 for the non-burned, spring-burned and autumn-burned plots) were pooled to obtain a composite sample per fraction, period and plot, as in the ICP Forests guidelines (Ukonmaanaho *et al.* 2016). The annual pool enabled comparison with data obtained by ICP Forests, Level II Plots for 2005–2014, in control *Pinus nigra* plots (ICP Forests 2011).

Finally, the carbon (C) and nitrogen (N) contents of samples were determined using a LECO analyser, in solid milled material. The concentrations of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) in samples (temperature 65°C) were determined by inductively coupled plasma optical mass spectrometry (ICP-MS) after wet digestion with HNO_3 (8 mL, 69%) and H_2O_2 (2 mL) at 190°C for 15 min in a microwave.

Statistical analysis

For the statistical analysis of the litterfall results, total litterfall and different fractions in kilograms per hectare were selected as target variables. A linear mixed model of repeated-measurements analysis of variance with two between-subjects factors was chosen: site (two levels: El Pozuelo and Beteta) and burning treatment (three levels: spring-burned, autumn-burned and non-burned plots) and their interactions. One within-subjects factor (repeated measurements) was selected (30 and 26 levels corresponding to months in temporal periods of spring and autumn PB respectively). A first-order autoregressive variance structure was considered for the errors in the linear mixed model.

With respect to the statistical analysis of the nutrient contents (target variables C, N, P, K, Ca and Mg), between-site differences in nutrient concentration varied depending on the nutrient and fraction considered. Therefore, the zones (El Pozuelo and Beteta) were considered independently. We used a linear mixed model with one between-subjects factor (three levels: spring-burned, autumn-burned and non-burned plots) and two within-subjects factors (litterfall fractions and the two defined periods; see *Nutrient content analyses* section) was applied. The variance–covariance matrix for the model errors was defined as an unstructured type for the fractions and a compound symmetry type for the years. The statistical analysis was segmented by site.

The statistical analyses were performed using *SAS 9.4* software (SAS 2013) and pairwise *t*-tests were used for all the comparisons of the treatments. A significance level of 95% to detect differences between treatments was established.

Results

Total litterfall

Annual litterfall biomass collected in the non-, spring- and autumn-burned plots in the mixed (El Pozuelo) and pure (Beteta) stands are shown in Table 3.

At El Pozuelo, although a slight increase in the litterfall in spring-burned plots was observed 4 months after PB, the differences were not significant (Fig. 2*a*) (Espinosa *et al.* 2018). In the second period, the biomass was greater in the non-burned plots than in the spring-burned plots. After autumn PB (i.e. in November), the differences between the non-burned and autumn-burned plots were highly significant, the biomass being greater in the non-burned plots. At Beteta (Fig. 2*b*), an increase in the litterfall in the spring-burned plots was observed immediately after spring PB and in subsequent periods (Espinosa *et al.* 2018). Treatment effects were observed after the autumn PB, with significant differences between November and February in the first period and also between November and January in the second period (Fig. 2*b*).

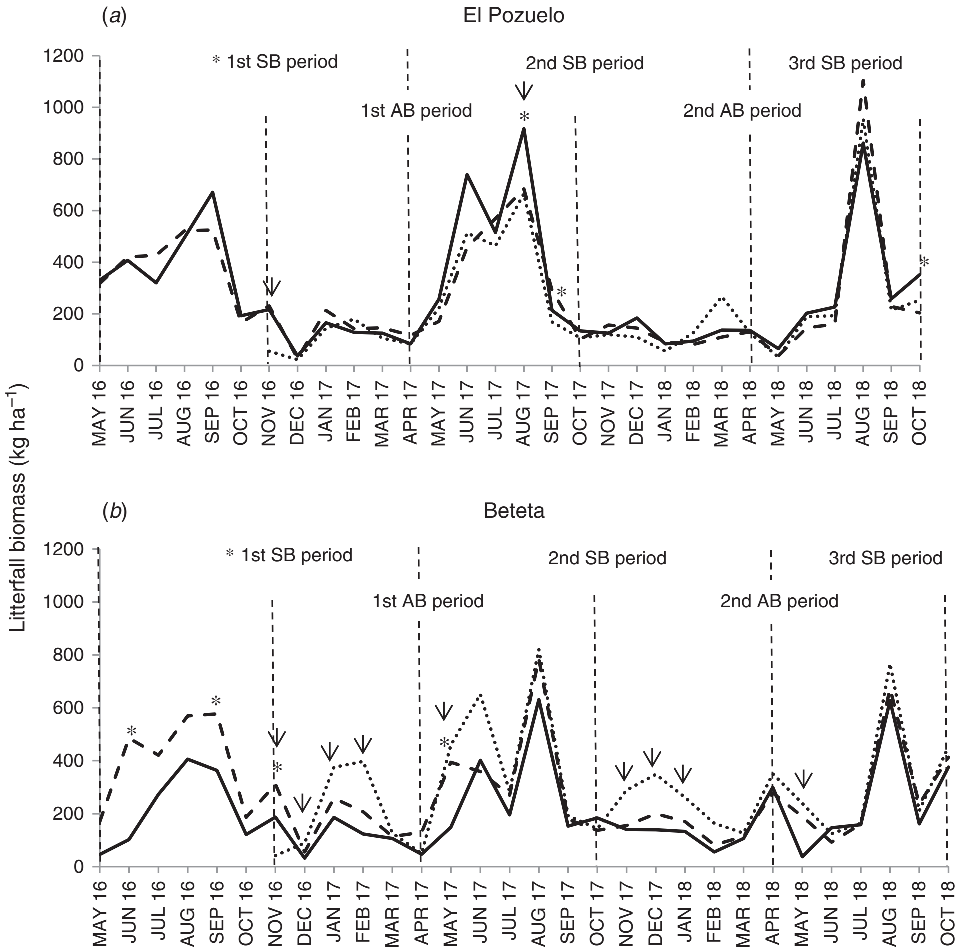

Fig. 2. Evolution of monthly collected litterfall biomass (kg ha^{-1}) in burned (spring and autumn burns) and non-burned plots, from May 2016 to October 2018 in (*a*) El Pozuelo, and (*b*) Beteta. Non-burned (NB) plots, solid line; spring-burned (SB) plot, dashed line; autumn-burned (AB) plots, dotted line. (*) represents significant differences in *t*-test of pairwise comparisons of non-burned and spring-burned plots $P < 0.05$ and (arrow) represent significant differences in *t*-test of pairwise comparisons of non-burned and autumn-burned plots $P < 0.05$. Significant differences are indicated in bold.

For all treatments, the months from June to September were those when the maximum litterfall was collected, accounting for a mean percentage of 63 ± 1 and 52 ± 6% of annual litterfall at El Pozuelo and Beteta respectively.

Intra-annual variability in litterfall was observed in both areas for all periods (Fig. 2*a* and 2*b*). In both stands, litterfall reached maximum levels in August (775 ± 217 kg ha^{-1} at El Pozuelo and 660 ± 135 kg ha^{-1} at Beteta) (Fig. 2*a* and 2*b*). At El Pozuelo, the lowest amount of litterfall was collected during winter months (December, January and February). The same occurred at Beteta, except in the autumn-burned plots, in which more variable amounts of litterfall were collected. Some secondary minimum peaks were also recorded in spring (March, April and May) in both areas (Fig. 2*a* and 2*b*).

Main litterfall fractions

Annual litterfall production per treatment and fraction is shown in Table 4. Needles comprised the largest fraction in both stands, accounting for 58% of the biomass at El Pozuelo and 57% at Beteta. The mean percentage of *Pinus nigra* needles in all plots at El Pozuelo was 76 ± 7%. The needle fraction reached similar maximum and minimum levels to the total litterfall at El Pozuelo (Fig. 3*a*) and Beteta (Fig. 3*b*). At El Pozuelo, the pattern after spring burning was similar to that observed for the total fraction. In the second period, the needle fraction was higher in the non-burned plots than in the spring-burned plots. After the autumn burning, the pattern was again similar to that observed for the total fraction, with the needle fraction being higher in the non-burned plots (Fig. 3*a*). At Beteta, the needle fraction was higher in the spring-burned plots than in the non-burned plots during the first period, confirming the significant differences between the plots (Fig. 3*b*). Although the differences were maintained, the effect was clearer at the start of the maximum litterfall period. After the autumn PB, significant differences between treatments were detected from November to February (Fig. 3*b*).

Table 4. Annual litterfall production (kg ha^{-1} year^{-1}) per treatment and fraction at El Pozuelo and Beteta
Z, zone; PT, plot treatment. Standard deviation in brackets

Z	PT	Needles (kg ha^{-1} year^{-1})	Cones (kg ha^{-1} year^{-1})	Inflorescences (kg ha^{-1} year^{-1})	Branches (kg ha^{-1} year^{-1})	Bark (kg ha^{-1} year^{-1})	Miscellaneous (kg ha^{-1} year^{-1})
El Pozuelo	Non-burned	1947 (152)	657 (195)	179 (9)	211 (201)	73 (20)	350 (102)
El Pozuelo	Spring-burned	2077 (161)	347 (260)	98 (3)	207 (164)	115 (38)	360 (79)
El Pozuelo	Autumn-burned	1480 (101)	351 (134)	177 (66)	266 (105)	95 (12)	339 (6)
Beteta	Non-burned	1423 (52)	169 (120)	55 (15)	274 (172)	98 (33)	334 (184)
Beteta	Spring-burned	2066 (556)	483 (20)	37 (1)	304 (232)	142 (47)	470 (204)
Beteta	Autumn-burned	1840 (20)	373 (354)	83 (29)	603 (30)	154 (20)	570 (217)

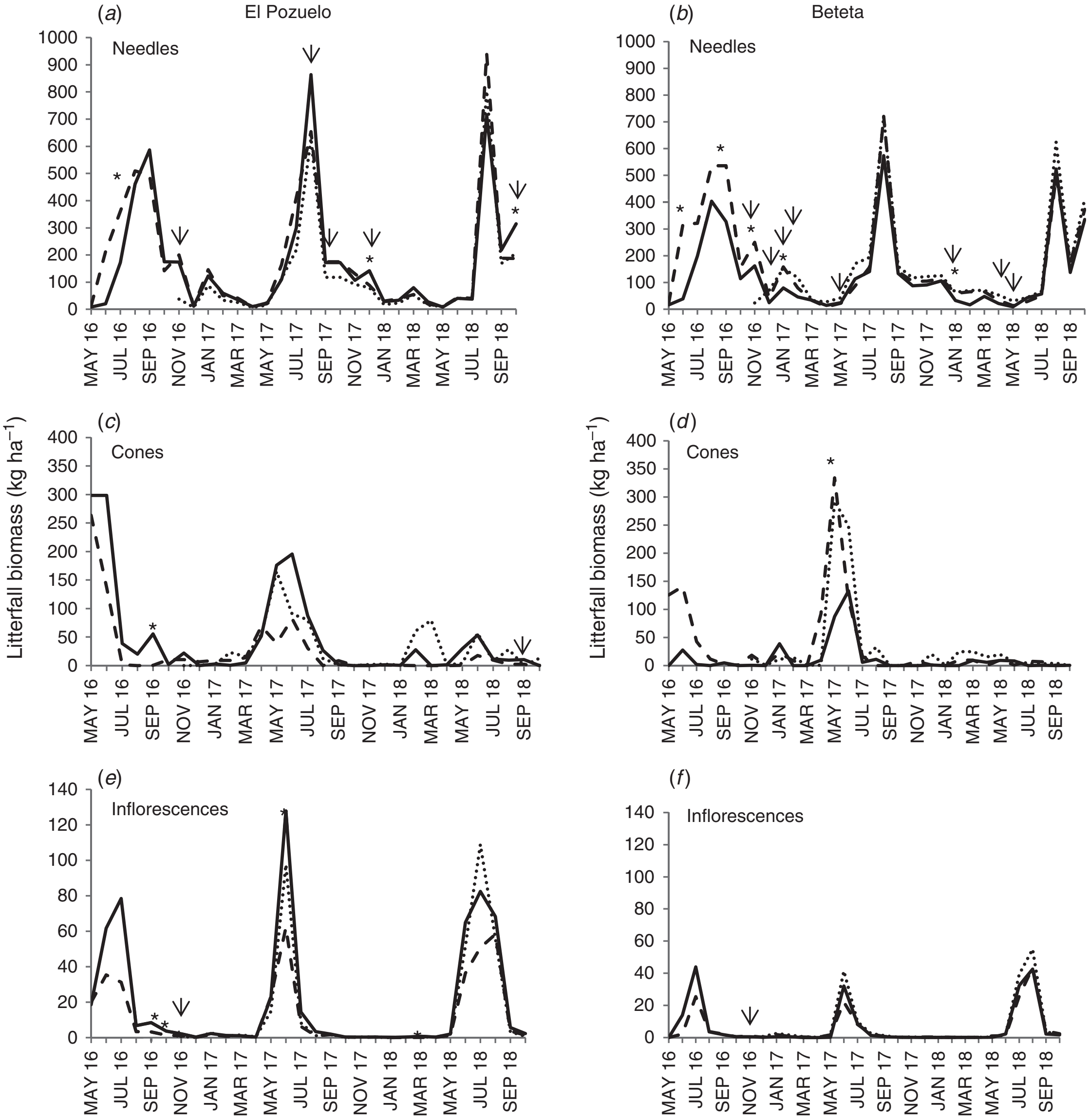

Fig. 3. Evolution of mean monthly collected litterfall (kg ha^{-1}) in (*a*) needles, (*c*) cones, and (*e*) inflorescences at El Pozuelo; and (*b*) needles, (*d*) cones, and (*f*) inflorescences at Beteta in burned (spring and autumn burns) and non-burned plots, from May 2016 to October 2018. Non-burned plots, solid line; spring-burned plots, dashed line; autumn-burned plots, dotted line. (*) represents significant differences in *t*-test of pairwise comparisons of non-burned and spring-burned plots $P < 0.05$ and (arrow) represents significant differences in *t*-test of pairwise comparisons of non-burned and autumn-burned plots $P < 0.05$.

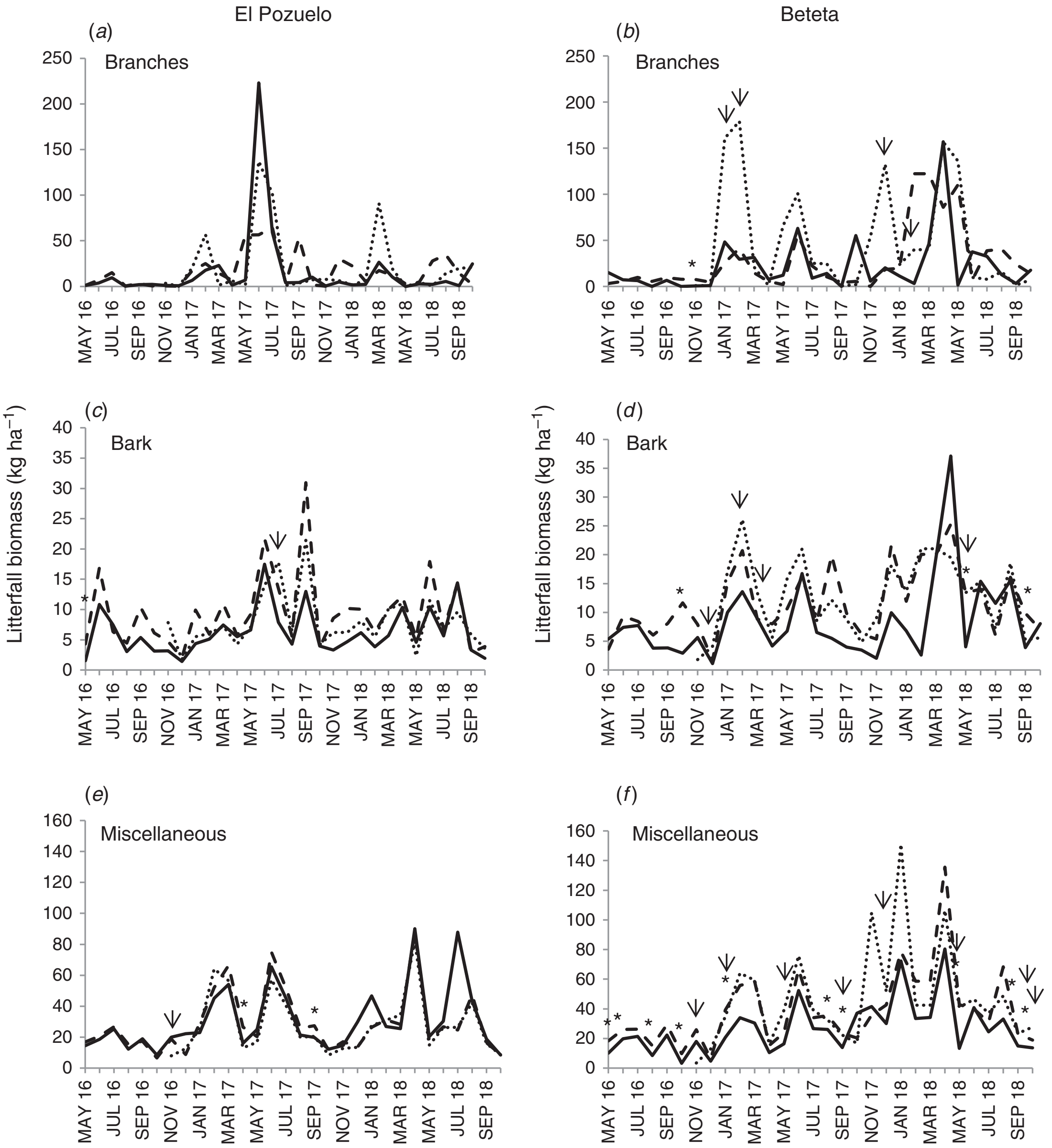

Fig. 4. Evolution of mean monthly collected litterfall (kg ha^{-1}) in (*a*) branches, (*c*) bark, and (*e*) miscellaneous fraction at El Pozuelo; and (*b*) branches, (*d*) bark, and (*f*) miscellaneous fraction at Beteta in burned (spring and autumn burns) and non-burned plots, from May 2016 to October 2018. The solid line corresponds to non-burned plots, the dashed line to spring-burned plots and the dotted line to autumn-burned plots. (*) represents significant differences in *t*-tests of pairwise comparisons of non-burned and spring-burned plots; $P < 0.05$ and arrow represent significant differences in *t*-test of pairwise comparisons of non-burned and autumn-burned plots; $P < 0.05$.

Cone fall peaked typically in May–July (Fig. 3*c* and 3*d*). Inflorescences differed significantly between zones ($P = 0.0051$), although not between treatments (Table 5). Significant differences were observed after spring burning at El Pozuelo and after autumn burning in both stands (Fig. 3*e* and 3*f*).

Branch fall was significantly higher at Beteta than at El Pozuelo. Overall, there was no significant difference between treated and untreated plots (Table 5). The inter- and intra-annual variability was high in both stands, with many peaks throughout the year. Some significant differences (Fig. 4*a* and 4*b*) were observed in winter months (particularly December, January and February).

The bark fraction differed significantly between areas ($P = 0.0384$). No differences between treatments were detected (Table 5). As with branches, high annual variability was observed in this fraction, with many peaks (Fig. 4*c* and 4*d*).

The miscellaneous fraction accounted for 10 and 12% of total biomass at El Pozuelo and Beteta respectively for all years and treatments. Seeds comprised 0.4% of total litterfall in both areas.

Table 5. Mean ± standard error for total and fractions of litterfall biomass (kg ha^{-1} $month^{-1}$) at El Pozuelo and Beteta

F, fraction; Z, zone; PT, plot treatment. Different letters indicate significant differences ($P < 0.05$) with *t*-test. Comparisons were made for all pairwise combinations of treatments and sites for each row and between sites in the final column. Significant differences are indicated in bold

F	Z	PT			–
		Non-burned	Spring-burned	Autumn-burned	–
Total	El Pozuelo	**291.02 ± 14.57 a**	**273.12 ± 14.57 a**	**224.39 ± 15.31 b**	265.59 ± 8.56 A
	Beteta	**206.17 ± 14.57 a**	**285.80 ± 14.57 b**	**300.40 ± 15.31 b**	261.53 ± 8.56 A
Needles	El Pozuelo	172.16 ± 17.84 a	182.57 ± 17.84 a	122.04 ± 15.92 a	161.56 ± 10.09 A
	Beteta	**130.98 ± 17.84 ab**	**174.24 ± 17.84 a**	**151.64 ± 15.92 b**	152.33 ± 10.09 A
Inflorescences	El Pozuelo	19.47 ± 3.30 a	11.60 ± 3.30 a	14.75 ± 3.28 a	**15.31 ± 1.91 A**
	Beteta	6.36 ± 3.30 a	5.10 ± 3.30 a	6.94 ± 3.28 a	**6.07 ± 1.91 B**
Cones	El Pozuelo	47.63 ± 14.03 a	24.21 ± 14.03 a	29.24 ± 12.38 a	34.01 ± 7.92 A
	Beteta	11.83 ± 14.03 a	32.76 ± 14.03 a	31.19 ± 12.38 a	24.84 ± 7.92 A
Branches	El Pozuelo	15.27 ± 5.27 a	16.67 ± 5.27 a	22.21 ± 6.57 a	**17.75 ± 3.26 A**
	Beteta	**21.77 ± 5.27 a**	**24.05 ± 5.27 a**	**49.69 ± 6.57 b**	**30.56 ± 3.26 B**
Bark	El Pozuelo	6.21 ± 1.37 a	9.36 ± 1.37 a	7.94 ± 1.64 a	**7.83 ± 0.84 A**
	Beteta	8.47 ± 1.37 a	11.38 ± 1.37 a	12.20 ± 1.64 a	**10.57 ± 0.84 B**
Miscellaneous	El Pozuelo	30.29 ± 6.66 a	28.72 ± 6.66 a	28.22 ± 8.16 a	29.14 ± 4.09 A
	Beteta	26.77 ± 6.66 a	38.29 ± 6.66 a	48.74 ± 8.16 a	37.16 ± 4.09 A

No clear pattern (Fig. 4*e* and 4*f*) or any differences between zones and treatments (Table 5) were detected.

Nutrient content

Carbon and macronutrients (N, P, K, Ca and Mg) were analysed in this study. The concentrations for each nutrient, fraction, period and treatment at El Pozuelo and Beteta are presented in Supplementary Table S1 (available in the Supplementary material) along with the mean and standard error in Table 6.

The mean concentration of C did not differ between El Pozuelo and Beteta. The only significant differences ($P = 0.0132$) detected were between *Pinus nigra* needles in non-burned and autumn-burned plots at El Pozuelo. Significant differences in N content of *Pinus nigra* needles were observed between non-burned and spring-burned plots in both stands, and differences between *Pinus pinaster* needles in non-burned and autumn-burned plots ($P = 0.0293$) were observed at El Pozuelo. In general, the P concentration was higher in needles from burned plots. As regards K, the only differences detected were between *Pinus nigra* needles in non-burned and autumn-burned plots ($P = 0.1140$) at El Pozuelo. Differences in Ca concentration between treatments (spring and autumn-burned plots) were detected in the cone and inflorescence fractions and also in Mg concentrations in *Pinus nigra* needles at Beteta.

Discussion

The PB treatments were of low intensity (typical type of burning conducted in the *Pinus nigra* stands in the study area). Overall, scorch height (Table 2) was lower than the height of the first living branch (Table 1). No trees were completely scorched, except seedlings under the canopy and small, dominated trees. The highest scorch marks on stems were mainly due to lichens present on the stem, which burned briefly, possibly explaining the occasional peaks in maximum temperature in the cambium area (Table 2). The mean bark thicknesses (Table 1) protected the cambium from temperatures higher than the critical threshold of 60°C (Hare 1965) and from a long flame residence time. Indeed, the temperature of the cambium was higher than 60°C in only a small percentage of trees (below 18%) (Table 2). Thus, neither transport of photosynthate to the crown nor nutrient and water storage were expected to be disrupted, and burning scarcely affected photosynthetic production in the upper part of the crown, explaining the negligible amount of live needles collected in plots.

The previous short-term study of spring PB (Espinosa *et al.* 2018) revealed an immediate effect in both areas (the total litterfall accumulated was greater in the spring-burned plots than in the non-burned plots). At El Pozuelo, this difference was only 3% whereas at Beteta, there was 75% more in the spring-burned plots. In the second period, the difference decreased at El Pozuelo and by the end of the study, the results were reversed (i.e. litterfall was greater in the non-burned plots than in the spring-burned plots). In this context, the significant differences observed may be explained by the fact that the fire advanced the needle fall cycle in spring-burned plots during the first year, which meant that the quantity of needles in non-burned plots was greater in subsequent years. According to Nárovec and Nárovcová (2012), natural senescence of needles begins in the third to fifth year depending on the area. By comparison, at Beteta, the amount of litterfall was higher in the spring-burned plots for all period studied, although the differences decreased steadily over time (a difference of 75% first period, 21% second period and 17% remaining period). Thus, although the differences between burned and non-burned plots initially appeared to stabilise after the summer months in the first year (Espinosa *et al.* 2018), the impact of the treatment was maintained until the third year of study (at least in the pure stand).

After autumn PB at El Pozuelo, no effect was observed. In fact, higher amounts of biomass were collected in the non-burned plots than in the autumn-burned plots (23% more first period and 3% more second period). Conversely, the effect of autumn burns was detected at Beteta. Three to four months after burning, significant differences existed, more evident in months

Table 6. Mean ± standard error of nutrient content for C and macronutrients in fractions of litterfall biomass for the three treatments at El Pozuelo and Beteta. C, N, K, Ca, Mg (mg g^{-1}) and P (mg kg^{-1})

NT, nutrient; F, fraction; NEN, *Pinus nigra* needles; NEP, *Pinus pinaster* needles; CON, cones; INF, inflorescences; BRA, branches; BAR, bark. Different letters indicate significant differences ($P < 0.05$) with *t*-test. Comparisons were made for all pairwise combinations of treatments and sites for each row. Significant differences are indicated in bold

NT	F	El Pozuelo			Beteta		
		Non-burned	Spring-burned	Autumn-burned	Non-burned	Spring-burned	Autumn-burned
C	NEN	**513 ± 1 a**	**515 ± 1 ab**	**519 ± 2 b**	523 ± 2 a	523 ± 2 a	521 ± 2 a
	NEP	504 ± 2 a	507 ± 2 a	505 ± 3 a	–	–	–
	CON	491 ± 2 a	493 ± 2 a	485 ± 4 a	487 ± 2 a	493 ± 2 a	493 ± 2 a
	INF	494 ± 2 a	493 ± 2 a	497 ± 3 a	497 ± 2 a	499 ± 2 a	504 ± 2 a
	BRA	494 ± 1 a	493 ± 1 a	492 ± 2 a	502 ± 2 a	501 ± 2 a	498 ± 2 a
	BAR	485 ± 2 a	486 ± 2 a	482 ± 2 a	488 ± 2 a	490 ± 2 a	488 ± 2 a
N	NEN	**4.0 ± 0.2 a**	**4.6 ± 0.2 b**	**4.4 ± 0.2 ab**	**4.3 ± 0.1 a**	**5.2 ± 0.1 b**	**4.8 ± 0.2 ab**
	NEP	**3.0 ± 0.1 a**	**3.1 ± 0.1 a**	**3.4 ± 0.1 b**	–	–	–
	CON	2.8 ± 0.3 a	2.5 ± 0.3 a	2.5 ± 0.4 a	2.3 ± 0.3 a	2.8 ± 0.3 a	2.3 ± 0.3 a
	INF	7.5 ± 0.5 a	7.1 ± 0.5 a	7.0 ± 0.6 a	7.7 ± 0.3 a	8.2 ± 0.3 a	8.2 ± 0.4 a
	BRA	4.1 ± 0.3 a	3.8 ± 0.3 a	4.2 ± 0.5 a	4.3 ± 0.3 a	4.3 ± 0.3 a	3.8 ± 0.4 a
	BAR	**4.3 ± 0.1 ab**	**4.1 ± 0.1 b**	**4.6 ± 0.1 a**	4.4 ± 0.1 a	4.4 ± 0.1 a	4.5 ± 0.1 a
P	NEN	**175 ± 17 a**	**248 ± 17 b**	**260 ± 20 b**	**317 ± 31 ab**	**312 ± 31 b**	**420 ± 40 a**
	NEP	**141 ± 30 ab**	**283 ± 30 b**	**197 ± 35 a**	–	–	–
	CON	187 ± 41 a	193 ± 41 a	117 ± 48 a	161 ± 42 a	236 ± 42 a	125 ± 55 a
	INF	**218 ± 27 a**	**220 ± 27 a**	**312 ± 31 b**	301 ± 33 a	368 ± 33 a	373 ± 43 a
	BRA	143 ± 39 a	168 ± 39 a	181 ± 46 a	241 ± 42 a	190 ± 41 a	129 ± 54 a
	BAR	157 ± 18 a	162 ± 18 a	163 ± 21 a	222 ± 40 a	209 ± 40 a	161 ± 52 a
K	NEN	**1.58 ± 0.22 a**	**2.15 ± 0.22 ab**	**2.53 ± 0.27 b**	1.80 ± 0.10 a	1.75 ± 0.10 a	1.86 ± 0.14 a
	NEP	0.98 ± 0.36 a	1.33 ± 0.36 a	1.43 ± 0.44 a	–	–	–
	CON	1.54 ± 0.29 a	1.37 ± 0.29 a	1.29 ± 0.36 a	2.61 ± 0.88 a	2.71 ± 0.88 a	1.51 ± 1.21 a
	INF	0.88 ± 0.21 a	0.87 ± 0.21 a	0.97 ± 0.26 a	1.77 ± 0.52 a	2.25 ± 0.52 a	1.05 ± 0.74 a
	BRA	0.59 ± 0.18 a	1.12 ± 0.18 a	0.53 ± 0.23 a	2.40 ± 0.69 a	2.11 ± 0.69 a	0.42 ± 0.98 a
	BAR	0.63 ± 0.21 a	0.89 ± 0.21 a	0.48 ± 0.25 a	1.97 ± 0.74 a	1.46 ± 0.74 a	0.50 ± 1.05 a
Ca	NEN	7.99 ± 0.70 a	8.19 ± 0.70 a	8.34 ± 0.96 a	5.22 ± 0.40 a	4.56 ± 0.40 a	5.37 ± 0.49 a
	NEP	8.95 ± 0.32 a	8.14 ± 0.32 a	8.38 ± 0.44 a	–	–	–
	CON	**1.78 ± 0.93 a**	**5.23 ± 0.93 b**	**0.54 ± 1.28 a**	1.62 ± 0.85 a	1.76 ± 0.85 a	0.43 ± 1.02 a
	INF	**4.95 ± 0.39 a**	**4.87 ± 0.39 a**	**1.00 ± 0.54 b**	2.12 ± 0.65 a	1.76 ± 0.65 a	1.68 ± 0.78 a
	BRA	8.22 ± 0.63 a	7.51 ± 0.63 a	6.42 ± 0.86 a	4.33 ± 0.87 a	3.20 ± 0.87 a	4.83 ± 1.06 a
	BAR	8.12 ± 0.66 a	8.50 ± 0.66 a	7.77 ± 0.91 a	6.05 ± 0.46 a	5.89 ± 0.46 a	6.52 ± 0.56 a
Mg	NEN	0.93 ± 0.17 a	1.08 ± 0.17 a	0.84 ± 0.28 a	**1.41 ± 0.19 ab**	**1.21 ± 0.19 b**	**1.87 ± 0.26 a**
	NEP	1.25 ± 0.12 a	1.35 ± 0.12 a	1.67 ± 0.19 a	–	–	–
	CON	0.61 ± 0.12 a	0.55 ± 0.12 a	0.36 ± 0.18 a	0.58 ± 0.09 a	0.58 ± 0.09 a	0.50 ± 0.12 a
	INF	0.74 ± 0.20 a	0.78 ± 0.20 a	0.59 ± 0.30 a	0.69 ± 0.08 a	0.75 ± 0.08 a	0.75 ± 0.10 a
	BRA	0.60 ± 0.15 a	0.61 ± 0.15 a	0.39 ± 0.23 a	0.64 ± 0.07 a	0.59 ± 0.07 a	0.51 ± 0.10 a
	BAR	0.48 ± 0.13 a	0.76 ± 0.13 a	0.34 ± 0.20 a	0.58 ± 0.05 a	0.58 ± 0.05 a	0.47 ± 0.10 a

of maximum litterfall (Espinosa *et al.* 2018) and even in the second period from November to January. The latter results obtained in winter months may be explained by a late perturbation effect, which was manifested in the snowfall or storm season. Blanco *et al.* (2006) also reported this delayed effect of perturbation. Indeed, although the influence of physiological drought on litterfall is recognised (García-Plé *et al.* 1995; Roig *et al.* 2005), it seems that snowfall and storms (mainly during winter months) may negatively impact litterfall. The differences observed decreased from one year to the next (51% more first period and 47% second period) although the rate of decrease was lower than in spring.

Although no significant differences were observed (Table 5) between the two stands (which may be due to all treatments being considered together), the contrasting results following spring and autumn burns may be explained by the composition of the stands. Several authors have reported that mixed stands are stabler than pure stands (e.g. Felton *et al.* 2010), with a lower response after disturbance and a faster recovery process (Loreau *et al.* 2001; Jactel *et al.* 2009).

No previous studies comparing the effects of PB on litterfall biomass have been conducted in pine forests. Thus, the findings of the present study were compared with previous data on disturbance caused by different thinning regimes. Although no trend of increasing litter production following treatment was found by Roig *et al.* (2005), the effects were perceived 2–3 years later and disappeared 5 years after thinning. Similarly, Ågren and Knecht (2001) suggested an increase in litterfall production 1 year after thinning, with values returning to normal in subsequent years. By contrast, data provided by Jiménez and Navarro (2016) indicate continuing differences in litterfall production after 8 years. This finding is further supported by Lado-Monserrat *et al.* (2016). These contrasting results highlight the fact that multiple factors condition the response of forest stands, making predictions difficult (Blanco *et al.* 2006) and highlighting the need for longer-term studies such as the present study.

Despite the disturbance to litterfall caused by burning treatments, the mean total litterfall for all treatments (3054 kg ha^{-1} $year^{-1}$ at El Pozuelo and 3050 kg ha^{-1} $year^{-1}$ at Beteta) is similar to those reported by ICP Forests (3337 ± 841 kg ha^{-1} $year^{-1}$) (ICP Forests 2011) after an 11-year-long study (2005–2014) of a *Pinus nigra* stand in Mora de Rubielos (Teruel), in which the altitude and latitude (1410 m asl and 40°19′00″ respectively) were similar to those of the present study area. Studies conducted in other areas of Europe, also focusing on *Pinus nigra*, reported values of ~2500 kg ha^{-1} $year^{-1}$ (Kavvadias *et al.* 2001). Roig *et al.* (2005) obtained values of 3284 kg ha^{-1} $year^{-1}$ for *Pinus pinaster* in central Spain. Overall, the findings are within the range (3000–11 000 kg ha^{-1} $year^{-1}$) reported for different types of forest worldwide (Zhang *et al.* 2014). However, the slight differences highlight the difficulty in comparing litterfall values due to the number of variables involved (Pausas *et al.* 1994; García-Plé *et al.* 1995; Berg and Meentemeyer 2001).

Litterfall patterns often show a seasonal distribution. In the present study, the maximum levels of litterfall in summer months (June–September) are consistent with the results obtained by other authors in Mediterranean ecosystems (Roig *et al.* 2005; Bueis *et al.* 2017). Litterfall usually peaked in August, which is consistent with results reported by Bueis *et al.* (2017) and Martínez-Alonso *et al.* (2007). Minor discrepancies may be mainly due to the phenology of the species (Bueis *et al.* 2017) and the relationship between litterfall and months with physiological drought (García-Plé *et al.* 1995; Santa Regina and Tarazona 2000; Roig *et al.* 2005; Blanco *et al.* 2006). Insect pests and other external variables may also be important. Minimum litterfall was recorded in winter months in both areas, although another minimum was observed at Beteta in spring. Blanco *et al.* (2006) also reported minimal production in winter and spring.

The most abundant fraction was needles, accounting for 58 and 57% of litterfall at El Pozuelo and Beteta, respectively. These results are closer to the values observed in a similar ecosystem, (62%) obtained at Mora de Rubielos (ICP Forests 2011) and the values reported by Pausas *et al.* (1994) and Martínez-Alonso *et al.* (2007) for *Pinus sylvestris* (~50%). Slightly higher values were reported by Kurz *et al.* (2000) for *Pinus pinaster* (60–80%) and by Blanco *et al.* (2006) for *Pinus sylvestris* (50–70%). The trend for needles is similar to that observed for total litterfall biomass (Pausas 1997; Blanco *et al.* 2006; Hansen *et al.* 2009).

The cone fraction accounted for 14% of total litterfall biomass at El Pozuelo and 10% at Beteta. A peak was almost always distinguishable in May and July, following pine flowering season (Blanco *et al.* 2006). Fluctuations in cone production were observed over the years considered, as also reported by Ordóñez *et al.* (2005) and Del Cerro Barja *et al.* (2009). Different responses between sites were found, although none were significant. At Beteta, there were more cones in the burned plots than in the non-burned plots, whereas at El Pozuelo, the opposite was found. Inflorescences account for a mean value of 2 and 5% of total litterfall for all periods and treatments at El Pozuelo and Beteta respectively. Pausas *et al.* (1994) pointed to a marked seasonality in shedding of inflorescences, with variation in peaks between May and August, which may also be due to weather conditions. The higher amount of inflorescences in control plots compared with burned plots at El Pozuelo and Beteta following spring burns is an effect that requires longer-term study. If fructification was similar among plots, inflorescence fall would not be a good index of fructification potential, probably because prescribed burns do not affect the female flowers mainly found in the apical fast-growing shoots at the top of the tree (Shmida *et al.* 2000). However, if the number of cones was higher in the control plots, we could assume that PB significantly affects the regeneration potential in *Pinus nigra* stands. Although it is difficult to determine the scope of fire effects on the cone and inflorescence fractions given the particular fructification characteristics of each species as well as other external factors (Del Cerro Barja *et al.* 2009), the findings are nonetheless important for forest managers, who will be able to plan PB in non-masting years or initial seedling recruitment to ensure periodic fructification and natural regeneration, thus contributing towards the persistence of black pine forests (Lucas-Borja and Vacchiano 2018).

As regards branches, this fraction accounted for a mean value of 7% at El Pozuelo and 12% at Beteta with respect to the total litter for all years and treatments. In a *Pinus nigra* stand at Mora de Rubielos, branches accounted for a mean of 9% of total litter biomass (ICP Forests 2011), this value being within the range recorded in the study plots. Certain peaks are due to snowfall in winter months and may also be associated with storms or episodes of high wind as well as with drier conditions (June–September). Self-pruning (Piqué and Domènech 2018) and high crown base height are characteristics of *Pinus nigra* that allow the species to adapt to low-intensity burning and also to prevent the possible effects of thermal pruning. Bark production accounted for 3% of total litter production at El Pozuelo and 4% at Beteta for all treatments in all years. Blanco *et al.* (2006) obtained slightly higher values, between 9 and 11%. This fraction exhibited interannual variability with no clear trend (Pausas 1997). As with branches, weather events may influence bark litter production (Blanco *et al.* 2006). Bark in maritime pine is laminated and the outer layers are exfoliated during combustion (Fernandes and Rigolot 2007). This fact may explain the significant differences between zones, although this cannot be confirmed given the irregularity of the patterns. Certain peaks at the end of the summer may be due to stem growth (García-Plé *et al.* 1995). The miscellaneous fraction shows several peaks. Some winter peaks may be due to leaves of other deciduous species, mainly *Quercus* sp., although there is a low presence of this species. Peaks in February and May–July may correspond to seeds, but the amount of seed is very small. Miscellaneous peaks may also be associated with heavy rain and storms (Navarro *et al.* 2013).

Litterfall influences post-fire recovery processes, providing a pathway for nutrient release through leaching, mineralisation or immobilisation. Differences in nutrient concentrations between sites and fractions were recorded. These differences were found to reflect the particular characteristics at each site. Needles constitute an important nutrient sink through which most nutrients return to the forest soil in both areas, as also highlighted by Blanco *et al.* (2008).

The burning treatments had little effect on the concentration of C in the different fractions at both sites. The results provided by ICP Forests in a *Pinus nigra* stand (ICP Forests 2011) reveal a mean concentration of carbon of 546 mg g^{-1} in the needle fraction, which is close to the mean concentrations obtained at El Pozuelo (499 mg g^{-1}) and Beteta (500 mg g^{-1}) for all periods and treatments. The findings for the branch fraction are similar.

A slight overall increase in N concentration in the needle fraction was detected in the burned plots in comparison with the non-burned plots; this was also reported by Tahmasbian *et al.* (2019) for suburban eucalyptus stands. However, other authors reported that foliar N concentration was not affected by prescribed fire (Landsberg *et al.* 1984). The needle fraction N values obtained at El Pozuelo and Beteta (4.49 and 5.06 mg g^{-1} mean value for all treatments and periods) were not within the range reported by ICP Forests (between 8.42 and 21.18 mg g^{-1}) (Rautio *et al.* 2016). This may be explained by the fact that the ICP Forests needle fraction included fresh needles, which can be assumed to contain more N. Thus, the N foliar values coincide with the N values in old needles, probably close the time of natural abscission, although nutrient concentrations in the needle fraction are also affected by factors such as nutrient availability in soil, climatic variables and site conditions (e.g. Kavvadias *et al.* 2001; Roig *et al.* 2005). However, N from needles is recycled back to the stem just before abscission, and the N concentration in fallen needles is therefore lower than in fresh needles (Bueis *et al.* 2017). Notable differences were observed in P concentrations between non-burned and burned plots in both stands. An increase in P concentration after the first year in all fractions was detected (notable at El Pozuelo). A similar increase in P in the foliar fraction after PB was also detected by Gillon *et al.* (1999) in Aleppo pine forests. However, Lado-Monserrat *et al.* (2016) observed little variation in P concentrations in response to different rates of tree removal. The P concentrations in the needle fraction were higher in the Beteta stand than in the El Pozuelo stand. Phosphorus is an essential nutrient for the generation of new tissues, so higher concentrations might be expected following a disturbance. The K concentration increased in spring-burned plots during the first period in all fractions at El Pozuelo and in the needle fraction at Beteta. A similar increase was also detected by Kuechler *et al.* (2006) after PB treatment in a long-term study. Foliar K fell beneath the range of natural concentrations in the area (1.53 and 1.79 mg kg^{-1} at El Pozuelo and Beteta respectively), 2.36 mg kg^{-1} at Mora de Rubielos in the needle fraction (ICP Forests 2011). Despite the increase, Lado-Monserrat *et al.* (2016) observed little variation in K concentrations in a study of nutrient fluxes in response to different rates of tree removal.

Calcium was the most abundant element, particularly in needles, as they have the greatest Ca requirement (higher mean values at El Pozuelo than Beteta) although also in branches and bark. Calcium is abundant in the soils of the study area and was expected to be a non-limiting element. A general reduction in Mg concentration in litterfall after burning was observed, mainly as a consequence of competition with other cations (Lado-Monserrat *et al.* 2016; Bueis *et al.* 2018). This decrease in Mg was not detected in the needle fraction at El Pozuelo, where there was a 53% increase in the case of *Pinus nigra* and 45% for *Pinus pinaster* in first year, although it was found in the other fractions. At Beteta, however, the decrease in Mg was detected in the needle fraction.

Conclusions

Overall, the study findings (biomass and nutrient content) suggest that low-intensity PB in both spring and autumn has a limited medium-term influence (i.e. 3 years after treatment) on litterfall dynamics in a mixed *Pinus nigra*–*Pinus pinaster* stand and a pure *P. nigra* stand.

The season in which the PB was carried out (spring or autumn) affected litterfall biomass, mainly when certain meteorological phenomena (snowfall or storms) occurred after the treatment. Stand composition (mixed or pure) and characteristics may also have influenced the results. As shown in a previous study with the same experimental design (Espinosa *et al.* 2018), the findings indicated a short-term effect on litterfall biomass following spring PB, particularly in the pure stand. The effect of the treatment decreased gradually over time. The effects of autumn PB were scarcely noticeable in the mixed stand and were delayed in the pure stand. The rate of recovery was faster after spring PB than after autumn PB in the pure stand.

Concentrations of carbon and macronutrients were not significantly modified by the burn treatment. Differences in nutrient concentrations between sites and fractions were detected and may be due to characteristics of the sites and stands. The concentrations of N, P and K increased in the needle fractions after burning, these nutrients being key to stand recovery following disturbance. It was found that the values obtained for N were similar to old needles, so no greater damage as regards crowns is expected. Calcium was not found to be a limiting factor. No competition between Mg and other cations following fire was detected, at least at El Pozuelo.

The litterfall data obtained during the study may provide information for present and future projections of climate change as needle fall is a sensitive indicator of this phenomenon.

Information about the influence of silvicultural treatments on litterfall biomass, litter dynamics and nutrient cycling processes remains limited, particularly in Mediterranean forests. Such knowledge is key to fire management, allowing us to determine the longevity of fuel reduction treatments and providing parameters to design, test and implement more effective prescriptions.

Conflicts of interest

The authors declare no conflicts of interest.

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