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Local basal area affects needle litterfall, nutrient concentration, and nutrient release during decomposition in *Pinus halepensis* Mill. plantations in Spain

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Abstract

• ***Key message*** **Stand density has a positive effect on C, K and Mg concentration in needle litterfall and a negative one on C, N, Ca, K, Mg, P, S, Zn, and Cu release from needle litter. Consequently, forest management practices such as thinning decrease nutrient concentration in needle litterfall and accelerate nutrient release from decomposing needles in *Pinus halepensis* plantations in Spain**.

• ***Context*** Silvicultural practices usually include stand density reduction resulting in changes in litterfall and litter decomposition rates. Little is known about the effect on nutrient concentrations in litterfall and nutrient release during decomposition even when this is the main path of nutrient return to soils.

• ***Aims*** The aims of the study are to evaluate the seasonal pattern of nutrient concentration in litterfall, to study how nutrients are released from needle litterfall during decomposition, and to assess whether local basal area of the stand affects nutrient concentration of litterfall and nutrient release during litter decomposition.

• ***Methods*** Eight plots were established on each of four stands covering the widest range in local basal area. A littertrap and 15 litterbags were placed on each plot. Periodically, needle litterfall and litter contained in the litterbags were analyzed for C, N, Ca, K, Mg, P, S, Fe, Cu, Mn, and Zn.

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Contributions of the co-authors Teresa BUEIS: designed the experiment, carried out the field and laboratory work, run the data analysis, discussed the results, and wrote the paper
Felipe BRAVO: designed the experiment, coordinated the research project, and corrected the manuscript
Valentín PANDO: supported the statistical analysis and corrected the manuscript
María-Belén TURRIÓN: designed the experiment, supervised the laboratory analysis, and corrected the manuscript

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• ***Results*** Local basal area had a positive effect on C, K, and Mg concentration in needle litterfall and a negative effect on the release of all the nutrients studied but Fe and Mn during the first 2 years of litter decomposition.
• ***Conclusion*** Density management of stands has an impact on nutrient cycling, reducing nutrient concentration in needle litterfall, and accelerating nutrient release during decomposition.

Keywords Nutrient cycle · Litterbag · Littertrap · Nutrient immobilization · Nutrient release

1 Introduction

Litterfall, together with root turnover, constitutes the main path of nutrient return to soil (Swift et al. 1979). Litterfall rate and the nutrient release through litter decomposition play a key role in the sustainability of forest ecosystems. The silvicultural treatments or management techniques are also crucial for sustainability. The nutrient concentration in needle litterfall is conditioned by soil nutrient availability, nutrient retranslocation during needle senescence, nutrient leaching, competition for resources, climatic parameters, and site productivity (Blanco et al. 2008; Kim et al. 2013; Nambiar and Fife 1991). Nutrient resorption during needle senescence is a nutrient conservative mechanism in nutrient-limited areas. The translocation process occurring during senescence consists of the resorption of some mobile nutrients from leaves to twigs to avoid their loss during leaf abscission. Leaching processes involve nutrient release and are especially important for elements such as K and P when forest growth is phosphorus limited (Swift et al. 1979).

Decomposition processes are driven by the physical environment, the substrate quality, and the performance of the microorganisms (Swift et al. 1979). Microbial activity seems to be the most determining factor for litter decomposition in nutrient-poor coniferous forests, and then, factors controlling the activity of microorganisms such as temperature, moisture, and physio-chemical characteristics of the substrate are usually the most important factors determining litter decomposition rates (Desanto et al. 1993; Prescott et al. 2004). Nutrients contained in litterfall may be released by leaching or mineralization or be immobilized. Mineralization consists of the release of inorganic forms of an element through catabolism reactions of organic substances. Immobilization involves the maintenance of nutrients in organic forms or even the uptake of inorganic forms from environmental sources by decomposers. Obviously, mineralization processes involve the uptake of nutrient elements by decomposers. Often, some elements limit decomposer activity and then, the immobilization of those nutrients will tend to prevail. Only when the availability of a nutrient element is non-limiting for decomposers activity, mineralization will prevail (Swift et al. 1979).

Forest management practices usually include stand density reduction to diminish tree competition and to improve the growth of the remaining trees. Stand density alteration usually results in changes in litterfall rates (Blanco et al. 2006; Lado-Monserrat et al. 2015; Navarro et al. 2013; Roig et al. 2005), microclimate conditions (Chase et al. 2016; Kunhamu et al. 2009) and, consequently, litter decomposition (Kim 2016; Ouro et al. 2001) due to variations in microbial performance. However, our knowledge about the effects of silvicultural treatments on litterfall and litter decomposition processes is still insufficient to carry out a sustainable forest management of stands (Lado-Monserrat et al. 2015). Blanco et al. (2006) suggested that there is a need for further studies focused on different forest species and varied geoclimatic conditions to understand properly the effects of silvicultural management on litterfall production considering that it is affected by several factors including geoclimatic and stand density-related parameters. Most previous studies were focused on studying the litterfall and litter decomposition rates but little attention has been given to the effect of silvicultural practices on nutrient concentrations in litterfall and nutrient release through decomposition (Blanco et al. 2008; Kim 2016). Moreover, nothing is known about litterfall and litter decomposition in *Pinus halepensis* plantations outside the natural distribution range of this species.

We hypothesize that (1) the needle litterfall concentration of mobile nutrients (N, P, K, Mg, S, Cu, and Zn) will show a decrease during summer months due to the resorption of these elements from needles during senescence, (2) the local basal area will have a positive effect on nutrient concentration in litterfall due to the dilution effect which causes lower nutrient concentrations in tissues as a result of higher productivity in sites with lower competence (lower local basal area), (3) different trends will be found in relation to the nutrient release from needle litterfall (nutrient immobilization or nutrient release) associated to the individual nutrient availability for decomposers, and (4) the local basal area of the stand will present a negative effect on nutrient release from decomposing needles due to the higher amount of water reaching the soil in plots with lower local basal area (Bueis et al. 2017) which may cause an increase in nutrient leaching as well as an increase in mineralization processes driven by soil microorganisms.

2 Material and methods

2.1 Study area

The study area is located in the centre of Castilla y León (Spain). The soils in the study area originate from carbonate-rich parent materials and can be classified as Calcixerepts (Llorente and Turrion 2010). The climate is Mediterranean, presenting summer drought. Mean annual temperature and precipitation are 12 °C and 457 mm. Mean maximum and minimum monthly temperatures are 18 and 5 °C (Ninyerola et al. 2005). The origin of the stands is the afforestation of abandoned crops and their main aim is protection against erosion.

Four *Pinus halepensis* stands were selected in the municipalities of Dueñas, Ampudia, Valoria la Buena, and Valle de Cerrato, in Castilla y León. They present an irregular spatial distribution of trees due to earlier thinnings. In an area of 1 ha of each stand, eight plots were established with no overlap covering the widest range in local basal area present in the stand (see Online Resources 1, 2, 3, and 4). Then, 32 plots were established. Local basal area was considered as the addition of the normal sections (cross-section area at breast height) of the trees included in a 6-m radius from the centre of the plot. Table 1 presents the main characteristics of the studied stands.

2.2 Litterfall and litter decomposition

In October 2013, a littertrap and 15 litterbags were established on each plot. Thirty two littertraps and 480 litterbags were set up. Littertraps consisted of a 50-cm diameter cone made of mesh and supported by three wooden stakes of 80 cm height. Litterbags were tied to the three wooden stakes in groups of five. Litterbags were 15 cm × 15 cm size, made of plastic mesh of 1.5 mm mesh size and filled with freshly fallen needles that were collected from the forest floor in September 2013. Each litterbag was labeled so as to identify them as their litter content was not exactly the same (about 5 g registered with 0.001 g precision). Monthly, the content of the 32 littertraps was collected. Every three months a litterbag was taken from each plot. The duration of the experiment was 24 months (from October 2013 to October 2015).

Samples were taken to the laboratory and dried until constant weight at 65 °C. Litter was then separated into different fractions (needles, branches, bark, flowers, buds, cones and nuts) and the dry weight of each fraction was registered. Dry weight of the residual mass of litterbags was also recorded.

2.3 Microclimate

Temperature and humidity of the 10 cm mineral topsoil were measured once a month with a CRISON 638pt thermometer and a DELTA-T thetha-meter-type HH1 humidity probe to study the microclimate dynamics in relation to the local basal area.

2.4 Nutrient content analyses

Needle fraction of litterfall corresponding to three consecutive months was pooled together to get a composite sample per season (October to December, January to March, April to Jun, and July to September). These samples were grinded with a ball mill. The litter contained in the collected litterbags was also grinded. Finally, grinded samples were analyzed for C

Table 1 Main characteristics of the studied stands

	Dueñas	Ampudia	Valoria la Buena	Valle de Cerrato
Latitude (ETRS 89)	41° 55′ 33″ N	41° 51′ 47″ N	41° 49′ 48″ N	41° 53′ 27″ N
Longitude (ETRS 89)	4° 33′ 18″ W	4° 46′ 9″ W	4° 30′ 8″ W	4° 23′ 40″ W
Mean age	55	50	58	63
Altitude (m)	860	859	870	875
MAP (mm $year^{-1}$)	457	441	467	462
N (trees ha^{-1})	531	564	553	1216
MLBA (m^2 ha^{-1})	28.2	31.3	30.4	45.8
Dg (cm)	26.0	26.6	26.5	21.9
Dm (cm)	25.7	26.0	25.8	21.1
D_0 (cm)	31.0	32.0	33.5	31.0
H_0 (m)	7.1	11.3	11.2	9.8
Hm (m)	5.9	9.7	9.6	8.3
SI (m)	8.4	14.1	12.9	10.9

MAP mean annual precipitation, *N* stand density, *MLBA* mean local basal area, *Dg* quadratic diameter, *Dm* mean diameter, D_0 dominant diameter, H_0 dominant height, *Hm* mean height, *SI* Site Index at a reference age of 80 years (Montero et al. 2001) and N content in a LECO 2000 autoanalyzer and for P, K, Ca, Mg, S, Fe, Cu, Mn, and Zn by inductively coupled plasma optical emission spectrometry (ICP-OES) after wet digestion with HNO_3 and H_2O_2 in microwave.

2.5 Data analyses

The accumulated nutrient release from needles in the litterbags (NR) through time was calculated with the equation by Entry et al. (1991):

$$\mathrm{NR} = \mathrm{N}_{\mathrm{fn}} - [(1-\mathrm{D}) \times N_{\mathrm{dn}}]$$

where NR is the amount of each element (C, N, P, K, Ca, Mg, S, Fe, Cu, Mn, and Zn) released during decomposition per unit mass of needles in the litterbags, N_{fn} is the nutrient concentration in fresh needles, N_{dn} is the nutrient concentration in decomposed needles, and D is the mass loss of the needle litter content.

To study the effect of local basal area on nutrient concentration in litterfall and nutrient release from needles during decomposition, a linear mixed model was used. The models have a random between-subjects factor (stand) with eight replicates (eight plots per stand), one regressor (local basal area), and a within-subjects factor of repeated measures (season). Those variables not normally distributed or presenting heteroscedasticity were transformed (N, C/N, P, K, Ca, S, Mn, and Zn concentrations in litterfall were transformed as log N, log C/N, log P, log K, log Ca, log S, log Mn, and log Zn). The formulation of the models is expressed by:

$$Y_{ij;t} = \mu + \alpha_i + \tau_t + \beta X_{ij} + \varepsilon_{ij;t}$$

where:

- i 1, 2, 3, 4 for the four stands
- j 1, 2, …, 8 for the eight plots within each stand
- t 1, 2, …, 8 for the seasons studied (24 months)
- $Y_{ij;t}$ nutrient concentration in the needle litterfall or nutrient release in the litterbags of plot j in stand i and season t
- μ average global effect
- α_i random effect of stand i, with $\alpha_i \rightarrow N\left(0, \sigma_S^2\right)$.
- τ_t main effect of season t
- X_{ij} local basal area of plot j in stand i ($m^2\ ha^{-1}$)
- β linear rate of change in the nutrient concentration of litterfall or in the nutrient release of the needles in the litterbags per unit local basal area
- $\varepsilon_{ij;t}$ random error in the nutrient concentration of litterfall or in the nutrient release of the needles in the litterbags of plot j in stand i and season t, with $\varepsilon_{ij;\,t} \rightarrow N(0, \sigma^2)$ and first order autoregressive AR(1) variance structure.

Correlations between the local basal area of the plots and the temperature and humidity of the 10 cm topsoil were studied by means of the Pearson correlation coefficient.

The statistical analyses were performed with SAS 9.4 software (SAS 2013).

3 Results

Macro and micronutrient concentrations found on needle litterfall and decomposing needle litter are shown in Supplementary Material 1, 2, 3, and 4.

Needle litterfall showed a clear seasonal pattern during the 2 years and for the four stands (Fig. 1). Maximum peaks of needle litterfall occurred during summer (July and August) with secondary peaks during spring (April, May, and June). The mean annual needle litterfall was 2144 kg ha^{-1}.

Nutrient concentrations in litterfall showed a clear seasonal pattern for C, N, Mg, K, P, S, Cu, and Zn with maximum concentrations in winter for N, Mg, K, P, S, Cu, and Zn and an opposite trend for C. Iron presented an erratic trend during the second year, but the first year behaved similarly to C, with minimum concentrations during winter. Manganese concentration in the litterfall was nearly the same throughout the year (Figs. 2 and 3).

According to the linear mixed model analysis of variance, the effect of local basal area on nutrient concentrations in needle litterfall was significant and positive for C, K, and Mg (Table 2). No significant effect of the local basal area on the rest of elements studied was found.

Soil humidity was negatively correlated to local basal area (Table 3). However, no correlation was found between soil temperature and local basal area of the stands.

Nutrient release in the needles presented different trends depending on the element (Figs. 4 and 5). C, K, Mg, and Mn presented a net release pattern throughout the whole study period. Some of them, displayed a first phase of rapid release (K, Mg, and Mn) followed by a phase of slower release (or even periods of nutrient immobilization). However, C release was more homogeneous through time. Other elements such as Fe or Cu displayed an almost continuous net immobilization while nutrients such as N, Ca, P, or Zn displayed an erratic trend, with phases of nutrient release followed by phases of immobilization. Sulfur presented a first phase of rapid release followed by a second phase of stabilization, followed by a third phase of immobilization.

The release of most nutrients was significantly affected by the local basal area of the plot (Table 4). The linear rate of change per unit local basal area in the release of C, N, Ca, K, Mg, P, S, Zn, and Cu was negative, and then, the release of these nutrients was higher in those plots with lower local basal

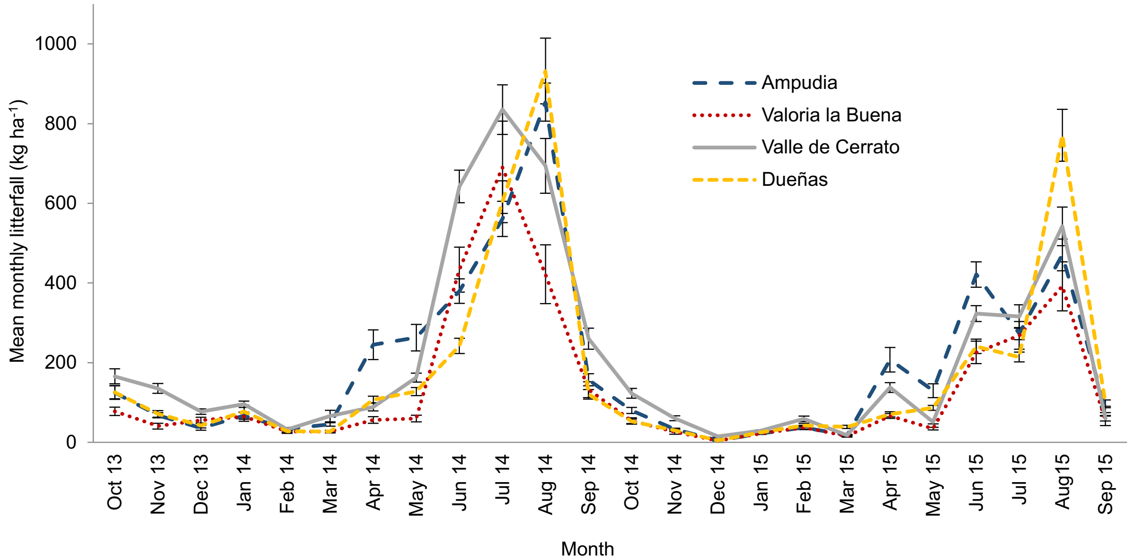


Fig. 1 Mean monthly needle litterfall in the four stands over 24 months (October 2013–September 2015; error bars represent the standard error of the mean)

area. In contrast, neither Fe nor Mn release was affected by the local basal area of the plot.

4 Discussion

4.1 Needle litterfall

The mean annual needle litterfall is similar to those found by Navarro et al. (2013) in southern Spain that ranged from 950 to 2280 kg dry matter ha^{-1}. Peaks of needle litterfall occurred during summer and spring (secondary peak). Navarro et al. (2013) found that peaks of litterfall occurred from July to October. These discrepancies may be due to the species phenology and the climatic differences between the study areas (Bueis et al. 2017) because the timing of foliar abscission under Mediterranean climate is determined by soil water deficit (Escudero and del Arco 1987).

4.2 Time course of nutrient concentrations in litterfall

Maximum needle litterfall for *Pinus halepensis* is concentrated in late spring and summer months when senescent needles are shed. Senescence is a process during which trees retranslocate mobile nutrients such as N, P, K, Mg, S, Cu, and Zn from senescing leaves to other parts of the plant for the production of new tissues (Nambiar and Fife 1991; Reuter and Robinson 1997). Then, the needles shed during summer presented low concentrations of these elements and higher concentrations of C. On the contrary, winter litterfall consists mainly of green needles shed because of wind or storms. Similar trends were observed by Blanco et al. (2008) in *Pinus sylvestris*. Ca, Fe, and Mn are not mobile nutrients and, therefore, no seasonal trend was observed in the concentration of these elements in needle litterfall.

4.3 Effect of local basal area on nutrient concentration in litterfall

The concentration of C, K, and Mg in needle litterfall was significantly lower in plots with lower local basal area. Lado-Monserrat et al. (2015) also found a lower concentration of Mg of needle litterfall in plots subjected to tree removal than in control plots in a *Pinus halepensis* Mediterranean forest. These authors suggested that the higher nutrient availability in plots subjected to thinning may diminish the uptake of nutrients such as magnesium because of competition with other cations such as ammonium. Besides, trees subjected to less competition present also higher productivity, and then, the nutrient concentration on their tissues may be lower. This fact is known as “dilution effect” (Jarrell and Beverly 1981). Sardans et al. (2005) also found that the increase on N and P availability after a fire was followed by a reduction on Mg concentration of litterfall. In addition, the most soluble C compounds and the high mobile character of K and Mg (Swift et al. 1979) may provoke their leaching from needles (Duchesne et al. 2001; Potter et al. 1991; Schlesinger et al. 2016) in lower local basal area plots because lower local basal area implies less aboveground tree biomass, allowing rainfall to have a higher impact on the needles in tree crowns. Kunhamu et al. (2009) also observed that the highest K concentration in litterfall occurred in control plots, while litterfall in plots subjected to thinning presented lower K concentration.

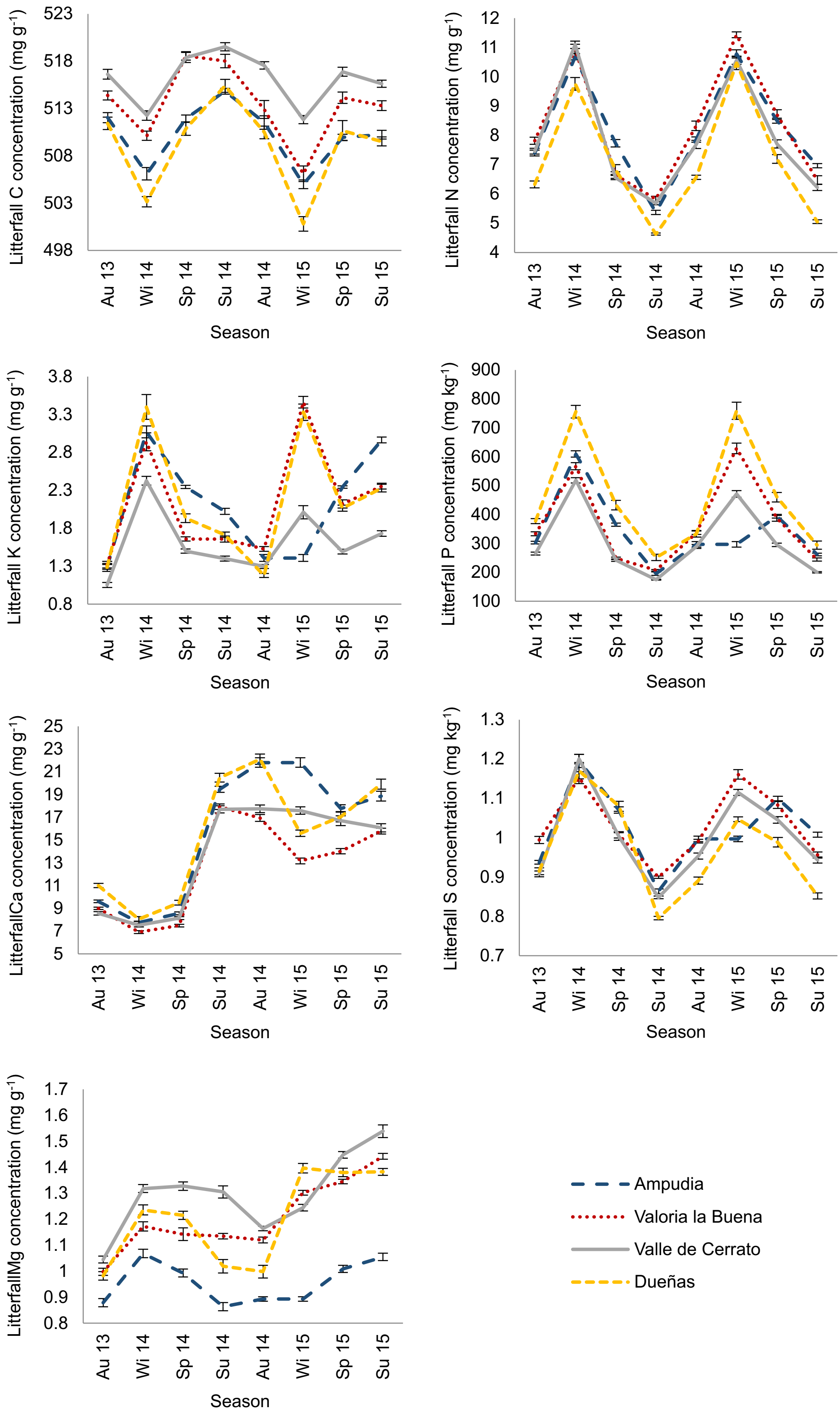
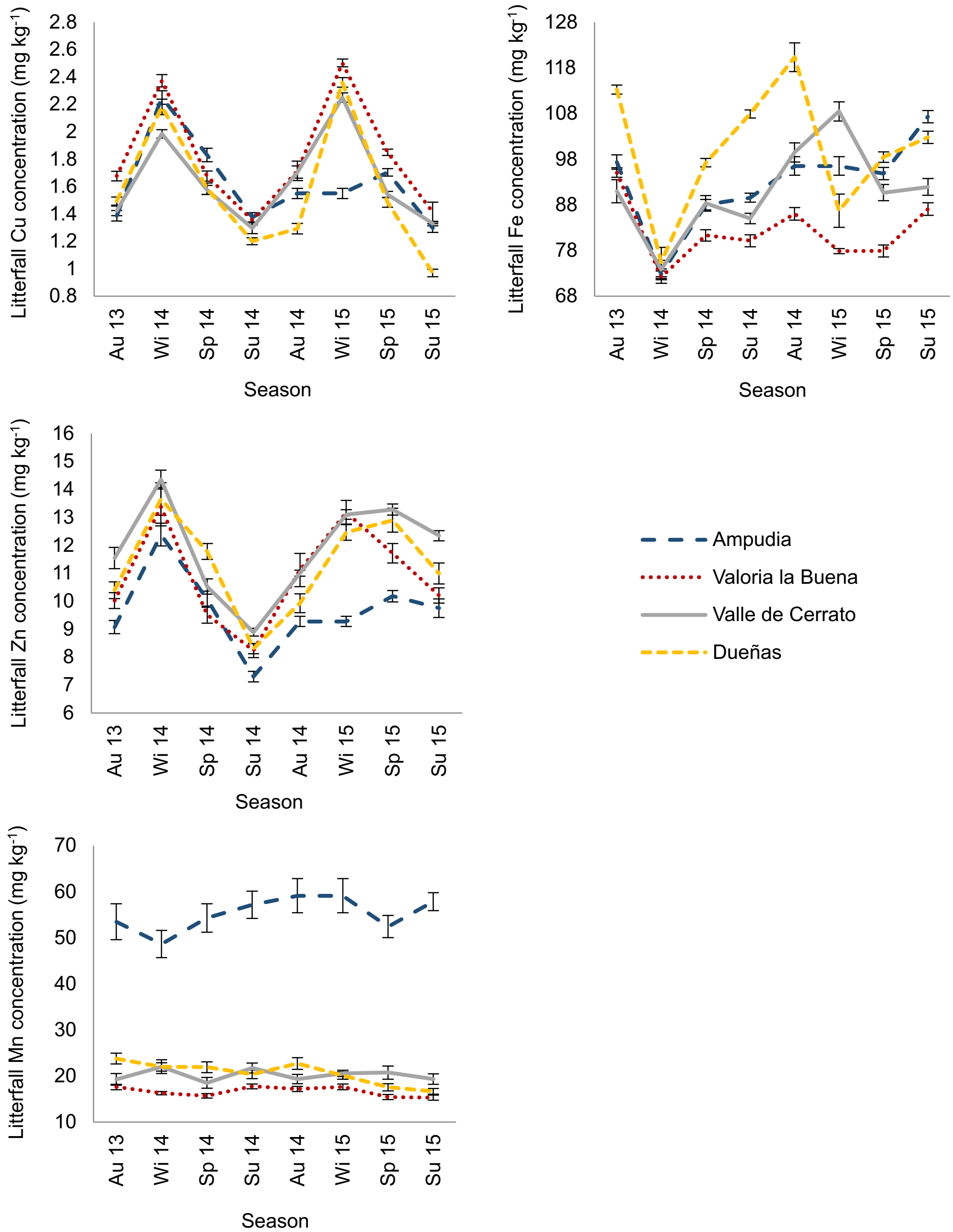


Fig. 2 Average macronutrient concentrations in litterfall of the four stands (Au: autumn; Wi: winter; Sp: spring; Su: summer; 13: 2013; 14: 2014; 15: 2015; error bars represent the standard error of the mean)

Fig. 3 Average micronutrient concentrations in litterfall of the four stands (Au: autumn; Wi: winter; Sp: spring; Su: summer; 13: 2013; 14: 2014; 15: 2015; error bars represent the standard error of the mean)



4.4 Effect of local basal area on soil temperature and humidity

Local basal area has a significant and negative effect on the humidity of the 10 cm mineral topsoil (Cotillas et al. 2009; Gebhardt et al. 2014) due probably to lower interception of precipitations which allows rainfall to reach the soil. However, an opposite trend can be found depending on the climate of the area studied (Blanco et al. 2011; Lado-Monserrat et al. 2015) with higher solar radiation reaching the soil surface and then, higher temperature and lower humidity in thinned plots.

4.5 Nutrient release in decomposing needle litter throughout time

It is generally accepted that nutrient dynamics in decomposing litter are determined by the nutrient availability for decomposers as well as the microclimate. Those nutrients appearing

Table 2 Linear rate of change (β) of the nutrient concentration of litterfall per unit of local basal area (m^2 ha^{-1}) and p values according to the linear mixed model analysis of variance

	β	p value
C (mg kg^{-1})	47.2	0.0097
log N (mg kg^{-1})	− 0.32	0.5174
log C/N	0.000410	0.4206
log P (mg kg^{-1})	0.000833	0.3744
log K (mg kg^{-1})	4.05	< 0.0001
log Ca (mg kg^{-1})	− 0.46	0.5250
Mg (mg kg^{-1})	1.518	0.0184
log S (mg kg^{-1})	0.478	0.0791
Fe (mg kg^{-1})	− 0.00284	0.9614
Cu (mg kg^{-1})	− 0.00081	0.4893
log Mn (mg kg^{-1})	− 0.00221	0.3554
log Zn (mg kg^{-1})	− 0.00085	0.4176

in limiting amounts tend to be immobilized by decomposers at the first phase of decomposition while nutrients appearing in non-limiting amounts tend to be released from litter from the beginning of decomposition (Swift et al. 1979).

Three main groups of elements may be distinguished regarding their release or immobilization during needle litter decomposition in the studied stands. The first one includes C, K, Mg, and Mn which presented a continuous net release pattern during the 2 years studied. Carbon release was almost homogeneous in time, while K, Mg, and Mn presented a clear first phase of rapid release which corresponds to the beginning of decomposition, when highly mobile nutrients such as K are leached. Besides, Mn presents a clear seasonal pattern, with fast nutrient release during autumn, when litter decomposition increases. The second group includes Fe and Cu that presented an almost continuous trend of net immobilization. The third group is made up of N, Ca, P, and Zn which presented an erratic trend with periods of nutrient release followed by phases of immobilization. N and Zn presented a net immobilization throughout nearly the 2 years studied. Besides, a clear seasonal pattern can be observed in N release, with immobilization during autumn and winter and release during spring and summer. However, P presented a net release most of the studied period. Sulfur presents a different trend, where three phases could be distinguished: a first phase of fast release, a second phase of stabilization, and a third phase of

Table 3 Pearson's correlation coefficients (r) and p values of the correlations between local basal area (m^2 ha^{-1}) and soil temperature ($n = 533$) and humidity ($n = 469$) in the plots studied

	r	p value
Temperature (°C)	− 0.00037	0.9932
Humidity (m^3 water m^{-3} soil)	− 0.34151	< 0.0001

accumulation. Sulfur accumulation in decomposing needles could be due to (wet or dry) atmospheric deposition because this is a major income of S for ecosystems (Quilchano et al. 2002).

Ouro et al. (2001) studied *Pinus radiata* needle decomposition in NW Spain and found a consistent decrease of K, P, and S during needle decomposition which is in accordance with the results observed in this study. However, they found that Ca and Mg accumulated in the needles during the first period of the experiment, and afterwards, Ca and Mg were gradually released. Nitrogen presented an initial period of accumulation in decomposing needles for all the treatments considered by those authors. Nitrogen accumulation is frequently observed when substrate presents a high C/N ratio indicating a N shortfall for the activity of the decomposing microorganisms. However, some other labile compounds such as carbohydrates decompose easily diminishing C/N ratio and then, beginning the activity of microorganisms and N release. In the studied stands, two consecutive periods of initial immobilization followed by N release were observed. Lado-Monserrat et al. (2015) observed K release from needles and Ca absorption and concluded that there had been contamination with mineral soil which can also be possible for the stands studied in the present work as soils are calcareous.

The observed Cu and Zn immobilization may respond to accumulation from the environment (soil and atmospheric deposition) as found by several authors for elements such as Fe, Cu, Mn, or Zn (He et al. 2016; Laskowski et al. 1995; Pourhassan et al. 2016).

4.6 Effect of local basal area on nutrient release from litter

The local basal area of the plot also presented a significant effect on the release of all elements analyzed with the exception of Fe and Mn. The release of all these nutrients (C, N, Ca, K, Mg, P, S, Zn, and Cu) was significantly lower in those plots with higher local basal area. For those elements which present immobilization processes instead of release, this result means that for plots with lower local basal area, immobilization is lower than in plots with higher local basal area. The observed trend may be related to the higher decomposition rate observed in plots with lower local basal area as higher rainfall reaching the soil implies higher soil humidity and higher microbial activity together with higher leaching. Besides, lower local basal area implies higher solar radiation reaching the soil which is a decisive factor of litter decomposition in arid zones (Pan et al. 2015). Kim (2016) found no difference in C, N, and P stocks remaining in decomposing needle litter in relation to basal area while the remaining K, Ca, and Mg were positively correlated with basal area during the first 3 months of decomposition: fact that they attributed to increased leaching losses in plots with lower basal areas. Blanco et al. (2011) observed

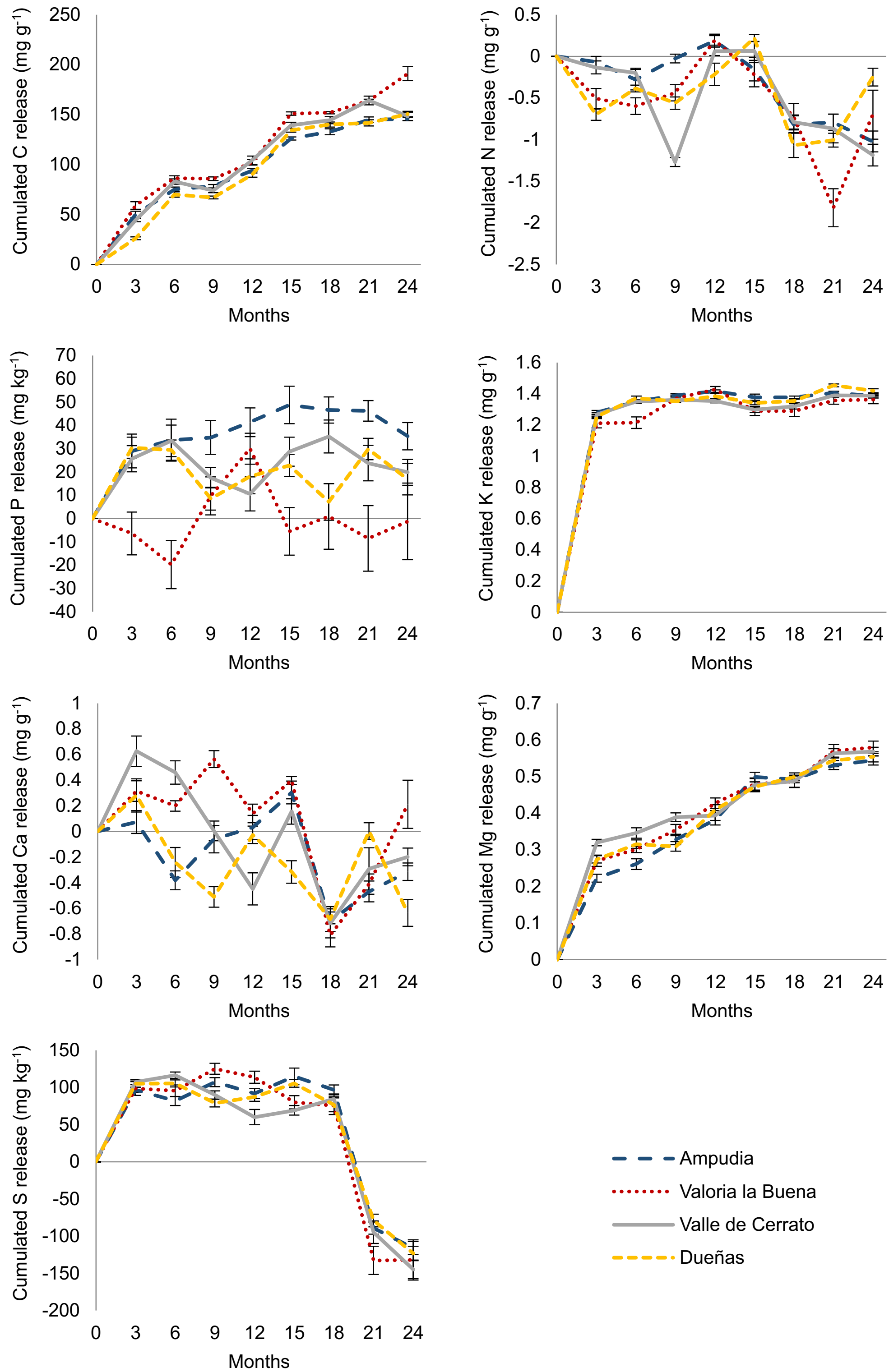


Fig. 4 Cumulated average macronutrient release during the 24 months of litter decomposition in the litterbags of the four stands (error bars represent the standard error of the mean)

the opposite trend. They found a decrease in litter moisture after thinning and lower decomposition rates together with an increase in N and P immobilization and a decrease in Ca immobilization. He et al. (2016) also observed higher immobilization of Cu and Zn in areas located under closed canopies (higher local basal area) compared to areas in forest gaps (lower local basal area) for several species in an Alpine forest in China. The differing trends found in these studies may be related to different microclimatic effects of the decrease in local basal area, with higher solar radiation reaching the soil and lower topsoil humidity instead of lower rainfall interception and higher topsoil humidity.

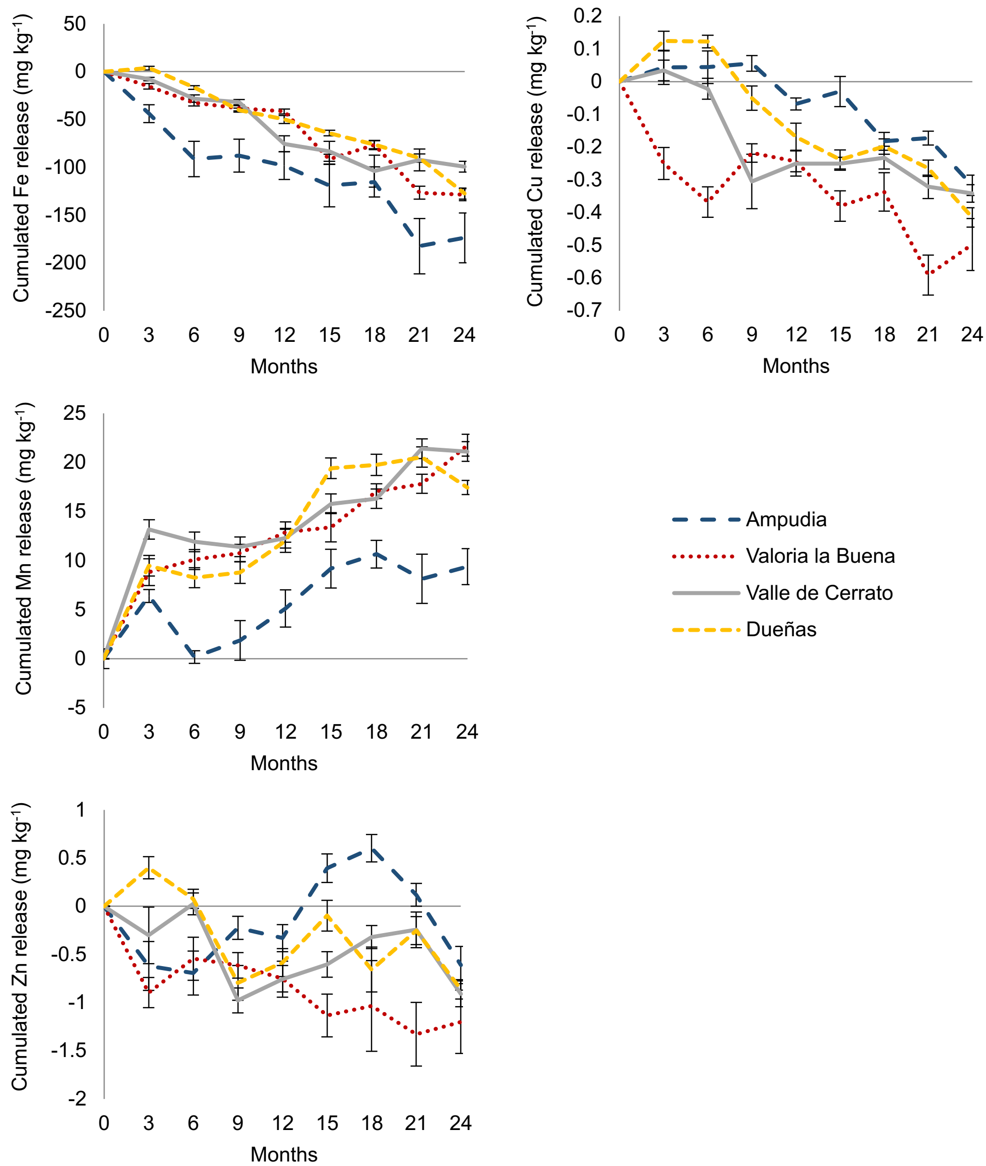


Fig. 5 Cumulated average micronutrient release during the 24 months of litter decomposition studied in the litterbags of the four stands (error bars represent the standard error of the mean)

Table 4 Linear rate of change (β) of the nutrient release in the litterbags per unit of local basal area (m^2 ha^{-1}) and p values according to the linear mixed model analysis of variance

	β	p value
C (mg kg^{-1})	− 308	< 0.0001
N (mg kg^{-1})	− 22.7	< 0.0001
P (mg kg^{-1})	− 1.34	< 0.0001
K (mg kg^{-1})	− 3.24	< 0.0001
Ca (mg kg^{-1})	− 5.49	0.0362
Mg (mg kg^{-1})	− 1.58	0.0003
S (mg kg^{-1})	− 1.75	< 0.0001
Fe (mg kg^{-1})	0.164	0.1183
Mn (mg kg^{-1})	0.0100	0.8003
Cu (mg kg^{-1})	− 0.00587	< 0.0001
Zn (mg kg^{-1})	− 0.0190	< 0.0001

5 Conclusion

Nutrient concentration in needle litter presents a clear seasonal pattern showing that winter litterfall implies important nutrient losses for trees as needles shed in this season are not senescent and have not retranslocated the mobile nutrients they contain.

Local basal area significantly affects nutrient concentration in needle litterfall, as well as soil microclimate and therefore, nutrient release during needle litter decomposition and then, sylvicultural practices involving density management of stands have an impact on nutrient cycling in *Pinus halepensis* Mediterranean forests of central Spain. Density reduction in those plots with higher local basal areas would result in higher water availability for trees as higher rainfall would reach the soil. It would also result in higher nutrient release (or lower nutrient immobilization) from decomposing needle litter, and therefore, in higher nutrient availability.

Nutrient release dynamics from decomposing needle litter differs among elements depending on the specific nutrient availability for decomposers. Thus, nutrients appearing in limiting amounts for microorganisms such as N present a first phase of immobilization, while nutrients appearing in non-limiting amounts such as C, K, Mg, and Mn are released from the beginning of decomposition.

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Compliance with ethical standards

Statement on data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest The authors declare that they have no conflicts of interest.

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