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Relationships between the dynamics of *Pinus halepensis* Mill. and *Pinus sylvestris* L. plantations and environmental parameters: a basis for sustainable management of stands

Relaciones entre las dinámicas de las plantaciones de *Pinus halepensis* Mill. y *Pinus sylvestris* L. y factores del medio: base para la gestión sostenible de las masas

Presentada por Teresa de los Bueis Mellado para optar al grado de Doctora por la Universidad de Valladolid

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Abstract

Pinus halepensis Mill. and *Pinus sylvestris* L. have been widely used for reforestation of poor and degraded soils in Spain. *Pinus halepensis* is a Mediterranean species adapted to drought and to a wide range of substrates and able to colonize very poor soils and improve them, promoting the growth of native broadleaved species such as *Quercus ilex* L. or *Quercus faginea* Lam. Notwithstanding the above, it has been poorly studied because of the limited economic interest of its wood. *Pinus sylvestris* presents great ecological amplitude responsible for its great distribution. *Pinus sylvestris* plantations were established in former *Quercus pyrenaica* Willd. stands that were converted into crops or overexploited for firewood. The aim of this thesis is to widen the knowledge about the existing relationships between the environmental parameters and the dynamics of these plantations to serve as a guide for sustainable forest management of stands.

Forest productivity determination is crucial to accomplish the established managerial objectives through sustainable forest management. It can be estimated through the site index of the stand and, when dominant height is not available, can also be estimated by means of environmental parameters (soil, climatic and physiographic). In this thesis, a discriminant model was developed to predict the site index for *Pinus sylvestris* by using latitude, soil porosity, inorganic Al and microbial biomass C as predictors. Besides, another discriminant model was developed to predict the site index for *Pinus halepensis* plantations with soil porosity, the Annual Hydric Index, the slope and the soil microbial biomass N as predictors.

As seen in the previous models, soil biochemical parameters are determining factors for forest productivity. Organic matter decomposition and nutrient cycling are mainly driven by the activities of the enzymes produced by bacteria and fungi. Therefore, it is essential to know how environmental parameters affect microbial performance in forest soils to understand how ecosystems function. The activities of several enzymes (FDA, DHA, catalase, urease and phosphatases) were studied in soils under *Pinus halepensis* and *Pinus sylvestris* plantations to determine those environmental parameters that influence microbial performance in these ecosystems. Hydric deficit seems to be the most limiting factor for enzyme activities in the calcareous soils under *Pinus halepensis* plantations. However, in soils under *Pinus sylvestris* plantations, the low pH and the high

amount of soluble phenols seem to limit both the activity and the composition of the microbial communities.

Litterfall is the main source of nutrients for forest soils. The amount of litterfall shed by the stand and the dynamics of litter decomposition are driving factors for soil fertility. Decomposition processes are driven by the abundance and diversity of microorganisms, the quality of the substrate and the climate, since temperature, humidity and nutrient availability drive, in turn, the decomposers performance. Usual silviculture often includes stand density management. These practices may alter the amount and chemical composition of litterfall and can also modify the microclimate altering the microbial performance and therefore, the litter decomposition processes. To shed light on these relationships, the effect of local basal area on litterfall, litter decomposition and soil temperature and humidity was studied in four *Pinus sylvestris* and four *Pinus halepensis* stands. The local basal area of the plot significantly affected the amount of litterfall in the stands of both *Pinus* species. The needle litter decomposition rate was significantly affected by the local basal area in *Pinus halepensis* stands, but not in *Pinus sylvestris* stands. Besides, a significant and negative correlation between the local basal area of the stand and the topsoil humidity was found in *Pinus halepensis* and *Pinus sylvestris* plantations. Therefore, the amount of litterfall is lower in plots with lower local basal area due to the lower aboveground tree biomass. The lower amount of tree biomass also intercept less amount of water from precipitations, and then, a higher amount of water reach the soil increasing soil humidity. The activity of decomposers is higher in plots with lower local basal area in *Pinus halepensis* plots (which are the ones limited by hydric deficit) because of the higher soil humidity and finally, the needle litter decomposition rate is also higher. The chemical composition of the litterfall in *Pinus halepensis* and the nutrient release from decomposing needle litter of both *Pinus* species is also affected by the local basal area of the stand. Therefore, silvicultural practices involving density management also have an impact on the nutrient cycling of the *Pinus sylvestris* and *Pinus halepensis* plantations studied.

Resumen

Pinus halepensis Mill. y *Pinus sylvestris* L. son especies ampliamente utilizadas en la repoblación de suelos pobres y degradados en España. *Pinus halepensis* es una especie mediterránea adaptada a la sequía y a un amplio rango de sustratos, capaz de colonizar suelos muy pobres mejorándolos, fomentando el crecimiento de especies nativas como *Quercus ilex* L. o *Quercus faginea* Lam. A pesar de lo anterior, no ha sido estudiado en demasiada profundidad debido al escaso interés económico de su madera. *Pinus sylvestris* presenta una gran amplitud ecológica, responsable de su amplísima distribución. Las plantaciones de *Pinus sylvestris* se establecieron en antiguas masas de *Quercus pyrenaica* Willd. que fueron roturadas o sobreexplotadas para leñas. El objetivo de esta tesis es ampliar el conocimiento acerca de las relaciones existentes entre los parámetros del medio y las dinámicas de estas plantaciones para que sirvan como guía para la gestión forestal sostenible de estas masas.

La determinación de la productividad forestal es crucial para conseguir los objetivos de gestión establecidos a través de un manejo sostenible. Puede estimarse a través del índice de sitio de la masa y, cuando la altura dominante no está disponible, se puede estimar a través de parámetros del medio (edáficos, climáticos y fisiográficos). En esta tesis, se ha desarrollado un modelo discriminante para predecir el índice de sitio para masas de *Pinus sylvestris* utilizando la latitud, la porosidad edáfica, el contenido en Al inorgánico y el C de la biomasa microbiana como variables predictoras. Asimismo, se ha desarrollado un modelo discriminante para predecir el índice de sitio para masas de *Pinus halepensis* que incluye la porosidad edáfica, el Índice Hídrico Anual, la pendiente y el N de la biomasa microbiana como variables predictoras.

Tal y como se ha observado en los modelos previamente desarrollados, los parámetros bioquímicos del suelo son factores determinantes de la productividad forestal. La descomposición de la materia orgánica y el reciclado de nutrientes están determinados por las actividades de las enzimas producidas por las bacterias y hongos del suelo. Por tanto, es esencial conocer cómo afectan los parámetros del medio al desempeño de los microorganismos edáficos en los suelos forestales para comprender el funcionamiento de los ecosistemas. Se han estudiado las actividades de diversas enzimas del suelo (FDA, DHA, catalase, urease and phosphatases) en los suelos bajo plantaciones de *Pinus halepensis* y *Pinus sylvestris* para determinar aquéllos parámetros

ambientales que tienen una influencia sobre el desempeño de los microorganismos edáficos en estos ecosistemas. El déficit hídrico parece ser el factor más limitante para las actividades enzimáticas en los suelos calizos bajo plantaciones de *Pinus halepensis*. Sin embargo, el bajo pH y la cantidad de fenoles solubles presente en los suelos bajo *Pinus sylvestris* parecen limitar tanto la actividad como la composición de las comunidades de microorganismos edáficos.

El desfronde es la principal fuente de nutrientes para los suelos forestales. La cantidad de desfronde aportado por la masa y las dinámicas de descomposición son factores que determinan la fertilidad edáfica. Los procesos de descomposición están determinados por la abundancia y diversidad de microorganismos, la calidad del substrato y el clima ya que la temperatura, la humedad y la disponibilidad de nutrientes determinan el desempeño de los microorganismos. La selvicultura habitual incluye frecuentemente el manejo de la densidad de las masas. Estas prácticas pueden alterar la cantidad y la composición química del desfronde y también modificar el microclima alterando el desempeño de los microorganismos, modificando a su vez los procesos de descomposición de la hojarasca. Para arrojar luz sobre estas relaciones, se estudió el efecto del área basimétrica de las masas sobre el desfronde, su descomposición y la temperatura y humedad del suelo en cuatro masas de *Pinus halepensis* y cuatro masas de *Pinus sylvestris*. El área basimétrica de las parcelas afectó significativamente la cantidad de desfronde en las masas de ambas especies de *Pinus*. La tasa de descomposición de las acículas senescentes de *Pinus halepensis* se vio afectada por el área basimétrica local de las parcelas, sin embargo no se encontró un efecto significativo sobre la tasa de descomposición de las acículas de *Pinus sylvestris*. Se halló también una correlación significativa y positiva entre el área basimétrica local de las parcelas y la humedad de los primeros centímetros del suelo en ambas especies. Por tanto, la cantidad de desfronde resultó ser significativamente menor en aquellas parcelas con menor área basimétrica local debido a la menor cantidad de biomasa aérea arbórea presente. Esta menor cantidad de biomasa arbórea también fue responsable de una menor interceptación del agua procedente de las precipitaciones, provocando que una mayor cantidad de agua alcance el suelo incrementando su humedad en relación a aquellas parcelas con mayor área basimétrica local. La actividad de los microorganismos descomponedores es mayor en aquellas parcelas con menor área basimétrica local en las masas de *Pinus halepensis* (limitadas por el déficit hídrico) debido a la mayor humedad del suelo y por tanto, la tasa de descomposición de las acículas es también mayor. La composición química del desfronde en *Pinus halepensis* y la liberación de nutrientes de las acículas senescentes durante la descomposición también se ve afectada por el área basimétrica de la parcela. Por tanto, las prácticas selvícolas que conllevan alteración de la densidad de la masa también presentan un impacto sobre el ciclo de nutrientes de las plantaciones de *Pinus halepensis* y *Pinus sylvestris* estudiadas.

Outline of the thesis

This thesis is focused on understanding the relationships between environmental factors (edaphic, climatic and topographic) and the productivity and the nutrient cycling dynamics of *Pinus halepensis* Mill. and *Pinus sylvestris* L. plantations in Spain. This information may provide a valuable insight for forest management decision making.

The first two studies (I and II) are focused on developing a model to discriminate the site index of both *Pinus halepensis* Mill. and *Pinus sylvestris* L. plantations in the area studied by using environmental predictors (edaphic, climatic and physiographic parameters). These models may help forest managers to achieve both protective and productive goals for these plantations, allowing them to define the best silvicultural treatments for these stands or even to select the most suitable species in new afforestation programs.

The third study (III) deals with the determination of those environmental factors that are more correlated to the enzymatic activities in soils under *Pinus halepensis* Mill. and *Pinus sylvestris* L., as enzymatic activities are responsible for nutrient cycling in soils. Basing on this information, some managerial proposals have been proposed so as to improve the microbial performance responsible for enzymatic activities and nutrient cycling.

The last three studies go deeper in the knowledge of the nutrient cycles in *Pinus halepensis* Mill. and *Pinus sylvestris* L. plantations and try to determine the effect of the stand density on litterfall and litter decomposition rates (study IV) and the associated nutrient fluxes (studies V and VI). Forest management is usually focused on stand density intervention through thinning practices, and then, the effect of those actions on nutrient cycling should be considered when targeting management practices towards sustainability.

A concept map of the thesis is shown in Figure 1.

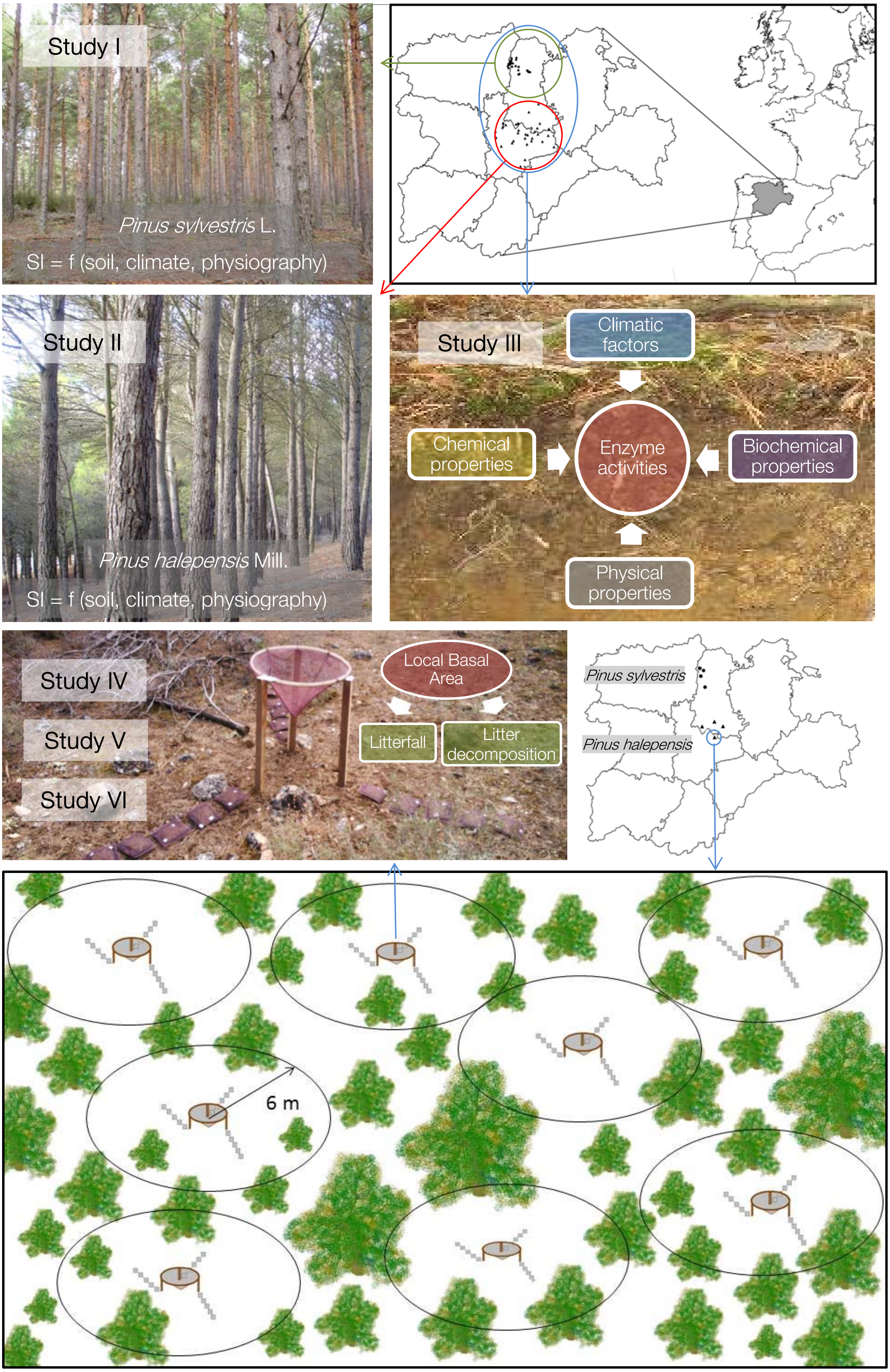

Figure 1. Concept map of the thesis including the six studies

This thesis has generated six original articles. The first of them is already published in a SCI journal, the next three articles are in the second phase of peer review in SCI journals and the last two are manuscripts in preparation:

I. Bueis, T.; Bravo, F.; Pando, V; Turrión, M.B. (2016) Relationship between environmental parameters and *Pinus sylvestris* L. site index in forest plantations in northern Spain acidic plateau. iForest – Biogeosciences and Forestry, 9: 394-401. DOI: 10.3832/ifor1600-008

II. Bueis, T.; Bravo, F.; Pando, V; Turrión, M.B. Site factors as predictors for *Pinus halepensis* Mill. productivity in Spanish plantations. (In Press: Annals of Forest Science) DOI: 10.1007/s13595-016-0609-7

III. Bueis, T.; Turrión, M.B. Bravo, F.; Pando, V; Muscolo, A. Factors determining enzyme activities in soils under *Pinus* plantations in Spain: a basis for establishing sustainable forest management strategies. (Second phase of peer review: European Journal of Soil Science)

IV. Bueis, T.; Bravo, F.; Pando, V; Turrión, M.B. Influencia de la densidad del arbolado sobre el desfronde y su reciclado en pinares de repoblación del norte de España. (Second phase of peer review: Bosque)

V. Bueis, T.; Bravo, F.; Pando, V; Turrión, M.B. Local basal area affects needle litterfall nutrient concentration and nutrient release during decomposition in *Pinus halepensis* Mill. plantations in Spain. (Manuscript in preparation)

VI. Bueis, T.; Bravo, F.; Pando, V; Turrión, M.B. Nutrient release of *Pinus sylvestris* L. decomposing needle litter: effect of local basal area. (Manuscript in preparation)

1. Introduction

1.1. *Pinus halepensis* Mill. and *Pinus sylvestris* L. plantations

Pinus species are very frugal species, able to survive in very nutrient poor soils, sometimes even in cracks in rock. *Pinus halepensis* Mill. is the most widely distributed *Pinus* species in the circum-Mediterranean area (Figure 2) and the second species in extension in Spain (only outnumbered by *Quercus ilex* L.) with near 1.7 million hectares. It is naturally distributed along the eastern half of Spain (Figure 3), from the sea level until 1000 m a.s.l., occasionally reaching 1600 m (EUFORGEN 2009). This species has been used in plantations in Spain since late XIX century, but it was from 1940 to 1980 when more than 500000 hectares were planted with *Pinus halepensis* with the objective of protecting the soil against erosion and vegetal cover restoration (Serrada et al. 2008) as it has the ability to improve soil and microclimatic conditions, promoting the growth of broadleave species such as *Quercus ilex* L. or *Quercus faginea* Lam. (Montero et al. 2001).

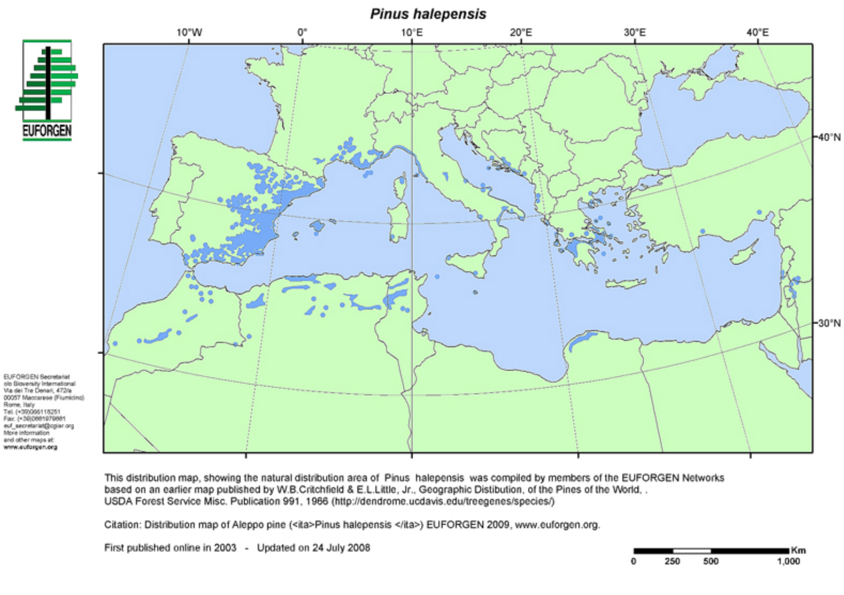

Figure 2. Natural distribution area of *Pinus halepensis* Mill. (EUFORGEN 2009)

Pinus halepensis has been frequently used in protective plantations because of its resistance to drought, its tolerance for a wide range of substrates and its ability to colonize bare soils. Despite the importance of the species (extension, fungal production, protective function for wildlife and against erosion…), it has not been sufficiently studied because of the limited economic interest of its wood (Serrada et al. 2008).

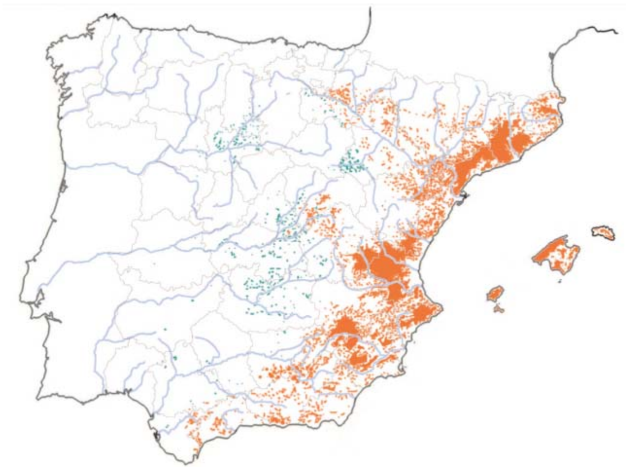

Figure 3. Distribution of *Pinus halepensis* Mill. in Spain (in red: natural stands; in green: plantations) (Serrada et al. 2008)

Pinus sylvestris L. is the most widely distributed *Pinus* species in the world. This species present great ecological amplitude, reason for its great distribution, which goes from Portugal to Siberia and from northern Norway to the south of Spain (Figure 4). In the north of Eurasia it is distributed from the sea level to 800 m a,s.l. It occupies higher altitudes in the south of its distribution, reaching 2500 m in some areas of the Caucasus (Nicolás & Gandullo 1969). Spanish stands constitute the southern limit of its distribution, where it occupies 1.28 million hectares (Serrada et al. 2008).

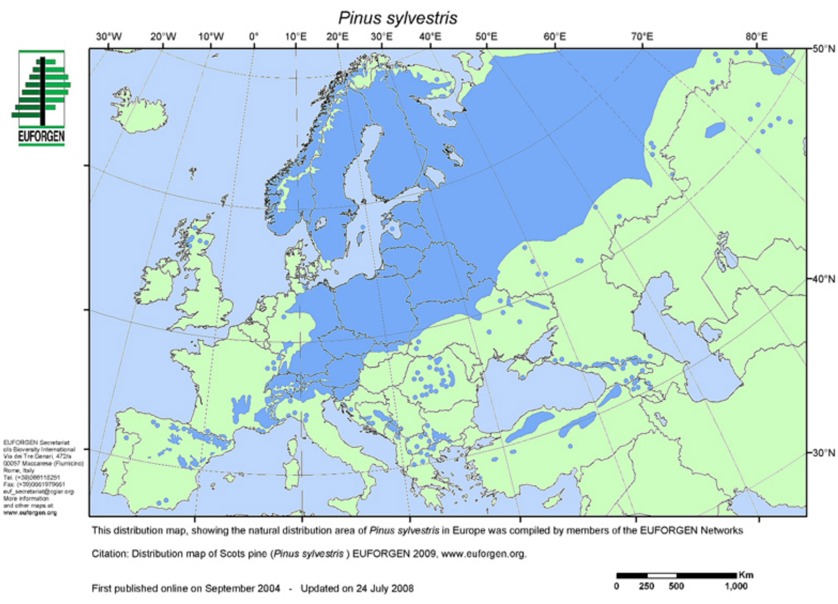

Figure 4. Natural distribution area of *Pinus sylvestris* L. (EUFORGEN 2009)

The objectives of these stands are varied, depending on the area and range, from strictly protective to mainly productive, with frequent situations of multi-functionality including wood and fungi production, hunting, recreation, wildlife and soil protection. The wood of *Pinus sylvestris* is of a high quality, very much appreciated in construction and carpentry and therefore, this species has been more extensively studied than *Pinus halepensis*. The 96% of *Pinus sylvestris* pure plantations in Spain (Figure 5) are located in the region of Castilla y León (Serrada et al. 2008).

Figure 5. Distribution of *Pinus sylvestris* L. in Spain (in red: natural stands; in green: plantations) (Serrada et al. 2008)

Most plantations of *Pinus halepensis* and *Pinus sylvestris* in Castilla and León region were established in degraded areas that formerly were natural stands of *Quercus ilex* L. and *Quercus pyrenaica* Willd. respectively, which were transformed into crops or overexploited for firewood.

The knowledge about the existing relationships between the environmental parameters and the dynamics of these stands is crucial to accomplish the established managerial objectives by means of sustainable forest management.

1.2. Forest productivity

Forest productivity determination as well as the identification of those environmental factors driving forest productivity is essential for the sustainable management of stands. Determining forest productivity can inform decision making in forest management in order to achieve both protective and productive goals for these stands. Useful guidelines for silvicultural practices, such as thinning in plantations on poor and limy soils (Montero et al. 2001) can avoid slowing down forest growth. Similarly, when forest potential productivity information is available prior to plantation, the most suitable species can be selected for afforestation projects (Bravo-Oviedo & Montero 2005). In short, reliable productivity models are necessary for sustainable forest management.

Forest productivity is usually estimated through the site index (dominant height of the stand at a reference age) because the height of the stand is highly correlated to forest productivity (Skovsgaard & Vanclay 2008). Sometimes, the dominant height of the stand is not available and then, other methods based on the study of environmental parameters are preferred (Bravo & Montero 2001). These methods are known as soil-site methods and usually include the study of soil, physiographic and climatic variables (Aertsen et al. 2010). The inclusion of soil physicochemical parameters as well as physiographic variables in this kind of studies is usual (Romanya & Vallejo 2004, Bravo-Oviedo & Montero 2005, Afif-Khouri et al. 2010), but parameters related to the soil organic horizon are less frequently considered (Romanya & Vallejo 2004, Laamrani et al. 2014). Studies including biochemical parameters are also scarce even when soil microorganisms are known to drive nutrient availability in soils not only because of their ability to transform the organic matter but also for their own fast turnover (Mahía et al. 2006).

Multiple linear regression has been widely used to relate site index and environmental parameters (Stendahl et al. 2002, Romanya & Vallejo 2004, Afif-Khouri et al. 2010). However, this approach may present problems when working with highly correlated variables. Soil variables are usually highly correlated and also climatic and physiographic variables often present significant correlations. Classification methods such as Discriminant Analysis are more appropriate in these cases (Bravo & Montero 2001).

Several studies, some of them focusing on *Pinus halepensis* to predict climate change impact on forest growth, tend to agree on climate as the main factor driving species growth (Gandullo et al. 1972, Sabate et al. 2002, Rathgeber et al. 2005, Girard et al. 2011, Condes & Garcia-Robredo 2012, Klein et al. 2014, Río et al. 2014). Río et al. (2014) also related the lower *Pinus halepensis* site index in south-eastern Spain to lower nutrient availability, lower cation exchange capacity, higher C to N ratio and lower soil clay content.

Soil textural parameters together with some climatic and physiographic variables are usually included in the models developed to predict *Pinus sylvestris* site index along its distribution (Hagglund & Lundmark 1977, White 1982, Bravo & Montero 2001, Sharma et al. 2012). Bravo & Montero (2001) developed a discriminant model for *Pinus sylvestris* L. in the Ebro Basin that included silt and clay content and cation exchange capacity as predictors and correctly classified 64% of plots within their site index classes. White (1982) found that the rate of height growth of *Pinus sylvestris* L. in Great Britain was mainly related to solar radiation, soil texture and soil moisture content. Hagglund & Lundmark (1977) developed several models to predict *Pinus sylvestris* L. site index in Sweden with latitude, altitude, soil depth and texture as predictors. For the same species, Aertsen et al. (2012) found that granulometric fractions and litterfall N content were the best predictors for forest productivity in Flanders, while Sharma et al. (2012) included several physiographic factors (latitude, aspect, slope) as well as soil depth, year of stand origin and sum of temperatures in their equations to predict site index for Scots pine in Norway.

1.3. Nutrient cycling

1.3.1. Enzymatic activities

Research on nutrient dynamics is vital to understanding forest ecosystem dynamics. As an active component of soil organic matter, microbial biomass participates in the transformations and accumulation of nutrients in soil and serves as a good measurement of organic matter turnover and biological activity in forest and agricultural ecosystems (Gartzia-Bengoetxea et al. 2009, Bueis et al. 2016). The enzymatic activity of microorganisms is crucial in nutrient poor ecosystems as the ones studied. Enzymes in soils are mainly produced by bacteria and fungi (Burns 1978, Sinsabaugh 1994), but also by plant roots and animals (Tabatabai 1994, Bloem et al. 2006). They are positively related to soil organic matter and are responsible for soil quality, crop productivity and energy transfer (Tabatabai 1994). They are in charge of the mineralization and humification processes of organic matter. Through mineralization, nutrients retained in the organic matter are released and become available for plant root uptake. By means of the humification processes, the organic matter is transformed into more stable organic forms (humus) that improve the soil water and nutrient retention capacity, act as filter of contaminants and have the ability to buffer soil pH (Stevenson 1994). Soil microbial biomass is considered the “eye of the needle” through which all organic material in soil must pass (Jenkinson 1977). Soil enzymes have also the potential to respond rapidly to environmental changes and serve as indicators of health and quality in planted and natural ecosystems (Bloem et al. 2006).

Most enzymes catalyse reactions inside living cells (intracellular enzymes), but many others function outside the cell (extracellular enzymes). Intracellular enzymes are also released when cells die and, together with extracellular enzymes, can be stabilized with organo-mineral complexes, enabling them to remain active for long periods of time (Bloem et al. 2006). Dehydrogenases (DHA) are the main oxidoreductase enzymes that oxidize organic compounds in soils by transferring electrons between substrates and acceptors (Das & Varma 2011). They are used as indicators of microbial redox systems and considered a measure of microbial oxidative activities in soils (Burns 1978, Tabatabai 1994).

Phosphatases have an essential function in the P cycle (Burns 1978), as they catalyse the hydrolysis of organic forms of P into inorganic forms that are available to plants (Alef & Nannipieri 1995). A negative correlation is usually found between P availability and phosphatase activity due to the negative feedback of phosphorus concentration on enzyme activity (Olander & Vitousek 2000).

Urease, an extracellular enzyme that catalyses the hydrolysis of urea to NH_3 and CO_2 (Das & Varma 2011), accounts for up to 63% of total enzyme activity in soil (Martínez-Salgado et al. 2010), and is often used as a soil biological indicator because of its high sensitivity to changes induced by external factors.

Catalase, an intracellular enzyme with detoxifying activity, is related to the abundance of aerobic microorganisms (Garcia & Hernandez 1997).

The Fluorescein Diacetate Hydrolysis reaction (FDA) reflects all hydrolytic activity in soil (Alef & Nannipieri 1995). It has been used as an indicator of general microbial activity in soil (Bandick & Dick 1999) and may provide detailed information about changes in soil organic matter dynamics.

Many environmental factors affect microbial performance and therefore, enzyme activities in soils (Tabatabai 1994). It is crucial to know the relationships between microbial activities and environmental factors such as litter chemistry, climate or vegetation to understand how ecosystems function. This knowledge can also guide forest management for sustainability.

1.3.2. Litterfall and litter decomposition

Litterfall, together with root turnover, is the main source of nutrients for soils. Litterfall rate and the nutrient release through litter decomposition play a key role in the sustainability of forest ecosystems. 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 (Nambiar & Fife 1991, Blanco et al. 2008, Kim et al. 2013). Needle senescence is a nutrient conservative mechanism in nutrient-limited areas. The translocation process occurring during senescence consists of the withdrawal of some mobile nutrients from leaves to twigs to avoid their loss during leaf abscission. Leaching processes are especially important for elements such as K and P (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 physicochemical 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 stress, and to improve the growth of the remaining trees. Stand density alteration usually result in changes in litterfall rates (Roig et al. 2005, Blanco et al. 2006, Navarro et al. 2013, Lado-Monserrat et al. 2015), microclimate conditions (Kunhamu et al. 2009, Chase et al. 2016) and consequently, litter decomposition (Ouro et al. 2001, Kim 2016) due to variations in microbial performance. Less attention has received the effect of these practices on nutrient concentrations in litterfall and nutrient release through decomposition (Blanco et al. 2008, Kim 2016).

2. Objectives of the thesis

The general aim of this thesis is to increase the knowledge of the relationships between the environmental parameters and the dynamics of *Pinus halepensis* Mill. and *Pinus sylvestris* L. plantations in northern Spain, useful for forest management decision making for these stands. The specific objectives of this thesis are:

– To develop a discriminant model to estimate site index for *Pinus sylvestris* L. plantations in northern Spain using soil (physical, chemical and biochemical), climatic and physiographic parameters *(Study I)*

– To develop a model for predicting the site index of *Pinus halepensis* Mill. plantations in northern Spain using soil (physical, chemical and biochemical), climatic and physiographic parameters *(Study II)*

– To assess the differences in enzyme activities (FDA, DHA, acid and alkaline phosphatases, urease and catalase) between the contrasting soils under *Pinus sylvestris* L. and *Pinus halepensis* Mill. plantations in Spain and to trace those differences back to edapho-climatic parameters *(Study III)*

– To study the dynamics of litterfall and litter decomposition in *Pinus sylvestris* L. and *Pinus halepensis* Mill. plantations in Castilla y León region and the effect of local density on these parameters *(Study IV)*

– To evaluate the seasonal pattern of nutrient concentration in the litterfall of *Pinus halepensis* Mill. plantations in northern Spain; to assess whether local basal area of these stands affects nutrient concentration of litterfall; to study how nutrients are released from needle litterfall during decomposition and to determine the effect of local basal area on nutrient release during the first two years of litter decomposition *(Study V)*

– To study how nutrients are released from the needle litterfall of *Pinus sylvestris* L. plantations in northern Spain during decomposition and to determine the effect of local basal area on nutrient release during the first 18 months of litter decomposition *(Study VI)*

3. Material and methods

3.1. Study area

The study area is located in the region of Castilla y León, in the northern half of Spain. The *Pinus halepensis* plantations studied are located in the south of the province of Palencia and the province of Valladolid. The *Pinus sylvestris* plantations studied are located in the north of the provinces of Palencia and León (Figure 6).

Figure 6. Location of the stands studied

The *Pinus sylvestris* plantations studied are located at altitudes that range from 800 to 1600 m a.s.l. The mean annual temperature of the area is 9.6ºC and the mean annual precipitation is 734 mm. Soils are classified as Inceptisols (Herrero de Aza et al. 2011) and they are strongly acidic (pH ranges from 3.7 to 5.6). The climate in the area studied is classified as humid according to the Lang (Lang 1915), Martonne (De-Martonne 1926) and the Annual Hydric (Thornthwaite 1949) Indexes. The understory of these stands is dominated by *Erica australis* L., *Erica cinerea* L., *Halimium alysoides* (Lam.) Spach, *Calluna vulgaris* (L.) Hull and *Pterospartum tridentatum* L. Willk. The ages of the studied *Pinus sylvestris* stands range from 28 to 63 years.

The *Pinus halepensis* plantations studied are located at altitudes that range from 769 to 915 m a.s.l. The mean annual temperature of the area is 11.7ºC and the mean annual precipitation is of 456 mm. Soils in this area are classified as Calcixerepts, within the Inceptisol order (Llorente & Turrion 2010) and their pH range from 8 to 8.9. The climate in this area is classified as arid / sub-humid according to the Lang (Lang 1915), Martonne (De-Martonne 1926) and the Annual Hydric (Thornthwaite 1949) Indexes. The understory is dominated by *Quercus ilex* L., *Quercus faginea* Lam., *Genista scorpius* (L.) D.C., *Dorycnium pentaphyllum* Scop., *Staehelina dubia* L. *Lithodora fruticosa* L. and *Salvia lavandulifolia* Vahl. The *Pinus halepensis* stand ages in the area studied range from 34 to 61 years.

3.2. Experimental plots

3.2.1. *Pinus sylvestris* plots belonging to the Sustainable Forest Management Research Institute (iuFOR)

A set of 35 plots belonging to the Sustainable Forest Management Research Institute (iuFOR) located in *Pinus sylvestris* plantations were selected (Figure 7), both to develop a discriminant model to predict the site index (SI) by means of environmental variables (Study I) and to study the factors determining enzyme activities in soils under *Pinus sylvestris* plantations (Study III). The dimensions of these plots were of 30 x 40 m. The coordinates of the studied plots are shown in Supplementary Material 1 and the main characteristics are summarized in Table 1.

Table 1 Stand characteristics of the *Pinus sylvestris* L. plots (n=35) belonging to the Sustainable Forest Management Research Institute

Parameters	Mean	SD[a]	Minimum	Maximum
Stand age (years)	39.8	7.4	28.0	54.0
Stocking (trees·ha^{-1})	1102.9	423.0	400.0	2083.3
Dominant height (m)	14.5	3.6	8.5	22.8
Mean height (m)	13.6	3.7	7.3	22.9
Quadratic mean diameter (cm)	20.3	4.1	13.9	34.7
Basal area (m^2·ha^{-1})	33.1	8.2	16.8	53.6
Site Index (m at 50 years age)	18.0	2.8	12.6	22.6

[a] SD: standard deviation

Figure 7. Location of the *Pinus sylvestris* plots belonging to the Sustainable Forest Management Research Institute (circles) and the *Pinus halepensis* plots belonging to the Spanish National Forest Inventory (triangles)

3.2.2. *Pinus halepensis* plots belonging to the Spanish National Forest Inventory (NFI)

A set of 35 plots belonging to the Spanish National Forest Inventory (NFI) in pure *Pinus halepensis* plantations were selected (Figure 7) to develop a discriminant model to predict the SI by using environmental parameters (Study II) and to study the factors determining enzyme activities in soils under *Pinus halepensis* plantations (Study III). Finally, 32 plots were studied because three of the selected plots were located within the limits of military facilities and we were not allowed to enter. The coordinates of the studied plots are shown in Supplementary Material 1 and the main characteristics are summarized in Table 2.

Table 2 Stand characteristics of *Pinus halepensis* Mill. plots (n=32) belonging to the Spanish National Forest Inventory

Parameters	Mean	S.D.[a]	Minimum	Maximum
Stand age (years)	53.8	4.3	45.0	61.0
Stocking (trees ha^{-1})	859.5	428.7	293.6	1711.8
Dominant height (m)	8.6	1.7	5.5	12.0
Mean height (m)	7.1	1.6	4.6	11.2
Quadratic mean diameter (cm)	16.3	3.6	10.3	26.2
Basal area (m^2 ha^{-1})	15.8	5.5	9.1	32.0
Site Index (m height at 80 years age)	10.9	2.2	6.8	15.0

[a] S.D.: standard deviation

3.2.3. *Pinus sylvestris* and *Pinus halepensis* stands selected to study the nutrient cycle

To study the litterfall and the needle litter decomposition in *Pinus halepensis* and *Pinus sylvestris* plantations, four stands were selected for each species (Figure 8). Therefore, eight stands were studied. The main characteristics of the studied stands are summarized in Table 3 (*Pinus halepensis*) and Table 4 (*Pinus sylvestris*).

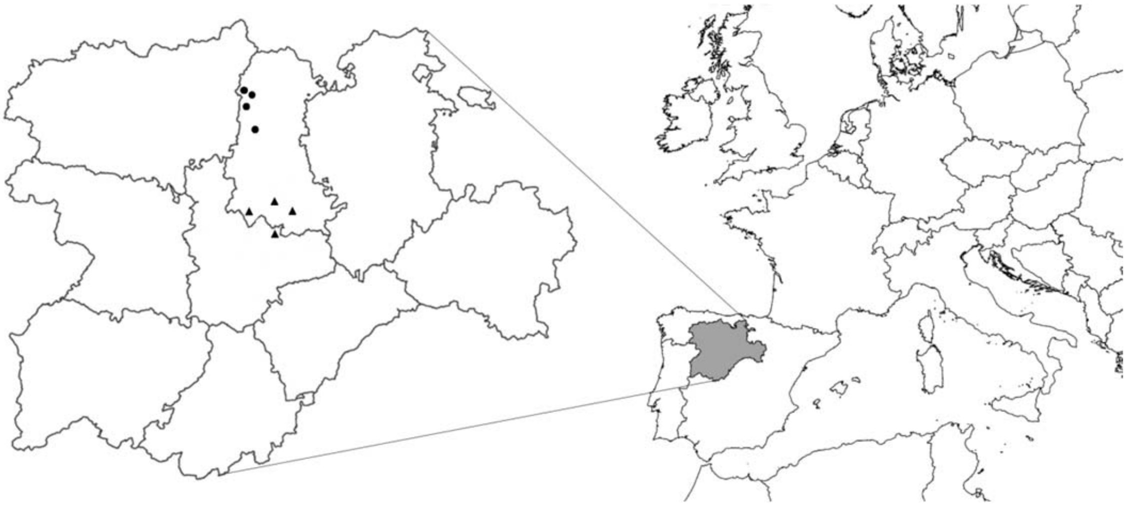

Figure 8. Location of the *Pinus sylvestris* and *Pinus halepensis* stands selected to study the nutrient cycle

Table 3 Characteristics of the *Pinus halepensis* stands selected to study the litterfall and the needle litter decomposition[a]

	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

[a] 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)

Table 4 Characteristics of the *Pinus sylvestris* stands selected to study the nutrient cycle[a]

Site	Saldaña	Pino del Río	Santibáñez de la Peña	Mantinos
Latitude (ETRS 89)	42° 33’ 10’’ N	42° 37’ 2’’ N	42° 44’ 39’’ N	42° 45’ 47’’ N
Longitude (ETRS 89)	4° 43’ 38’’ W	4° 46’ 40’’ W	4° 47’ 43’’ W	4° 50’’ 17’’ W
Mean age	57	53	34	55
Altitude (m)	980	1053	1151	1130
MAP (mm $year^{-1}$)	616	698	901	943
N (trees ha^{-1})	619	508	531	597
LBA (m^2 ha^{-1})	26.27	31.45	26.29	32.19
Dg (cm)	23.25	28.08	25.11	26.20
Dm (cm)	23.00	27.75	24.82	25.68
D_0 (cm)	27.65	32.61	29.36	32.15
H_0 (m)	14.1	18.5	11.9	15.2
Hm (m)	13.5	17.7	11.4	13.3
SI (m)	12.4	17.6	17.2	13.9

[a]MAP: mean annual precipitation; MINT: mean minimum temperature; MAXT: mean maximum temperature (Ninyerola et al. 2005); N: stand density; LBA: 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 50 years (Río et al. 2006).

On each stand, eight circular plots of six meters radius were established covering the widest range of local basal area present in the stand. Local basal area was considered as the addition of the normal sections of the trees included on each plot. Then, 32 plots were studied for each species (64 plots in total). On each plot, a littertrap and 15 litterbags (Figure 9) filled with senescent needles were set up (32 littertraps and 480 litterbags for each species). 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 x 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 for *Pinus halepensis* and in September 2014 for *Pinus sylvestris*. Each litterbag was labelled so as to identify them as their litter content was not exactly the same (about 5 g registered with 0.001 g precision).

Figure 9. Littertrap and litterbags placed on each of the 64 plots studied

Figure 10 depicts the experimental design set up on each stand studied. Litterfall and needle litter decomposition were studied for two years in *Pinus halepensis* plots (from October 2013 to October 2015) and for 18 months in *Pinus sylvestris* stands (from October 2014 to April 2016).

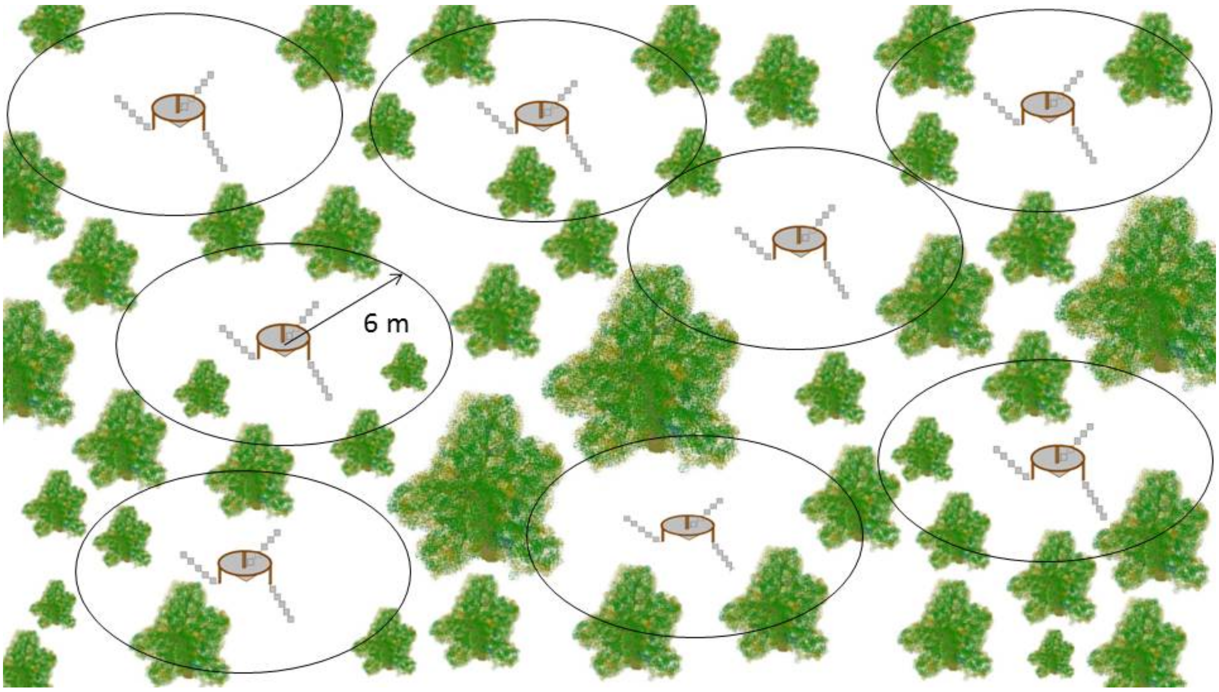

Figure 10. Experimental design established on each of the four stands studied in *Pinus halepensis* plantations and the four stands studied in *Pinus sylvestris* plantations

3.3. Sampling

3.3.1. Soil sampling

Soil sampling in the 35 *Pinus sylvestris* plots (iuFOR) and the 32 *Pinus halepensis* plots (NFI) included the forest floor or organic horizon and 10 cm of mineral topsoil, based on the method of Jokela *et al.* (1988). Bravo et al. (2011) also adopted this method, as environmental changes are more strongly reflected in this layer. The organic horizon was divided into two fractions: almost undecomposed litter fraction (L), and fragmented fraction plus humified fraction (FH). Each plot had four sampling points located 5 m from the centre of the plot in N, S, E and W directions. At each point, the organic horizon was sampled in 20x20 cm quadrants and mixed to get a composite sample of each fraction (L and FH) per plot (Figure 11). The total organic horizon thickness (OHT) was also measured in the four sampling points per plot.

Figure 11. Organic horizon sampling

Four undisturbed samples of mineral soil were collected on each plot with steel cylinders (5 cm diameter and 5 cm height) to maintain their original structure. One disturbed sample was taken from each sampling point per plot. The four disturbed samples per plot were grouped together to obtain a composite soil sample per plot (Figure 12).

Figure 12. Mineral soil sampling

3.3.2. Litterfall and decomposing needle litter sampling

In the 32 *Pinus sylvestris* plots and the 32 *Pinus halepensis* plots established to study the nutrient cycle (Study IV, V and VI) the content of the littertraps was collected every month. Temperature and humidity of the first 10 cm mineral soil were also measured on a monthly basis in every plot with a CRISON 638pt thermometer and a DELTA-T Thetha-Meter type HH1 humidity probe. Every three months a litterbag was collected from each plot (one extraction per season).

3.4. Laboratory analyses

3.4.1. Soil analyses

Organic horizon samples were dried at 60ºC and weighed to determine the amount of biomass per hectare for L (O_L) and FH (O_{FH}) fractions. A representative portion was ground up and analysed with a LECO-CHN 2000 element analyser to determine total C, and total N concentrations of L and FH fractions, as well as the $(TC/TN)_L$ and $(TC/TN)_{FH}$ ratios.

Disturbed soil mineral samples were air dried and sieved (2mm) before physical, chemical and biochemical analyses (done in duplicate). The four undisturbed samples were used to determine soil bulk density and field capacity.

Physical analyses included percentage of coarse particles (>2 mm) (CO) and fine particles (< 2 mm) (FI), particle distribution determined by pipette method (MAPA 1993) and subsequent determination of clay content and sand and silt contents following the International criteria (SANDIS, SILTIS) and the USDA criteria (SANDUS, SILTUS); porosity (PO) using bulk density and real density determination and available water (AW) as the difference between water contents at field capacity and permanent wilting point determined using Eijkelkamp pF-Equipment.

Chemical parameters included: pH using a 1:2.5 (soil:water) suspension (MAPA 1993); total C (TC) and total N (TN) by dry combustion using a Leco CHN 2000 elemental analyzer to determine TC/TN ratio; easily oxidizable carbon (EOC) (Walkley & Black 1934); cation exchange capacity (CEC); exchangeable acidity (EA; only in acidic soils) (Mehlich 1953); exchangeable cations (Ca^{+2}, Mg^{+2}, K^+ and Na^+) by means of extracting with 1N ammonium acetate (pH=7) (Schollenberger & Simon 1945); base saturation (SAT) as the ratio between total exchangeable cations and cation exchange capacity; available P (AP) extracted using anion exchange membranes (Turrión et al. 1997) and colorimetric determination of P in the extracts (Murphy & Riley 1962). In samples of acid soils (*Pinus sylvestris*) amorphous Fe, Al and Mn (Fe_A, Al_A, Mn_A) were extracted with 0.2 M (pH=3) ammonium oxalate (Blakemore et al. 1987); organically bound Fe, Al and Mn (Fe_O, Al_O, Mn_O) were extracted with 0.1M Na4P2O7 (Bascomb 1968) and exchangeable Al (Al_E; only in acidic soils) was extracted with 1M KCl (Bertsch & Bloom 1996). Subsequently, Fe, Al and Mn were determined in all these extracts using inductively coupled plasma/optical emission spectrometry (ICP-OES). Inorganic Al (Al_I) was determined in these samples as the difference between amorphous and organically bound fractions of this element (McKeague et al. 1971). In the samples of calcareous plots (*Pinus halepensis*) Fe, Al, Zn and Mn contents were determined following the DTPA-TEA method (Lindsay & Norvell 1978); gypsum content following the method by Richards (1954); total calcium carbonates following the methodology of Bundy & Bremner (1972) and reactive calcium carbonates following the Bashour & Sayegh (2007) modification of the Drouineau (1942) method.

Biochemical parameters included: mineralizable C (Cmin) (Isermeyer 1952); microbial biomass C, N and P (Cmic, Nmic and Pmic) using the fumigation-extraction method (Vance et al. 1987) with determination of C and N content in extracts with Skalar TOC autoanalyser and colorimetric determination of P content (Murphy & Riley 1962). The relationships Cmic/Nmic, Cmic/TC, Cmin/TC and the microbial metabolic quotient (qCO2 = Cmin/Cmic) were calculated. Fluorescein Diacetate Hydrolysis reaction (FDA) was determined through the method by Alef & Nannipieri (1995), the activity of the dehydrogenases (DHA) was determined with the method by

Casida et al. (1964), alkaline (AlkPhos) and acid (AcPhos) phosphatase activities were determined with the Tabatabai & Bremner (1969) method, urease activity with the method by Hofmann (1963) and catalase activity with the method by Beck (1971).

3.4.2. Needle litter analysis

The litterfall collected in the littertraps was separated into needles, branches, bark, flowers, buds, cones and nuts. All these fractions were dried at 65ºC until constant weight and they were then weighed. The needle litterfall collected in the littertraps during three consecutive months was mixed to have a composite sample per season (autumn: October, November and December; winter: January, February and March; spring: April, May and June and summer: July, August and September). A representative portion of the composite samples per season was grinded with a ball mill and analysed for C and N in a Leco CHN 2000 autoanalyser 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.

The content of the litterbags was extracted and the remains of other plants or mosses were removed. These samples were also grinded with a ball mill and analysed for C, N P, K, Ca, Mg, S, Fe, Cu, Mn, and Zn with the same methodologies followed with the needle litterfall fraction mentioned before.

3.5. Climatic parameters

The Digital Climatic Atlas for the Iberian Peninsula (Ninyerola et al. 2005) was used to obtain precipitation and temperature data for each plot: mean seasonal precipitation (PW: winter precipitation; PSP: spring precipitation; PSU: summer precipitation; PA: autumn precipitation), annual total precipitation (TP), mean annual temperature (MAT), mean temperature of the coldest and warmest month (MTCM and MTWM, respectively), mean minimum temperature in the coldest month (MMCM), mean maximum temperature in the warmest month (MMWM), potential evapotranspiration (PET) following the Thornthwaite (1949) method; actual evapotranspiration, deficit and surplus were calculated based on climatic data (temperature and precipitation) by computing the Monthly Water Balance as described by Thornthwaite & Mather (1955); Martonne Index (De-Martonne 1926); Lang Index (Lang 1915) and Annual Hydric Index as described by Thornthwaite (1949).

3.6. Stand and physiographic data

Stand and physiographic data was collected in the field for *Pinus sylvestris* plots (iuFOR) and obtained from the Third Spanish National Inventory (DGCN 2002) for *Pinus halepensis* plots. Slope was measured in the field with the aid of a clinometer.

Current age and dominant height (H_0) defined according to the Assmann (1970) criterion (medium height of the 100 thickest trees per hectare) were determined for the *Pinus sylvestris* plots belonging to the iuFOR. Site index of *Pinus sylvestris* plots was calculated based on the current dominant height and age of each plot, using the equation developed by Río et al. (2006):

$$H_{02} = \frac{40.3331}{1-\left[\left(1-\frac{40.3331}{H_{01}}\right)\left(\frac{T1}{T2}\right)^{1.5003}\right]}$$

where H_{01} is the current dominant height in meters (at current age T_1) and H_{02} is the site index: dominant height at the reference age of 50 years (T_2). The plots were assigned to quality classes based on their site index and the site index limits between classes established by Río et al. (2006). The plots were assigned to five quality classes: Class I = 24 m of dominant height at a reference age of 50 years (one plot), Class II = 21 m (12 plots), Class III = 18 m (8 plots), Class IV = 15 m (13 plots) and Class V = 12 m (one plot); based on Río et al. (2006).

Classes I and V were represented by only one plot; therefore, Classes I and II were merged and Classes IV and V were also merged. Finally, three different site productivity classes were redefined as follows: high productivity (Classes I and II), medium productivity (Class III) and low productivity (Classes IV and V).

Current dominant height (H_0) following the Assmann (1970) criterion and age were determined for the *Pinus halepensis* plots with the data from the Third National Forest Inventory (DGCN 2002) and the plantation date of the stand provided by the regional government (Junta de Castilla y León). Site Index (SI) was estimated for each plot using the equation developed by Montero et al. (2001):

$$H_0 = a \cdot \left(1-e^{-0.203954t}\right)^{1/1.046295}$$

where H_0 is the dominant height in meters and t is the age in years. The value of a was determined for every plot from the previous equation and the current H_0 and t values. To determine site index for each plot (dominant height at the reference age of 80 years), the value of a for each plot and the reference age (t = 80 years) were introduced into the equation and the resulting value of H_0 was the site index. Three quality classes were established based on the site index value for each plot: low (site index ranging between 6.5 and 9.5), medium (site index between 9.5 and 12.5) and high (site index between 12.5 and 15.5). Accordingly, eight plots were classified into the lowest quality class, nine into the highest quality class and fifteen into the medium quality class.

Stand and physiographic data were collected in the field in the *Pinus sylvestris* and *Pinus halepensis* plots selected to study the litterfall and needle litter decomposition.

3.7. Data analysis

3.7.1. Principal Component Analysis

Principal Component Analysis (PCA) was applied to each group of variables studied in the *Pinus sylvestris* (iuFOR) and the *Pinus halepensis* (NFI) plots (soil physical, chemical, biochemical, and related to the organic horizon, climatic and physiographic variables) to reduce the dimensionality of the data and select the non-correlated variables that accounted for most of the data variability. Those principal components that presented an eigenvalue higher than 0.7 and accounted for at least 70% of the overall data variability were selected. The variable with the highest absolute value coefficient on each principal component was selected as proposed by Jolliffe (1973). The Shapiro-Wilk test was applied to test the normality of the selected variables. Those variables showing lack of normality were transformed. Transformed variables showing lack of normality were replaced by the variable with the next highest absolute value coefficient in the PCA. The variables selected through PCA were tested for correlation using Pearson's correlation coefficient to avoid including strongly correlated variables in the discriminant analysis. This statistical analysis was performed with Statgraphics Centurion XVI software for Windows (Statgraphics 2014).

3.7.2. Discriminant Analysis

Discriminant analysis was performed to develop a model to predict site index with some of the soil, climatic and physiographic variables selected through the PCA in *Pinus sylvestris* (iuFOR) and *Pinus halepensis* (NFI) plots. Discriminant analysis classifies new cases into established groups according to their properties; discriminant functions have the following general structure:

$$Y = \beta_0 + \sum_{j=1}^{p} \beta_j X_j$$

where Y is the score obtained for each group, β_0, β_1, … β_p are the coefficients obtained and X_j is the value of the p variable selected as the predictor to represent soil, physiographic and climatic factors (Hair et al. 1999). New observations are assigned to the group with the highest score. This classification technique has been used in similar studies (Harding et al. 1985, Bravo & Montero 2001, Bravo-Oviedo & Montero 2005, Bravo et al. 2011). In the discriminant analysis, equal prior probabilities of belonging to a group were considered for the three groups. Resubstitution was used to evaluate the discriminant models. The whole dataset was used to define and evaluate the model so the estimation of the rates of correct resubstitution presents an optimistic bias. Models including combinations of three, four and five variables coherent with biological processes and dynamics were tested. No model included two variables belonging to the same group. Then, the three, four or five variables included on each model belonged to different groups of variables (soil physical, chemical and biochemical, related to the organic horizon, climatic and physiographic variables). The model presenting the highest correct resubstitution rate (percentage of observations correctly classified into their actual class) with the least number of predictor variables was selected. This statistical analysis was performed with Statgraphics Centurion XVI software for Windows (Statgraphics 2014).

3.7.3. Wilcoxon-Mann-Whitney Test

A non-parametric test, the Wilcoxon-Mann-Whitney test, was performed (*wilcox.test* in R; see the Statistical Appendix) to assess whether the variables included in the Study III significantly differed in the soils under *Pinus halepensis* and *Pinus sylvestris* plantations because some of the variables were not normally distributed even after the removal of the outliers and transformations. This statistical analysis was performed with R software (TeamR 2015).

3.7.4. Spearman's correlation coefficient

The Spearman's correlation coefficient (in R: *cor.test*, *method="spearman";* see the Statistical Appendix) was used to study the factors determining the enzyme activities in the soils under *Pinus halepensis* and *Pinus sylvestris* plantations (Study III). This statistical analysis was performed with R software (TeamR 2015).

3.7.5. Olson' s equation

The data of needle mass loss in the litterbags (Study IV) was fitted to the exponential equation by Olson (1963) where X is the weight of the needle litterfall remaining in the litterbag in time t, X_0 is the initial weight of the needle litterfall put into the litterbag and k is the needle litter decomposition rate:

$$X = X_0 e^{-kt}$$

The half-life of the needle litter was also calculated (Olson 1963):

$$t_{0.5} = \frac{\ln 0.5}{-k}$$

3.7.6. Entry et al. equation

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

$$NR = N_{fn} - \left[(1 - D)N_{dn}\right]$$

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 in the litterbag per gram of initial needle litter into the litterbag.

3.7.7. Linear Mixed Model of Analysis of Variance

The influence of local basal area (LBA) of the stand on the needle litter decomposition rate (k) and the half-life of the needle litter ($t_{0.5}$) was determined by means of a linear mixed model analysis of variance with a random between-subjects factor (stand) with eight replicates (eight plots per stand) and one regressor (LBA).

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

where:

i = 1, 2, 3, 4 for the four stands
j = 1, 2,…, 8 for the eight plots within each stand
Y_{ij} = Value of the parameter (k, $t_{0.5}$) in plot *j* of the stand *i*
$\mu =$ Average global effect
α_i = Random effect of stand *i*, with $\alpha_i \sim N(0, \sigma_S^2)$
X_{ij} = LBA of plot *j* in stand *i* (m^2 ha^{-1})
$\beta =$ Linear rate of change in the parameter (k, $t_{0.5}$) per unit LBA
$\varepsilon_{ij} =$ Random error in the value of the parameter (k, $t_{0.5}$) for plot *j* in stand *i*, with $\varepsilon_{ij;t} \sim N(0, \sigma^2)$.

To study the effect of LBA of the plot on monthly needle litterfall, a linear mixed model of analysis of variance with a random between-subjects factor (stand) with eight replicates (eight plots per stand), one regressor (LBA) and a within-subjects factor of repeated measures (season) was used:

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

where:

i = 1, 2, 3, 4 for the four stands
j = 1, 2, …, 8 for the eight plots within each stand
t = 1, 2, …, 24 months studied in *Pinus halepensis* and *t* = 1, 2, …, 18 months studied in *Pinus sylvestris*
$Y_{ij;t}$ = Logarithm of the weight of needle litterfall of plot *j* in stand *i* and season *t* (kg ha^{-1})
$\mu =$ Average global effect
α_i = Random effect of stand *i*, with $\alpha_i \sim N(0, \sigma_S^2)$
$\tau_t =$ Main effect of month *t*
X_{ij} = LBA of plot *j* in stand *i* (m^2 ha^{-1})
$\beta =$ Linear rate of change in the logarithm of the weight of needle litterfall per unit LBA
$\varepsilon_{ij;t} =$ Random error in the the logarithm of the weight of needle litterfall of plot *j* in stand *i* and

month t, with $\varepsilon_{ij;t} \sim N(0,\sigma^2)$ and first order autoregressive AR(1) variance structure.

To study the effect of LBA on nutrient concentration in litterfall and nutrient release from needles during decomposition, linear mixed model analysis of variance was used. The models have a random between-subjects factor (stand) with eight replicates (eight plots per stand), one regressor (LBA) and a within-subjects factor of repeated measures (season). The formulation of the models is expressed by the next equation:

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

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
$\mu =$ Average global effect
α_i = Random effect of stand i, with $\alpha_i \sim N(0,\sigma_S^2)$
$\tau_t =$ Main effect of season t
X_{ij} = LBA of plot j in stand i (m^2 ha^{-1})
$\beta =$ Linear rate of change in the nutrient concentration of litterfall or in the nutrient release of the needles in the litterbags per unit LBA
$\varepsilon_{ij;t} =$ 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 $\varepsilon_{ij;t} \sim N(0,\sigma^2)$ and first order autoregressive AR(1) variance structure.

Those variables not normally distributed or presenting heteroscedasticity were previously transformed (see the Statistical Appendix). These statistical analyses were performed with SAS 9.4 software (SAS 2013).

3.7.8. Pearson's correlation coefficient

The correlation between the LBA of the plot and the temperature and humidity of the 10 cm topsoil was studied by means of the Pearson correlation coefficient (see the Statistical Appendix). This statistical analysis was performed with SAS 9.4 software (SAS 2013).

4. Results

4.1. Site index from environmental parameters in *Pinus sylvestris* plantations

To develop a discriminant model to classify the site index of *Pinus sylvestris* plantations, 59 soil, climatic and physiographic parameters were studied (Supplementary materials 2, 3 and 4 respectively).

From the PCA performed on the soil physical variables studied in *Pinus sylvestris* plots four principal components were selected, which accounted for 93.5% of site variability. Sand defined following the ISSS criteria (SANDIS), CO, silt defined following USDA criteria (SILTUS) and PO were selected as the best soil physical variables. From the PCA of the soil chemical variables, four principal components accounted for 84.6% of the variability. Soil chemical variables selected were Al_E, EOC, Al_I and TC/TN. Two principal components were selected from PCA performed on the soil biochemical variables, with 87.4% variability explained. The variables selected were Cmic and Cmin/TC. Three principal components were selected from PCA of organic horizon variables accounting for 79.6% variability. The variables selected were $[TC/TN]_{FH}$, OHT and $[TC/TN]_L$. Two principal components were selected from the PCA of climatic variables explaining 96% variability. The climatic variables selected were Lang Index and MTWM(93) . Finally, two principal components accounting for 97.4% variability were selected from the physiographic variables; the variables selected were LAT and ELV. Table 5 presents summarized statistics for the 17 variables selected based on PCA.

At 5% significance level, the normality hypothesis was rejected for several variables by using the Shapiro-Wilk test: SILTUS, Al_E, Al_I, Cmin/TC, MTWM and ELV. Several transformations were applied to these variables (Log (X), exp (X), 1/X, X^2, and $\sqrt{X}$). Transformations of ELV and MTWM also showed lack of normality and were not considered further. The rest of the variables were transformed as follows: 1/SILTUS, exp (Al_E), $\sqrt{Al_I}$, log (Cmin/TC).

Finally, the variables selected to be used in the discriminant analysis were SANDIS, CO, SILTUS, PO, exp (Al_E), EOC, $\sqrt{Al_I}$, TC/TN, Cmic, log (Cmin/TC), $[TC/TN]_{FH}$, OHT, $[TC/TN]_L$, LAT and Lang Index.

Table 5 Summary of principal component analysis and environmental variables selected for each principal component in the plots belonging to the iuFOR in *Pinus sylvestris* plantations

Group of variables	Component number	Accumulated Variance Percentage	Variable Selected
Soil Physical Variables	1	55.5	SANDIS
	2	71.9	CO
	3	85.9	SILTUS
	4	93.5	PO
Soil Chemical Variables	1	51.0	Al_E
	2	73.4	EOC
	3	79.4	Al_I
	4	84.6	TC/TN
Soil Biochemical Variables	1	54.2	Cmic
	2	87.4	Cmin/TC
Organic Horizon Variables	1	35.3	$[TC/TN]_{FH}$
	2	59.4	OHT
	3	79.6	$[TC/TN]_L$
Climatic Variables	1	82.1	LANG
	2	96.0	MTWM
Physiographic Variables	1	65.8	LAT
	2	97.4	ELV

[a] SANDIS: Sand following ISSS criteria; CO: Coarse particles; SILTUS: Silt following USDA criteria; PO: Porosity; Al_E: Exchangeable Al; EOC: Easily Oxidizable Carbon; Al_I: Inorganic Al; TC/TN: Total C/Total N; Cmic: Microbial Biomass C; Cmin/TC: Mineralizable C/Total C; $[TC/TN]_{FH}$: Total C/Total N in fragmented plus humified fraction of organic horizon; OHT: Organic Horizon Thickness; $[TC/TN]_L$: Total C/Total N in litter fraction of organic horizon; LANG: Lang Index; MTWM: Mean Temperature of the Warmest Month; LAT: Latitude; ELV: Elevation.

The correlation matrix for the 15 variables selected (Table 6) shows that LAT and Lang Index, LAT and Al_E, Al_E and SILTUS, SANDIS and SALTUS are strongly correlated (Pearson's correlation coefficient > 0.7). Consequently, these pairs of variables were not used in the discriminant analysis. Therefore, variables used in the classification functions studied were normally distributed and not strongly correlated.

Table 6 Correlation matrix for the environmental variables selected in the plots belonging to the iuFOR in *Pinus sylvestris* plantations[a]

	TC/TN	$\sqrt{Al_I}$	exp(Al_E)	EOC	CO	SANDIS	1/SILTUS	PO	Cmic	log(Cmin/TC)	$[TC/TN]_{FH}$	$[TC/TN]_L$	OHT	LANG
LAT	0.49	0.53	0.70	0.42	-0.13	0.36	0.60	0.09	-0.32	-0.69	0.24	0.23	0.44	0.93
TC/TN		0.38	0.57	0.19	0.10	0.65	0.57	-0.27	-0.47	-0.30	0.22	0.37	0.05	0.38
$\sqrt{Al_I}$			0.55	0.36	-0.23	0.14	0.31	0.21	-0.28	-0.51	0.26	0.26	0.39	0.42
exp(Al_E)				0.32	-0.21	0.44	0.70	-0.14	-0.34	-0.67	0.31	0.18	0.38	0.60
EOC					-0.25	-0.18	0.05	0.09	0.41	-0.57	-0.13	0.27	0.30	0.50
CO						0.37	0.12	-0.11	-0.36	0.24	-0.18	-0.09	0.10	-0.19
SANDIS							0.81	-0.26	-0.52	-0.21	0.25	0.12	0.14	0.21
1/SILTUS								-0.23	-0.33	-0.54	0.36	0.20	0.28	0.46
PO									0.08	0.06	0.39	-0.05	0.00	0.10
Cmic										0.03	-0.08	0.04	-0.05	-0.23
log(Cmin/TC)											-0.15	-0.36	-0.35	-0.63
$[TC/TN]_{FH}$												0.29	-0.10	0.08
$[TC/TN]_L$													-0.16	0.07
OHT														0.42

[a] LAT: Latitude; C/N: Total C/Total N; Al_I: Inorganic Al; Al_E: Exchangeable Al; EOC: Easily Oxidizable Carbon; CO: Coarse particles; SANDIS: Sand ISSS criteria; SILTUS: Silt following USDA criteria; PO: Porosity; Cmic: Microbial Biomass C; Cmin/C: Mineralizable C/Total C; $[C/N]_{FH}$: Total C/Total N in fragmented plus humified fraction of organic horizon; $[C/N]_L$: Total C/Total N in litter fraction of organic horizon; OHT: Organic Horizon Thickness; LAT: Latitude; LANG: Lang Index.

Twelve models were biologically consistent and presented a resubstitution error (percentage of plots classified into an incorrect quality class) lower than 35%. Selected discriminant models are shown on Table 7.

The resubstitution error rates of the selected discriminant models ranged from 28.6% (Models 3, 6, 7, 9 and 11) to 34.3% (Models 4 and 10). Model 12 misclassified 31.4% of plots within an incorrect quality class with only three parameters (see Table 3). However, the Model 12 misclassifications are considerable for the highest quality class (46% error rate). Models 3, 6, 7, 9 and 11 classified correctly 78.6% of plots belonging to the lowest quality class, 75.0% belonging to the medium quality class and 61.5% of plots belonging to the highest quality class. Nevertheless, Models 3, 7, 9 and 11 misassigned 7.1% of plots belonging to the lowest quality class into the highest quality class. With Model 6, no inferior-quality plot was misassigned to the highest quality class (see Table 8).

Table 7 Discriminant models studied to predict site index class of *Pinus sylvestris* plantations[a]

	Discriminant models	Correct classification resubstitution rate (%)
1	constant + LAT + $\sqrt{Al_I}$ + PO + Cmic + $[TC/TN]_{FH}$	68.6
2	constant + LAT + $\sqrt{Al_I}$ + CO + log (Cmin/TC) + $[TC/TN]_{FH}$	68.6
3	constant + LAT + $\sqrt{Al_I}$ + SANDIS + log(Cmin/TC) + $[TC/TN]_{FH}$	71.4
4	constant + LAT + TC/TN + SANDIS + log(Cmin/TC) + $[TC/TN]_{FH}$	65.7
5	constant + LAT + TC/TN + SANDIS + Cmic + $[TC/TN]_{L}$	68.6
6	constant + LAT + $\sqrt{Al_I}$ + PO + Cmic	71.4
7	constant + LAT + $\sqrt{Al_I}$ + SANDIS + Cmic	71.4
8	constant + LAT + TC/TN + SANDIS + log(Cmin/TC)	68.6
9	constant + LAT + $\sqrt{Al_I}$ + SANDIS + $[TC/TN]_{FH}$	71.4
10	constant + LAT + TC/TN + SANDIS + $[TC/TN]_{FH}$	65.7
11	constant + LAT + TC/TN + SANDIS + $[TC/TN]_{L}$	71.4
12	constant + LAT + TC/TN + SANDIS	68.6

[a] LAT: Latitude; TC/TN: Total C/Total N; Al_I: Inorganic Al; CO: Coarse particles; SANDIS: Sand ISSS criteria; PO: Porosity; Cmic: Microbial Biomass C; Cmin/TC: Mineralizable C/Total C; $[TC/TN]_{FH}$: Total C/Total N in fragmented plus humified fraction of organic horizon; $[TC/TN]_{L}$: Total C/Total N in litter fraction of organic horizon.

Table 8 Correct classification resubstitution rates of the model developed to predict site index class of *Pinus sylvestris* plantations (Model 6)

Actual quality class	Predicted quality class		
	Lowest	Medium	Highest
Lowest	78.6%	21.4%	0.0%
Medium	12.5%	75.0%	12.5%
Highest	23.1%	15.4%	61.5%

Figure 13 presents a plot of the discriminant functions of the model. Function 1 (mainly influenced by latitude and Al_I) discriminated quite well among the lowest quality class and the others. Function 2 (mainly influenced by porosity and Cmic) discriminated between the medium and highest quality classes. Function 1 was negatively influenced by Al_I but positively influenced by latitude. Function 2 was positively influenced by porosity and Cmic. As can be seen in Figure 13, the lower quality class presents lower latitude and higher inorganic aluminium content. Medium and higher quality classes present higher latitude and lower inorganic aluminium content. Medium and higher quality classes differ as to their porosity and Cmic (both are higher in the highest quality class).

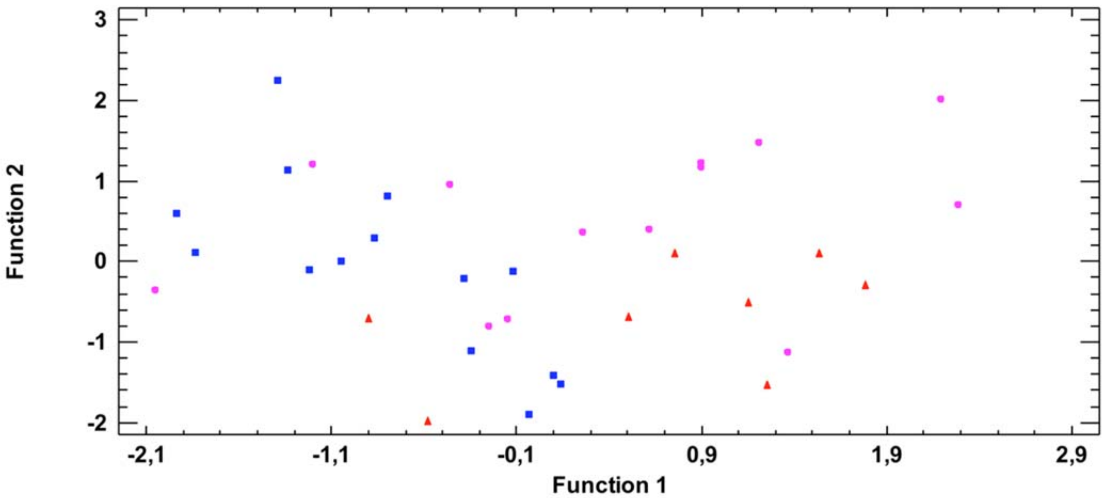

Figure 13 Plot of discriminant functions for the discriminant model selected to predict site quality for *Pinus sylvestris* plantations (blue squares represent the lowest quality class, red triangles represent the medium quality class and pink circles represent the highest quality class)

For forest management purposes, we aimed to identify the most productive stands accurately in order to focus managerial attention. It is important to select models with a high correct classification rate for the higher quality class. Model 6 was consequently selected to predict site index class of *Pinus sylvestris* L. plantations located in Northern Spain acidic plateau. Model 6 parameters are shown in Table 9.

Table 9 Classification functions in the model selected (Model 6) to predict site index class of *Pinus sylvestris* plantations[a]

	Site index class		
	Lower	Medium	High
LAT	25357.4	25395.4	25383.5
$\sqrt{Al_I}$	-894.859	-896.121	-895.783
PO	9.29309	9.2923	9.39763
Cmic	5.62468	5.62664	5.6414
CONSTANT	-540528	-542150	-541648

[a] LAT: Latitude; Al_I: Inorganic Al; PO: Porosity; Cmic: Microbial Biomass C.

4.2. Site index from environmental parameters in *Pinus halepensis* plantations

To develop a discriminant model to classify the site index of *Pinus halepensis* plantations 57 stand, edaphic, climatic and physiographic parameters were studied (Supplementary material 5, 6 and 7 respectively).

From the PCA performed on the soil physical properties four principal components were selected, which accounted for 93.8% of the data variability (Table 10). The variables selected for those four principal components were: silt (ISSS), coarse particles, porosity and clay. From the PCA of soil chemical properties, seven principal components (accounting for 87.5% of data variability) were selected and EOC, carbonates, Zn, reactive carbonates, TOC/TN, Fe and gypsum were chosen to represent them. The PCA of soil biochemical properties informed the selection of four principal components that represented 97.8% of data variability; the biochemical variables selected to represent them were Nmic, qCO_2, Cmin and Pmic. The two principal components selected from the organic horizon PCA accounted for 74.9% of data variability and the variables chosen were O_{FH} and $(TC/TN)_L$. Four principal components from the PCA of climatic parameters accounted for 93.6% variability and correspond to the Martonne index, MTWM, MMWM and PSU. Latitude and slope were the variables selected for the two principal components from the PCA of physiographic parameters, which accounted for 86% of data variability. In summary, 23 variables were selected from the PCAs of groups of variables, including 17 edaphic variables (silt, coarse particles, porosity, clay, EOC, carbonates, Zn, reactive carbonates, TOC/TN, Fe, gypsum, Nmic, qCO_2, Cmin, Pmic, O_{FH}, $(TC/TN)_L$); four climatic variables (Martonne index, MTWM, MMWM, PSU) and two physiographic variables (latitude and slope).

Eight principal components (accounting for 86.9% of the variability) were selected from the PCA of the 17 edaphic variables (physical, chemical, biochemical and related to the organic horizon), and the variables chosen to represent those principal components were Nmic, silt, qCO_2, gypsum, Zn, porosity, Pmic and clay (Table 11).

Table 10 Summary of the Principal Component Analysis for each group of variables studied in the plots belonging to the NFI in *Pinus halepensis* plantations[a]

Group of variables	Component number	Principal Component Accumulated Variance Percentage	Selected Variable [a]	Factor Loadings of the variable selected
Soil Physical	1	43.7	Silt (ISSS)	-0.4877
	2	74.1	Coarse particles	-0.5361
	3	85.6	Porosity	-0.7457
	4	93.8	Clay	0.6813
Soil Chemical	1	28.9	EOC	0.4049
	2	48.0	Carbonates	-0.4140
	3	60.2	Zn	-0.6433
	4	69.7	Reactive Carbonates	0.5077
	5	76.5	TOC/TN	-0.7105
	6	82.2	Fe	0.4876
	7	87.5	Gypsum	0.5808
Soil Biochemical	1	48.1	Nmic	0.4880
	2	72.2	qCO_2	-0.6214
	3	87.4	Cmin	0.5600
	4	97.8	Pmic	0.8634
Organic Horizon	1	54.2	O_{FH}	0.5416
	2	74.9	$(TC/TN)_L$	0.8376
Climatic	1	56.7	Martonne	-0.3180
	2	78.9	MTWM	0.4239
	3	88.6	MMWM	-0.4889
	4	93.6	PSU	0.6913
Physiographic	1	51.9	Latitude	0.7119
	2	86.0	Slope	0.9694

[a] Silt ISSS (%); Coarse particles (%); Porosity (%); Clay content (%); EOC: easily oxidizable C (%); Carbonates (mg kg-1); Reactive carbonates (mg kg^{-1}); TOC/TN: total organic C/total N ratio; Gypsum (mg kg^{-}1); Nmic: microbial biomass N (mg kg^{-1}); qCO_2: microbial metabolic quotient (g $week^{-1}$ g^{-1}); Cmin: mineralizable C (g $week^{-1}$ kg^{-1}); Pmic: microbial biomass P (mg kg^{-1}); O_{FH}: biomass of fragmented plus humified fraction in organic horizon (t ha^{-1}); $(TC/TN)_L$: total C/total N in litter fraction of organic horizon; Martonne: Martonne Index; MTWM: mean temperature of the warmest month (ºC); MMWM: mean value of maxima temperature in the warmest month (ºC); PSU: summer precipitation (mm); Latitude (º); Slope (%)

Table 11 Principal Component Analysis summary performed on the 17 edaphic variables selected in the previous PCA performed in the plots belonging to the NFI in *Pinus halepensis* plantations[a]

Group of variables	Component number	Accumulated Variance Percentage	Factor loadings	Selected Variable
Soil Variables	1	24.2	0.4478	Nmic
	2	41.2	-0.4729	Silt (ISSS)
	3	53.2	-0.5095	qCO_2
	4	62.1	-0.4670	Gypsum
	5	70.0	0.5002	Zn
	6	77.0	-0.3469	Porosity
	7	82.7	-0.5951	Pmic
	8	86.9	0.5245	Clay

[a] Nmic: microbial biomass N (mg kg^{-1}); Silt ISSS (%); qCO_2: microbial metabolic quotient (g $week^{-1}g^{-1}$); Gypsum (mg kg-1); Porosity (%); Pmic: microbial biomass P (mg kg^{-1}); Clay content (%)

The normality hypothesis was rejected (5% significance level) for the Zn, Martonne index and MTWM variables. No transformation of these variables presented a normal distribution, so they were replaced by the variable with the next highest absolute value coefficient in the PCA: TOC/TN, Ih and PET, respectively. Both TOC/TN and PET followed a normal distribution but Ih was transformed into Ih^2. The final 14 variables selected for the Discriminant Analysis were silt, clay, porosity, gypsum, TOC/TN, Nmic, qCO_2, Pmic, Ih^2, PET, MMWM, PSU, latitude, and slope. Correlations between selected variables were studied (Table 12) and strong correlations were found between MMWM and PET and latitude, so these pairs of variables were not included together in the Discriminant Analysis.

Discriminant models including three, four and five variables as predictors were studied. More than a hundred biologically consistent combinations of three, four and five variables belonging to different groups (soil physical, chemical and biochemical variables, along with climatic and physiographic variables) were tested. The resubstitution error rates of the discriminant models studied ranged from 37.50% to 59.37%. As a general rule, models with three predictor variables have a higher resubstitution error than those using four or five variables as predictors. Models that included a soil physical variable (especially clay and porosity), a soil nutrient related variable (especially chemical or biochemical), a climatic variable (especially Ih^2) and a physiographic variable (especially slope) presented the best correct classification rates. Besides, all models with a correct classification rate higher than 60% included a biochemical parameter.

Table 12 Pearson's correlation coefficients among the variables selected to be used in the discriminant analysis to classify the site index of *Pinus halepensis* plantations[a]

	Clay	Porosity	Gypsum	TOC/TN	Nmic	qCO2	Pmic	Ih^2	PET	MMWM	PSU	Latitude	Slope
Silt (ISSS)	-0.541	0.143	0.315	-0.117	0.149	-0.221	0.084	-0.029	0.054	0.233	-0.237	-0.245	0.302
Clay		0.082	-0.113	-0.279	-0.323	-0.085	-0.276	0.296	0.166	-0.095	-0.119	0.075	-0.257
Porosity			-0.008	-0.029	0.371	-0.340	0.175	0.067	0.248	0.294	-0.212	-0.238	0.275
Gypsum				0.014	0.476	-0.064	0.003	-0.037	-0.131	-0.281	0.262	0.453	0.231
TOC/TN					0.258	0.203	0.227	-0.412	-0.102	0.134	0.326	0.119	0.250
Nmic						-0.268	0.354	-0.482	-0.286	-0.148	0.395	0.182	0.430
qCO2							-0.232	-0.024	-0.146	-0.097	-0.038	0.043	0.092
Pmic								-0.084	0.167	0.186	-0.023	0.030	0.203
Ih^2									0.520	0.032	-0.531	0.235	-0.187
PET										0.724	-0.193	-0.275	0.037
MMWM											-0.111	-0.668	0.229
PSU												0.348	0.111
Latitude													-0.139

[a] Silt ISSS (%); Clay content (%); Porosity (%); Gypsum (mg·kg-1); TOC/TN: total C/total N ratio in mineral soil; Nmic: microbial biomass N (mg kg^{-1}); qCO_2: microbial metabolic quotient (g $week^{-1}$ g^{-1}); Pmic: microbial biomass P (mg kg^{-1}); Ih: Annual Hydric Index; PET: potential evapotranspiration (mm); MMWM: mean value of maxima temperature in the warmest month (ºC); PSU: summer precipitation (mm); Latitude (º); Slope (%)

The model selected to predict the site index for *Pinus halepensis* plantations in northern Spain had four variables – porosity, Nmic, Ih^2 and slope – and presented a correct classification rate of 62.50%. Extreme quality classes (highest and lowest) had a very high correct classification rate (75.00% and 77.78%, respectively). No plot belonging to the highest quality class was misassigned to the lowest quality class and only 12.5% of plots belonging to the lowest quality class were misassigned to the highest quality class (Table 13). Table 14 presents the parameters of the discriminant model selected to predict site quality in *Pinus halepensis* plantations in northern Spain.

Table 13 Correct classification resubstitution rates of the model selected to classify the site quality in *Pinus halepensis* plantations

Actual quality class (%)	Predicted quality class (%)		
	Lowest	Medium	Highest
Lowest	75.00 %	12.50 %	12.50 %
Medium	20.00 %	46.67 %	33.33 %
Highest	0.00 %	22.22 %	77.78 %

Table 14 Coefficients of the discriminant functions for classifying the site quality in *Pinus halepensis* plantations[a]

	Lowest quality class	Medium quality class	Highest quality class
Porosity	0.898422	1.04481	1.0651
Nmic	0.268951	0.163837	0.124966
Ih^2	0.0502579	0.0359449	0.0292166
Slope	0.038075	0.0370905	-0.00344083
CONSTANT	-36.9303	-34.9499	-31.5711

[a] Porosity (%); Nmic: microbial biomass N (mg kg^{-1}); Ih: Annual Hydric Index; Slope (%).

4.3. Factors determining enzyme activities in soils under *Pinus sylvestris* and *Pinus halepensis* plantations

Soil, climatic and stand variables were studied to assess the differences between the contrasting soils under *Pinus sylvestris* and *Pinus halepensis* plantations.

Table 15 shows the climatic and stand density data for the forest plots studied. *Pinus halepensis* plots had significantly higher MAT and DEF than *Pinus sylvestris* plots, which presented significantly higher TP and stand density.

Table 15 Median values for climatic and stand density data[a] of studied plots in *Pinus sylvestris* (n = 35) and *Pinus halepensis* (n = 32) plantations and p-values of the Wilcoxon-Mann-Whitney test

	Pinus halepensis	*Pinus sylvestris*	p-value
MAT (°C)	12.0	9.4	<0.0001
TP (mm)	448	755	<0.0001
DEF (mm)	256	125	<0.0001
Stand Density (trees ha^{-1})	766	1033	0.0227

[a] MAT: mean annual temperature; TP: total precipitation; DEF: hydric deficit.

No significant differences in CEC and TN were detected between the two soil types (see Table 16). In the soils under *Pinus halepensis* pH, K, Ca and Mg were higher than in the soils under *Pinus sylvestris*. In contrast, EOC, AP, TOC/TN and WSP were significantly higher in the acidic soils under *Pinus sylvestris* than in the calcareous soils under *Pinus halepensis*.

Table 17 shows that no significant differences in FDA were found in the soils under the two species studied. However, Cmic, Nmic, DHA, Urease and Catalase activity were significantly higher in the soils under *Pinus halepensis*. We found no significant differences in AlkPhos activity for the soils under each species, but AcPhos, Cmin, Pmic and qCO_2 were significantly higher in the acidic soils under *Pinus sylvestris*.

The correlations between enzyme activities and microbial-related parameters are reported in Table 18 for *Pinus halepensis* plots and Table 19 for *Pinus sylvestris* plots.

Table 16 Median values for soil variables[a] in *Pinus sylvestris* (n = 35) and *Pinus halepensis* (n = 32) plantation plots and p-values of the Wilcoxon-Mann-Whitney test

	Pinus halepensis	*Pinus sylvestris*	p-value
CEC ($cmol_{(+)}$ kg^{-1})	20.4	19.6	0.0695
EOC (%)	1.54	2.26	0.0003
AP (mg kg^{-1})	2.23	3.62	<0.0001
TN (%)	0.13	0.13	0.3923
TOC/TN	14.5	30.4	<0.0001
pH	8.4	4.5	<0.0001
K ($cmol_{(+)}$ kg^{-1})	0.70	0.17	<0.0001
Ca ($cmol_{(+)}$ kg^{-1})	16.60	0.73	<0.0001
Mg ($cmol_{(+)}$ kg^{-1})	2.82	0.09	<0.0001
WSP (µg TAE g^{-1})	25.0	70.0	<0.0001

[a] CEC: cation exchange capacity; EOC: easily oxidizable C; AP: available P; TN: total N; TOC/TN: total organic C to total N ratio; WSP: water soluble phenols.

Table 17 Median values for microbial and enzymatic variables[a] in *Pinus sylvestris* (n = 35) and *Pinus halepensis* (n = 32) plots and p-values of Wilcoxon-Mann-Whitney test

	Pinus halepensis	*Pinus sylvestris*	p-value
FDA (µg g^{-1} h^{-1})	20.3	17.7	0.4964
DHA (µg g^{-1} h^{-1})	8.2	0.6	<0.0001
Urease (µg N h^{-1} g^{-1})	71.3	38.2	<0.0001
AcPhos (µg g^{-1} h^{-1})	4.0	7.6	0.0011
AlkPhos (µg g^{-1} h^{-1})	5.4	5.0	0.915
Catalase (O_2 $3min^{-1}$ g^{-1})	1.1	0.6	<0.0001
Cmin (mg C-CO_2 kg^{-1} $week^{-1}$)	31.2	51.4	<0.0001
Cmic (mg C kg^{-1})	184.0	112.9	<0.0001
Nmic (mg N kg^{-1})	25.4	12.9	<0.0001
Pmic (mg P kg^{-1})	7.1	10.6	0.0089
qCO_2 (mg C-CO_2 week-1 mg C^{-1})	0.2	0.6	<0.0001

[a] FDA: fluorescein diacetate hydrolysis reaction; DHA: dehydrogenase activity; Urease: urease activity; AcPhos: acid phosphatase activity; AlkPhos: alkaline phosphatase activity; Catalase: catalase activity; Cmin: mineralizable C; Cmic: microbial biomass C; Nmic: microbial biomass N; Pmic: microbial biomass P; qCO_2: metabolic quotient.

Table 18 Spearman's correlation coefficients and p-values (in parenthesis) for enzyme activities in calcareous soils under *Pinus halepensis* plantations and edaphic and climatic parameters[a]

	FDA	DHA	AcPhos	AlkPhos	Urease	Catalase
Cmin	0.5663 (0.001)	0.6822 (0.000)	0.2892 (0.109)	0.5139 (0.003)	0.5216 (0.003)	0.6078 (0.000)
Cmic	0.7955 (0.000)	0.7130 (0.000)	0.2346 (0.196)	0.4479 (0.011)	0.7485 (0.000)	0.7097 (0.000)
Nmic	0.8292 (0.000)	0.7324 (0.000)	0.2830 (0.117)	0.4644 (0.007)	0.7546 (0.000)	0.7192 (0.000)
Pmic	0.2907 (0.107)	0.3640 (0.041)	-0.1338 (0.464)	0.1400 (0.443)	0.2775 (0.124)	0.4194 (0.018)
qCO_2	-0.3039 (0.091)	-0.0550 (0.764)	0.1287 (0.481)	-0.0139 (0.940)	-0.3548 (0.047)	-0.1884 (0.300)
EOC	0.7031 (0.000)	0.7331 (0.000)	0.3695 (0.038)	0.4853 (0.005)	0.6928 (0.000)	0.8292 (0.000)
TOC/TN	0.3739 (0.036)	0.1463 (0.423)	-0.1444 (0.429)	0.0095 (0.959)	0.0539 (0.769)	-0.0685 (0.708)
AP	0.5927 (0.000)	0.6789 (0.000)	0.3508 (0.050)	0.2155 (0.235)	0.5143 (0.003)	0.7405 (0.000)
TN	0.3831 (0.031)	0.5084 (0.003)	0.2874 (0.111)	0.3691 (0.038)	0.4736 (0.007)	0.6650 (0.000)
CEC	0.3919 (0.027)	0.5224 (0.002)	0.3057 (0.089)	0.5062 (0.003)	0.6745 (0.000)	0.7606 (0.000)
Ca	0.5249 (0.002)	0.5612 (0.001)	0.3156 (0.079)	0.4260 (0.016)	0.4795 (0.006)	0.7225 (0.000)
Mg	-0.0707 (0.700)	-0.0121 (0.948)	0.0077 (0.967)	0.2324 (0.200)	0.2958 (0.100)	0.1661 (0.362)
K	-0.0154 (0.934)	0.1184 (0.517)	0.3262 (0.069)	0.1316 (0.471)	0.2423 (0.181)	0.2592 (0.152)
pH	-0.2086 (0.252)	-0.1333 (0.467)	-0.1381 (0.451)	-0.0136 (0.941)	-0.1886 (0.301)	-0.2292 (0.207)
WSP	0.2253 (0.215)	0.1990 (0.275)	0.3055 (0.089)	0.4044 (0.022)	0.1866 (0.306)	0.4439 (0.011)
MAT	-0.2221 (0.222)	-0.2070 (0.256)	-0.0038 (0.984)	0.0565 (0.759)	-0.2597 (0.151)	-0.0941 (0.609)
TP	0.3587 (0.044)	0.4911 (0.004)	0.4549 (0.009)	0.4414 (0.011)	0.3573 (0.045)	0.3416 (0.056)
DEF	-0.4454 (0.011)	-0.4857 (0.005)	-0.4633 (0.008)	-0.3823 (0.032)	-0.3185 (0.076)	-0.3618 (0.043)

[a] FDA: fluorescein diacetate hydrolysis reaction; DHA: dehydrogenase activity; AcPhos: acid phosphatase activity; AlkPhos: alkaline phosphatase activity; Cmin: mineralizable C; Cmic: microbial biomass C; Nmic: microbial biomass N; Pmic: microbial biomass P; qCO_2: metabolic quotient; EOC: easily oxidizable C; TOC/TN: total organic C/total N; AP: available P; TN: total N; CEC: cation exchange capacity; WSP: water soluble phenols; MAT: mean annual temperature; TP: total precipitation; DEF: hydric deficit.

Table 19 Spearman's correlation coefficients and p-values (in parenthesis) for enzyme activities in acidic soils under *Pinus sylvestris* plantations and edaphic and climatic parameters[a]

	FDA	DHA	AcPhos	AlkPhos	Urease	Catalase
Cmin	0.0821 (0.638)	0.3826 (0.024)	-0.2140 (0.216)	0.0112 (0.949)	0.4319 (0.010)	0.5151 (0.002)
Cmic	0.7389 (0.000)	-0.0877 (0.615)	0.1401 (0.421)	0.2207 (0.203)	0.3611 (0.034)	0.0518 (0.767)
Nmic	0.4403 (0.009)	-0.1835 (0.290)	-0.0641 (0.714)	0.1015 (0.562)	0.1196 (0.492)	-0.0515 (0.768)
Pmic	0.7067 (0.000)	-0.1835 (0.290)	0.2611 (0.130)	0.3892 (0.021)	0.3745 (0.027)	0.0611 (0.727)
qCO_2	-0.6126 (0.000)	0.2571 (0.136)	-0.2314 (0.181)	-0.1257 (0.472)	-0.0014 (0.994)	0.2978 (0.083)
EOC	0.7336 (0.000)	-0.1824 (0.293)	0.0815 (0.640)	0.5358 (0.000)	0.0227 (0.897)	0.0319 (0.855)
TOC/TN	-0.2737 (0.112)	0.1120 (0.520)	-0.2104 (0.224)	0.2153 (0.214)	-0.3728 (0.028)	-0.2429 (0.159)
AP	0.6361 (0.000)	-0.0742 (0.671)	0.2042 (0.238)	0.3162 (0.064)	0.4028 (0.017)	-0.0325 (0.853)
TN	0.8639 (0.000)	-0.1499 (0.389)	0.2412 (0.162)	0.3951 (0.019)	0.3669 (0.031)	0.2440 (0.157)
CEC	0.6541 (0.000)	-0.1754 (0.312)	0.2045 (0.238)	0.4113 (0.014)	-0.1204 (0.489)	-0.1891 (0.276)
Ca	0.5188 (0.002)	-0.1174 (0.501)	0.0709 (0.685)	0.1480 (0.396)	0.5810 (0.000)	0.2465 (0.153)
Mg	0.4392 (0.009)	-0.0476 (0.785)	0.1339 (0.442)	0.0896 (0.609)	0.6154 (0.000)	0.3448 (0.043)
K	0.4062 (0.016)	-0.0112 (0.949)	0.1992 (0.250)	0.0648 (0.712)	0.4123 (0.014)	0.0317 (0.857)
pH	0.2375 (0.170)	-0.0416 (0.812)	0.0621 (0.723)	-0.0564 (0.748)	0.6374 (0.000)	0.4619 (0.005)
WSP	-0.3716 (0.028)	0.3471 (0.041)	0.0452 (0.797)	-0.0239 (0.892)	0.1590 (0.362)	0.3350 (0.049)
MAT	-0.0021 (0.990)	-0.1889 (0.277)	0.1095 (0.531)	-0.0871 (0.619)	0.1275 (0.466)	-0.0439 (0.802)
TP	0.0200 (0.909)	-0.1115 (0.524)	0.0371 (0.832)	0.1407 (0.420)	-0.3243 (0.057)	-0.1468 (0.400)
DEF	-0.1354 (0.438)	0.2647 (0.124)	0.0618 (0.725)	-0.0210 (0.905)	0.4321 (0.110)	0.2625 (0.128)

[a] FDA: fluorescein diacetate hydrolysis reaction; DHA: dehydrogenase activity; AcPhos: acid phosphatase activity; AlkPhos: alkaline phosphatase activity; Cmin: mineralizable C; Nmic: microbial biomass N; Pmic: microbial biomass P; Cmic: microbial biomass C; qCO_2: metabolic quotient; EOC: easily oxidizable C; TC/TN: Total C/Total N; AP: available P; TN: total N; CEC: cation exchange capacity; WSP: water soluble phenols; MAT: mean annual temperature; TP: total precipitation; DEF: hydric deficit.

In the soils under *Pinus halepensis*, Cmic, Nmic and Cmin were significantly correlated to all the enzyme activities studied except AcPhos. Only catalase activity and DHA were significantly correlated to Pmic. No significant correlation was found between enzyme activities and Mg, K, pH and MAT (Table 18) and AcPhos only correlated with EOC, TP and DEF. Other enzyme activities (FDA, DHA, AlkPhos, Urease and Catalase) were significantly correlated with organic matter and nutrient-related parameters such as EOC, TOC/TN, AP, TN, CEC and Ca. Significant correlations were also found between TP and all enzyme activities except Catalase. All enzyme activities except Urease were significantly correlated to DEF, but only AlkPhos and Catalase were significantly correlated to WSP.

With the exception of FDA, a different trend was observed in the enzyme activities in soils under *Pinus sylvestris* (Table 19), where DHA, AcPhos and Catalase were not significantly correlated to organic matter or nutrient related parameters (EOC, TOC/TN, AP, TN, CEC, Ca and K). Significant correlations between FDA and microbial biomass (Cmic, Nmic and Pmic) and qCO_2 were found, but Catalase, Urease and DHA were significantly correlated to Cmin. Significant correlations were also found between AlkPhos and Pmic. Urease was significantly correlated to Cmic, Nmic and Cmin and we found significant correlations between WSP and FDA, DHA and Catalase. Catalase and Urease activities were also significantly correlated to pH.

4.4. Needle litterfall and decomposition rates

The annual average needle litterfall observed in *Pinus halepensis* stands was 2144 kg ha^{-1} while in *Pinus sylvestris* was 2357 kg ha^{-1}. In the stands of both species, the month with the higher litterfall was August (836 kg ha^{-1} in *Pinus sylvestris* and 635 kg ha^{-1} in *Pinus halepensis*). The higher peak of litterfall was during the months of July to September in *Pinus sylvestris* and the months of June to August in *Pinus halepensis* (Figure14 and Figure 15).

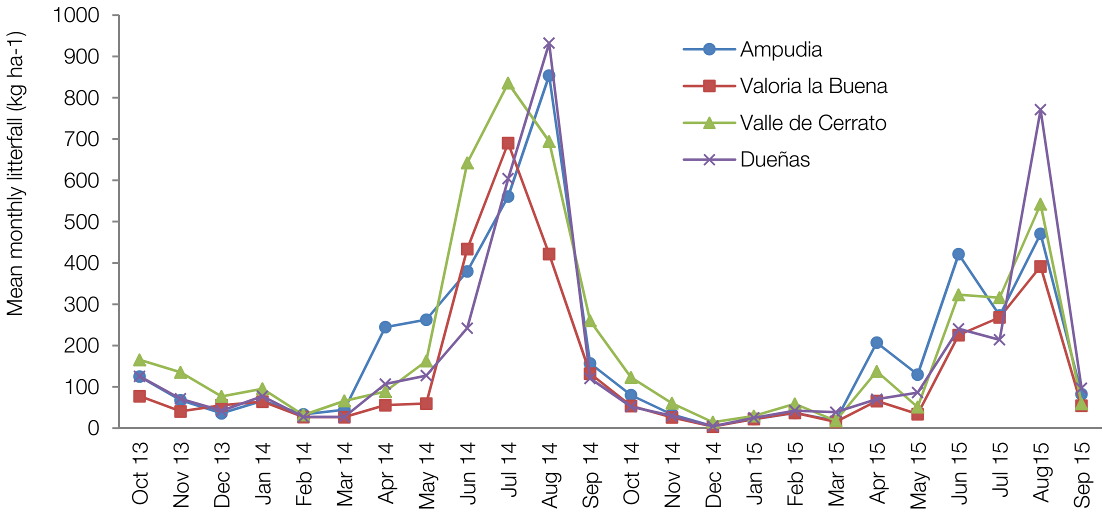

Figure 14. Mean monthly litterfall (kg ha^{-1}) observed in the four *Pinus halepensis* stands studied

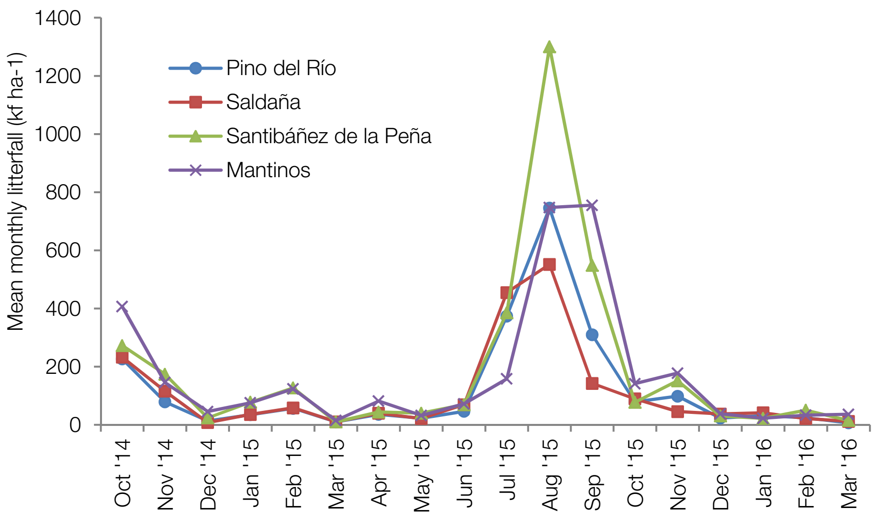

Figure 15. Mean monthly litterfall (kg ha^{-1}) observed in the four *Pinus sylvestris* stands studied

The linear mixed model of analysis of variance showed a significant effect of the LBA on the litterfall of both species (P < 0.0001; $\beta_{(P.\ halepensis)}$ = 0.0339 y $\beta_{(P.\ sylvestris)}$= 0.0197); therefore, the higher the LBA of the plot, the higher is the litterfall rate. This trend can also be observed in Figure 16. Besides, the effect of the LBA of the plot on the parameters related to decomposing needle litter (k y $t_{0,5}$) was significant for *Pinus halepensis* (P > 0.0001) meaning that the higher the LBA of the plot, the lower the needle litter decomposition rate and the higher the half-life of the needle litter (Figure 16). No significant effect was found of the LBA on the parameters related to needle litter decomposition in *Pinus sylvestris* (Table 20 and Figure 17).

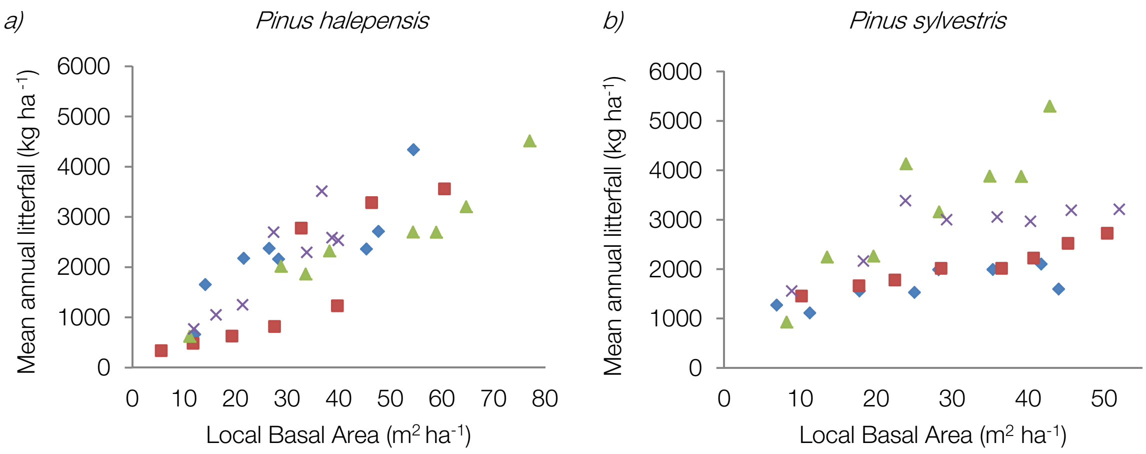

Figure 16. Relationship between mean annual litterfall and the local basal area of the studied plots: a) *Pinus halepensis*, b) *Pinus sylvestris*

Table 20. Decay rate coefficients (k), half-life for the decomposing litter ($t_{0,5}$), linear rate of change (β) per unit of basal area and P-values given by the analysis of variance of the linear mixed model for the two *Pinus* species studied

Species	Parameter	Estimator	β	*P* value
Pinus halepensis	k	0,0248	-0,00009	<0,0001
	$t_{0,5}$	29,3	0,1253	<0,0001
Pinus sylvestris	k	0,0306	-0,00002	ns
	$t_{0,5}$	22,8	0,01616	ns

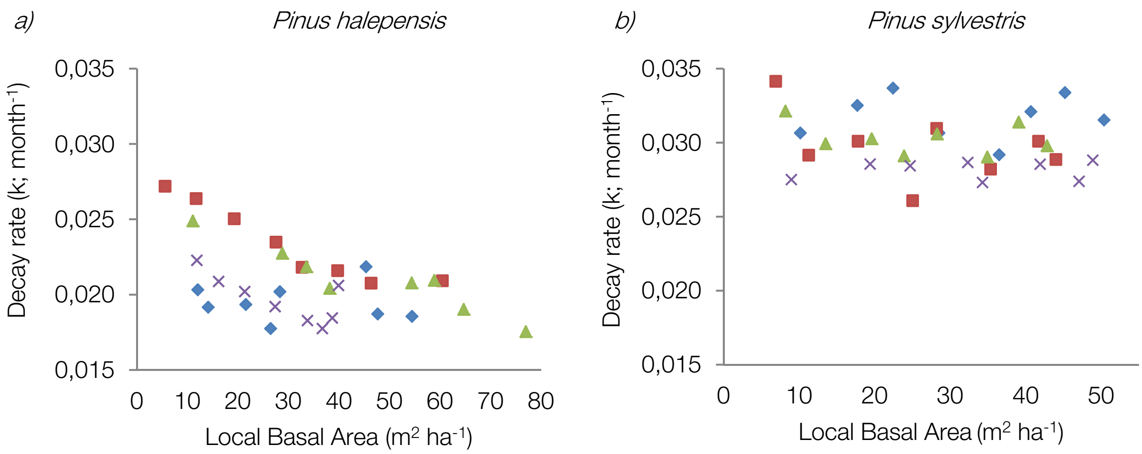

Figure 17. Relationship between the decay rates and stand basal area in the plots studied: a) *Pinus halepensis*, b) *Pinus sylvestris*

Significant and negative correlations were found between the LBA of the plot and the soil humidity for both species: *Pinus sylvestris* ($r = -0.209$; $P = 0.0002$) and *Pinus halepensis* ($r = -0.3415$; $P < 0.0001$). However, no significant correlation was found between the LBA of the plot and the soil temperature for both species studied.

4.5. Nutrient concentrations in needle litterfall and nutrient release during needle decomposition in *Pinus halepensis* plantations

Nutrient concentrations in *Pinus halepensis* 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 of the study behaved similarly to C, presenting minimum concentrations in winter. Manganese concentration in the litterfall was nearly the same throughout the year (Figure 18, Figure 19 and Supplementary material 8 and 9).

According to the linear mixed model analysis of variance, the effect of LBA on nutrient concentrations in needle litterfall is significant for C, K and Mg (Table 21). As shown by the positive linear rate of change in the concentrations of these nutrients per unit of LBA, the higher the local basal area, the higher the concentration of C, log K and Mg in needle litterfall of the plots studied. No significant effect of LBA on the rest of elements studied was found.

Table 21. Linear rate of change (β) of the nutrient concentration of *Pinus halepensis* litterfall per unit of local basal area and p-values according to the linear mixed model analysis of variance

	β	p-value
C (mg g^{-1})	0.04724	0.0097
log N (mg g^{-1})	-0.00032	0.5174
log C/N	0.000410	0.4206
log P (mg kg^{-1})	0.000833	0.3744
log K (mg g^{-1})	0.004051	<0.0001
log Ca (mg g^{-1})	-0.00046	0.5250
Mg (mg g^{-1})	0.001518	0.0184
log S (mg g^{-1})	0.000478	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

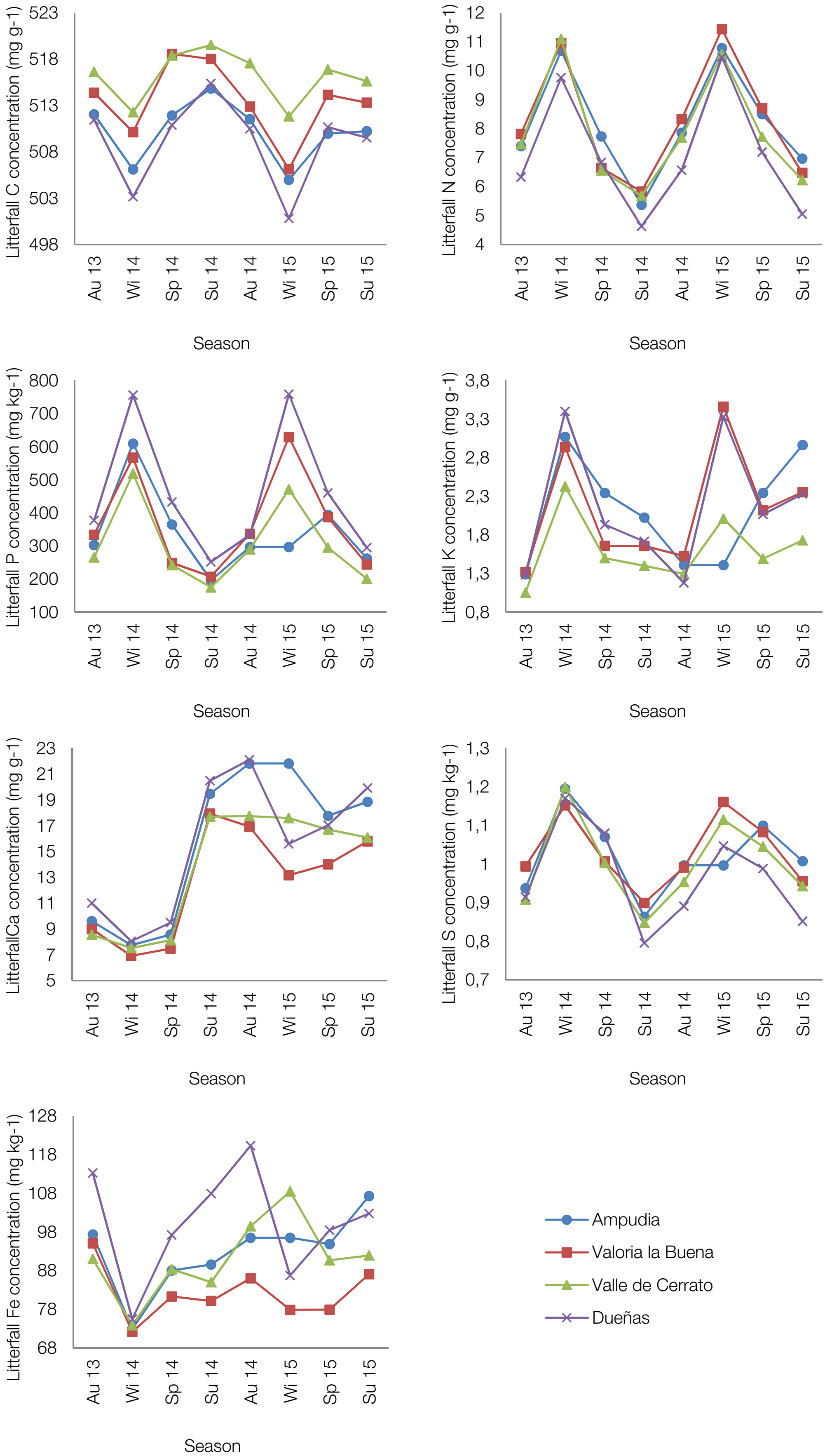

Figure 18. Seasonal average macronutrient concentrations in *Pinus halepensis* litterfall of the four stands studied (Au: autumn; Wi: winter; Sp: spring; Su: summer; 13: 2013; 14: 2014; 15: 2015)

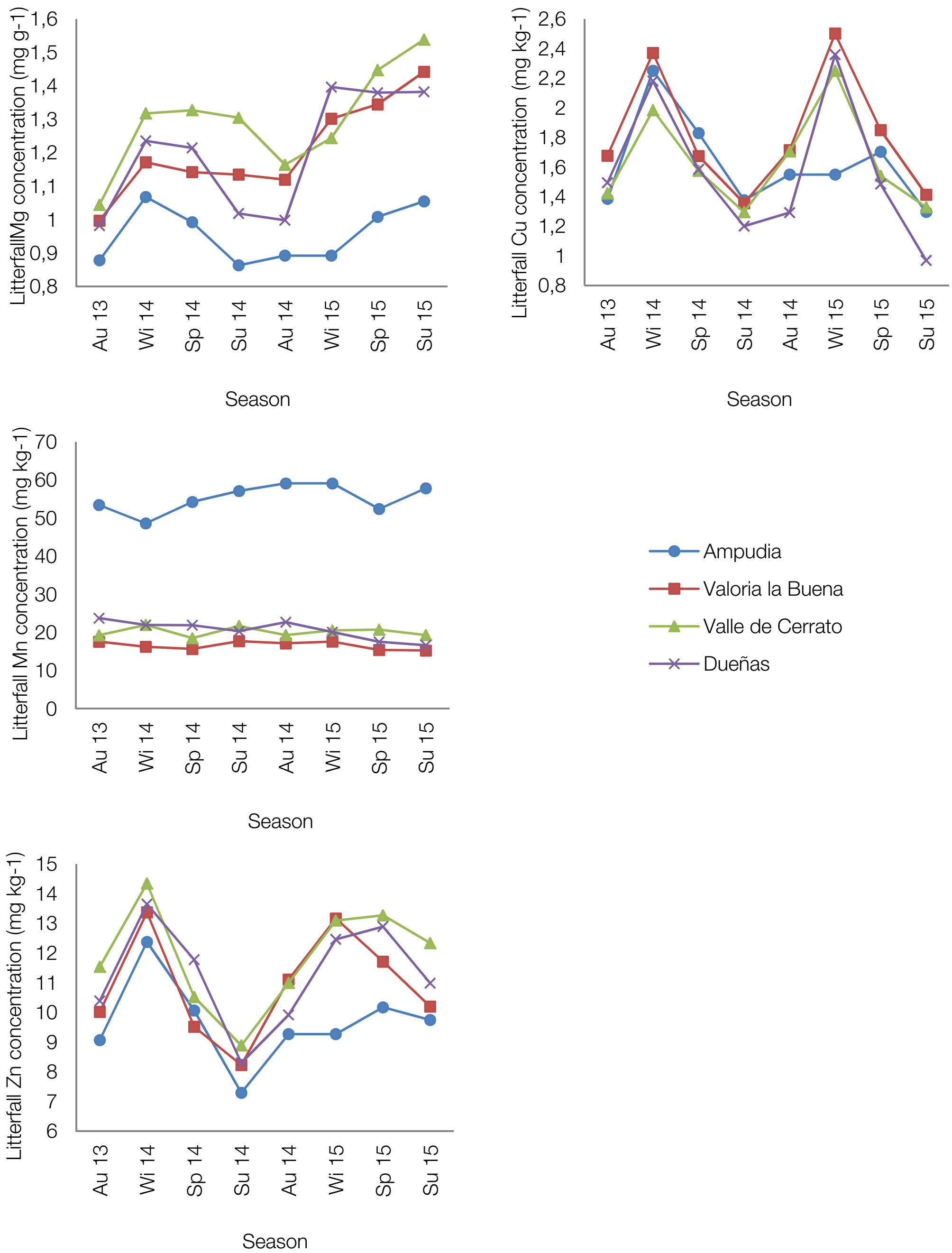

Figure 19. Seasonal average micronutrient concentrations in *Pinus halepensis* litterfall of the four stands studied (Au: autumn; Wi: winter; Sp: spring; Su: summer; 13: 2013; 14: 2014; 15: 2015)

The correlation between soil humidity and LBA of the plot was significant and negative (Table 22). Plots with higher LBA presented lower mineral topsoil humidity than those plots with lower LBA. However, soil temperature was not significantly correlated to the LBA of the plot in the stands studied.

Table 22. Pearson's correlation coefficients (r) and p-values of the correlations between local basal area and soil temperature (n = 533) and humidity (n = 469) for the *Pinus halepensis* plots studied

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

The nutrient release in the needles contained in the litterbags presented different trends depending on the element studied (Figures 20 and 21 and Supplementary material 10 and 11).

Elements such as C, K, Mg and Mn presented a net release pattern throughout the whole study period. Some of them, presented a first phase of rapid release (K, Mg and Mn) followed by a phase of slower release (or even periods of slight nutrient immobilization). However, C release is more homogeneous through time. Other elements such as Fe or Cu presented an almost continuous trend of net immobilization while nutrients such as N, Ca, P or Zn presented an erratic trend, with phases of nutrient release followed by phases of nutrient immobilization. Sulphur presented a first phase of rapid release followed by a second phase of stabilization and a third phase of very fast immobilization.

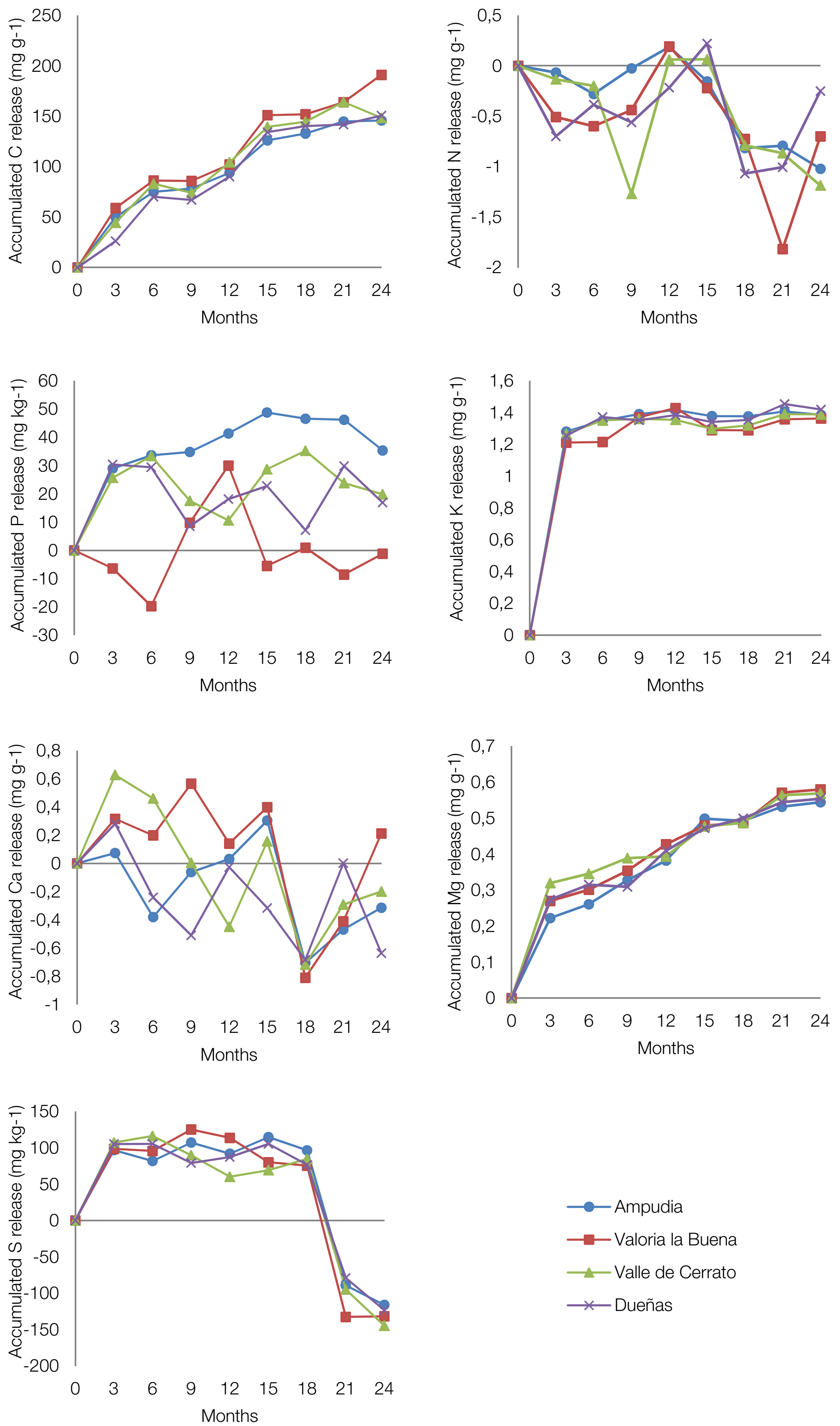

Figure 20. Accumulated average macronutrient release during the 24 months of *Pinus halepensis* litter decomposition in the litterbags of the four stands studied

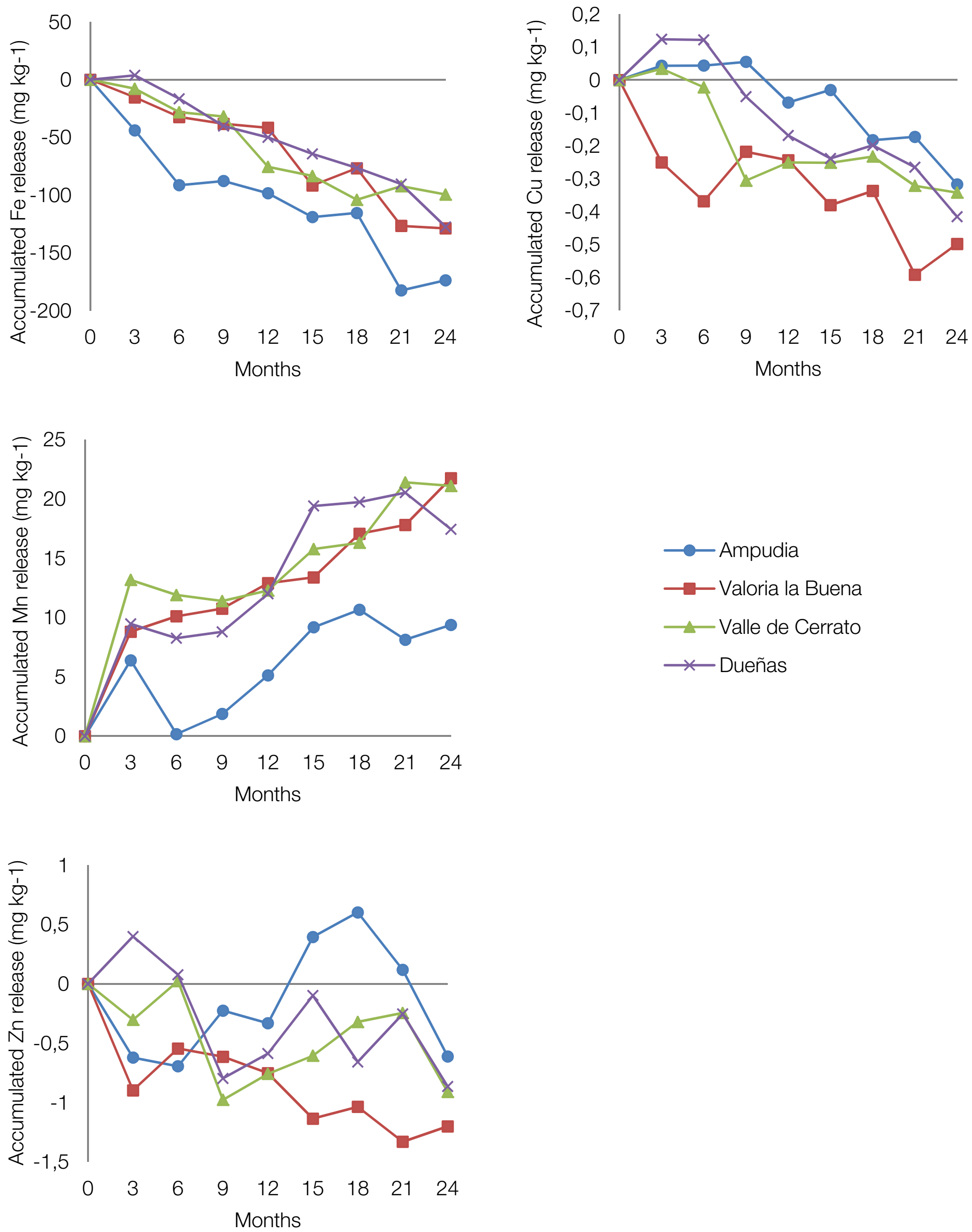

Figure 21. Accumulated average micronutrient release during the 24 months of *Pinus halepensis* litter decomposition in the litterbags of the four stands studied

The release of most nutrients considered in needle decomposition was significantly affected by the LBA of the plot (Table 23). The linear rate of change per unit LBA 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 LBA. Nor Fe, neither Mn release was significantly affected by the LBA of the plot.

Table 23. Linear rate of change (β) of the nutrient release in the *Pinus halepensis* litterbags per unit of local basal area and p-values according to the linear mixed model analysis of variance

	β	p-value
C (mg g^{-1})	-0.3079	<0.0001
N (mg kg^{-1})	-22.6615	<0.0001
P (mg kg^{-1})	-1.3401	<0.0001
K (mg g^{-1})	-0.00324	<0.0001
Ca (mg g^{-1})	-0.00549	0.0362
Mg (mg kg^{-1})	-1.5790	0.0003
S (mg kg^{-1})	-1.7527	<0.0001
Fe (mg kg^{-1})	0.1641	0.1183
Mn (mg kg^{-1})	0.01001	0.8003
Cu (mg kg^{-1})	-0.00587	<0.0001
Zn (mg kg^{-1})	-0.01904	<0.0001

4.6. Nutrient release during needle decomposition in *Pinus sylvestris* plantations

Accumulated nutrient release of the needles contained in the litterbags set in the *Pinus sylvestris* stands studied over time is represented in Figures 22 and 23 (Supplementary material 12 and 13). Some elements such as C, K, Mg, Mn, Zn, Ca and P generally present a net release from needles contained in the litterbags even when some of them presented some phase of nutrient immobilization. Potassium, Mg, Mn and Zn also presented a first phase of fast release followed by a phase of slower release or even some phase of immobilization. Nitrogen, however, presented a permanent net immobilization. Some other nutrients such as S, Fe and Cu presented a first phase of net release followed by a phase of net immobilization.

According to the linear mixed model analysis of variance, the release of N, P, K, S and Fe from the needles contained in the litterbags were significantly affected by the LBA of the plot during the 18 months studied (Table 24). The linear rates of change of N, P, K and S release were negative, indicating that the lower the basal area of the stand, the higher the nutrient release (or lower the nutrient immobilization). That is to say, that plots with lower LBA presented higher P, K and S release and lower N immobilization. However, the rate of change of Fe release in the litterbags was positive and then, Fe release was higher in plots with higher LBA during the first phase of net release and Fe immobilization was lower in the following phase of net immobilization.

Correlations between temperature and humidity and LBA are presented in Table 25. Significant and negative correlation was found between the 10 cm topsoil humidity and the LBA of the plot. Then, soil humidity was significantly higher in those plots with lower LBA. However, no significant correlation was found between the 10 cm topsoil temperature and the LBA of the plots studied.

Table 24. Linear rate of change in the nutrient release in the *Pinus sylvestris* litterbags (β) per unit of local basal area and p-values according to the linear mixed model analysis of variance

	β	p-value
1/C (mg g^{-1})	5.88 10^{-6}	0.0945
N (mg g^{-1})	-0.01103	0.0001
P (mg kg^{-1})	-0.5732	0.0024
K (mg kg^{-1})	-2.4361	<0.0001
Ca (mg g^{-1})	0.000387	0.8738
Mg (mg g^{-1})	0.02555	0.9194
S (mg kg^{-1})	-0.6238	0.0024
Fe (mg kg^{-1})	0.4369	<0.0001
Mn (mg kg^{-1})	0.000961	0.1249
Cu (mg kg^{-1})	-0.00178	0.3527
Zn (mg kg^{-1})	-0.00381	0.6392

Table 25. Pearson's correlation coefficients (r) and p-values of the correlations between local basal area and soil temperature (n = 480) and humidity (n = 416) in the *Pinus sylvestris* plots studied

	r	p-value
Temperature (ºC)	0.0207	0.6510
Humidity (m^3 water m^{-3} soil)	-0.1629	0.0009

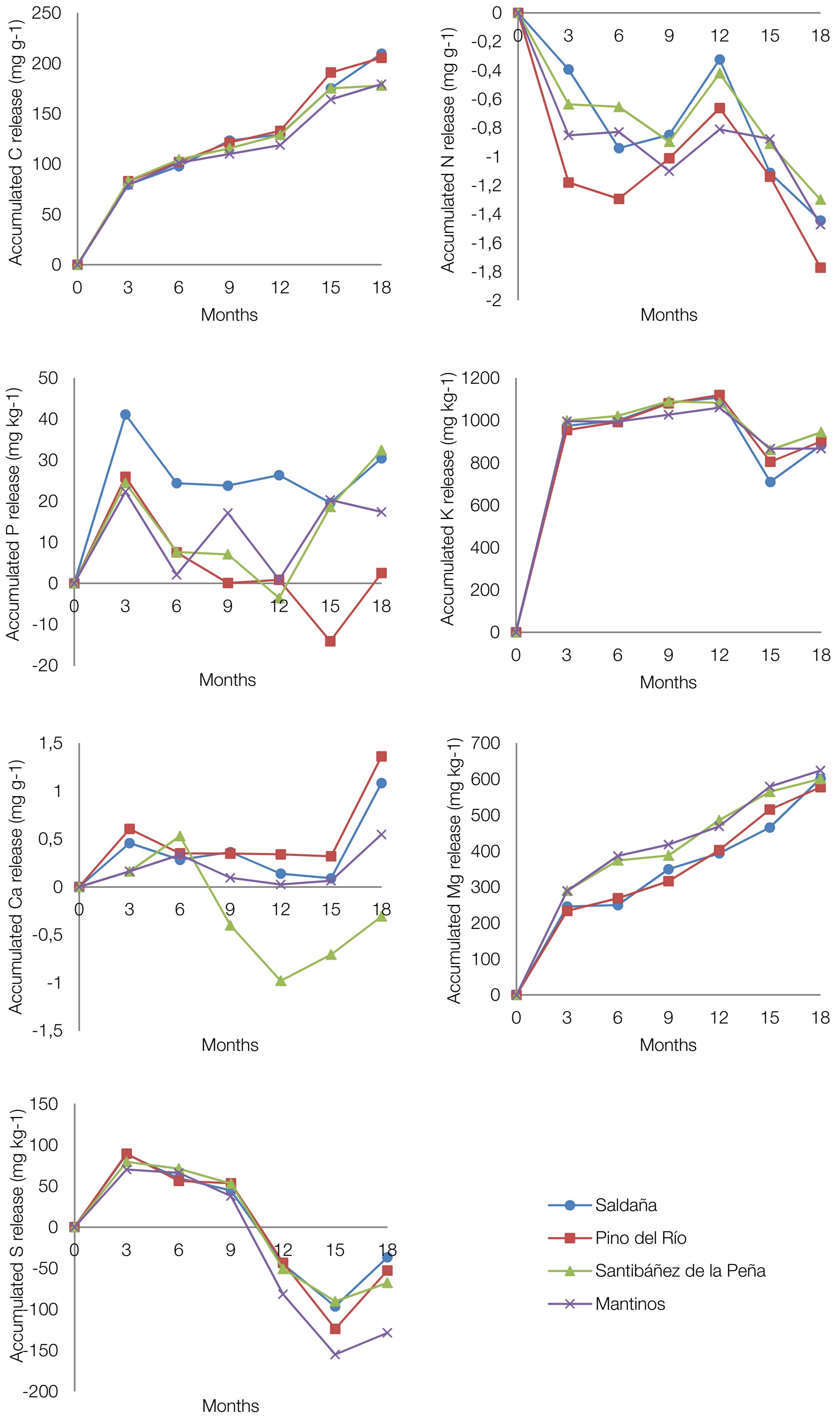

Figure 22. Accumulated average macronutrient release during the 18 months of *Pinus sylvestris* litter decomposition in the litterbags of the four stands studied

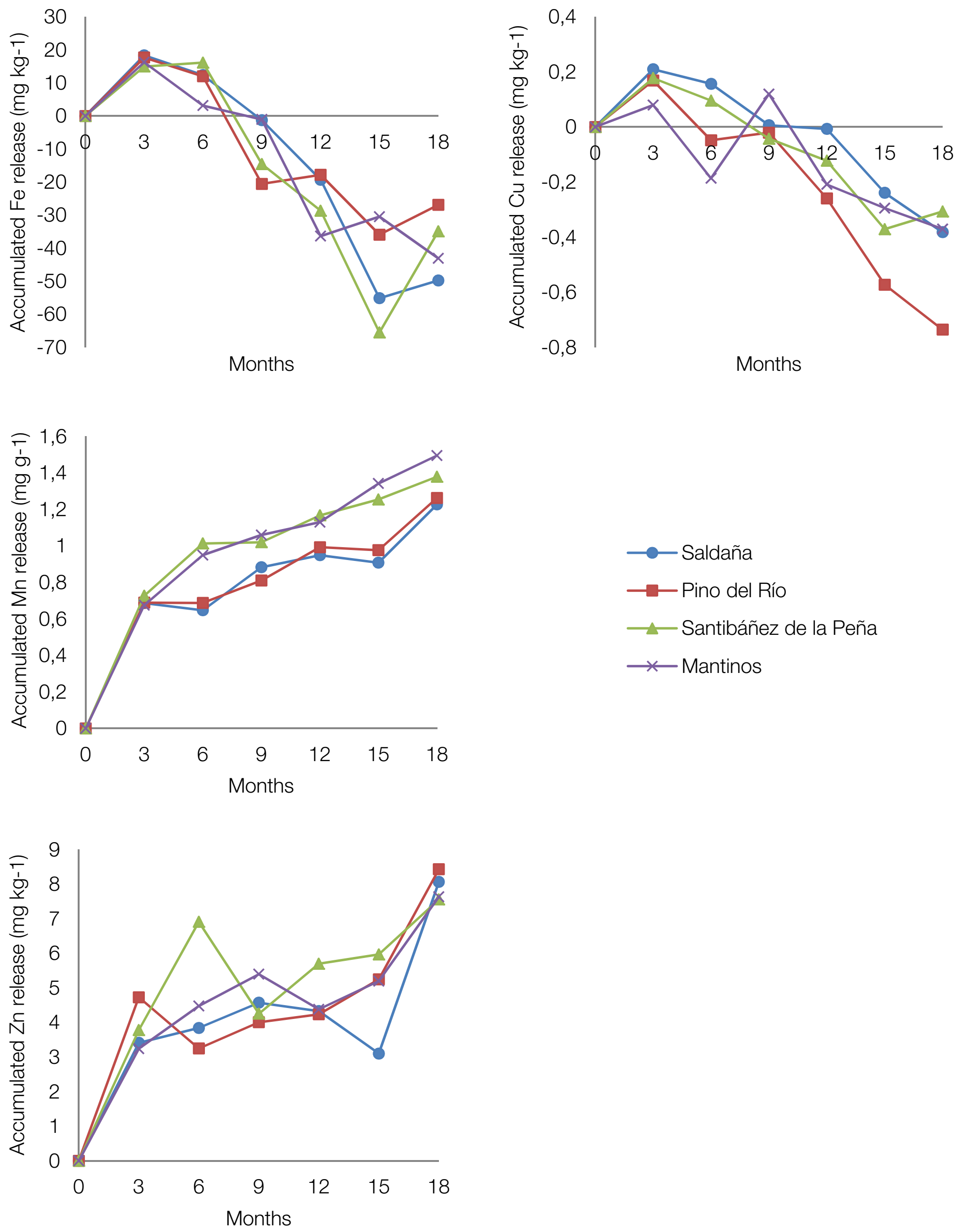

Figure 23. Accumulated average micronutrient release during the 18 months of *Pinus sylvestris* litter decomposition in the litterbags of the four stands studied

5. Discussion

5.1. Site index from environmental parameters in *Pinus sylvestris* plantations

The 12 models selected included latitude as a predictor variable, which means that latitude is a determinant factor of forest productivity in the area studied. All these models contained one soil physical variable (PO, CO or SANDIS) and one soil chemical variable (TC/TN or Al_l). Some of them also included a biochemical variable (Cmic or Cmin/TC) and/or an organic horizon related variable ($[TC/TN]_L$ or $[TC/TN]_{FH}$).

The model selected to predict *Pinus sylvestris* L. site index class (Model 6) included LAT, Al_l, PO and Cmic as predictor variables. These variables represent three environmental aspects that affect tree growth: physiography, soil physics and nutrient availability.

The physiographic variable included in the model was LAT, an easily obtainable variable. Positive significant correlations (at 5% significance level) were found between latitude and climatic parameters such as precipitations, SUR and Lang, Martone and Hydric indexes. The correlations between LAT and temperatures and DEF were significant and negative (at 5% significance level). Therefore, LAT indirectly includes climatic information in the model. *Pinus sylvestris* L. is sensitive to drought (Eilmann & Rigling 2012) and growth is partly driven by water availability. In this area, lower latitudes present higher hydric deficit and tree growth is lower, as observed in previous studies (Candel-Perez et al. 2012, Sanchez-Salguero et al. 2012, Taeger et al. 2013). Hagglund & Lundmark (1977) and Sharma et al. (2012) also found that latitude was a good predictor variable for *Pinus sylvestris* L. site index in Sweden and Norway stands.

Soil porosity (spaces between soil particles) adds soil physical information into the model. This variable combines textural and structural information and determines aeration of soil and its water retention capacity. Together with LAT, PO determines soil water availability for the trees. Textural parameters have frequently been used to predict *Pinus sylvestris* L. forest productivity all over Europe (Hagglund & Lundmark 1977, White 1982, Bravo & Montero 2001, Aertsen et al. 2012, Sewerniak & Piernik 2012, Sharma et al. 2012)

Inorganic Al and Cmic represent the nutritional aspect. Trees require the same nutrients to grow and reproduce as other superior plants. However, due to nutrient cycling and the deep roots of most tree species, as well as mycorrhizal associations that allow taking minimally available nutrients from soil, nutrient deficiencies are rare in forests (Pritchett 1986). Nevertheless, some studies in northern and north-eastern Spain have shown nutrient deficiencies in several *Pinus* species stands, mainly due to P in acidic soils (Romanya & Vallejo 2004, Afif-Khouri et al. 2010). Available P is an important factor in the area studied because the soils are strongly acidic. Soil acidity is related to limiting nutrient (such as P) availability and also influences soil microbial populations and their activity (Binkley et al. 1993). Sewerniak & Piernik (2012) found than pH was one of the best variables to describe site index for *Pinus sylvestris* L. in southwestern Poland. Molina et al. (1991) found that inorganic Al correlated significantly with P immobilization, so this variable introduces information about P availability into the model. The biochemical variable included in the model was Cmic. This parameter indicates the amount of microflora present in the soil; this is a very active soil component because it takes part in mineralization processes (Duchaufour 1984), playing a key role in nutrient cycling (Jenkinson & Ladd 1981) and determining plant availability of nutrients such as N, P and S (He et al. 1997). Mahía et al. (2006) found higher values of biochemical parameters (such as microbial biomass C) in higher site index stands of *Pinus sylvestris* L. and *Pinus pinaster* Ait. in north-western Spain.

The soil-site method developed allows predicting site index by means of a relatively small set of easily measurable parameters.

5.2. Site index from environmental parameters in *Pinus halepensis* plantations

The model selected to predict the site index for *Pinus halepensis* plantations in northern Spain presented a correct classification rate of 62.50% and included porosity, Nmic, Ih and slope as the four predictor variables.

Climate is the main driver of Mediterranean forest growth in general and *Pinus halepensis* growth in particular (Gandullo et al. 1972, Olarieta et al. 2000, Rathgeber et al. 2005, Río et al. 2014, del Castillo et al. 2015). The correlation between precipitation and *Pinus halepensis* growth is usually significant and positive while the correlation between growth and temperature is significant and negative, because higher temperature provokes higher evapotranspiration and reduces water reserves (Condes & Garcia-Robredo 2012). The discriminant model developed includes Ih as a predictor, combining information about temperature and humidity. The area studied presents an arid climate, so Ih always had a negative value. Because this variable was not normally distributed, it was transformed into Ih^2 (a positive value) for inclusion in the Discriminant Analysis. Thus, the higher the Ih^2, the drier the climate and the lower the predicted site quality (Table 6).

Water availability does not entirely depend on supply through precipitation and loss through evapotranspiration. Soil physical parameters such as particle size distribution or porosity determine the amount of water that percolates down into the soil profile during precipitations as well as the water retention capacity of the soil. Río et al. (2014) found that higher *Pinus halepensis* site indexes presented soils with clay or loamy clay textures while stands with lower site indexes had lower amounts of clay and were more sensitive to climate. Rathgeber et al. (2005) developed a model that included information about soil water capacity, in addition to precipitation and temperature, to simulate radial *Pinus halepensis* growth in France. The model selected to predict the *Pinus halepensis* site index in northern Spain includes porosity, a parameter that can be determined easily, that integrates information about water and the soil aeration regime. In calcareous soils, physical limitations are likely to be compounded by the fine texture and cementing action of calcareous materials. Kishchuk (2000) indicated that calcareous soils may physically affect root penetration, water infiltration, and gas exchange in ways similar to compacted soils, with fewer physical limitations as soil porosity increased. Higher porosity in the area studied would thus predict higher *Pinus halepensis* site quality, as porosity makes it possible for water to penetrate the soil, reach the rhizosphere and aerate the roots properly.

Physiographic parameters such as slope are often related to forest growth in *Pinus halepensis* stands all over the Mediterranean region (Al Omary 2011, Condes & Garcia-Robredo 2012). Slope increases water runoff by diminishing the water percolation into the soil profile and is also related to higher nutrient loss and soil erosion. Eroded materials from steep slopes accumulate in areas with less slope, creating greater depth to carbonates in those areas. Kishchuk (2000) stated that the deeper carbonates in soil correspond to greater forest growth. In other words, as the slope of the plot increased, predicted site quality decreased for *Pinus halepensis* plantations in northern Spain, what is in accordance with the findings by Al Omary (2011) in *Pinus halepensis* plantations in Jordan.

Several studies found that *Pinus halepensis* growth (which is associated with the site index defined as dominant height at a reference age) is mainly driven by water availability in stands within the natural distribution area of the species in Spain (Gandullo et al. 1972, Condes & Garcia-Robredo 2012, Río et al. 2014, del Castillo et al. 2015). The same trend was found by Olarieta et al. (2000) in *Pinus halepensis* plantations in northeast Spain. Therefore, water availability seems to be the most limiting factor for the species productivity in Spain, regardless of being within or outside the natural distribution of the species. Moreover, similar results were achieved by Rathgeber et al. (2005) in *Pinus halepensis* stands in France, Klein et al. (2014) and Maseyk et al. (2011) in Israel and Toromani et al. (2015) in Albania, so this conclusion may be generalizable to the entire Mediterranean area.

Usually, water availability is included in related studies by means of climatic parameters (Pasho et al. 2011, Condes & Garcia-Robredo 2012, del Castillo et al. 2015). However, the amount of water that is actually available for plant roots is not only determined by the contribution of water from precipitations but also by the site factors allowing the water to percolate down the soil profile (Gandullo et al. 1972) and the water retention capacity of soils (Olarieta et al. 2000, Rathgeber et al. 2005) as reflected in the present study.

The model developed to predict *Pinus halepensis* productivity also included Nmic as a predictor. Higher Nmic resulted in lower site productivity in the area studied. As seen in Study I, higher values for biochemical properties in soils are generally related to higher forest productivity (Mahía et al. 2006, Foote et al. 2015, Bueis et al. 2016), as the microorganisms responsible for soil nutrient turnover and availability participate in mineralization processes. However, in some ecosystems an opposite trend has been observed: microorganisms may actually immobilize N in soils with very low N availability or litter input with a very high C/N ratio (Recous et al. 1995, Song et al. 2007). Microorganisms can uptake N very quickly because of their high surface-area ratio, which prevents nutrient loss from leaching but creates an N deficit for the plants (Kuzyakov & Xu 2013). This in turn diminishes stand productivity as N limits productivity in forest ecosystems.

Models with a correct classification rate higher than 60% included a biochemical parameter, indicating that biochemical parameters are determining factors in the *Pinus halepensis* site index. However, laboratory soil analyses do not usually include biochemical analyses and not all laboratories are equipped for them. When the Nmic biochemical parameter was removed from the model developed here, the error rate increased by 6.25%. Nevertheless, this reduced model could be an interesting alternative when biochemical soil analyses are not available.

5.3. Factors determining enzyme activities in soils

Enzymatic and microbial activities

Decomposition of organic matter is an important process through which nutrients are released into soil. It affects ecosystem productivity, particularly in forests and nutrient-poor ecosystems (Muscolo et al. 2007), such as those of the Mediterranean. Nutrient release from plant litter takes place through the enzymatic activities of microorganisms in the soil and depends on several complex and interacting mechanisms. Besides, enzymatic activities are also responsible for the organic matter stabilization through the humification process. Humus improves the soil water and nutrient retention, presents a hormonal role for plants, act as a filter for contaminants and present soil pH buffering capacity.

Our results indicate that soil enzymatic activities (dehydrogenase, urease and catalase) and microbial biomass (Cmic and Nmic) tended to be significantly higher in the calcareous soils under *Pinus halepensis* than in the acidic soils under *Pinus sylvestris.* Each forest species has different nutrient release and humification patterns that depend on litter quality and environmental factors. In our case, litter quality was similar: both forest ecosystems presented *Pinus* species with similar chemical composition in leaves, similar strategies for nutrient conservation in their tissues and similar decomposition rates when other conditions affecting the process remained constant. Litter C/N ratio is very high in coniferous species and such is in these *Pinus* species. The litter half-life of the studied species is about 24 months and then, litter accumulates in the forest floor with an average thickness of 4 cm (unpublished results). Environmental factors must therefore be responsible for the differences in nutrient release and humification processes between the two types of soil. Our results indicated differences in climatic and edaphic properties between the two soil types. However, while correlations between enzymatic activities, microbial parameters and environmental factors (soil and climatic characteristics) can help us understanding the behaviour of these soils, correlation between two variables does not imply that one causes the other, so caution is required.

Dehydrogenase activity is broadly used as an indicator of biological activity in soils (Casida et al. 1964). It reflects the activity of a group of enzymes that are present inside cells and do not accumulate outside the cell (Tabatabai 1994). Dehydrogenase activity was almost fifteen times lower in the acidic soils than in the calcareous soils. Since these enzymes intervene in soil processes that create metabolic pathways for soil microorganisms, they may give some idea of the potential of the soil to harbour biochemical activities which are crucial to soil fertility and health (Das & Varma 2011). The dehydrogenase enzyme is also frequently used as a direct measure of soil microbial activity in relation to mineralization and the formation of humic substances.

Many factors affect enzymatic activities in soils (Tabatabai 1994). Our results showed significant positive correlations of DHA, urease and catalase with Cmin for both soil types when studied separately (Tables 4 and 5). Several authors have found significant correlations between enzyme activities and Cmic, Nmic and Cmin (García et al. 1994, Muscolo et al. 2015). In laboratory conditions Cmin values were significantly higher in acidic soil than in calcareous soil maybe due to the significantly higher EOC in these stands. Enzyme activities are also highly correlated to soil organic matter, which constitutes the energy source for microorganisms and can also contain stabilized enzymes (Alef & Nannipieri 1995, Lucas-Borja et al. 2012). We found significant positive correlations of DHA, urease and catalase with EOC in the calcareous soils, but not in the acidic soils studied. As EOC increases in soil, so does microorganism activity and the decomposition rate of organic matter. This is reflected in soil respiration, indicating that DHA is positively correlated with EOC content. The quality of organic matter, represented by TOC/TN, correlated significantly with urease activity in the acidic soils under *Pinus sylvestris*. Urease activity in this soil is therefore determined by N availability, as indicated by TN and TOC/TN, but not by the amount of organic matter (McCarty et al. 1992, Alef & Nannipieri 1995).

Phosphatase activity plays a crucial role in the P cycle (Burns 1978) and is correlated to P stress and plant growth. In P-deficient soils, acid phosphatase secretion from plant roots increases to enhance phosphate availability to plants (Nannipieri et al. 2011). AcPhos was significantly higher in the acidic soils under *Pinus sylvestris,* but AlkPhos did not differ significantly between the two soil types. AcPhos is usually higher in acidic soils, while AlkPhos prevails in alkaline soil, but they can coexist (Burns 1978). Our results showed very low AP concentration in both soils. Phosphorus availability limits microbial biomass in some forest ecosystems (Scheu 1990) because P is immobilized by Al and Fe sesquioxides at low pH and by Ca at high pH (Gallardo & Schlesinger 1994). We found Pmic to be three times higher than AP in both soils. AP and Pmic were also significantly higher in the acidic soils under *Pinus sylvestris* than in the calcareous soils studied. This suggests a high degree of P immobilization by microorganisms, which limits

AP to plants but could be important for organic P mineralization in these Mediterranean forest soils.

Some environmental factors can negatively affect enzymes by reducing their activity. In the soils under *Pinus sylvestris*, significant correlations were found between urease and catalase activities and pH. Significant negative correlations were also found between FDA, which is used as an indicator of general microbial activity in soil (Bandick & Dick 1999), and the concentration of water soluble phenols (WSP). Low pH is known to limit bacterial communities (Blagodatskaya & Anderson 1998) and high WSP can inhibit enzymatic activities. In the soils under *Pinus sylvestris,* significant correlations were also found between FDA and microbial biomass, indicating that part of the soil microbial biomass is inactive due to inhibitory factors such as low pH (which limits bacterial forms) or high WSP, which affects the amount and activity of soil microbial decomposers (Hattenschwiler & Vitousek 2000). It might also be related to the presence of enzymes of plant rather than microbial origin; plant roots can also exude enzymes and plant density was significantly higher in *Pinus sylvestris* stands (see Table 1).

Significant and negative correlations have also been found between enzyme activities and hydric deficit in calcareous soils, but not in acidic soils. Our results indicated that the higher the hydric deficit, the lower the enzyme activity in Mediterranean ecosystems under dry conditions such as those of the calcareous soils studied. In the long term, decreased soil enzyme activities will affect soil nutrient availability by reducing the nutrient supply to plants. DEF was not significantly correlated with any enzyme activity in the acidic soils under *Pinus sylvestris*, where the mean annual rainfall was around 750 mm, so hydric deficit was not a limiting factor for enzyme activity there. Lucas-Borja et al. (2012) also found higher microbial biomass and activities in areas with higher precipitations in pine forests in central Spain. No significant correlation was detected between enzyme activities and MAT, indicating that temperature did not influence enzyme activities in the soils under either *Pinus* species.

The metabolic quotient (qCO_2), which expresses the amount of C released as CO_2 by microbial respiration per unit microbial biomass, was significantly higher in the soils under *Pinus sylvestris*. Microorganisms use only part of the C contained in the substrates for growth and the maintenance of microbial structures; the rest is released into the atmosphere as CO_2. Thus, qCO_2 reflects microbial efficiency and can be interpreted as a measure of stress, because greater amounts of CO_2 are produced under stressed conditions (Gonzalez-Quinones et al. 2011). The stressful soil conditions under *Pinus* *sylvestris* are likely related to low pH (3.7 to 5.6), a condition known to inhibit microbial activities.

Microbial biomass C was found to be significantly higher in the calcareous soils under *Pinus halepensis* even when EOC and AP were significantly higher in the acidic soils under *Pinus sylvestris*. Correlations between organic matter and nutrient-related parameters in soil indicate microbial biomass dependence on an energy source and association with organic matter (Muscolo et al. 2015). Soil pH strongly influences microbial biomass, activity and composition. These results suggest that pH limits both P availability and the bacterial community in the highly acidic soils under the *Pinus sylvestris* plantations.

Forest management

Forest management for sustainability must assess measures to improve ecosystem functioning, which crucially involves nutrient cycling and humification processes and the soil enzymes responsible for them. This work provides knowledge that can inform managerial alternatives for improving soil nutrient conditions by enhancing enzyme performance. Low pH significantly limits enzyme activities in the acidic soils under *Pinus sylvestris* plantations, but soil pH can be modified in several ways. The most natural proposal consists of transitioning to mixed stands by promoting the growth of native broadleaf species such as *Quercus pyrenaica* Willd., as the litter inputs from this species may increase soil pH (Marcos et al. 2010). However, further studies are needed to confirm whether broadleaf species in these stands would actually or sufficiently increase soil pH and enzyme activities.

Enzyme activities in the calcareous soils under *Pinus halepensis* plantations are mainly limited by hydric deficit. Forest management alternatives might involve modulating stand density to minimize tree competition for water. However, the idea should be weighed carefully, as these stands primarily serve as protection against erosion. Extremely low densities may threaten soil retention and increase evaporation as more radiation reaches the soil. Soil preparation in new afforestation projects may also improve soil water availability. Creating suitable micro-topography, especially on steep slopes, can help water percolate into the soil where it is available for plant roots. Again, additional studies are required to determine optimal stand densities and soil preparation techniques for maximizing water availability.

5.4. Needle litterfall and decomposition rates

The mean annual needle litterfall observed in *Pinus sylvestris* stands (2357 kg ha^{-1}) was slightly lower that the litterfall observed by Santa-Regina & Tarazona (2001) in a *Pinus sylvestris* plantation (2907 kg ha^{-1}) in Sierra de la Demanda (Spain) and by Gallardo-Lancho & Santa-Regina (1991) in Sierra de Béjar (3631 kg ha^{-1}). The maximum litterfall was observed in the months of July to September in *Pinus sylvestris* stands, with the highest litterfall peak in August. These results slightly differed from those found by Pausas (1997) and Blanco et al. (2005) in *Pinus sylvestris* stands in Pirineos (Spain). They found that the maximum litterfall occurred in the months of August to October.

The needle litterfall rate observed in the *Pinus halepensis* stands studied (2144 kg ha^{-1}) were similar to those found by Navarro et al. (2013) in southern Spain (that ranged from 950 kg ha^{-1} to 2280 kg ha^{-1}). These authors observed that the months with higher litterfall were July to October. In the *Pinus halepensis* stands of the present study, June, July and August presented the maximum litterfall rates. The small differences found with regard to the months with maximum litterfall rates may be due to the phenology of the species and the climatic differences present between the different study areas since, as described by Escudero & del Arco (1987), the time where abscission occur is determined by the hydric stress, directly related to the climatic conditions (Roig et al. 2005). It is an adaptation of forest species against the hydric deficit through which the transpiration surface is diminished, decreasing the water losses.

The effect of the LBA on litterfall production observed in the stands of both *Pinus* species was significant and positive and coincided with the findings of several authors for different species (Kunhamu et al. 2009, Navarro et al. 2013, Lado-Monserrat et al. 2015). Those findings mean that higher stand densities (in terms of LBA) imply larger quantities of litter biomass per unit area in the forest stand and then, bigger amount of litterfall.

Regarding the rate of needle litter decomposition, no significant differences were found with respect to the LBA of the plot for *Pinus sylvestris*. However, for *Pinus halepensis* stands a significant effect of the LBA of the stand on needle litter decomposition rate (k) and needle litter half-life ($t_{0.5}$) was observed. Lado-Monserrat et al. (2015) observed a significant decrease of the rate of decomposition of the needle litter in areas subjected to clearcut, in relation to the control treatment (not managed stand) in *Pinus halepensis* stands in the east of Spain. However, they found no significant differences between the control treatment and different levels of thinning. Besides, they found that the needles in the litterbags presented higher humidity in the control plots during the dry periods. In the present study, an opposite trend was found. The rate of needle litter decomposition was higher in plots with lower LBA and the LBA was significant and negatively correlated to the soil humidity and then, plots with lower densities presented higher soil moisture. Desanto et al. (1993) also observed a relationship between the needle mass loss and a parameter related to soil humidity, the daily precipitation, in *Pinus sylvestris* stands. Thus, the water availability seems to be a key factor for litter decomposition but the density of the stand does not trigger the same effects on microclimate in different climatic areas. Apparently, the process that prevails in the area studied is the interception of precipitations by tree crowns, from which the water evaporates and then, less amount of water reaches the soil in plots with higher densities. In other studies, the process that may prevail is the increment of the solar radiation reaching the soil in plots with lower densities, increasing the temperature and diminishing the soil moisture (Lado-Monserrat et al. 2015). Therefore, in the *Pinus halepensis* stands studied, the higher rate of needle litter decomposition that has been found in plots with lower LBA seem to be related to the higher humidity present in these plots, since higher humidity implies higher activity of the decomposer microorganisms in these plots where hydric deficit is limiting, as seen in Study III. However, this effect was not significant in *Pinus sylvestris* stands, probably because of the higher precipitation regime, where humidity may not limit the activity of the decomposers (Study III), with similar microbial performance in plots with different levels of LBA.

5.5. Nutrient concentrations in needle litterfall and nutrient release during needle decomposition in *Pinus halepensis* plantations

Nutrient concentration in needle litterfall through time

Nutrient concentration in needle litterfall showed a clear seasonal pattern for elements such as C, N, Mg, K, P, S, Cu and Zn probably due to the nature of the litterfall throughout the year. Carbon concentration presented minimum values during winter while N, Mg, K, P, S, Cu and Zn presented minimum values during summer. As shown in Figure 2, maximum needle litterfall for *Pinus halepensis* is concentrated in late spring and summer months (Study IV) 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 & Fife 1991, Reuter & Robinson 1997). Then, the needles shed during summer present low concentrations of these elements. On the contrary, the litterfall occurring in winter do not consist of senescent needles, but of green needles shed because of wind or storms and therefore, these needles have not retranslocated the mobile nutrients to plant. Similar trends were observed by Blanco et al. (2008) in two *Pinus sylvestris* stands in Pyrenees (Spain). Carbon concentration is low in summer months because the needle content of the mobile elements is higher and then, C concentration diminishes. Calcium, Fe and Mn are not mobile nutrients and then, the observed trends are not related to their retranslocation. The trend observed for Ca in needle litterfall, showing the maximum concentration during the summer months and early autumn is a common trend that has already been observed on previous studies (Swift et al. 1979).

Effect of local basal area on nutrient concentration in litterfall

Regarding the effect of the LBA of the plot on the element concentration of needle litterfall, significant and positive effect was found for C, K and Mg. The concentration of these elements in needle litterfall is significantly lower in those plots with lower LBA. 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 (where no tree removal was carried out) in a *Pinus halepensis* Mediterranean forest. These authors suggested that the reason could be the higher nutrient availability in plots where cuttings were performed as the uptake of nutrients such as magnesium could be diminished because of competition with other cations as ammonium. Besides, trees subjected to less competence present also higher productivity and then, the nutrient concentration on their tissues may be lower. Therefore, the litterfall nutrient concentration may also be lower. This fact is known as "dilution effect" (Jarrell & 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 in lower LBA plots because lower LBA 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.

Effect of local basal area on soil temperature and humidity

The LBA of the plot present a significant and negative effect on the humidity of the 10 cm mineral topsoil. This fact may respond to the lower aboveground biomass present in those plots with lower LBA producing less interception of precipitations and allowing 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. In the area studied in the present work, the higher amount of precipitation reaching the soil in plots with lower local basal area may prevail over the desiccation increase due to the higher solar radiation reaching the soil surface observed on previous studies.

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 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 two years studied. Carbon release was almost homogeneous in time (except for summer months, when C release seemed to halt probably because of summer drought; months 9 and 18 in Figure 5), while K, Mg and Mn presented a clear first phase of rapid release which correspond to the beginning of decomposition, where highly mobile nutrients such as K are leached. Besides, Mn presented 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. Nitrogen and Zn presented a rate of net immobilization throughout nearly the two years studied. Besides, a clear seasonal pattern can be observed in N accumulated release, with faster immobilization during autumn and winter, and nutrient release during spring and summer. However, P presented a net release rate through most of the studied period. Sulfur presented 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 very fast immobilization. Sulphur immobilization 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, Ca and Mg accumulated in the needles during the first period of the experiment and afterwards, Ca and Mg were progressively 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 (Laskowski et al. 1995, He et al. 2016, Pourhassan et al. 2016).

Effect of local basal area on needle litter nutrient release

The LBA of the plot also presented a significant effect on the elements analyzed but Fe and Mn in the decomposing needles. The release of all these nutrients (C, N, Ca, K, Mg, P, S, Zn and Cu) along the period studied 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 LBA, immobilization is lower than in plots with higher LBA. The observed trend may be related to the higher decomposition rate observed in plots with lower LBA (Study IV) as higher rainfall reaching the soil implies higher soil humidity and higher microbial activity together with higher leaching. Kim (2016) found no differences 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 three months of decomposition, fact that they attributed to increased leaching losses in plots with lower basal areas. Blanco et al. (2011) observed 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 LBA) compared to areas in forest gaps (lower LBA) for several species in an Alpine forest in China.

5.6. Nutrient release during needle litter decomposition in *Pinus sylvestris* plantations

The accumulated nutrient release from the decomposing needle litter contained in the litterbags presented varied trends for the eleven elements studied. This may respond to the availability of these nutrients for decomposers as nutrients tend to be released from decomposing organic matter when appear in limiting amounts, but are immobilized (decomposers import nutrients from the environment) when nutrients present limiting amounts.

The decomposing needle litter showed net release patterns for C, P, K, Mg, Ca and Mn during the 18 months studied. All these elements were released fast during the first three months of the study and the following periods presented slower release or even immobilization in some cases. Net release pattern was observed for N during the whole study period indicating that this element appears in limiting amounts and therefore, decomposers import nitrogen from other sources, but 18 months are not enough to achieve non-limiting N amounts in the decomposing needle litter of *Pinus sylvestris* studied. During humification processes, decomposers incorporate N and S into humic substances and humus form complexes with Cu, Mn, Zn and other polyvalent cations (Stevenson 1994). Manganese and Zn are highly available in the acidic soils under the studied *Pinus sylvestris* plantations but Cu is not. Therefore, Mn and Zn are released because they appear in non-limiting amounts, but Cu present a first phase of fast release followed by a phase of continuous immobilization, probably being complexed with humic substances. Copper and Fe are probably imported from soil by decomposers and S may come from atmospheric depositon (Quilchano et al. 2002).

A seasonal trend has also been detected in the accumulated nutrient release from decomposing needle litter. Nutrients such as C, N or P presented a faster release or immobilization in autumn and slower variations in winter, spring and summer when low temperatures and low water availability may be limiting the activity of the decomposers.

The LBA of the plot presented a significant and negative effect on N, P, K and S accumulated release (or immobilization). Besides, a significant and negative effect of LBA on topsoil humidity was found. The higher humidity found in plots with lower LBA did not provoke faster decomposition as seen for other species such as *Pinus halepensis* (Study IV). Therefore, this effect may respond to leaching, as lower local basal area implies less tree aboveground biomass able to intercept precipitations, which finally reaches the soil and the content of the litterbags, leaching the most soluble compounds as found by other authors (Kim 2016).

An opposite trend was found for accumulated Fe release from needle litter contained in the litterbags. The LBA of the plot significantly and positively affected the accumulated Fe release (or immobilization) from decomposing needle litter. Then, lower amounts of Fe were released during the first three months of decomposition, or higher amounts were immobilized during the following phase of Fe immobilization in plots with lower LBA. This trend may be attributed to a higher importation of Fe by decomposers or even contamination from soil source as plots with lower LBA present a narrower organic horizon because of the lower amount of litterfall produced and the closer contact between litter and mineral soil.

6. Conclusions

Soil physical, chemical and biochemical as well as physiographic parameters are determining factors for *Pinus sylvestris* L. site index in acidic plateau plantations in northern Spain, which may be predicted by means of a discriminant model including latitude, soil porosity, soil inorganic aluminium and microbial biomass carbon as predictors with a correct resubstitution rate of 71.4% of cases. The model includes information about climatic parameters (highly correlated to latitude), about aeration and water retention capacity of the soil (porosity), about soil acidity (inorganic aluminium) related to nutrient immobilization and limiting for bacterial communities of soil decomposers and finally, about the amount of microbial decomposers responsible for the nutrient cycle (microbial biomass C).

Climatic, soil physical and biochemical parameters are determining factors for *Pinus halepensis* site index in northern Spain plantations which may be predicted by means of a discriminant model including soil porosity, the Annual Hydric Index, slope and microbial biomass nitrogen as predictors with a correct resubstitution rate of 62.5%. This model indicates that water availability is crucial for *Pinus halepensis* productivity in these stands, as porosity is responsible for water penetration in soil and retention in the rhizosphere, the Annual Hydric Index combines information about precipitation and evapotranspiration and slope reflects the water runoff of the soil surface. Besides, slope also includes information about nutrient and soil losses due to erosion and microbial biomass N reflects the N deficit due to microbial immobilization, a common reality in N-limited ecosystems.

Significant differences in enzyme activities were found between the calcareous soils under *Pinus halepensis* and the acidic soils under *Pinus sylvestris*. The soil under *Pinus sylvestris* presented low pH and high amounts of water-soluble phenols, both of which limit the activity and composition of the microbial community. However, hydric deficit seemed to be the most limiting factor for enzyme activities in the calcareous soils under *Pinus halepensis*. Over time, decreased soil enzyme activity will affect humification processes and soil nutrient availability. The promotion of native broadleaf species such as *Quercus pyrenaica* in *Pinus sylvestris* stands may improve soil pH due to their litter quality and adjusting stand density in *Pinus halepensis* stands, and improving soil preparation in new afforestations may improve water availability, especially in areas with steep slopes.

The litterfall rates of the *Pinus halepensis* and *Pinus sylvestris* plantations studied in northern Spain present a slight temporal lag with other stands of the same species probably related to the different climatic conditions between the areas subject of study. The local basal area of the plot has a significant and positive effect on litterfall, as aboveground tree biomass is also significantly related to local basal area of the plot. The local basal area of the plot also has a significant but negative effect on needle litter decomposition rate in *Pinus halepensis* stands due to the significantly higher soil moisture found in plots with lower local basal area, related to lower canopy interception of precipitations which lead to higher activity of microbial decomposers. However, the local basal area of the *Pinus sylvestris* stands studied do not present a significant effect on needle litter decomposition rate, even when soil moisture content is significantly affected by the local basal area of the plot. Therefore, the decomposition processes in *Pinus sylvestris* stands may not be limited by water availability.

Needle litterfall nutrient concentration presents a clear seasonal pattern in the *Pinus halepensis* stands studied showing that winter litterfall contains high nutrient concentrations. Needles shed in this season are not senescent needles and thus, have not retranslocated the mobile nutrients they contain. The local basal area of the stand significantly affects nutrient concentration in needle litterfall, soil microclimate and nutrient release during needle litter decomposition and then, silvicultural practices involving density management of stands have an impact on nutrient cycling in *Pinus halepensis* Mediterranean forests of northern Spain. Nutrient release dynamics from decomposing needle litter differ among elements depending on the specific nutrient availability for decomposers.

The local basal area of the plot significantly affects the release of some nutrients from of *Pinus sylvestris* decomposing needle litter. Therefore, silvicultural practices involving density management of *Pinus sylvestris* plantations also have an impact on nutrient cycling. The nutrients analyzed presented different release dynamics in relation to their availability for decomposers.

7. Conclusiones

Los parámetros edáficos físicos, químicos y bioquímicos así como los parámetros fisiográficos son factores determinantes del índice de sitio de las repoblaciones de *Pinus sylvestris* L. de los páramos ácidos del norte de España, el cual puede predecirse a partir de un modelo discriminante que incluye la latitud, la porosidad, el aluminio inorgánico y el carbono de la biomasa microbiana del suelo como predictores con una tasa de resustituciones correctas del 71.4%. El modelo incluye información acerca de parámetros climáticos (altamente correlacionados con la latitud), acerca del régimen de humedad y aireación del suelo (porosidad), acerca de la acidez del suelo (aluminio inorgánico) relacionado con la inmovilización de nutrientes y la limitación que supone para las comunidades de descomponedores bacterianos del suelo y finalmente, acerca de la cantidad de organismos descomponedores microbianos presentes en el suelo y responsables del reciclado de los nutrientes (C de la biomasa microbiana).

Los parámetros climáticos así como los edáficos físicos y bioquímicos son factores determinantes de índice de sitio en las repoblaciones de *Pinus halepensis* Mill. del norte de España, el cual se puede predecir a través de un modelo discriminante que incluye como predictores la porosidad edáfica, el Índice Hídrico anual, la pendiente y el nitrógeno de la biomasa microbiana con una tasa de resustituciones correctas del 62.5%. Este modelo indica que la disponibilidad hídrica es crucial para la productividad de *Pinus halepensis* en estas masas ya que la porosidad es responsable de la penetración del agua en el suelo y su retención en la rizosfera, el Índice Hídrico Anual combina información acerca de precipitación y evapotranspiración y la pendiente refleja la escorrentía superficial del suelo. Además, la pendiente incluye información acerca de la pérdida de suelo y nutrientes por causa de la erosión y el N de la biomasa microbiana informa de la inmovilización del N por parte de los microorganismos del suelo, una realidad común en ecosistemas con limitaciones de nitrógeno.

Se han hallado diferencias significativas entre las actividades enzimáticas de los suelos calizos bajo *Pinus halepensis* Mill. y los suelos ácidos bajo *Pinus sylvestris* L. estudiados. Los suelos bajo *Pinus sylvestris* presentan un pH ácido y elevados contenidos de fenoles solubles que limitan la actividad y composición de las comunidades microbianas del suelo. Sin embargo, el déficit hídrico parece ser el factor más limitante para la actividad de las enzimas del suelo en los suelos calizos bajo *Pinus* *halepensis.* Con el tiempo, bajas actividades enzimáticas afectan los procesos de humificación de la materia orgánica y la disponibilidad de nutrientes edáficos. La promoción del crecimiento de especies de frondosas nativas como Quercus pyrenaica in las masas de *Pinus sylvestris* puede mejorar el pH del suelo dada la calidad de su hojarasca. Asimismo, el ajuste de la densidad de las masas de *Pinus halepensis* así como la optimización de las técnicas de preparación del terreno acometidas en las nuevas repoblaciones pueden mejorar la disponibilidad hídrica, especialmente en áreas con pendientes elevadas.

Las tasas de desfronde de las repoblaciones de *Pinus sylvestris* y *Pinus halepensis* estudiadas presentan un ligero desfase temporal con respecto a otras masas de las mismas especies que probablemente se deba a las diferencias climáticas existentes entre las distintas áreas objeto de estudio. El área basimétrica de la parcela tiene un efecto significativo y positivo sobre el desfronde ya que la biomasa arbórea aérea también está significativamente relacionada con el área basimétrica de la masa. El área basimétrica también tiene un efecto significativo pero negativo sobre la descomposición de la hojarasca de acículas por la mayor humedad del suelo observada en las parcelas con menor área basimétrica local, debida a la menor interceptación de las precipitaciones llevada a cabo por las copas de los árboles que provoca una mayor actividad de los microorganismos descomponedores. Sin embargo, el área basimétrica local de las parcelas de *Pinus sylvestris* estudiadas no presenta un efecto significativo sobre la tasa de descomposición de las acículas senescentes, a pesar de haberse constatado un efecto significativo sobre la humedad del suelo. Por tanto, los procesos de descomposición en las masas de *Pinus sylvestris* estudiadas no parecen estar limitados por la disponibilidad hídrica.

La concentración de nutrientes del desfronde de acículas presenta un claro patrón estacional en las masas de *Pinus halepensis* estudiadas reflejando que el desfronde que se produce en invierno presenta elevadas concentraciones de nutrientes puesto que las acículas que se pierden en esta estación no han retranslocado los nutrientes móviles que contienen. El área basimétrica local de las masas afecta significativamente la concentración de nutrientes en el desfronde de acículas, así como el microclima del suelo y por tanto, la liberación de nutrientes durante la descomposición de la hojarasca. Las prácticas selvícolas que implican un manejo de la densidad de las masas tienen, en consecuencia, un impacto sobre el ciclo de nutrientes en las repoblaciones de *Pinus halepensis* del norte de España. Las dinámicas de liberación de nutrientes del desfronde de acículas durante la descomposición difieren en relación al nutriente estudiado y la disponibilidad de dicho nutriente para los organismos descomponedores.

El área basimétrica de la parcela afecta significativamente a la liberación de algunos nutrientes durante la descomposición del desfronde de acículas de *Pinus sylvestris* en las masas estudiadas. El manejo de la densidad de las masas de *Pinus sylvestris* estudiadas conlleva, por tanto, un impacto sobre el ciclo de nutrientes en las plantaciones de *Pinus sylvestris* estudiadas.

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Supplementary material

Supplementary material 1 Location of the plots studied to develop a model for classifying the site index for *Pinus sylvestris* L. and *Pinus halepensis* Mill. plantations

UTM Coordinates (datum ED50)			
Pinus sylvestris plots		*Pinus halepensis* plots	
X	Y	X	Y
356689	4711709	333000	4640000
356510	4718046	333000	4639000
346008	4735864	337000	4637000
345449	4732431	333000	4635000
356953	4723227	332000	4633000
352284	4724256	321000	4627000
370257	4717777	322000	4618000
371299	4717225	368000	4623000
371111	4716897	367000	4617000
372303	4715356	330000	4605000
356791	4722980	349000	4613000
358125	4712512	347000	4610000
356874	4723451	370000	4608000
353086	4733717	377000	4613000
353515	4736657	394000	4612000
347849	4728273	412000	4604000
374732	4715297	373000	4656000
341138	4727330	388000	4668000
343309	4731280	367000	4585000
344755	4731657	356000	4639000
344069	4729889	357000	4639000
344273	4727795	353000	4638000
343114	4726676	386000	4632000
340167	4724006	404000	4631000
340347	4724323	360000	4575000
341275	4721130	390000	4639000
344662	4728832	382000	4627000
345725	4733054	357000	4629000
343620	4729463	356000	4625000
341554	4727760	371000	4622000
344540	4729354	378000	4617000
345010	4728213	403000	4621000
344987	4728181		
345075	4728213		
345080	4728126		

Supplementary material 2 Summary statistics for soil variables used to develop a discriminant model to classify the site index for *Pinus sylvestris* plantations[a]

Soil Variables	Mean	SD	Min.	Max.
Available water (%) AW	7.1	2.7	2.3	13.4
Coarse particles (%) CO	27.1	16.3	0.4	56.4
Clay (%) CLAY	15.9	3.3	9.0	26.4
Sand ISSS criteria (%) SANDIS	70.3	7.4	55.1	83.7
Sand USDA criteria (%) SANDUS	58.8	10.7	40.2	75.5
Silt ISSS criteria (%) SILTIS	13.8	5.7	6.1	28.0
Silt USDA criteria (%) SILTUS	25.4	9.5	13.4	45.7
Porosity (%) PO	49.9	7.1	35.4	65.1
pH	4.6	0.5	3.7	5.6
Exchangeable acidity ($cmol_{(+)}\cdot kg^{-1}$) EA	13.4	4.5	5.6	23.6
Total C/Total N TC/TN	29.6	5.0	19.2	41.3
Available P ($mg\cdot kg^{-1}$) AP	4.1	1.7	1.4	7.3
Ca^{+2} ($cmol_{(+)}\cdot kg^{-1}$)	0.9	0.7	0.2	2.9
K^{+} ($cmol_{(+)}\cdot kg^{-1}$)	0.2	0.1	0.1	0.6
Mg^{+2} ($cmol_{(+)}\cdot kg^{-1}$)	0.1	0.1	0.0	0.5
Cation exchange capacity ($cmol_{(+)}\cdot kg^{-1}$) CEC	18.8	3.1	11.8	24.2
Base saturation (%) SAT	7.5	5.4	2.4	21.1
Easily oxidizable carbon (%) EOC	2.2	0.5	1.3	3.4
EOC/TC	0.6	0.1	0.4	0.7
Amorphous Al ($mg\cdot g^{-1}$) Al_A	6.6	2.5	2.5	11.6
Exchangeable Al ($mg\cdot g^{-1}$) Al_E	0.6	0.4	0.0	1.3
Inorganic Al ($mg\cdot g^{-1}$) Al_I	2.4	2.0	0.0	8.8
Organically bound Al ($mg\cdot g^{-1}$) Al_O	9.0	3.8	2.7	17.9
Amorphous Fe ($mg\cdot g^{-1}$) Fe_A	4.0	1.5	1.7	7.9
Organically bound Fe ($mg\cdot g^{-1}$) Fe_o	4.6	1.7	1.8	7.7
Amorphous Mn ($mg\cdot g^{-1}$) Mn_A	0.8	1.4	0.0	6.6
Organically bound Mn ($mg\cdot g^{-1}$) Mn_O	0.3	0.4	0.0	1.2
Microbial biomass C ($mg\cdot kg^{-1}$) Cmic	115.1	47.8	45.5	232.9
Microbial Biomass C/Total C ($g\cdot kg^{-1}$) Cmic/TC	3.0	1.2	1.3	6.1
Mineralizable C ($mg\cdot kg^{-1}\cdot week^{-1}$) Cmin	56.7	21.4	22.0	112.1
Mineralizable C/Total C ($g\cdot week^{-1}\cdot kg^{-1}$) Cmin/TC	1.5	0.7	0.6	3.3
Microbial Biomass N ($mg\cdot kg^{-1}$) Nmic	14.0	7.2	3.6	30.7
Microbial biomass P ($mg\cdot kg^{-1}$) Pmic	11.1	5.7	4.6	32.2
Microbial metabolic quotient (Cmin/Cmic) ($g\cdot week^{-1}\cdot g^{-1}$) qCO_2	0.6	0.2	0.1	1.2
Total C/Total N in FH fraction of organic horizon $[TC/TN]_{FH}$	38.1	5.0	28.6	52.1
Total C/Total N in L fraction of organic horizon $[TC/TN]_{L}$	69.5	10.2	48.5	90.8
Organic horizon thickness (cm) OHT	5.1	1.8	2.1	10.0
Biomass per hectare of organic horizon FH fraction ($t\cdot ha^{-1}$) O_{FH}	185.2	62.3	100.6	346.3
Biomass per hectare of organic horizon L fraction ($t\cdot ha^{-1}$) O_{L}	58.6	23.5	32.7	128.1

[a] SD: standard deviation; FH: fragmented plus humified; L: litter; Min.: Minimum; Max.: Maximum

Supplementary material 3 Summary statistics for climatic variables used to develop a discriminant model to classify the site index for *Pinus sylvestris* plantations[a]

Climatic Variables	Mean	S.D.	Min.	Max.
Total precipitation (mm) TP	734.2	80.3	596.8	942.5
Winter precipitation (mm) PW	235.6	32.5	182.0	318.8
Autumn precipitation (mm) PA	207.4	26.2	159.1	264.0
Spring precipitation (mm) PSP	183.0	16.2	158.3	237.1
Summer precipitation (mm) PSU	108.0	6.9	92.9	122.6
Mean annual temperature (ºC) MAT	9.6	0.4	8.8	10.4
Mean value of maximum temperature in the warmest month (ºC) MMWM	26.0	0.4	25.2	26.9
Mean temperature of the warmest month (ºC) MTWM	18.1	0.4	17.4	19.0
Mean temperature of the coldest month (ºC) MTCM	2.4	0.4	1.5	3.1
Mean value of minimum temperature in the coldest month (ºC) MMCM	-2.1	0.4	-2.9	-1.3
Deficit (mm) D	133.0	17.9	99.6	172.6
Surplus (mm) S	249.3	72.3	130.8	445.9
Potential evapotranspiration (mm) PET	617.8	11.6	596.2	641.9
Real evapotranspiration (mm) RET	484.8	10.7	456.9	498.0
Lang Index	77.1	10.9	57.9	107.1
Martonne Index	37.6	4.7	29.4	50.1
Annual Hydric Index (Im)	27.6	13.7	4.3	64.8

[a] SD: standard deviation: Min.: Minimum; Max.: Maximum

Supplementary material 4 Summary statistics for physiographic variables used to develop a discriminant model to classify the site index for *Pinus sylvestris* plantations[a]

Physiographic Variables	Mean	SD[a]	Minimum	Maximum
Elevation (m) ELV	1067.4	72.0	926.0	1180.0
Latitude (º) LAT	42.7	0.1	42.6	42.8
Slope (%) SLP	2.3	3.2	0.0	12.0

[a]SD: standard deviation

Supplementary Material 5 Summary of soil parameters used to develop a discriminant model for classifying the site index for *Pinus halepensis* plantations[a]

Soil Variables	Mean	S.D	Min	Max
Available water (%)	8.2	3.5	1.2	16.0
Coarse particles (%)	27.6	16.2	1.1	62.2
Clay (%)	22.4	10.0	4.5	43.2
Sand ISSS criteria (%)	35.4	14.4	7.5	65.0
Sand USDA criteria (%)	24.4	14.7	1.3	61.1
Silt ISSS criteria (%)	42.2	17.1	6.4	76.2
Silt USDA criteria (%)	53.2	18.5	13.3	88.6
Porosity (%)	46.1	6.0	37.1	58.7
pH	8.4	0.2	8.0	8.9
Electrical Conductivity (µS/cm)	228.3	60.3	129.8	395.0
Cation exchange capacity ($cmol_{(+)}$ kg^{-1})	21.0	4.8	14.7	38.4
Easily oxidizable carbon (%)	1.7	0.8	0.9	4.3
Available P (mg kg^{-1})	2.6	1.7	1.0	9.8
Total organic C/Total N	17.3	10.1	1.9	51.4
Calcium carbonates (mg kg^{-1})	54.3	19.5	1.4	79.1
Reactive calcium carbonates (mg kg^{-1})	1.59	0.76	0.02	3.20
Gypsum (mg kg^{-1})	293.5	123.0	102.9	587.6
Ca ($cmol_{(+)}$ kg^{-1})	38.50	7.58	12.65	57.30
K ($cmol_{(+)}$ kg^{-1})	0.76	0.24	0.46	1.45
Mg ($cmol_{(+)}$ kg^{-1})	3.15	1.92	0.55	7.58
Na ($cmol_{(+)}$ kg^{-1})	0.10	0.04	0.04	0.21
Fe ($cmol_{(+)}$ kg^{-1})	7.79	4.64	3.20	26.71
Mn ($cmol_{(+)}$ kg^{-1})	16.03	6.45	6.98	32.81
Cu ($cmol_{(+)}$ kg^{-1})	0.71	1.11	0.18	6.67
Zn ($cmol_{(+)}$ kg^{-1})	0.78	1.35	0.15	7.97
Microbial biomass C (mg kg^{-1})	209.7	82.5	96.0	445.3
Microbial Biomass C/Total organic C (g kg-1)	13.4	10.5	6.3	55.9
Mineralizable C (mg kg^{-1} $week^{-1}$)	34.2	11.7	17.3	62.4
Mineralizable C/Total organic C (g $week^{-1}$ kg^{-1})	2.16	1.53	0.84	8.79
Microbial Biomass N (mg kg^{-1})	26.9	11.6	10.4	50.1
Microbial biomass P (mg kg^{-1})	7.7	4.3	1.4	17.2
Microbial metabolic quotient (g $week^{-1}$ g^{-1})	0.17	0.05	0.10	0.31
Total C/Total N in FH fraction of organic horizon	30.4	7.0	20.5	46.9
Total C/Total N in L fraction of organic horizon	54.2	9.3	39.1	80.4
Organic horizon thickness (cm)	3.3	1.9	0.5	7.0
Biomass of organic horizon FH fraction (t ·ha^{-1})	31.9	22.3	3.8	89.4
Biomass of organic horizon L fraction (t ·ha^{-1})	5.5	2.7	1.3	16.1

[a] S.D.: standard deviation; Min: minimum; Max: maximum; FH: fragmented plus humified; L: litter

Supplementary Material 6 Summary of climatic parameters used to develop a discriminant model for classifying the site index for *Pinus halepensis* plantations[a]

Climatic Variables	Mean	S.D.[a]	Min	Max
Total precipitation (mm)	456.1	27.6	405.0	548.0
Winter precipitation (mm)	129.8	8.3	107.3	156.7
Autumm precipitation (mm)	123.7	7.5	109.8	142.1
Spring precipitation (mm)	123.7	7.9	108.3	147.6
Summer precipitation (mm)	73.4	5.1	63.5	83.1
Mean annual temperature (ºC)	11.7	0.5	11.0	12.0
Mean maximum temperature of the warmest month (ºC)	29.5	0.4	28.6	30.5
Mean temperature of the warmest month (ºC)	20.9	0.3	20.4	21.9
Mean temperature of the coldest month (ºC)	3.8	0.3	3.2	4.7
Mean minimum temperature of the coldest month (ºC)	-0.7	0.2	-1.3	-0.4
Deficit (mm)	254.0	16.4	222.9	282.8
Surplus (mm)	22.4	15.6	0	73.9
Potential evapotranspiration (mm)	682.2	7.7	667.8	698.5
Actual evapotranspiration (mm)	428.2	13.1	402.6	455.5
Lang Index	39.0	2.9	35.8	46.5
Martonne Index	21.0	1.4	19.3	24.9
Annual Hydric Index	-19.0	3.3	-24.8	-9.6

[a] S.D.: standard deviation; Min: minimum; Max: maximum

Supplementary Material 7 Summary of physiographic parameters used to develop a discriminant model for classifying the site index for *Pinus halepensis* plantations[a]

Physiographic Variables	Mean	S.D.[a]	Minimum	Maximum
Elevation (m)	821.4	35.0	769.0	915.0
Latitude (º)	41.8	0.2	41.3	42.2
Slope (%)	25.5	14.0	0.0	55.0

[a] S.D.: standard deviation; Min: minimum; Max: maximum.

Supplementary Material 8 Macronutrient concentration in *Pinus halepensis* needle litterfall

Site	Plot	LBA	Carbon (mg g^{-1})				Nitrogen (mg g^{-1})				Potassium (mg g^{-1})				Phosphorus (mg kg^{-1})				Calcium (mg g^{-1})			
			Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
Ampudia	1	28.3	510.9	504.5	513.5	2.8	8.38	5.38	11.65	2.01	2.18	1.26	3.12	0.70	329.4	211.6	584.9	119.6	14.7	6.7	21.6	5.9
	2	54.5	512.1	506.5	517.0	3.4	7.89	5.14	10.05	1.59	2.31	1.48	3.31	0.61	372.5	237.7	616.9	114.5	14.8	7.4	20.2	5.4
	3	12.1	510.6	501.0	517.6	5.3	8.04	5.02	11.58	2.03	2.21	1.11	2.94	0.62	340.0	181.7	537.9	126.0	12.6	7.0	18.7	5.0
	4	21.6	508.1	501.6	512.4	3.9	8.47	5.30	11.65	2.20	2.08	1.10	3.90	0.98	355.1	187.4	693.8	155.7	16.5	8.0	24.5	6.8
	5	47.7	508.7	502.4	515.0	4.0	7.95	5.31	11.08	1.95	2.02	1.26	2.87	0.67	311.1	181.6	563.6	116.6	16.3	8.5	22.7	6.2
	6	26.5	508.6	504.4	514.0	3.1	8.61	6.00	11.56	1.71	2.05	1.12	3.42	0.81	294.6	143.1	571.7	127.8	16.6	7.7	23.0	7.0
	7	14.1	508.6	504.1	514.8	3.2	7.94	4.87	10.74	1.99	1.98	1.23	2.78	0.59	341.0	184.6	598.5	122.9	17.6	9.1	22.8	6.4
	8	45.4	513.8	508.8	517.7	3.5	8.01	5.93	10.38	1.56	2.22	1.25	3.25	0.74	390.1	239.7	708.6	140.9	14.1	7.5	18.9	4.9
Valoria la Buena	1	60.4	514.2	509.9	518.9	3.0	7.45	5.35	10.98	2.16	2.20	1.35	3.77	0.86	416.4	219.9	766.1	202.5	14.0	7.5	20.0	5.0
	2	11.7	510.4	501.8	518.4	5.5	8.05	5.56	11.11	2.06	1.73	1.21	2.39	0.45	324.0	230.7	474.5	91.9	11.6	7.0	17.9	4.3
	3	32.7	515.7	508.2	518.5	3.3	8.49	5.45	12.21	2.49	2.06	1.29	3.09	0.67	354.1	190.0	609.9	161.2	13.0	7.1	19.4	4.6
	4	39.7	516.0	509.9	520.4	4.0	8.42	6.02	11.76	2.20	2.17	1.39	3.46	0.80	357.6	202.1	632.6	161.9	11.9	6.5	18.1	4.3
	5	46.4	515.9	508.6	526.5	5.7	8.21	5.25	11.88	2.42	2.47	1.50	3.93	0.92	356.4	187.3	608.9	166.2	12.8	6.4	18.0	4.5
	6	19.3	512.4	505.8	522.7	5.4	8.79	6.78	11.95	1.93	2.02	1.27	3.52	0.87	349.2	199.2	571.1	147.0	11.5	5.8	16.3	4.1
	7	27.5	512.8	502.7	519.0	5.2	7.96	6.02	10.83	1.93	1.91	0.90	2.64	0.62	341.9	210.6	549.6	123.6	12.3	6.6	17.3	4.2
	8	5.6	510.0	501.3	516.0	4.6	8.81	5.93	11.34	1.81	1.94	1.36	2.52	0.48	344.9	217.7	468.3	103.3	12.5	7.2	18.8	5.0
Valle de Cerrato	1	11.1	513.2	506.3	517.9	4.4	7.84	5.87	11.19	1.86	1.33	1.05	1.92	0.36	261.7	169.4	425.1	87.8	14.1	9.1	19.7	5.4
	2	77.0	514.6	509.8	520.3	3.0	7.74	5.82	11.10	1.79	1.56	1.04	2.65	0.50	296.0	175.3	533.8	117.3	15.8	8.0	20.9	5.7
	3	54.4	517.6	508.6	524.3	5.4	8.19	5.92	11.59	2.17	1.77	0.95	2.74	0.64	305.0	163.8	544.2	151.8	13.5	7.1	18.0	4.6
	4	38.2	516.9	514.3	519.7	2.0	7.11	5.39	10.16	1.88	1.51	0.72	2.33	0.46	302.6	177.8	544.6	131.7	14.4	7.8	19.1	5.1
	5	64.7	517.5	514.3	522.6	2.6	8.16	5.49	12.28	2.34	1.79	1.21	2.74	0.57	326.5	172.5	582.8	148.3	12.6	6.8	16.2	4.4
	6	28.8	517.7	510.7	522.8	3.5	8.33	5.87	11.77	2.19	1.52	0.98	2.15	0.36	314.2	180.1	519.0	131.7	12.1	6.9	17.7	4.3
	7	33.6	514.7	510.7	518.9	3.2	8.23	5.96	11.00	1.75	1.50	1.09	2.16	0.33	297.2	178.6	458.4	97.0	14.3	7.8	18.7	5.1
	8	58.9	516.6	512.5	521.0	3.0	7.37	5.13	10.85	2.08	1.84	1.33	2.72	0.43	324.6	181.3	542.9	128.1	12.3	6.3	17.4	4.4
Dueñas	1	38.7	506.7	499.5	512.1	4.0	7.62	4.71	11.52	2.57	2.37	1.14	5.47	1.43	416.5	203.7	770.7	223.7	15.8	6.1	24.3	6.3
	2	16.2	509.5	502.1	516.3	5.3	7.05	4.62	10.55	2.03	2.01	0.98	3.27	0.77	405.6	219.2	723.3	190.8	15.9	8.9	24.9	5.9
	3	39.9	506.9	498.4	516.9	6.1	7.98	4.67	12.25	2.45	2.60	1.40	3.90	0.85	494.4	236.1	892.1	222.7	15.8	8.5	22.2	5.6
	4	27.4	514.5	509.1	519.7	4.1	6.94	4.69	10.15	1.86	1.90	1.07	2.87	0.60	329.1	182.5	547.1	127.8	12.8	6.4	19.3	4.8
	5	36.7	506.8	499.9	511.6	4.7	7.71	4.95	11.27	2.33	2.30	1.21	3.65	0.89	521.5	281.3	885.6	225.3	16.6	7.8	23.1	5.8
	6	21.3	513.0	500.3	521.0	7.7	6.28	4.26	9.50	1.84	1.86	0.96	3.22	0.78	524.5	365.7	935.5	200.5	14.1	8.4	19.7	5.0
	7	11.9	507.4	496.9	515.0	5.3	6.43	4.43	9.34	1.70	1.76	0.99	2.29	0.46	461.5	285.8	714.5	149.9	15.9	9.2	22.9	5.9
	8	33.8	507.4	500.1	512.3	4.5	6.80	4.67	10.62	1.99	2.12	1.18	3.40	0.85	460.5	225.7	854.8	237.1	15.9	9.0	23.4	5.5

LBA: local basal area (m^2 ha^{-1})

Supplementary material 9 Micronutrient concentration in *Pinus halepensis* needle litterfall

Site	Plot	LBA	Magnesium (mg g^{-1})				Sulphur (mg g^{-1})				Iron (mg kg^{-1})				Copper (mg kg^{-1})				Manganese (mg kg^{-1})				Zinc (mg kg^{-1})			
			Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
Ampudia	1	28.3	0.97	0.87	1.09	0.08	1.00	0.85	1.18	0.11	90.6	63.7	100.6	11.7	1.71	1.25	2.47	0.43	66.2	52.1	72.7	6.6	8.89	6.72	11.47	11.47
	2	54.5	1.02	0.92	1.20	0.10	1.02	0.88	1.13	0.08	85.7	70.5	98.4	8.5	1.52	1.03	2.11	0.32	37.4	30.2	44.1	4.7	9.32	8.17	10.70	10.70
	3	12.1	0.96	0.80	1.15	0.11	0.99	0.83	1.13	0.11	88.3	63.7	101.2	13.4	1.55	1.03	2.18	0.51	65.0	55.6	79.0	8.1	7.30	4.78	8.50	8.50
	4	21.6	0.95	0.83	1.14	0.12	1.08	0.89	1.35	0.14	96.2	78.7	113.5	11.1	1.70	1.25	2.61	0.45	85.7	74.3	97.3	8.9	10.18	7.60	14.91	14.91
	5	47.7	1.01	0.89	1.13	0.10	1.02	0.86	1.13	0.09	106.0	82.0	120.2	12.4	1.61	1.39	2.13	0.25	56.2	51.7	64.9	4.6	9.37	7.39	11.69	11.69
	6	26.5	0.97	0.87	1.16	0.11	1.02	0.83	1.26	0.13	93.7	75.1	111.5	11.3	1.74	1.40	2.56	0.39	47.8	32.7	58.3	9.7	10.80	7.84	15.09	15.09
	7	14.1	0.91	0.74	1.10	0.13	1.01	0.85	1.23	0.11	94.4	76.8	110.0	10.9	1.45	1.22	1.78	0.18	43.3	32.9	50.0	4.9	10.44	7.78	14.29	14.29
	8	45.4	0.89	0.77	1.09	0.11	1.03	0.92	1.23	0.10	86.1	72.1	103.0	9.6	1.64	1.15	2.16	0.37	41.9	33.4	48.1	5.1	10.50	7.40	13.21	13.21
Valoria la Buena	1	60.4	1.21	1.03	1.48	0.16	1.07	0.92	1.27	0.13	86.4	67.3	98.9	10.3	1.62	1.14	2.62	0.51	15.0	13.3	16.5	1.3	9.86	6.81	13.16	13.16
	2	11.7	1.16	0.92	1.44	0.19	0.98	0.89	1.08	0.06	75.2	67.1	84.5	6.7	1.62	1.04	2.12	0.40	15.8	11.9	20.2	3.4	11.85	8.30	21.30	21.30
	3	32.7	1.22	1.00	1.47	0.15	1.05	0.91	1.29	0.12	84.2	70.2	100.2	9.4	1.82	1.40	2.40	0.38	15.8	13.1	18.0	1.5	9.10	6.28	11.56	11.56
	4	39.7	1.16	0.97	1.34	0.13	1.00	0.89	1.13	0.09	83.7	69.6	94.4	7.6	1.78	1.32	2.59	0.46	14.6	11.8	16.5	1.6	9.79	8.32	12.58	12.58
	5	46.4	1.24	1.12	1.45	0.12	1.02	0.89	1.15	0.10	86.7	64.9	102.9	11.5	1.89	1.11	2.78	0.57	17.7	16.2	19.2	1.1	9.24	7.16	12.07	12.07
	6	19.3	1.24	1.03	1.43	0.15	1.01	0.88	1.14	0.10	76.7	68.6	88.7	6.5	1.81	1.35	2.35	0.37	19.9	15.5	22.8	2.5	12.74	10.04	16.47	16.47
	7	27.5	1.28	1.03	1.55	0.19	1.00	0.88	1.08	0.08	77.8	65.4	97.0	10.5	1.75	1.08	2.60	0.53	14.3	10.6	20.3	3.1	11.84	8.36	14.51	14.51
	8	5.6	1.10	0.87	1.39	0.21	1.04	0.92	1.19	0.09	86.3	79.2	95.0	5.7	2.10	1.69	2.45	0.31	19.5	16.6	22.4	2.2	12.87	10.30	14.95	14.95
Valle de Cerrato	1	11.1	1.30	1.03	1.51	0.18	0.98	0.83	1.12	0.10	95.7	88.3	107.1	7.1	1.62	1.29	2.17	0.33	31.2	28.1	36.3	3.3	12.62	8.89	16.32	16.32
	2	77.0	1.43	1.16	1.77	0.21	1.05	0.88	1.35	0.15	102.5	77.9	125.0	14.2	1.70	1.26	2.36	0.40	29.9	26.9	32.0	1.7	13.10	9.06	16.68	16.68
	3	54.4	1.28	1.01	1.45	0.14	0.99	0.84	1.19	0.13	95.6	71.9	117.1	13.2	1.73	1.29	2.38	0.41	17.7	15.9	19.8	1.4	11.74	9.47	14.85	14.85
	4	38.2	1.27	0.96	1.55	0.17	0.97	0.85	1.19	0.12	83.9	66.9	110.1	12.3	1.57	1.18	2.50	0.43	15.2	11.7	20.2	3.1	11.20	8.72	13.76	13.76
	5	64.7	1.27	1.09	1.45	0.13	1.00	0.84	1.23	0.13	79.5	61.0	92.5	10.7	1.51	1.18	2.07	0.31	18.9	12.0	22.3	3.1	12.14	9.18	15.06	15.06
	6	28.8	1.34	1.00	1.64	0.19	0.98	0.84	1.16	0.11	84.3	77.2	105.9	10.2	1.60	1.11	2.25	0.40	14.5	12.8	16.9	1.4	10.09	7.37	12.23	12.23
	7	33.6	1.32	1.09	1.61	0.19	1.04	0.87	1.17	0.11	100.3	83.6	119.7	11.0	1.73	1.26	2.20	0.31	21.3	17.2	25.9	3.0	12.69	9.67	15.73	15.73
	8	58.9	1.21	0.98	1.41	0.14	0.98	0.82	1.18	0.12	84.7	59.6	100.0	12.4	1.57	1.14	1.99	0.28	15.6	11.4	18.7	2.2	11.57	8.35	13.59	13.59
Dueñas	1	38.7	1.33	1.06	1.53	0.17	1.03	0.82	1.42	0.19	101.6	69.1	124.0	19.6	1.71	1.00	2.83	0.63	28.9	21.4	35.0	5.3	11.61	8.19	19.37	19.37
	2	16.2	1.21	0.93	1.43	0.20	0.94	0.76	1.09	0.12	109.4	85.6	141.7	16.6	1.57	1.03	2.43	0.45	22.1	17.5	26.7	3.2	11.17	8.26	13.77	13.77
	3	39.9	1.14	0.84	1.48	0.24	1.01	0.80	1.18	0.14	98.6	71.3	120.0	17.5	1.71	1.10	2.58	0.48	22.6	19.8	25.2	2.3	9.06	6.31	11.62	11.62
	4	27.4	1.20	1.03	1.38	0.13	0.95	0.81	1.07	0.09	105.1	72.8	132.7	16.8	1.51	1.13	2.07	0.37	14.6	13.3	16.4	1.3	10.32	8.98	11.74	11.74
	5	36.7	1.29	1.13	1.42	0.13	0.94	0.79	1.13	0.12	87.6	41.6	106.4	20.5	1.60	0.88	2.32	0.50	23.1	19.1	29.4	3.6	12.54	9.66	14.43	14.43
	6	21.3	1.04	0.86	1.27	0.17	0.90	0.81	1.08	0.11	97.1	75.3	111.8	12.4	1.21	0.96	1.88	0.32	18.1	13.0	23.3	3.5	9.64	7.67	11.96	11.96
	7	11.9	1.15	0.85	1.38	0.22	1.00	0.80	1.20	0.15	105.0	96.3	119.6	8.1	1.49	0.67	2.44	0.57	19.1	14.4	29.8	5.8	13.91	8.99	16.89	16.89
	8	33.8	1.19	0.88	1.42	0.22	0.95	0.76	1.25	0.15	99.3	66.5	125.6	18.2	1.55	0.87	2.34	0.46	15.6	12.1	18.0	2.3	12.46	8.35	15.60	15.60

LBA: local basal area (m^2 ha^{-1})

Supplementary material 10 Macronutrient concentration in *Pinus halepensis* decomposing needle litter into the litterbags

Site	Plot	LBA	Carbon (mg g^{-1})				Nitrogen (mg g^{-1})				Potassium (mg g^{-1})				Phosphorus (mg kg^{-1})				Calcium (mg g^{-1})			
			Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
Ampudia	1	12.1	504.9	462.2	529.2	19.5	7.93	6.89	9.76	1.11	463.5	303.9	570.5	101.2	203.6	150.4	261.1	40.2	11.91	9.29	14.49	1.83
	2	14.1	515.2	504.1	540.8	11.9	7.51	6.54	10.00	1.14	379.7	318.4	464.1	47.5	268.3	250.6	287.6	12.7	11.11	9.39	12.37	1.07
	3	21.6	514.1	502.2	532.4	9.1	7.73	6.68	9.20	0.97	390.7	302.0	444.1	47.1	216.0	190.9	236.3	14.8	11.60	10.44	13.12	1.08
	4	26.5	512.9	502.1	538.5	12.6	7.33	6.05	8.92	1.01	477.1	338.5	653.9	98.2	275.9	237.6	308.2	29.3	10.76	9.29	12.58	1.25
	5	28.3	510.4	497.1	537.4	13.3	8.12	6.72	9.58	1.06	418.3	345.2	517.2	57.7	244.1	205.4	333.3	46.0	11.48	10.34	12.92	0.95
	6	45.4	510.7	494.0	536.8	13.0	8.68	6.77	11.72	1.73	471.8	377.2	632.3	91.2	322.6	251.8	397.1	48.3	11.88	9.62	14.20	1.60
	7	47.7	514.1	505.2	520.3	5.5	7.92	6.78	9.38	0.90	476.9	395.0	568.0	56.4	278.7	251.5	316.3	26.7	10.46	8.37	12.17	1.43
	8	54.5	507.9	491.0	532.2	13.7	7.66	5.87	9.20	1.13	576.7	484.1	852.6	130.3	301.1	218.4	420.7	68.5	11.900	9.50	14.22	1.46
Valoria la Buena	1	5.6	510.0	498.9	528.8	10.7	7.77	6.53	9.66	1.07	385.1	233.4	469.4	87.3	299.2	246.5	337.0	33.5	11.33	9.06	13.65	1.84
	2	11.7	510.6	494.6	532.2	11.6	7.59	6.71	9.34	0.99	318.3	231.4	384.2	65.0	231.0	196.3	261.3	21.6	12.26	9.56	14.46	1.97
	3	19.3	514.9	502.8	538.1	12.3	7.77	6.54	9.60	1.12	433.2	290.6	527.0	69.4	305.3	240.3	345.5	32.3	11.24	9.45	14.37	1.75
	4	27.5	509.0	477.9	540.4	19.5	8.17	6.43	10.86	1.55	483.1	365.1	579.0	76.8	345.2	278.3	402.7	45.6	11.49	9.30	13.22	1.32
	5	32.7	502.4	471.9	522.3	15.0	9.19	6.34	12.96	2.26	728.1	415.6	1056.2	204.7	347.9	223.4	525.0	112.0	11.69	8.87	14.52	2.07
	6	39.7	505.8	481.7	520.6	13.0	7.86	6.29	11.02	1.54	499.0	352.2	653.8	103.5	269.3	213.2	325.4	42.4	11.77	9.29	14.28	1.86
	7	46.4	506.2	473.0	523.6	16.0	9.46	6.96	12.69	2.13	869.2	568.1	1094.1	198.3	435.4	310.0	592.8	99.6	11.34	9.24	13.68	1.78
	8	60.4	509.5	497.2	531.7	11.2	9.85	7.64	14.28	2.24	740.1	558.7	886.2	107.0	425.7	332.2	562.9	80.3	11.99	10.02	14.38	1.78
Valle de Cerrato	1	11.1	516.5	508.9	528.7	6.4	7.84	6.27	10.13	1.53	441.4	274.1	571.9	92.6	263.0	237.7	278.6	15.6	12.27	7.59	15.62	2.71
	2	28.8	513.3	503.4	528.8	7.5	7.53	6.44	8.93	1.00	490.6	414.8	587.2	60.8	304.4	265.5	327.8	25.0	10.73	8.68	12.89	1.50
	3	33.6	500.4	468.9	512.1	13.9	7.37	6.13	9.13	0.95	482.8	393.5	567.7	52.6	308.8	285.6	348.3	23.6	11.70	9.60	14.32	1.57
	4	38.2	512.0	500.5	529.4	8.5	7.25	6.05	9.31	1.26	454.1	402.7	521.9	40.8	236.6	179.7	291.1	34.1	11.47	9.34	13.61	1.61
	5	54.4	502.0	488.7	522.9	10.0	7.04	5.56	8.76	1.40	489.5	401.0	618.8	71.8	265.7	202.3	330.0	45.6	11.94	9.80	14.26	1.76
	6	58.9	513.9	507.8	531.7	8.2	8.28	6.69	9.80	1.22	630.2	422.0	888.0	159.5	366.4	270.6	429.0	60.4	11.49	8.99	13.68	1.65
	7	64.7	501.7	471.3	519.0	13.9	8.03	6.36	9.96	1.50	533.8	411.8	812.6	130.5	281.7	200.3	330.6	49.8	10.95	9.43	12.12	1.03
	8	77.0	514.5	496.8	533.8	12.2	8.65	6.30	11.12	1.91	559.1	475.1	617.9	46.2	297.0	257.9	387.6	44.1	11.28	9.28	12.86	1.40
Dueñas	1	11.9	510.5	497.9	534.4	12.8	8.26	6.27	10.41	1.61	354.9	255.1	478.4	87.2	270.8	221.0	307.8	30.7	11.81	8.86	14.39	1.91
	2	16.2	509.4	492.4	524.3	12.3	8.52	6.92	11.01	1.58	435.1	285.4	678.5	120.7	250.0	188.2	329.0	47.6	12.23	9.09	15.16	2.05
	3	21.3	517.0	503.4	538.8	12.2	8.33	6.66	10.46	1.42	416.0	291.0	537.9	82.0	290.2	220.5	332.0	40.4	10.91	8.55	12.30	1.32
	4	27.4	513.3	498.4	531.0	10.8	7.55	6.08	9.09	1.07	480.0	407.6	546.0	51.0	266.1	199.1	332.0	41.0	11.41	9.42	13.82	1.26
	5	33.8	510.8	498.5	533.6	13.3	8.70	7.24	10.88	1.44	530.9	388.0	656.4	93.3	336.3	235.5	435.5	69.6	11.31	9.11	13.55	1.65
	6	36.7	513.0	493.8	531.1	12.9	8.23	6.16	10.35	1.54	498.8	402.4	622.7	78.8	322.9	269.5	409.3	50.2	10.67	8.42	12.47	1.50
	7	38.7	499.3	484.2	525.9	15.7	7.72	6.59	8.97	0.99	474.7	384.5	595.1	80.8	282.0	253.9	326.1	25.6	11.70	9.37	13.76	1.53
	8	39.9	509.6	494.9	523.4	10.0	7.77	5.95	9.52	1.32	510.5	353.2	677.1	98.1	294.8	220.7	364.3	54.1	11.80	9.79	13.59	1.24

LBA: local basal area (m^2 ha^{-1})

Supplementary material 11 Micronutrient concentration in *Pinus halepensis* decomposing needle litter into the litterbags

Site	Plot	LBA	Magnesium (mg kg^{-1})				Sulphur (mg kg^{-1})				Iron (mg kg^{-1})				Copper (mg kg^{-1})				Manganese (mg kg^{-1})				Zinc (mg kg^{-1})			
			Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
Ampudia	1	12.1	634.4	435.7	824.7	134.6	0.722	0.568	0.977	0.165	600.7	269.7	955.1	259.4	1.56	0.92	2.26	0.51	86.0	61.3	111.5	16.7	8.87	7.70	10.23	1.04
	2	14.1	676.6	565.7	783.5	82.4	0.730	0.590	1.050	0.173	208.7	144.4	293.1	54.4	1.30	0.98	1.60	0.22	58.8	49.9	61.5	3.8	9.60	8.52	11.17	0.90
	3	21.6	704.1	483.9	893.5	144.1	0.751	0.607	1.053	0.176	285.3	150.8	473.8	98.6	1.62	0.80	2.12	0.40	64.7	55.5	87.1	9.6	9.05	7.99	10.32	0.88
	4	26.5	740.8	596.5	961.6	135.9	0.756	0.614	1.073	0.189	208.1	112.7	327.8	80.7	1.48	0.94	1.88	0.35	53.4	43.0	61.4	6.9	10.59	9.47	11.91	0.95
	5	28.3	727.6	576.8	818.7	82.5	0.760	0.573	1.080	0.194	211.1	131.1	324.2	64.1	1.50	0.83	2.02	0.45	67.8	57.3	76.8	5.7	10.2	6.85	13.65	2.38
	6	45.4	699.3	570.5	1008.7	154.6	0.787	0.621	1.141	0.208	221.1	124.6	316.9	67.9	1.61	1.27	2.16	0.29	54.8	41.9	71.5	9.9	9.80	8.59	11.17	0.86
	7	47.7	557.2	416.3	692.7	103.3	0.751	0.591	1.046	0.186	359.8	197.5	567.7	115.3	1.65	1.29	2.28	0.36	54.2	42.6	70.0	9.4	9.69	8.34	11.10	0.89
	8	54.5	798.8	617.9	907.7	115.1	0.857	0.643	1.179	0.198	232.4	164.3	325.9	59.5	1.84	1.16	2.33	0.42	58.6	48.2	66.3	5.9	11.11	9.74	14.77	1.66
Valoria la Buena	1	5.6	576.6	370.4	792.0	134.5	0.749	0.539	1.293	0.263	271.8	166.4	468.3	116.8	1.74	1.34	2.23	0.37	55.4	44.5	63.9	6.8	10.26	7.43	12.30	1.46
	2	11.7	616.9	419.3	850.1	161.1	0.761	0.582	1.100	0.201	250.1	135.7	385.7	88.6	1.76	1.25	2.36	0.35	56.7	51.1	61.1	3.1	11.09	9.83	13.83	1.23
	3	19.3	588.1	449.7	724.4	96.3	0.775	0.568	1.172	0.224	247.9	132.0	417.0	104.3	1.91	1.45	2.45	0.31	43.3	36.3	46.9	3.5	11.39	7.74	13.70	1.93
	4	27.5	665.7	546.0	789.6	97.3	0.779	0.562	1.142	0.218	234.0	119.1	346.8	80.2	1.94	1.48	2.40	0.36	60.7	51.1	69.8	5.4	11.49	9.39	14.24	1.69
	5	32.7	792.9	723.5	866.7	52.4	0.913	0.656	1.472	0.334	249.9	125.5	388.2	94.7	2.46	1.58	3.41	0.68	56.1	49.2	61.7	4.5	12.02	9.11	17.26	3.06
	6	39.7	764.0	576.9	911.1	113.3	0.790	0.595	1.170	0.223	286.9	156.0	488.6	132	1.98	1.53	2.52	0.39	58.2	49.9	61.6	3.9	9.94	8.23	13.10	1.67
	7	46.4	798.7	693.5	899.1	73.5	0.894	0.646	1.362	0.273	229.1	150.4	336.0	71.2	2.47	1.70	3.42	0.64	50.3	40.7	60.6	6.7	13.60	9.49	20.75	3.81
	8	60.4	703.6	563.6	818.6	91.2	0.911	0.661	1.402	0.291	193.9	110.7	316.6	73.1	2.11	1.20	2.78	0.54	54.8	36.9	80.1	13.5	12.40	9.51	17.19	2.82
Valle de Cerrato	1	11.1	614.3	460.8	876.9	159.7	0.745	0.589	1.020	0.172	385.0	138.3	685.0	192.9	1.64	1.09	2.20	0.42	60.1	51.1	70.2	7.1	10.77	9.03	12.60	1.17
	2	28.8	562.5	456.7	674.9	85.8	0.788	0.585	1.144	0.205	198.5	116.0	267.8	56.8	1.91	1.14	3.12	0.62	36.9	32.2	43.2	4.0	10.47	7.91	12.99	1.37
	3	33.6	609.2	484.2	735.9	103.3	0.833	0.617	1.231	0.240	210.4	127.3	291.0	60.0	1.75	1.04	2.21	0.40	49.9	39.1	59.9	6.4	11.13	8.96	12.89	1.29
	4	38.2	720.0	625.1	794.7	63.1	0.781	0.600	1.113	0.194	221.1	140.5	303.2	58.7	1.63	1.17	1.99	0.30	51.6	46.2	57.6	4.1	9.72	7.63	12.27	1.50
	5	54.4	774.3	672.8	927.5	85.0	0.789	0.597	1.123	0.200	225.7	137.0	341.5	69.6	1.79	1.27	2.43	0.40	57.3	49.7	67.9	5.5	10.66	7.83	14.31	1.97
	6	58.9	703.6	618.7	773.5	64.6	0.854	0.612	1.197	0.223	198.9	114.2	280.8	55.8	2.06	1.42	2.59	0.43	55.1	46.9	63.1	5.4	11.55	8.98	13.74	1.64
	7	64.7	641.9	505.4	785.1	106.3	0.804	0.569	1.145	0.216	208.6	136.8	283.8	49.7	1.75	1.12	2.14	0.35	46.1	35.1	55.8	6.9	9.85	6.07	12.22	1.97
	8	77.0	663.3	514.7	778.0	105.1	0.810	0.595	1.193	0.233	205.8	117.8	283.8	69.8	1.74	1.27	2.36	0.40	52.6	44.7	61.6	6.2	10.58	8.62	12.79	1.51
Dueñas	1	11.9	612.4	430.8	808.0	121.8	0.742	0.564	1.063	0.190	227.6	104.2	337.2	87.8	1.70	0.93	2.37	0.45	55.4	48.7	62.1	4.5	10.26	7.44	13.32	1.90
	2	16.2	690.3	456.9	853.3	145.3	0.762	0.577	1.101	0.187	243.8	118.1	423.1	103.6	1.60	0.86	2.33	0.49	55.5	49.0	60.7	4.7	9.62	8.09	11.52	1.27
	3	21.3	551.0	378.2	722.5	128.4	0.729	0.556	1.044	0.176	189.8	95.3	303.1	64.7	1.62	0.88	2.21	0.50	40.1	33.3	48.2	5.8	9.59	6.94	11.93	1.59
	4	27.4	771.3	676.0	855.3	60.9	0.764	0.580	1.149	0.203	220.4	115.4	329.8	74.3	1.69	0.98	2.42	0.48	55.7	49.1	63.2	5.1	9.85	7.48	11.90	1.50
	5	33.8	682.9	557.2	788.2	84.1	0.805	0.578	1.198	0.220	189.6	101.1	322.4	72.7	1.70	1.24	2.72	0.54	50.9	37.8	59.4	8.3	10.49	7.02	12.55	1.69
	6	36.7	661.7	550.6	745.5	68.3	0.764	0.565	1.081	0.192	202.2	100.9	300.5	71.1	1.54	0.98	2.12	0.42	41.4	38.3	45.7	2.5	10.69	8.62	14.01	1.82
	7	38.7	672.5	550.0	794.1	85.8	0.791	0.603	1.140	0.205	211.8	121.4	352.5	75.6	1.59	0.98	2.11	0.39	54.7	43.7	60.2	5.5	10.51	7.93	13.50	2.18
	8	39.9	722.4	579.9	932.6	116.9	0.796	0.589	1.124	0.200	242.2	128.8	399.8	86.5	1.77	1.13	2.29	0.47	54.8	48.3	65.5	5.1	10.07	8.12	12.42	1.82

LBA: local basal area (m^2 ha^{-1})

Supplementary material 12 Macronutrient concentration in *Pinus sylvestris* decomposing needle litter into the litterbags

Site	Plot	LBA	Carbon ($mg\ g^{-1}$)				Nitrogen ($mg\ g^{-1}$)				Potassium ($mg\ kg^{-1}$)				Phosphorus ($mg\ kg^{-1}$)				Calcium ($mg\ g^{-1}$)			
			Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
Pino del Río	1	28.5	507.7	502.9	512.1	3.9	6.73	6.03	8.04	0.85	518.9	354.8	765.1	174.4	257.7	208.0	320.2	43.9	7.87	7.25	9.27	0.76
	2	50.4	507.2	501.0	510.2	3.7	6.66	4.89	8.44	1.37	636.9	390.0	1287.0	348.8	289.7	221.0	398.4	70.6	7.71	6.55	8.98	0.83
	3	40.7	507.8	500.0	514.4	5.4	7.60	5.80	11.27	1.97	755.5	469.7	1207.6	292.1	368.7	253.6	541.0	100.4	8.13	7.04	9.74	0.94
	4	22.4	507.3	498.8	510.7	4.5	6.87	5.99	7.98	0.79	606.1	360.3	943.7	217.0	314.3	245.1	416.8	60.8	8.09	6.92	9.51	0.87
	5	36.5	510.1	505.3	513.7	3.2	6.14	4.68	8.71	1.43	579.0	275.7	854.0	228.3	276.1	210.8	357.2	51.3	8.07	6.70	9.40	0.91
	6	10.2	511.4	507.8	517.0	3.1	6.23	4.94	8.46	1.36	492.9	263.6	708.3	182.0	274.4	220.0	327.7	51.0	7.99	7.00	9.73	0.99
	7	17.7	509.4	506.4	512.8	2.1	6.40	4.95	9.03	1.56	554.2	303.3	914.9	248.6	283.5	210.4	351.0	55.2	8.04	6.56	10.23	1.26
	8	45.2	508.2	502.9	511.5	3.4	7.34	5.64	11.09	2.06	739.4	399.2	1233.1	319.3	343.5	214.7	458.1	100.0	8.03	6.26	9.26	1.06
Saldaña	1	11.3	505.3	497.2	511.1	5.2	5.93	5.08	7.09	0.75	548.4	314.8	785.6	196.4	238.4	182.6	284.8	44.8	8.31	7.11	10.02	1.14
	2	35.3	504.7	502.0	507.6	2.2	5.23	4.11	7.27	1.16	487.9	323.3	768.2	197.4	223.3	182.3	272.5	33.6	7.95	6.34	9.51	1.20
	3	28.2	506.8	495.4	512.8	7.2	6.46	5.06	9.10	1.53	657.4	357.6	1113.5	287.3	273.9	227.3	342.8	44.3	8.24	7.10	9.57	0.91
	4	44.0	507.1	504.1	511.5	2.7	6.18	4.61	8.75	1.61	549.3	372.8	881.7	205.5	241.6	195.3	302.8	38.8	7.96	6.78	9.42	0.95
	5	41.7	512.0	499.4	517.6	6.6	6.97	4.85	10.48	1.94	690.2	464.5	1137.2	277.5	285.9	219.1	409.2	65.1	8.33	6.98	9.51	0.93
	6	6.9	504.1	500.6	508.5	2.8	6.60	4.65	9.35	1.97	604.2	281.2	1048.6	343.8	292.0	208.0	393.4	69.7	8.35	6.99	9.61	0.88
	7	25.0	504.8	502.5	509.5	2.7	5.94	4.76	7.66	1.26	866.1	486.5	2318.9	717.6	263.2	234.8	372.0	53.5	7.74	6.89	8.41	0.69
	8	17.8	506.2	499.5	512.2	4.9	6.42	4.50	9.55	1.76	588.6	405.8	1153.5	300.5	280.6	199.2	407.2	72.0	7.88	6.94	9.28	0.89
Santibáñez de la Peña	1	8.2	508.4	504.1	516.1	4.1	5.71	4.90	7.30	0.94	409.6	223.1	534.1	126.0	235.5	204.9	279.7	25.2	9.16	6.85	11.40	1.76
	2	28.3	513.6	503.3	526.2	7.6	6.34	4.77	7.78	1.07	646.8	445.7	1099.6	241.9	310.0	246.0	369.6	41.5	9.13	7.20	10.83	1.54
	3	42.8	513.7	507.9	524.7	6.3	6.67	5.69	8.16	1.09	608.9	470.2	1016.1	218.5	293.3	233.4	355.6	50.7	9.00	7.09	10.62	1.58
	4	23.9	516.3	511.3	525.3	4.8	5.97	4.52	7.75	1.18	561.5	399.6	754.9	141.3	274.9	219.7	315.2	35.5	9.32	7.22	11.72	1.90
	5	19.6	507.6	494.3	516.9	7.8	5.78	4.78	8.61	1.45	469.7	287.4	689.1	176.5	261.3	229.7	302.3	25.4	8.97	7.56	10.27	1.21
	6	34.9	512.8	504.8	520.2	5.2	5.97	4.69	7.37	0.99	643.3	423.3	1087.6	261.0	290.7	203.3	364.0	57.9	8.67	6.99	10.25	1.39
	7	39.1	514.5	509.1	525.5	6.1	6.58	5.47	8.96	1.36	699.7	460.8	1070.4	250.3	323.6	274.9	385.5	46.3	9.46	7.64	11.62	1.67
	8	13.5	513.6	508.0	523.9	6.0	5.60	4.51	7.09	0.87	424.5	292.9	612.8	119.4	227.5	192.9	248.7	22.1	8.82	6.82	10.52	1.43
Mantinos	1	8.9	510.8	506.0	516.9	3.7	5.90	5.11	7.35	0.89	555.8	371.6	781.7	177.4	268.1	225.7	305.2	29.4	8.12	7.22	9.29	0.82
	2	35.9	511.0	504.4	518.7	4.7	5.91	4.84	8.40	1.27	511.3	377.6	894.6	192.5	241.1	202.6	301.6	38.2	8.14	7.35	9.09	0.67
	3	52.0	509.4	505.7	515.1	3.8	6.76	5.36	8.67	1.31	711.5	521.3	1029.2	220.4	320.3	270.1	374.2	40.9	8.24	6.87	9.45	0.95
	4	23.8	511.2	506.1	517.2	4.1	6.75	5.16	8.75	1.23	659.2	561.3	867.9	140.8	302.2	242.1	348.1	36.0	8.11	6.84	9.25	0.98
	5	18.3	508.4	502.2	515.2	4.6	5.80	4.75	7.61	1.12	535.5	335.9	890.8	247.1	250.5	201.5	318.5	50.3	8.29	6.85	9.60	1.08
	6	40.3	511.3	504.2	515.2	4.2	6.31	5.28	9.06	1.39	575.6	384.6	884.1	208.3	281.7	207.5	353.4	53.0	8.18	6.79	9.44	1.08
	7	29.3	512.1	502.7	521.2	6.1	6.17	5.31	6.99	0.66	632.7	463.7	904.6	201.8	271.5	218.6	315.2	34.5	8.17	7.24	9.22	0.68
	8	45.7	511.9	502.4	520.5	6.4	6.17	4.97	7.43	0.99	564.0	449.1	775.9	135.0	258.3	226.9	291.0	22.2	8.24	7.36	9.44	0.74

LBA: local basal area ($m^2\ ha^{-1}$)

Supplementary material 13 Micronutrient concentration in *Pinus sylvestris* decomposing needle litter into the litterbags

Site	Plot	LBA	Magnesium (mg kg^{-1})				Sulphur (mg kg^{-1})				Iron (mg kg^{-1})				Copper (mg kg^{-1})				Manganese (mg g^{-1})				Zinc (mg kg^{-1})			
			Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
Pino del Río	1	28.5	672.9	497.2	814.3	119.2	596.7	417.4	842.1	186.7	146.6	104.9	202.7	38.7	1.34	0.52	2.26	0.67	2.02	1.77	2.18	0.14	30.7	28.9	32.9	1.7
	2	50.4	676.9	450.9	808.7	138.4	618.2	415.9	970.1	222.1	157.5	86.7	226.6	51.5	1.38	0.66	2.25	0.66	2.06	1.93	2.22	0.11	30.6	26.4	34.1	2.7
	3	40.7	712.7	602.0	796.0	80.7	679.3	426.2	964.5	231.7	175.1	109.3	285.9	68.7	1.72	1.08	2.62	0.59	1.98	1.76	2.23	0.16	33.0	28.8	38.6	3.5
	4	22.4	684.4	479.9	817.8	132.2	632.8	436.1	916.8	187.8	192.1	127.8	247.4	45.8	1.67	0.71	2.52	0.72	2.15	1.83	2.52	0.25	33.8	27.9	38.8	3.8
	5	36.5	656.3	422.8	787.1	139.0	593.6	402.9	821.7	185.3	191.1	104.5	313.5	81.8	1.43	0.83	2.86	0.78	1.96	1.72	2.22	0.20	31.2	27.9	36.0	2.6
	6	10.2	687.9	567.7	782.4	77.4	593.3	415.6	856.3	194.4	171.4	105.9	246.9	61.4	1.62	0.55	3.40	1.13	2.03	1.77	2.37	0.22	32.4	28.2	38.4	3.6
	7	17.7	681.9	552.9	754.5	81.0	613.8	398.1	889.6	207.7	183.6	105.7	299.7	76.9	1.61	0.85	2.96	0.84	2.13	1.84	2.43	0.21	32.3	27.6	38.5	3.9
	8	45.2	678.8	480.7	845.9	153.4	696.6	382.1	988.4	222.2	158.4	101.9	220.1	50.5	2.21	0.75	4.56	1.30	2.16	1.94	2.49	0.19	33.2	26.7	39.8	4.2
Saldaña	1	11.3	692.0	637.8	750.1	40.5	590.1	426.0	784.5	165.5	190.0	113.3	278.2	66.9	1.10	0.63	1.75	0.41	2.15	2.04	2.28	0.09	32.7	29.1	39.6	4.1
	2	35.3	701.9	509.3	837.0	111.6	566.9	374.0	770.6	163.3	155.5	102.2	235.6	56.0	1.00	0.59	1.70	0.43	2.08	1.90	2.32	0.18	32.5	27.6	38.0	3.7
	3	28.2	696.6	536.5	795.2	114.5	625.9	430.4	807.8	161.2	172.0	90.1	264.5	66.7	1.63	1.12	2.34	0.49	2.09	1.89	2.27	0.13	33.1	30.5	37.6	2.5
	4	44.0	636.0	433.3	795.9	139.9	608.7	394.5	836.0	188.9	141.5	96.6	194.3	37.4	1.21	0.72	1.81	0.45	1.91	1.61	2.15	0.19	31.8	28.7	36.3	3.0
	5	41.7	625.9	313.4	789.6	168.4	631.6	418.5	879.0	185.2	147.2	94.1	240.7	56.5	1.41	0.75	3.10	0.86	2.01	1.80	2.23	0.18	31.8	28.9	37.2	3.0
	6	6.9	661.8	403.9	798.1	152.5	624.5	412.6	904.8	206.3	239.1	118.4	470.5	144.2	1.76	0.80	3.08	0.92	2.12	1.88	2.40	0.17	33.1	29.6	41.0	4.3
	7	25.0	711.0	503.7	838.3	120.3	593.7	409.7	825.4	164.8	170.7	125.1	249.0	48.9	1.02	0.57	1.52	0.36	2.07	1.85	2.49	0.24	31.5	28.5	41.7	5.1
	8	17.8	661.9	470.5	799.7	118.4	624.7	412.5	839.5	168.5	201.6	109.6	389.3	103.9	1.30	0.45	2.49	0.76	2.05	1.80	2.17	0.13	32.0	28.6	37.1	3.3
Santibáñez de la Peña	1	8.2	592.5	463.0	794.1	138.0	565.7	431.4	748.8	130.8	200.6	132.5	281.3	57.8	1.36	1.01	1.97	0.40	1.86	1.62	2.20	0.20	32.5	25.4	41.6	5.7
	2	28.3	576.5	388.3	705.1	112.8	634.6	441.9	868.5	172.8	167.0	101.4	246.2	50.9	1.71	0.96	2.80	0.70	1.88	1.73	2.03	0.13	31.3	26.8	35.2	2.9
	3	42.8	583.8	438.9	659.7	100.5	632.1	429.0	906.7	200.5	146.6	87.6	221.2	49.7	1.28	0.62	1.97	0.48	1.69	1.43	1.88	0.16	30.4	25.6	35.2	3.4
	4	23.9	595.4	466.1	765.0	116.4	601.1	420.9	807.0	168.9	172.6	95.1	248.3	65.2	1.05	0.67	1.47	0.31	1.68	1.46	2.01	0.19	29.4	25.8	33.2	2.9
	5	19.6	555.9	362.9	725.3	147.6	608.1	430.7	843.1	175.6	236.6	101.7	526.1	154.5	1.47	0.59	2.76	0.81	1.70	1.37	2.07	0.25	29.9	27.3	32.7	2.0
	6	34.9	634.6	514.6	772.7	93.8	596.4	396.3	785.8	166.4	164.9	113.8	207.9	42.8	1.23	0.46	1.77	0.49	1.80	1.59	2.12	0.18	30.1	27.4	32.9	2.0
	7	39.1	572.9	450.8	701.4	91.0	660.0	451.1	920.0	213.4	180.3	119.1	260.0	57.4	1.60	0.87	2.68	0.76	1.75	1.57	1.96	0.16	32.0	29.0	37.3	3.1
	8	13.5	562.7	432.2	663.3	92.6	569.2	397.8	763.6	154.2	158.0	98.4	219.3	48.8	1.10	0.75	1.44	0.26	1.70	1.45	1.84	0.15	29.3	26.4	32.5	2.6
Mantinos	1	8.9	572.5	454.8	743.2	96.3	611.6	428.1	862.5	192.5	173.2	120.4	249.9	56.8	1.22	0.74	1.75	0.41	1.78	1.65	2.13	0.18	30.7	27.6	34.9	2.7
	2	35.9	498.1	324.7	707.7	131.5	607.0	418.6	852.8	188.5	157.0	104.4	229.1	49.1	1.08	0.65	1.79	0.39	1.48	0.87	2.08	0.42	28.8	26.5	30.6	1.6
	3	52.0	557.5	339.3	709.4	157.5	687.8	437.9	1006.9	248.6	181.3	114.7	266.1	53.8	1.86	1.05	2.28	0.52	1.86	1.66	2.12	0.17	31.5	27.9	34.5	2.3
	4	23.8	567.8	406.4	700.6	112.3	667.5	431.7	927.1	215.3	183.9	119.9	252.1	57.0	1.67	1.11	2.36	0.50	1.69	1.42	2.00	0.21	30.9	27.6	34.0	2.4
	5	18.3	587.8	505.2	693.1	81.7	626.3	417.8	902.7	216.6	177.2	101.4	274.9	62.4	1.29	0.72	2.17	0.57	1.82	1.63	1.94	0.14	31.9	27.3	36.8	3.9
	6	40.3	609.5	486.0	728.6	94.0	659.3	393.6	1011.4	244.4	180.8	105.4	265.2	62.0	1.39	0.61	2.33	0.59	1.73	1.40	1.97	0.20	31.3	26.2	35.8	3.4
	7	29.3	545.7	326.0	715.0	143.4	633.1	427.4	843.4	176.2	149.5	102.4	207.2	42.0	1.30	0.81	1.86	0.39	1.62	1.12	2.03	0.32	31.5	28.9	34.5	2.0
	8	45.7	531.5	369.0	673.6	110.4	651.2	430.2	905.2	202.8	154.4	94.1	210.8	44.5	1.28	0.68	1.68	0.36	1.58	1.16	1.92	0.30	30.6	26.5	32.3	2.3

LBA: local basal area (m^2 ha^{-1})

Statistical appendix

Factors determining enzyme activities in soils under *Pinus sylvestris* and *Pinus halepensis* plantations [Developed in R; TeamR (2015)]

```
enzymes<-read.csv2(file="E:/enzymes.csv".header=T)
halep<-enzymes[c(1:32).]
sylv<-enzymes[c(33:67).]
#Summary of the variables studied. Example: FDA#
with(sylv. summary (FDA))
#Normality of the variables studied. Example: FDA#
with(enzymes.shapiro.test(FDA)$p.value)
#Boxplot of the variables studied. Example: FDA#
with(enzymes.boxplot(FDA))
#Wilcoxon-Mann-Whitney test. Example: FDA#
wilcox.test(sylv$FDA.halep$FDA.paired=F)
#Spearman’s test. Example: correlation between FDA and EOC in soils
under Pinus halepensis#
with(halep.cor.test(FDA.EOC.method="spearman"))
```

Effect of local basal area on needle litterfall and correlation between the local basal area and the soil temperature and humidity [Developed in SAS (2013)]

```
/*Example for Pinus halepensis*/
PROC IMPORT OUT= WORK.datos
            DATAFILE= "D:\desf\desfrondeHAL.xlsx"
            DBMS=EXCEL REPLACE;
     RANGE="Hoja1$";
     GETNAMES=YES;
     MIXED=NO;
     SCANTEXT=YES;
     USEDATE=YES;
     SCANTIME=YES;
RUN;
data datos;
set datos;
lnkg=log(kgha1);
run;
options pagesize=max;
ods pdf file="d:\desf\desfrondeH.pdf";
ods graphics on;
proc mixed data=datos method=reml convh=1E-32 convf=1E-8 convg=1E-6
maxiter=1000;
      class parcela sitio mes;
      model lnkg=AB mes /outpm=datos1 outp=datos2 residual;
      random sitio;
      repeated mes/ subject=parcela type=AR(1);
      estimate 'intercept' intercept 12 mes 1 1 1 1 1 1 1 1 1 1 1
1/divisor=12 cl;
      estimate 'pendiente' AB 1/cl;
      lsmeans mes/pdiff cl AT means;
run;
```

```
proc univariate data=datos2 normal;
var studentresid;
run;
proc reg data=datos2;
model lnkg=pred;
test pred=1 ;
run;
proc corr data=datos;
var AB Temp Hdad;
run;
proc sort data=datos;
by sitio;
run;
proc corr data=datos;
var AB Temp Hdad;
by sitio;
run;
ods graphics off;
ods pdf close;
QUIT;
```

Effect of local basal area on needle litter decomposition rate (k) and half-life ($t_{0.5}$) [Developed in SAS (2013)]

```
/*Example for Pinus halepensis*/
PROC IMPORT OUT= WORK.datos
            DATAFILE= "D:\halep\kbolsitasHALEP.xlsx"
            DBMS=EXCEL REPLACE;
     RANGE="Valores k y t";
     GETNAMES=YES;
     MIXED=NO;
     SCANTEXT=YES;
     USEDATE=YES;
     SCANTIME=YES;
RUN;
options pagesize=max;
ods pdf file="d:\halep\kbolsitasHALEP.pdf";
ods graphics on;
proc mixed data=datos method=reml convh=1E-32 convf=1E-8 convg=1E-6
maxiter=1000;
      class sitio;
      model k=AB/outpm=datos1 residual;
      random sitio;
      estimate 'intercept' intercept 1/cl;
      estimate 'pendiente' AB 1/cl;
run;
proc univariate data=datos1 normal;
var studentresid;
run;
proc reg data=datos1;
model k=pred;
test pred=1;
run;
proc mixed data=datos method=reml convh=1E-32 convf=1E-8 convg=1E-6
maxiter=1000;
      class sitio;
      model t50=AB/outpm=datos2 residual;
```

```
      random sitio;
      estimate 'intercept' intercept 1/cl;
      estimate 'pendiente' AB 1/cl;
run;
proc univariate data=datos2 normal;
var studentresid;
run;
proc reg data=datos2;
model t50=pred;
test pred=1;
run;
ods graphics off;
ods pdf close;
quit;
```

Effect of local basal area on nutrient concentration in litterfall [Developed in SAS (2013)]

```
/*Example for Ca concentration in Pinus halepensis needle litterfall*/
PROC IMPORT OUT= WORK.datos
            DATAFILE= "E:\halepensis\NutrDesfrondeHAL.xlsx"
            DBMS=EXCEL REPLACE;
     RANGE="Hoja1$";
     GETNAMES=YES;
     MIXED=NO;
     SCANTEXT=YES;
     USEDATE=YES;
     SCANTIME=YES;
RUN;
data datos;
set datos;
lnCa=log(Ca);
run;
ods pdf file="E:\halepensis\CadesfrondeHAL.pdf";
ods graphics on;
proc sort data=datos;
by parcela trimestre;
run;
proc mixed data=datos method=reml convh=1E-32 convf=1E-8 convg=1E-6
maxiter=1000;
      class parcela sitio trimestre;
      model lnCa=AB trimestre /outpm=datos3 outp=datos4 residual;
      random sitio;
      repeated trimestre/ subject=parcela type=AR(1);
      estimate 'pendiente' AB 1/cl;
      lsmeans trimestre/pdiff cl AT means;
run;
proc univariate data=datos4 normal;
var studentresid;
run;
proc reg data=datos4;
model lnCa=pred;
test pred=1 ;
run;
ods graphics off;
ods pdf close;
```

```
QUIT;
```

Effect of local basal area on nutrient release from decomposing needle litter [Developed in SAS (2013)]

```
/*Example for Ca release from Pinus halepensis decomposing needle
litter*/
PROC IMPORT OUT= WORK.datos
            DATAFILE= "E:\halepensis\NutrLiberadosBolsitas.xlsx"
            DBMS=EXCEL REPLACE;
     RANGE="Hoja1$";
     GETNAMES=YES;
     MIXED=NO;
     SCANTEXT=YES;
     USEDATE=YES;
     SCANTIME=YES;
RUN;
data datos;
set datos;
options pagesize=max;
ods pdf file="E:\halepensis\CaLiberadoBolsitas.pdf";
ods graphics on;
proc sort data=datos;
by parcela trimestre;
run;
proc mixed data=datos method=reml convh=1E-32 convf=1E-8 convg=1E-6
maxiter=1000;
      class parcela sitio trimestre;
      model CaR=AB trimestre /outpm=datos1 outp=datos2 residual;
      random sitio;
      repeated trimestre/ subject=parcela type=AR(1);
      estimate 'pendiente' AB 1/cl;
      lsmeans trimestre/pdiff cl AT means;
run;
proc univariate data=datos2 normal;
var studentresid;
run;
proc reg data=datos2;
model CaR=pred;
test pred=1 ;
run;
ods graphics off;
ods pdf close;
QUIT;
```