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Master Forest Management based on Data Science (DATAFOREST)

Small-scale early effects of thinning on the topsoil in Scots Pine-Pyrenean Oak mixed stands approached through new computational tools.

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Resumen

Los bosques mixtos de pino y roble han emergido como un componente significativo del paisaje forestal en España. A pesar de su amplia distribución y valor ecológico y socioeconómico, no existe un enfoque silvicultural específico para estos ecosistemas. Este estudio investiga los efectos de las cortas y la mezcla de especies en las propiedades del suelo superficial en estos bosques mixtos de pino silvestre (*Pinus sylvestris* L.) y roble melojo (*Quercus pyrenaica* Willd.) en el noroeste de España a corto plazo y a pequeña escala.

Para ello, se estableció un diseño experimental con tres tipos de tratamientos: control sin corta, corta moderada (25% del área basimétrica) y corta intensa (50% del área basimétrica). La toma de datos se realizó en 36 parcelas de 10x10 m, divididas en tres áreas rectangulares de 50x40 m, correspondientes a cada tratamiento. Se analizaron muestras de los primeros 5 cm de suelo un año después de los tratamientos para evaluar sus propiedades físicas y químicas, recogiendo datos de densidad aparente, porosidad, agua disponible, pH, conductividad eléctrica, carbono fácilmente oxidable, fósforo disponible, capacidad de intercambio catiónico, carbono orgánico total, nitrógeno total y cationes intercambiables.

Para el análisis de los datos, se utilizaron se utilizaron análisis de la varianza de una vía, tal como se hace habitualmente, junto con nuevas herramientas computacionales que utilizan modelos mixtos para identificar y cuantificarlos efectos del aclareo e investigar su interacción con el nivel de mezcla de especies arbóreas. Estas nuevas técnicas permitieron examinar las complejas relaciones entre las características del bosque y las variables edáficas.

Este estudio contribuye al desarrollo de estrategias de gestión forestal sostenible ante el cambio climático, en bosques mixtos de pino-roble de alto valor ecológico y socioeconómico España, proporcionando información valiosa sobre la respuesta a corto plazo de los suelos a las prácticas de gestión forestal en este tipo de sistemas.

Los resultados de este estudio son particularmente importantes dado que especies como *Quercus pyrenaica* son altamente sensibles al cambio climático, y la mezcla de *Pinus* - *Quercus* puede ser una estrategia de forestación adecuada para compensar parcialmente las pérdidas de productividad y mejorar su adaptabilidad.

Palabras clave: Aclareo, bosque mixto, *Pinus sylvestris*, *Quercus pyrenaica*, capa superficial del suelo, modelos lineales mixtos, manejo forestal, servicios ecosistémicos, datos.

Abstract

Mixed pine-oak forests have emerged as a significant component of the forest landscape in Spain. Despite their wide distribution and ecological and socioeconomic value, there is no specific silvicultural approach for these ecosystems. This study investigates the effects of cutting and species mixing on surface soil properties in these mixed Scots pine (*Pinus sylvestris* L.) and oak (*Quercus pyrenaica* Willd.) forests in northwestern Spain on a short-term, small-scale basis.

For this purpose, an experimental design was established with three types of treatments: control without thinning, moderate felling (25% of the basal area) and intense felling (50% of the basal area). Data collection was carried out in 36 plots of 10x10 m, groupedinto three rectangular areas of 50x40 m, corresponding to each treatment. Samples of the first 5 cm of soil were analysed one year after the treatments to evaluate their physical and chemical properties, collecting data on bulk density, porosity, available water, pH, electrical conductivity, readily oxidisable carbon, available phosphorus, cation exchange capacity, total organic carbon, total nitrogen and exchangeable cations.

For the data analysis, one-way analysis of variance was used as usual, together with new computational tools using mixed models to identify and quantify the effects of thinning and investigate their interaction with the level of tree species mix. These new techniques made it possible to examine the complex relationships between forest characteristics and soil variables.

This study contributes to the development of sustainable forest management strategies against climate change impacts in mixed pine-oak forests, which have high ecological and socio-economic value in Spain, providing valuable information on the short-term response of soils to forest management practices in this type of system.

The results of this study are particularly important given that species such as *Quercus pyrenaica* are highly sensitive to climate change and that the *Pinus* - *Quercus* mixture may be a suitable afforestation strategy to partially compensate for productivity losses and improve their adaptability.

Key words: Thinning, mixed forest, *Pinus sylvestris*, *Quercus pyrenaica*, topsoil, linear mixed models, forest management, ecosystem services, data.

1. Introduction

1.1 European pine-oak forest as Ecosystem services promoters

European forests have long been recognized as valuable sources of biological services, goods and socio-cultural benefits (Stenger et al., 2009) as air quality regulation, carbon storage, recreational value, timber production, forest biodiversity, erosion control and soil fertility (Lambini et al., 2018).

According to the European Parlament, the Union's forests have extended over 158 million hectares (Unión Europea, 2023) with the mixed forests occupying the 23%of this territory (Food and Agriculture Organization of the United Nations., 2011). Focused on Spain, this forest type occupied the 19% of the total forest surface (MAGRAMA, 2012) and they are mainly formed by combinations of broadleaf-broadleaf or broadleaf-conifer species (Riofrío, 2018).

The latest Spanish forest map (Ministerio de Agricultura y Pesca,2006) identify several broadleaved mixed forests, conifer mixed forests and broadleaved-conifer mixed forests, being the Pine-oak mixed forests, in their different combinations, the most important in terms of area (de Dios et al., 2019).

It´s widely known that the increase of tree species richness, may contribute to stabilise forest functioning and ecosystem services supply in response to disturbances (Gamfeldt et al., 2013). In fact, recent studies have highlighted the benefits provided by mixed forests as higher growth rates (Piotto, 2008), the soil conditions improvement (Davidson et al., 1998), the carbon sequestration increment (Andivia et al., 2016; López-Marcos et al., 2018), the creation a better habitat for wildlife (Carnus et al., 2006) participation in biodiversity conservation (Felton et al., 2010; López Marcos, 2020; López-Marcos et al., 2019) and, in some cases, a higher recreational value for tourism, as highlighted by socio-economic studies (Grilli et al., 2014; Norman et al., 2010).

1.2 Pine-Oak mixed forest management

The prominence of Pine-Oak mixed forests, in terms of area, is a result of forest management strategies implemented, which involved introducing pine trees into oak coppice stands (Aldea, 2018) that, have been traditionally managed to produce fuel, wood, and charcoal (Valbuena-Carabaña et al., 2010). Conversely, *Pinus* spp. have thrived due to large-scale afforestation policies implemented in the 19th and 20th centuries (Vadell et al., 2016).

The most prevalent combination of species found in these forests is *Pinus sylvestris* L. - *Quercus pyrenaica* Willd., which coexist in moderate slopes of mountainous regions characterized by a continental and montane climate in western Spain. These mixed stands cover approximately 97,300 hectares (Ministerio de Agricultura y Pesca, 2006). Despite their extensive distribution and forested area, and significant ecological and socio-economic value, there isn't a specific silviculture or forest management approach dedicated to the mixed stands like those examined in this study.

The Scots pine holds the distinction of being the most widely distributed pine species across the globe, spanning across Eurasia. However, its southern latitudinal limit is reached in the mountains of Sierra Nevada in southern Spain at approximately 37° N. In Europe alone, Scots pine forests cover over 28 million hectares (Figure 1A), with Spain accounting for around 1.3 million hectares (Serrada et al., 2008). While Scots pine in Spain is typically found at elevations between 800 and 2000 meters above sea level, it predominantly thrives in montane climates characterized by mean annual precipitation ranging from 600 to 1200 mm, with summer precipitation exceeding 100 mm (Serrada et al., 2008).

Scots pine is classified as a light-demanding pioneer species, although it can also tolerate partially shaded environments. It displays remarkable resistance to frost and drought and can flourish even in nutrient-poor soils, which allows it to occupy a diverse range of ecological habitats. The trees possess/have a deep root system, consisting of dominant oblique and long secondary roots. Scots pine timber is highly valued for its favorable strength-to-weight ratio, and it holds significant commercial and cultural importance in several European countries, particularly in the northern regions (Aldea, 2018).

Pyrenean oak, is a deciduous and marcescent species found in the western Atlantic areas of the Mediterranean, such as western France, Portugal, Spain, and northern Morocco (Fig.1B). In Spain it occupies 214,000 hectares in plantation forest systems and 375,300 hectares in coppice systems with the majority found in the Castilla y León region (67% of its natural range). This oak can be located between 400 and 1600 meters above sea level, in a sub-humid, continental Mediterranean climate, receiving an average yearly rainfall of 600 mm and over 125 mm of rainfall during the summer months (Serrada et al., 2008). It has a short growing season, which may determine its distribution. Summer drought is one of its limiting factors, and it avoids the driest areas. Hereafter we will refer to *Q. pyrenaica* as oak (Aldea, 2018).

The oak is a tree that can partially tolerate shade and belongs to the group of temperate and Mediterranean tree species, typically found in mid-mountain regions on siliceous soils. The plant has a robust root system, consisting of many shallow secondary roots that spread horizontally, extending to 50 cm in depth. Due to its ability to resprout vigorously, oak forests are commonly managed for silvopastoral purposes, including firewood, grazing, and charcoal production (Benito Garzón et al., 2008). However, this species is limited to high mountain areas at the edge of its distribution r, forming isolated nuclei with unique ecological conditions compared to the main distribution area (García-Valdés et al., 2013) and thus, many authors consider *Q. pyrenaica* as one of the Mediterranean species that is highly susceptible to climate change (Pérez-Luque et al., 2020).

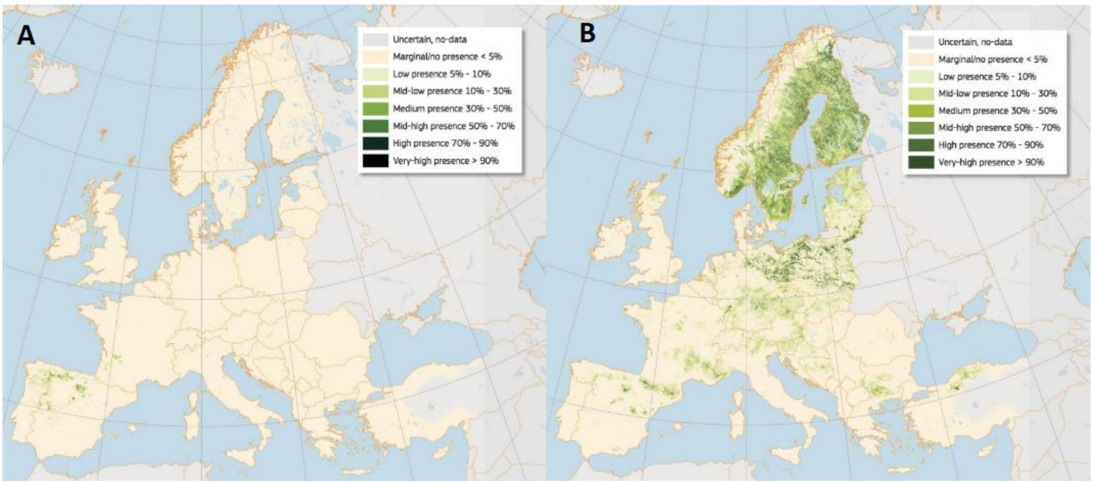


Figure 1. Distribution map for (A) *Quercus pyrenaica* (Nieto Quintano, 2016) and (B) *Pinus sylvestris* (Houston Durrant et al., 2016) estimating the relative probability of presence (Aldea, 2018).

The Scots Pine – Pyrenean oak stands are notable for their complementarity and long-term stability under average climate conditions. Pyrenean oak exhibits low resistance to drought but with rapid recovery rates, whereas Scots pine displays the opposite behavior (Muñoz-Gálvez et al., 2021). Variations in shade tolerance, leaf habits, and root depth contribute to enhanced resource use efficiency in these mixed stands compared to monocultures of either species (Forrester, 2014).

Under climate change scenarios, the productivity of species such as *Quercus robur* L., *Quercus petraea* (Matt.) Liebl. and *Pinus sylvestris* is significantly affected. However, it was observed that the species mixture can provide intermediate resilience to more severe climatic scenarios. Mixing *P. sylvestris* with *Quercus* spp. could be a suitable silvicultural strategy to partially compensate for productivity losses and improve the adaptability of forests to climate change, in combination with other practices such as thinning and uneven-aged management.

Many studies have investigated the short- and long-term impacts of these interventions on forest ecosystems, revealing a complex interplay of factors influencing soil response (Olander et al., 2005). In the short term, logging and thinning operations can cause significant changes in soil structure, including compaction and topsoil disturbance, which can affect porosity, infiltration rates and erosion risk. Effects on nutrient dynamics, such as carbon, nitrogen and phosphorus, vary with time and intensity of intervention. In the long term, impacts on soil structure and nutrient dynamics may persist, albeit in a more subtle way. Importantly, thinning has been shown to have positive effects on drought management in forests, improving ecosystem resilience to periods of water scarcity (Siebers & Kruse, 2019).

In Spain, research on the management of mixed stands has been limited, although it has started to receive increasing attention. According to a study by (Condés et al., 2013), mixed stands can offer significant advantages in terms of productivity compared to monospecific stands, thanks to complementarity interactions between species, which can result in more efficient growth.

1.3 New computational tools

The use of computational techniques in analysing forestry data has transformed the assessment and management of forest resources (e.g, (Ciceu et al., 2020), (Ciceu et al., 2022)(García-Duro et al., 2021) and are expected to be very useful for pine - oak mixed stands research and management. These techniques help with handling vast amounts of data, allowing scientists to gain valuable insights that guide sustainable forestry practices. As the need for precise and timely data on forest ecosystems grows, computational tools are now essential for improving the efficiency and effectiveness of forest inventory assessments.

Several approaches have been succesfully used to address forest-soil relationships, among them traditional statistical approaches and multivariant analyses (Bock & Van Rees, 2011), meta-analyses (James et al., 2021) and mechanistic models (Gustafson et al., 2016), revealing the complexity of the plant-soil relationships and the need of better tools to identify the better predictors for each soil variable. An important development in this field is the use of machine learning algorithms and statistical modelling techniques like Linear Mixed Models (LMM; e.g., (Ciceu et al., 2020) (Ciceu et al., 2022)), enabling the assessment of intricate connections between different forest compartments, characteristics and environmental variables (e.g., USDA, 2012).

Big data analytics in forestry is also being increasingly used, allowing for the integration of data from many sources such as satellite imagery, ground-based measurements, and ecological models, improving forest inventory estimates accuracy and enabling real-time forest monitoring. New research has shown that integrating such data with forest inventory data can greatly enhance the accuracy of estimating forest biomass and carbon stocks, crucial for comprehending the impact of forests on mitigating climate change (Marsel et al., 2021).

Nevertheless, although the progress in computational tools and algorithms in general have made the model selection process more efficient and despite that these tools can contribute to the research of the complexity of the mixed forests, and particularly their functioning and management, they have been little used for mixed forests and further developments are still needed to adapt the new tools to the mixed forests research and their management needs.

2. Objetives

Our hypothesis is that just one year after the thinning treatment (1) the level of thinning influences the topsoil layer (5 cm depth); (2) this influence interacts with the tree mixing level. However, it is difficult to have a complete understanding of which forest mixing or thinning variables are exerting their influence with conventional models.

Therefore, the objectives of this study were: (a) to quantify thinning on topsoil properties with conventional mixed models, and (b) to evaluate whether this effect interacts with the mixing level of trees through new computational model and new tools, where all the mixing and thinning variables available are tested.

3. Material and methods

3.1 Study site

The experimental setup is located in the North-West Iberian Peninsula (Palacios de Valdellorma, León; 42º 45´40´´N 5º 12´41´´ W; Fig.2) at 990 m.a.s.l., under a temperate with dry summer climate (Nafría García et al., 2013) according to Köppen classification (1936) for the Iberian Peninsula. The mean annual temperature is 11.1 ºC and the annual precipitation is 515 mm (Aldea et al., 2023). The geological parent materials are Cenozoic gravels, sands, clays and silts (IGME, 2015) with a smoooth landscape and moderate slopes of 16 % gradient. The soils are Inceptisols with a xeric soil moisture regime and mesic soil temperature regime and they are classified as *Typic Dystroxerep* (United States Department of Agriculture Natural Resources Conservation Service, 2022) with a clay-loam texture and an acid pH (Annex 1). The potential vegetation is a Pyrenean oak forest (Rivas-Martínez et al., 2007); however, the oak forest that occupied the study area was highly degraded in the past due to harvest and bulldozer ripping and later re-introduction of pine during the 1970s (Aldea et al., 2023). The reforestation was carried out after harvest by planting pines in strips. The oaks grew, mostly between pines strips. Pine trees nowadays are even aged of around 40 years old, but/although the real cambial age of oak trees is unknown (Aldea et al., 2023). The stand is a mixed forest of Scots pine (PS: *Pinus sylvestris*) and Pyrenean oak (QP: *Quercus pyrenaica*) with a clumped spatial pattern with both species occupying alternating rows. These plots belong to the network of permanent plots of Sustainable Forest Management Institute(iuFOR).

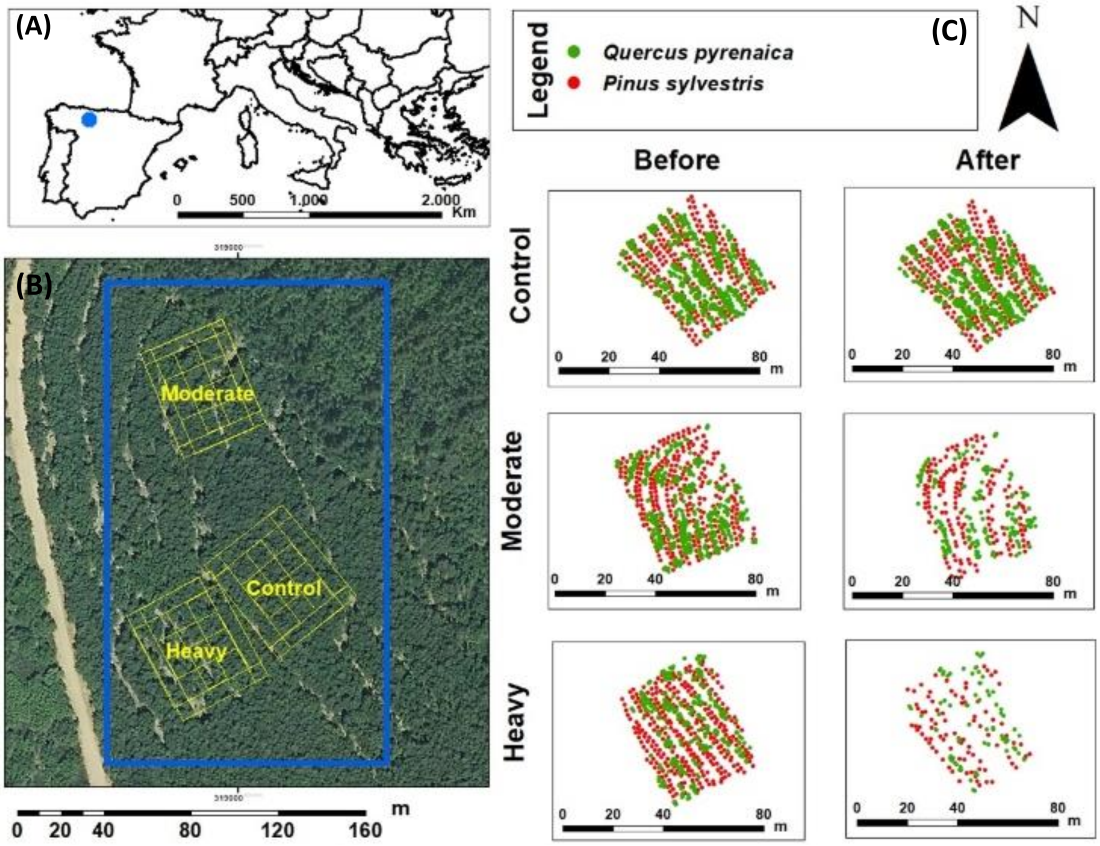


Figure 2. Location of the study area in the North-West Spain (A). location of the plots in each treatment (B; control. moderate and heavy thinning) and tree location before and after the thinning (C; *P. sylvestris*: red circles; *Q. pyrenaica*: green circles).

3.2 Experimental design

A nested essay of 36 10x10 m plots divided into 3 treatments of 50x40 m rectangular area with a buffer edge of 5 m surrounding it (see Figure 2) was used to conduct the research.

The basal area (G), density (N) and quadratic mean diameter (dq) before the treatments were 95.5 m^2 ha^{-1} (%GPS: 66.71%; %GQP: 33.29%), 3759 stems ha^{-1} (%NPS: 39.20%; %NQP: 60.80%) and 9.12 cm (dq_PS: 12.80 cm; dq_QP: 6.75 cm) respectively.

The treatments consisted of two commercial thinning with different intensities, moderate (25% G removed) and heavy (50% G removed) thinning, and unthinned control. The thinning was carried out at the end of 2015 removing the suppressed and intermediate trees of both species (see Table 1,

Annex 2). The felled logs and branches were not removed from the plots.

Table 1. overstory basal area (G), density (N) and quadratic mean diameter (dq) by treatment (control, moderate and heavy thinning) and by forest species and total (Trees: both species; PS: *Pinus sylvestris;* QP: *Quercus pyrenaica*) before and after the treatment.

		G (m^2 ha^{-1})			N (trees ha^{-1})			dq (cm)		
		Trees	PS	QP	Trees	PS	QP	Trees	PS	QP
Control	Before	32.09	19.59	12.50	4175	1400	2780	8.60	12.54	6.62
	After	32.09	19.59	12.50	4175	1400	2780	8.60	12.54	6.62
Moderate	Before	33.63	23.02	10.61	3740	1440	2300	9.36	13.51	6.72
	After	20.71	13.45	7.26	1590	750	169	12.05	14.61	9.77
Heavy	Before	29.62	20.99	8.63	3370	1790	1580	9.50	12.40	6.93
	After	12.92	7.98	2.92	795	425	375	12.59	15.28	9.53

3.3 Data collection and laboratory analises

Within each 10x10 m plot before and after the thinning treatments the number (N), diameter (dg), and basal area (G) of every stem found of PS and QP were computed. In June 2017, were collected soil samples composed by four disturbed and four undisturbed topsoil sub-samples, randomly located within each 10x10m plot for the next analyses. and disturbed were collected up to 5 cm depth

The undisturbed topsoil sub-samples, collected by steel cylinders (251.3 cm^3), were dried at 105°C during 24 h and weighed (±0.001 g) to calculate the soil bulk density (bD). The disturbed topsoil sub-samples were collected up to 5 cm depth, air-dried until constant weight, and homogenized to obtain a uniform composite disturbed sample that were sieved (2 mm) before physical and chemical analyses.

The physical properties measured included percentage by weight of coarse fraction (>2 mm; stones) and earth fraction earth fraction (< 2 mm; EF); the porosity and available water (AW) by (Ministerio de Agricultura Pesca y Alimentación, 1993) methods. The chemical properties analysed: soil pH and electrical conductivity (EC) using a conductivity meter in a 1:2.5 soil/deionized water slurry (Allen et al., 1974); easily oxidizable carbon (OxC) using the K-dichromate oxidation method (Walkey, 1947); available phosphorous (Pav) using the Olsen method (Olsen & Sommers, 1982); cation exchange capacity (CEC) according to (Mehlich, 1953); total carbon (TOC) and total nitrogen (TN) with a LECO CHN-2000 autoanalyzer; exchangeable cations (Ca^{+2}, $Mg+^2$, K^+, Na^+) were extracted with 1 N ammonium acetate at pH = 7 (Schollenberger & Simon, 1945) and determined using an atomic absorption/emission spectrometer.

3.4 Data treatment

From the measurements above we calculated the ratio of total carbon to total nitrogen (C/N) and the ratio OxC/TOC; the sum of bases (SB) was the sum of the Ca^{+2}, Mg^{+2}, K^+ and Na^+ concentrations ($cmol_+kg^{-1}$); base saturation percentage (V) was calculated as the ratio of SB divided by the CEC and expressed as a percentage; water holding capacity (WHC) according to (López-Marcos et al., 2019).

The overstory inventory measurements were used to calculate within each 10x10m plot the next variables: basal area before the treatment (G_Befo), and thinned basal area by the treatment (G_t) as well as the basal area of every species thinned by the treatment (G_PS_t: PS thinned basal area; G_QP_t: QP thinned basal area) and their percentages (%G_t: percentage of G_t respect to G_Befo; %GPS_t: the percentage G_PS_t respect to G_t; %GQP_t: the percentage G_QP_t respect to G_t). Basal area (G), as well as the basal area of every species after the treatment (G_PS: PS basal area after treatment;

G_QP: QP basal area after treatment), and their percentages (%PS: percentage of G_PS respect to G; %QP: percentage of G_QP respect to G). The same for density: [density before the treatment (N_Befo), and both species density thinned by the treatment (N_t) as well as the density of every- species thinned by the treatment (N_PS_t: PS thinned density; G_QP_t: QP thinned density) and their percentages (%N_t: percentage of N_t respect to N_Befo; %NPS_t: the percentage N_PS_t respect to N_t; %NQP_t: the percentage N_QP_t respect to N_t). density (N), as well as the density of every species after the treatment (N_PS: PS density after treatment; N_QP: QP density after treatment)]; and for the quadratic mean diameter (dq_t: quadratic mean diameter thinned by the treatment; dq_PS_t: PS´quadratic mean diameter thinned by the treatment; dq_QP_t: QP´quadratic mean diameter thinned by the treatment; dq: quadratic mean diameter after the treatment; dq_PS: PS´quadratic mean diameter after the treatment; dq_QP: QP´quadratic mean diameter after the treatment). In addition, the admixture level (Mix) from the proportion of each tree species in each 10x10 m plots according (Andivia et al., 2016); 1 corresponds to areas in which the basal area of each tree species was the same, whereas admixture level equal to 0 corresponds to those areas where only one tree species was found).

3.5 Conventional model and new approach definition

The effects of thinning were compared among treatments by a conventional approach using a one-way anova in R (R Core Team, 2021) using the thinning treatment as factor, and assuming that all the observations within each treatment were independent. The pairwise comparisons were performed by Bonferroni test (package multcomp; (Hothorn et al., 2008)). Complementary, beanplots (beanplot package; (Kampstra, 2008)) with the soil values distribution within each plot and aggregating thinning plots were also built to facilitate the interpretation of the results.

Contrasting with this conventional approach, we deepened into the effects of thinning on the soil properties by quantifying with LMMs the change in the soil properties as a function of the change in forest structural properties induced by the thinning.

There are several functions available, e.g., like the stepwise algorithms step (Venables & Ripley, 2002), stepAIC, stepBIC (MASS; (Venables & Ripley, 2002)) and dredge (MuMIn; (Barton, 2024)) that may/could help in finding early effects of thinning. However, these functions were used to explore relationships between the response soil properties and forest potential predictors, and they resulted in errors: "*Error: cons memory exhausted (limit reached?). Error: no more error handlers available (recursive errors?); invoking 'abort' restart*”

Therefore, these relationships were approached by constructing LMM regressions for every forest predictor and for every pair of forest predictors, that were compared against the null models, with only intercept. As a result of the high number of response soil variables (17, stones and EF results not reported here) and forest variables (22) the number of models built reached 24.000 approximately (note that predictors order affects variables fitting, so every pair of predictors must be tested twice). The selection of the better models for every response soil variable was done by AIC, and BIC (Grove et al., 1988).

However, there is no straightforward solution because non-linearity, error biases, heteroscedasticity and the specification of the random effects may raise the number of potential combinations and invalid models that should be tested in a time-consuming process. Also, multicollinearity is a problem for applying the selected models to other datasets. Therefore, the next step of this work consisted in contributing to develop new computational tools by testing the outputs of an algorithm developed within the Restoration

Ecology research group that performs all the calculations autonomously, scoring the models, and returning the selection of the best models (Fig. 3 and Fig.4).

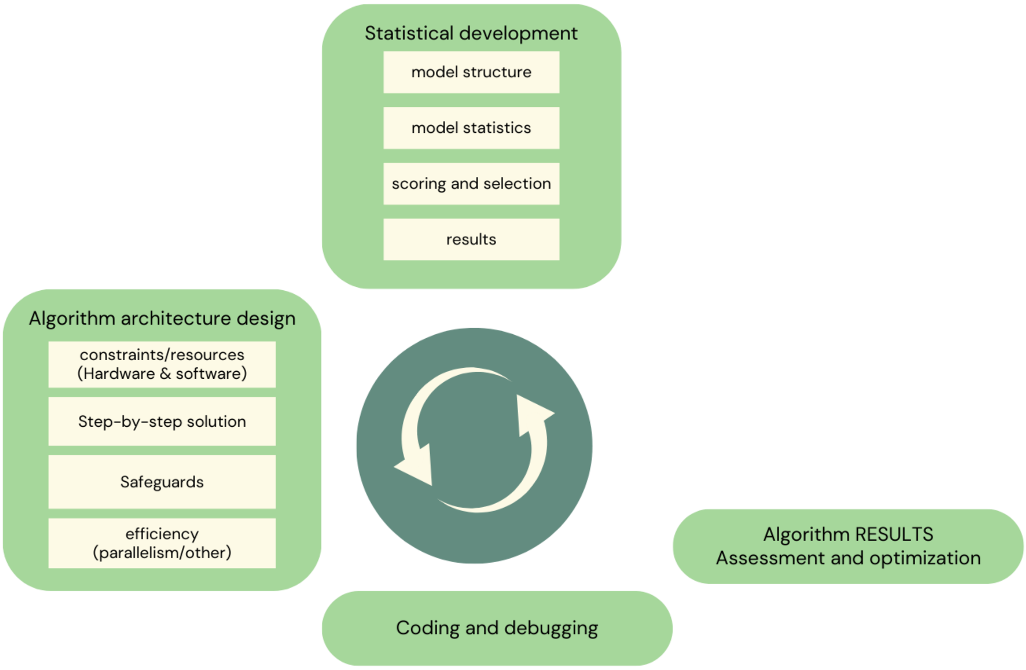


Figure 3. Development of the algorithm for modeling soil variables.

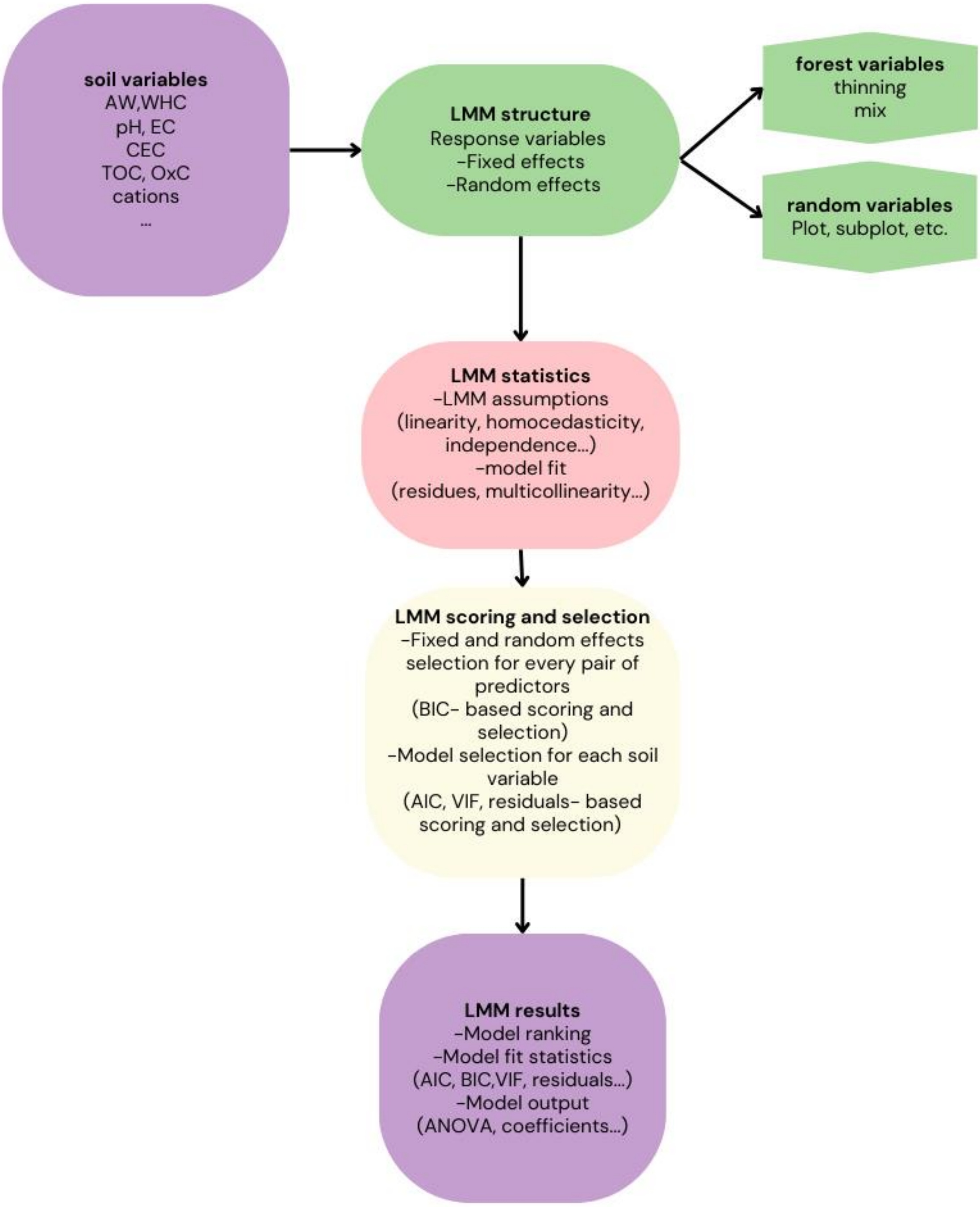


Figure 4. Design of the algorithm for model for every soil variable.

The inputs of the algorithm are the soil variables as response variables, the forest variables as predictors and the variables of the experimental set-up as random effects (Fig. 4). The statistics used by the algorithm are indicators of the accomplishment of the LMM assumptions and model fit, and their results are used for scoring the different models and for the model selection within the algorithm, which is developed in 2 separate stages: a) for establishing the fixed and random effects of interest for every soil variable and every pair of forest predictor, by selecting the model (e.g., with/without interaction) that best suits data, solves potential heteroskedasticity and manages properly data dependence, and b) for selecting the best model among all the pre-selected models for every soil response variable. The first selection based on BIC comparisons for every predictor or pair of predictors, while the second, more complex, included scoring AIC, VIF, regressions testing for residuals nonlinearity to compare models fit with different predictors and pairs of predictors. Within this step, models with non-significant fixed-effects variables were also penalized.

The criteria for weighting the selection parameters above were established during the development of the algorithm, based on statistical criteria and slightly fine-tuned though the interpretation of the results. Within this work we reported the LMMs that obtained the best score for each soil variable. For clarity, all the predictor coefficients whose significance is not reported is assumed lower than 0.05.

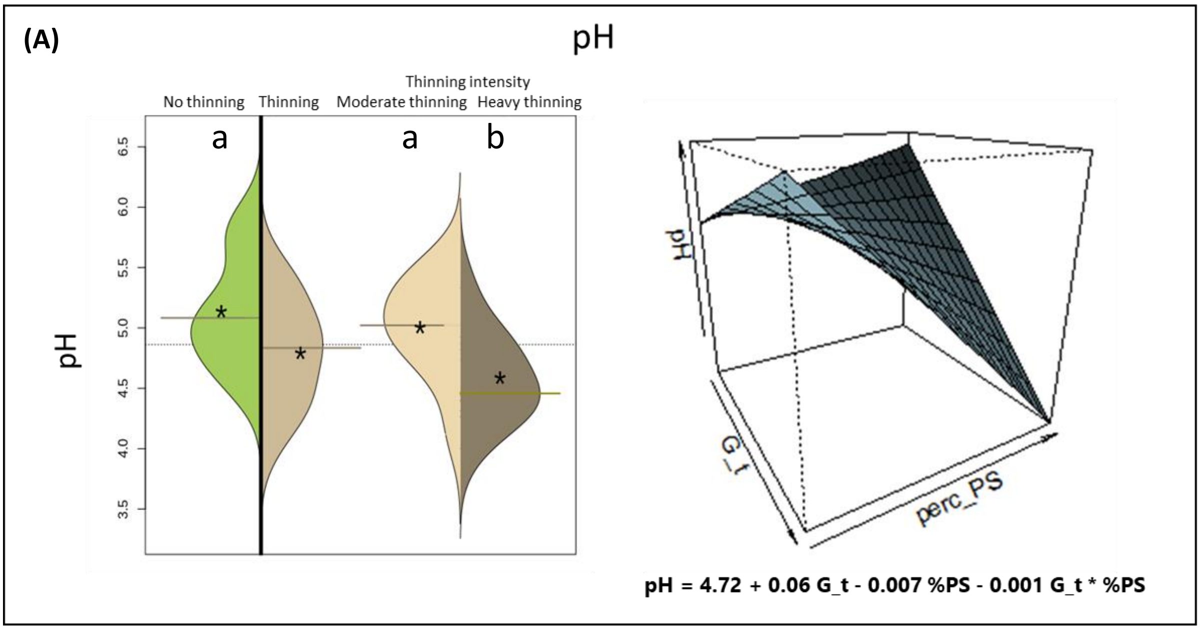
All these calculations/routines were done in R environment, with packages nlme (Pinheiro & Bates, 2000) for LMMs and parallel (R Core Team, 2021) for parallel computing.

4. Results

4.1 pH and electrical conductivity

Following the conventional one-way ANOVA model, pH values decrease significantly with thinning (p-value < 0.05) and the decrease is greater in plots where cutting is stronger (Fig. 6), although significant only with the heavy thinning (No thinning: 5.13 ± 0.13; Thinning: 4.79 ± 0.09; moderate thinning: 5.01 ± 0.12; Heavy thinning: 4.58 ± 0.11). In the case of EC there is a slight, non-significant increase in the values in the plots where thinning has been carried out and this increase is somewhat greater in the plots where the cutting is stronger (p-value =0.07; No thinning: 111.69 ± 3.70 dS.m^{-1}; Thinning: 124.51 ± 3.48 dS.m^{-1}; moderate thinning: 122.20 ± 4.19 dS.m^{-1}; Heavy thinning: 126.82 ± 5.65 dS.m^{-1}).

According to the regression LMM, pH values have a positive relationship with G_t (0.06) and %PS (0.007), with a small negative interaction among them (-0.001) and EC values have a negative relationship with %PS (-0.11) and G_t (-1.2), and a small positive interaction effect (0.03).



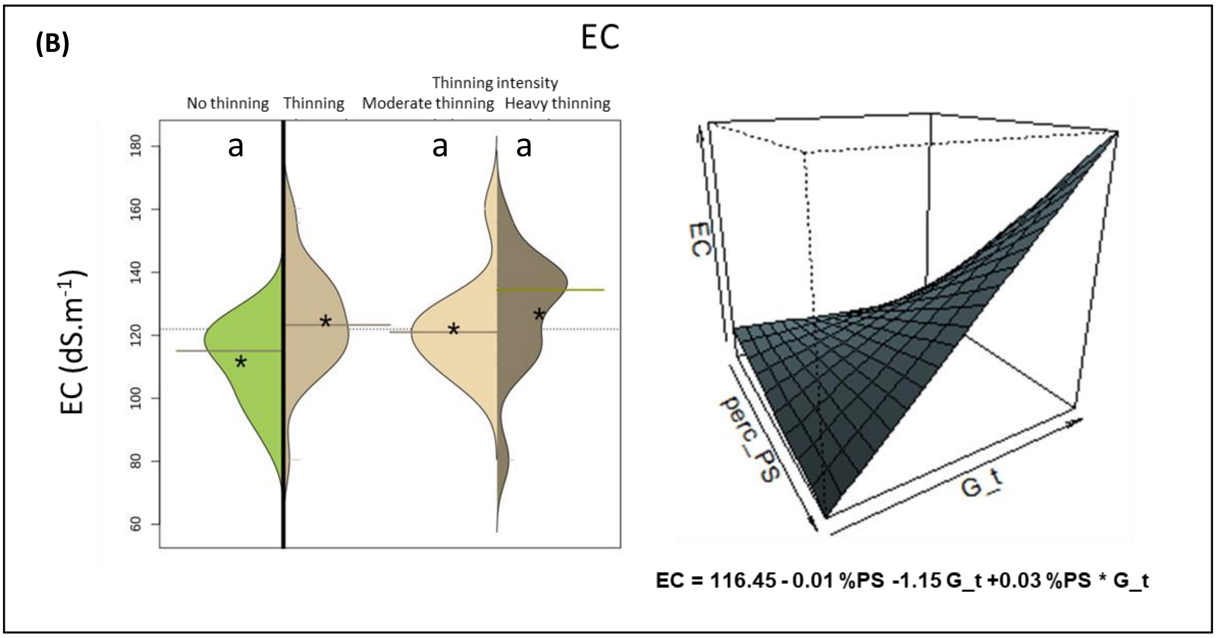


Figure 6. pH (A) and EC (B) bean-plots of no thinning vs thinning observations (green vs brown; left) and by thinning intensity (light brown and dark brown; right), and pH and EC 3D-plot predictions of the LMM models selected.

4.2 Soil carbon forms

Following the one-way ANOVA models, oxC and TOC values decrease slightly (Fig. 7), but not significantly, with thinning and the decrease is greater in the plots where thinning has been lighter (p-value = 0.96; No thinning: 31.47 ± 2.11 mg.kg^{-1}; Thinning: 32.32 ± 2.15 mg.kg^{-1}; moderate thinning: 32.09 ± 3.79 mg.kg^{-1}; Heavy thinning: 32.56 ± 2.22 mg.kg^{-1}) for oxC and (p-value = 0.15; No thinning: 44.44 ± 3.68 mg.kg^{-1}; Thinning: 37.76 ± 1.98 mg.kg^{-1}; moderate thinning: 35.71 ± 1.93 mg.kg^{-1}; Heavy thinning: 39.80 ± 3.46 mg.kg^{-1}) for TOC.

The LMMs shows that oxC depends positively on G_PS (0.65) and %QP (0.54) with a positive interaction among them (0.04) and in the case of TOC, LMM shows that TOC values have a negative relationship both with G_PS (-0.24) and G_QP_Befo (-1.61) with a positive interaction among them (0.12).

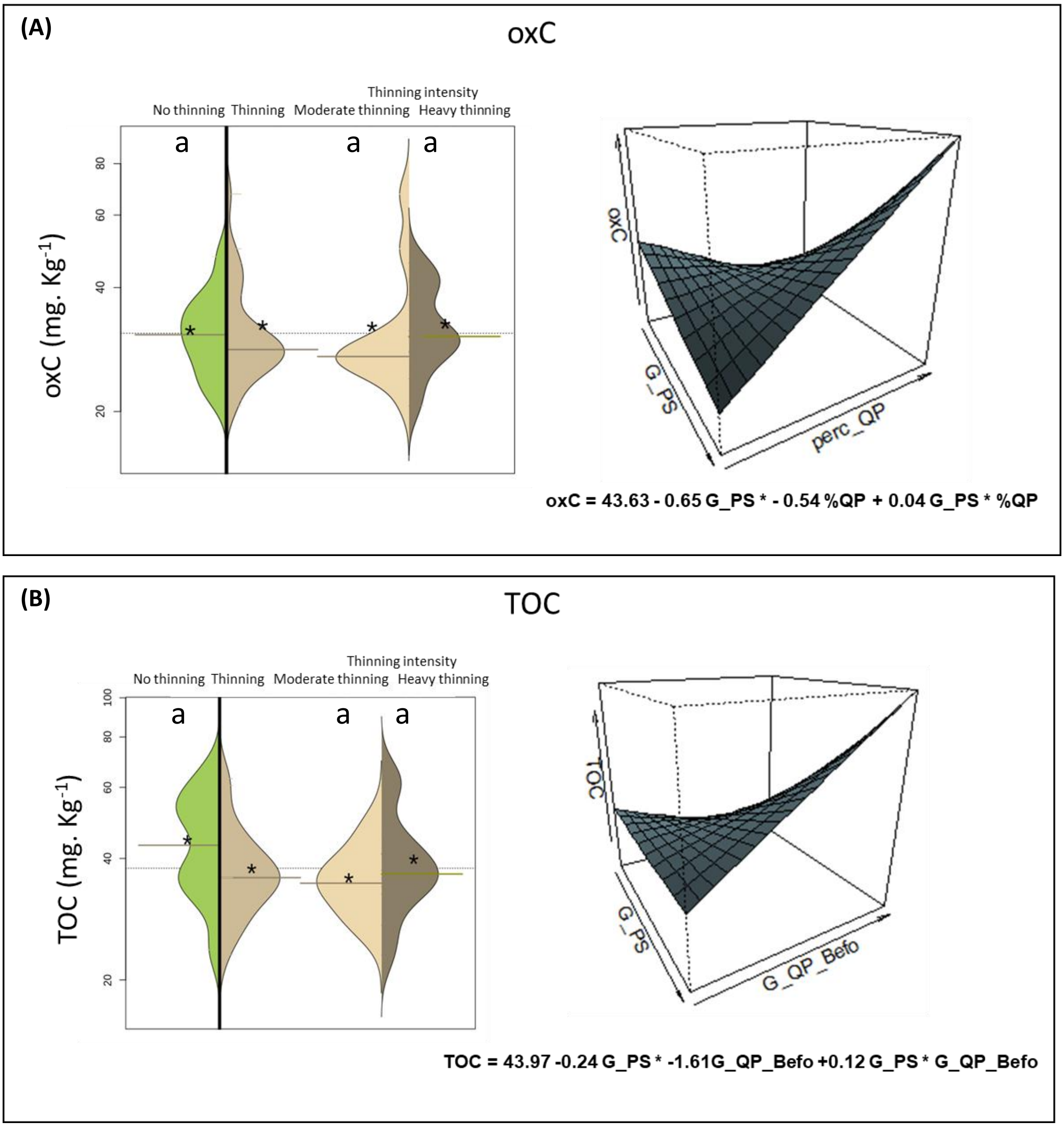


Figure 7. OxC (A) and TOC (B) bean-plots of no thinning vs thinning observations (green vs brown; left) and by thinning intensity (light brown and dark brown; right), and 3D-plot prediction of the LMM models selected by the new approach

4.3 Total nitrogen

With the one-way ANOVA model, it is observed that nitrogen values (Fig. 8) do differ between control and the different thinning intensities (p-value <0.05; No thinning: 2.62 ± 0.35 mg.kg^{-1}; Thinning: 1.20 ± 0.09 mg kg^{-1}; moderate thinning: 1.21 ± 0.14 mg kg^{-1}; Heavy thinning: 1.18 ± 0.14 mg kg^{-1}) although no significant differences were found among thinning treatments.

The regression LMM that best fit TN values have N, number of trees after thinning, as a predictor (0.004).

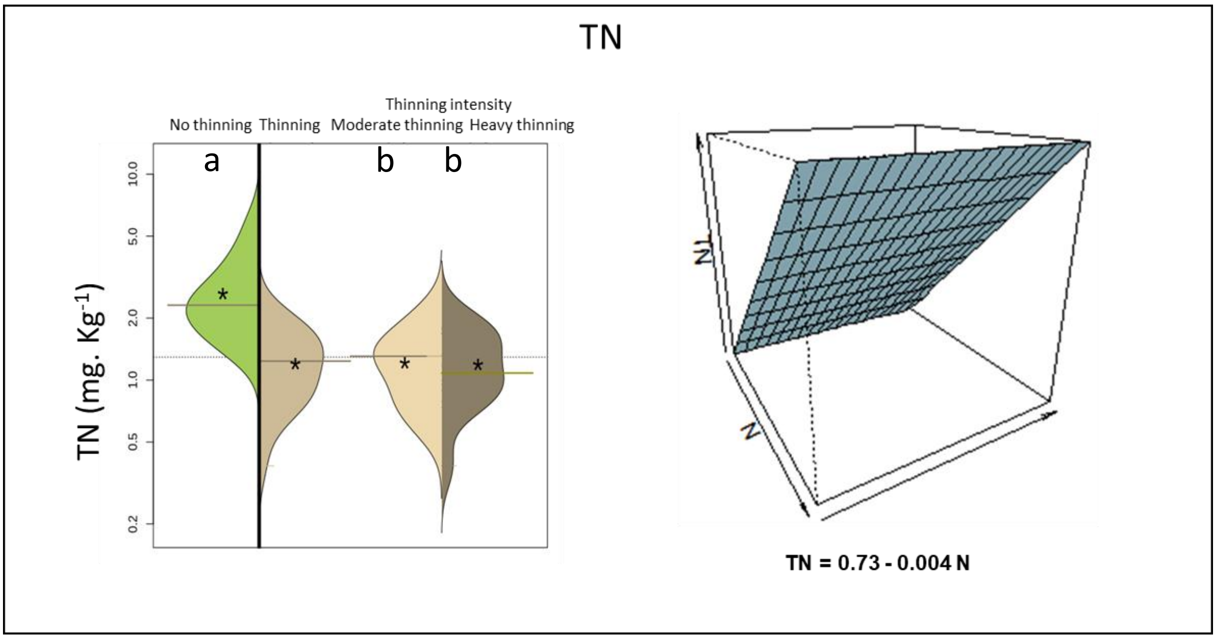


Figure 8. TN bean-plots of no thinning vs thinning observations (green vs brown; left) and by thinning intensity (light brown and dark brown; right), and 3D-plot predictions of the LMM models selected by the new approach.

4.4 Available phosphorous

In the conventional one-way ANOVA model, avP values decrease slightly (Fig. 9), although non-significantly (p-value = 0.42;), after thinning and there is little variation between plots with different thinning intensities (No thinning: 8.67 ± 0.01 mg.kg^{-1}; Thinning: 6.83 ± 0.90 mg kg^{-1}; moderate thinning: 7.07 ± 1.49 mg kg^{-1}; Heavy thinning: 6.59 ± 1.08 mg kg^{-1}). However, thinning might have caused an increase in the avP variability at the plot level, with the thinning plots tending to a bimodal distribution of the observations, and consequently of the model errors.

According to the LMM models, avP values have a positive relationship with avP (0.17; p-value = 0.25) and Mix (6.13), although the interaction among them has a negative coefficient (-0.5) that leads to the lowest avP values when G_t and Mix are high.

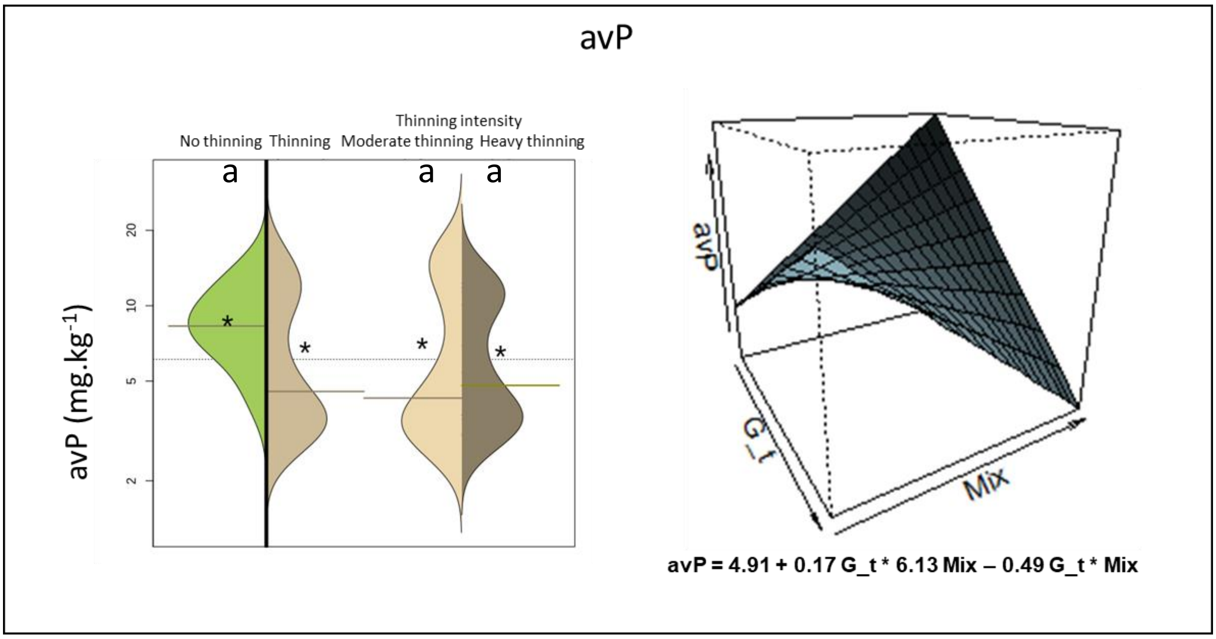


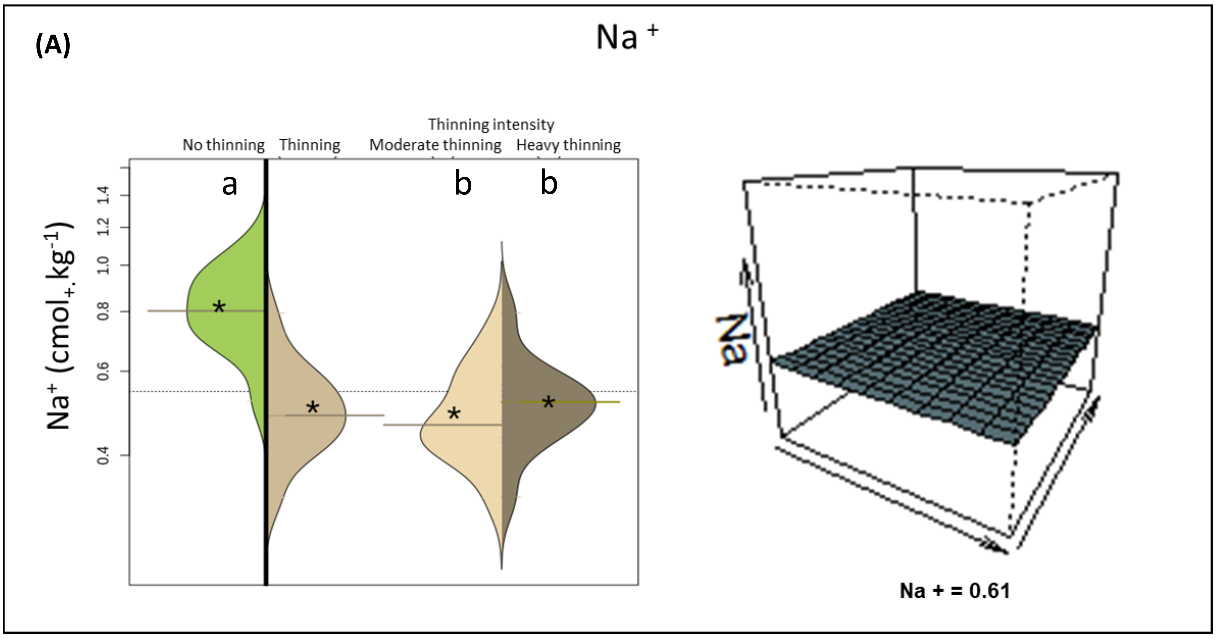
Figure 9. avP bean-plots of no thinning vs thinning observations (green vs brown; left) and by thinning intensity (light brown and dark brown; right), and 3D-plot prediction of the LMM models selected by the new approach.

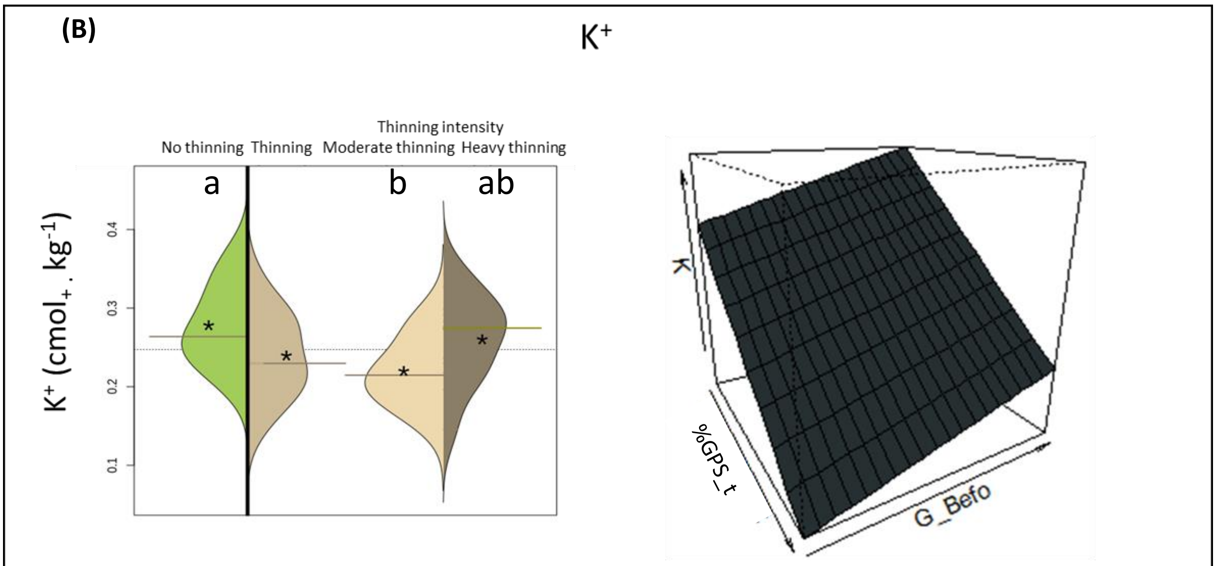
4.5 Exchangeable cations

The one-way ANOVA model showed that exchangeable cations decrease by thinning, but no differences were found between the two thinning intensites. (Fig. 11; Na^+: No thinning: 0.82 ± 0.05 $cmol_+ \, kg^{-1}$; Thinning: 0.50 ± 0.02 $cmol_+ \, kg^{-1}$; moderate thinning: 0.49 ± 0.03 $cmol_+ \, kg^{-1}$; Heavy thinning: 0.52 ± 0.03 $cmol_+ \, kg^{-1}$; K^+: No thinning: 0.28 ± 0.01 $cmol_+ \, kg^{-1}$; Thinning: 0.24 ± 0.01 $cmol_+ \, kg^{-1}$; moderate thinning: 0.22 ± 0.01 $cmol_+ \, kg^{-1}$; Heavy thinning: 0.26 ± 0.02 $cmol_+ \, kg^{-1}$; Ca^{+2}: No thinning: 3.34 ± 0.20 %$cmol_+ \, kg^{-1}$; Thinning: 2.27 ± 0.14 $cmol_+ \, kg^{-1}$; moderate thinning: 2.41 ± 0.22 $cmol_+ \, kg^{-1}$; Heavy thinning: 2.14 ± 0.17 $cmol_+ \, kg^{-1}$; Mg^{+2}: No thinning: 0.54 ± 0.02 $cmol_+ \, kg^{-1}$; Thinning: 0.40 ± 0.02 $cmol_+ \, kg^{-1}$; moderate thinning: 0.40 ± 0.03 $cmol_+ \, kg^{-1}$; Heavy thinning: 0.32 ± 0.03 $cmol_+ \, kg^{-1}$).

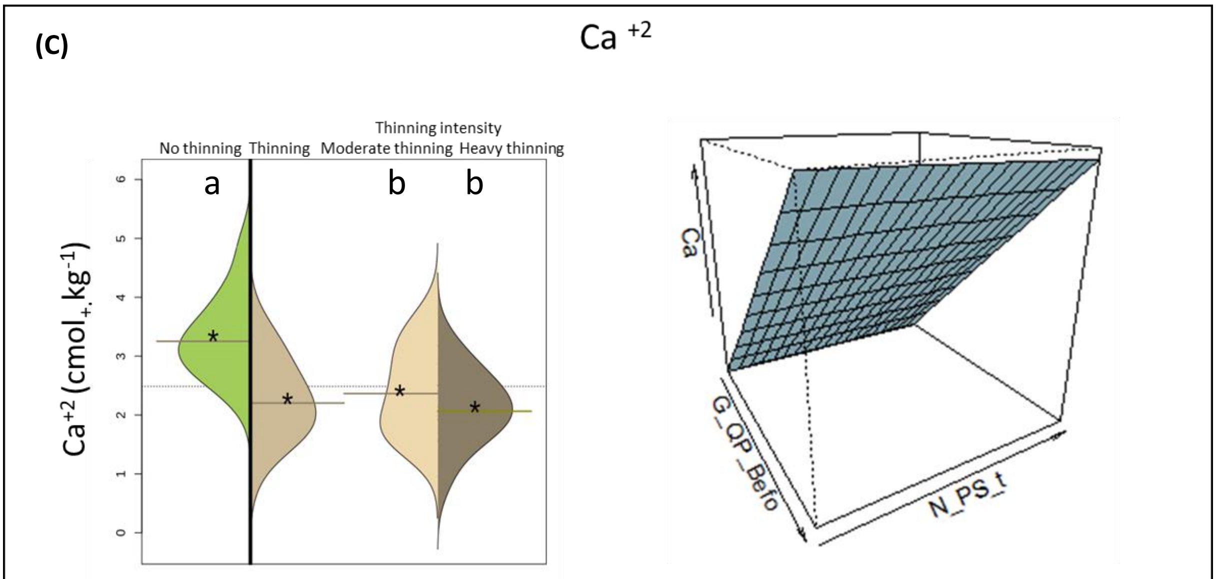
The LMM of Na^+ that fit the better to the dataset was the null model, and therefore didn't include any thinning predictor. K^+, $Mg+^2$ did, with best fit provided by simple-effects models with no interaction, although the p-values of the coefficient predictors were higher than 0.05. K^+ LMM included the predictors %_GPS_t (-0.00026) and G_Befo (0.00033) while $Mg+^2$ LMM %_QP (0.00059) and G_Befo (-0.00127). The LMM models that best fit Ca^{+2} values included G_QP_Befo (0.087) and N_PS_t (aprox 0.0003 with p-values > 0.5) as predictors and a small negative interaction among them (-0.0001).

In the case of SB values decrease after thinning and are higher in plots where thinning has been lighter (No thinning: 4.98 ± 0.24 $cmol_+kg^{-1}$; Thinning: 3.41 ± 0.16 $cmol_+kg^{-1}$; moderate thinning: 3.52 ± 0.25 $cmol_+kg^{-1}$; Heavy thinning: 3.30 ± 0.22 $cmol_+kg^{-1}$). The LMM models that best fit SB values have a positive relationship with G_QP_Befo (0.11) and N_PS_t (aprox 0.0003 with p-values > 0.5) and a small negative interaction among them (–0.0002).





$K^+ = 0.27 - 0.0002\ G\_PS\_t + 0.0003\ G\_Befo$



$Ca^{+2} = 2.32 + 0.08\ G\_QP\_Befo * 0.0002\ N\_PS\_t - 0.0001\ G\_QP\_Befo * N\_PS\_t$

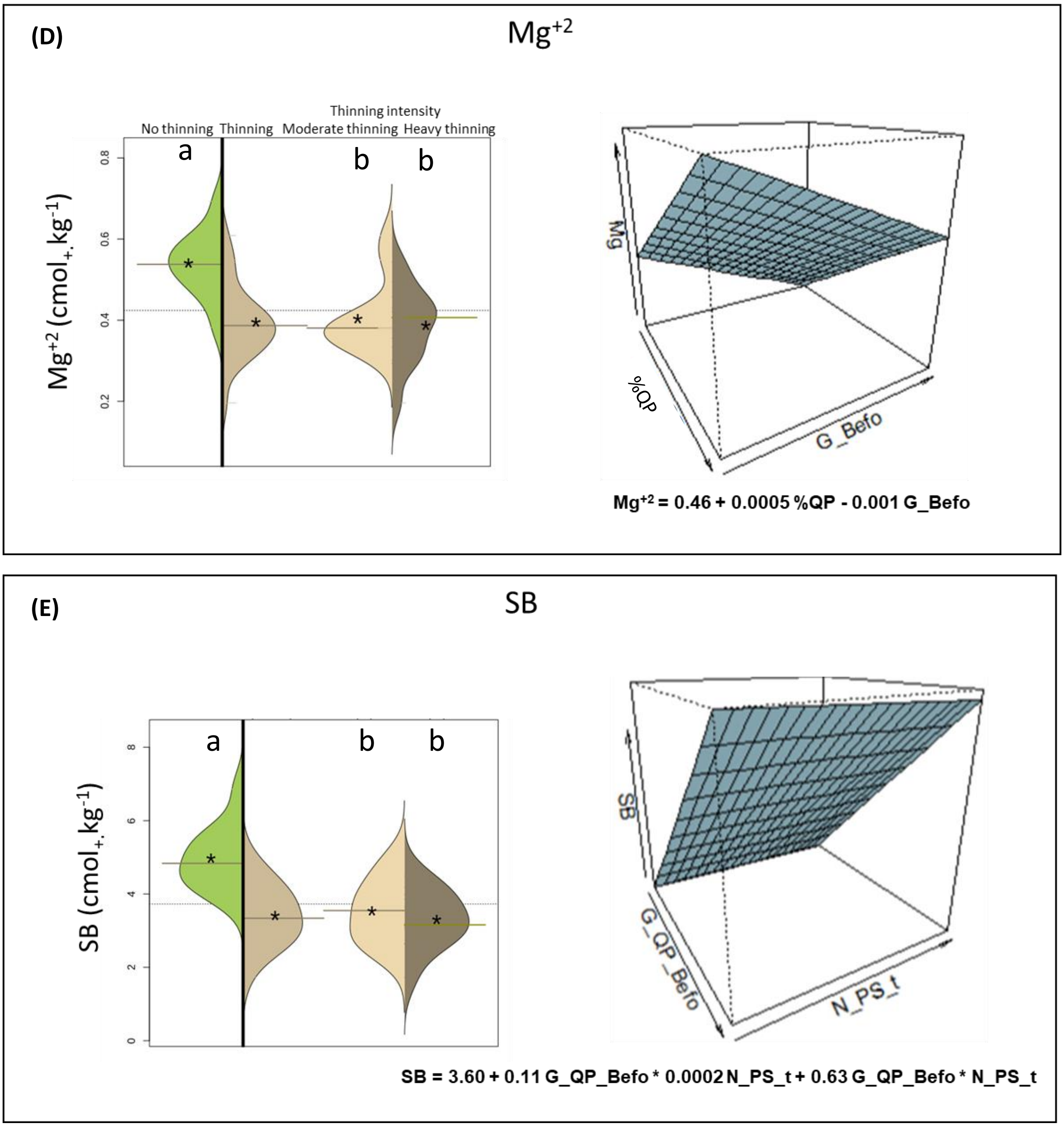


Figure 11. Na^{+} (A), K^{+} (B), Ca^{+2} (C), Mg^{+2} (D) and SB (E) bean-plots of no thinning vs thinning observations (green vs brown; left) and by thinning intensity (light brown and dark brown; right), and 3D-plot prediction of the LMM models selected by the new approach.

4.6 Cation exchange capacity and base saturation

According to the one-way ANOVA model, the CEC values decrease after thinning and do not vary between plots with different thining intensities (Fig. 12; No thinning: 14.32 ± 0.35 $cmol_{+}kg^{-1}$; Thinning: 6.70 ± 0.31 $cmol_{+}kg^{-1}$; moderate thinning: 6.73 ± 0.25 $cmol_{+}kg^{-1}$; Heavy thinning: 6.66 ± 0.58 $cmol_{+}kg^{-1}$). However, V values increase after thinning (No thinning: 35.14 ± 2.17 %; Thinning: 53.14 ± 3.57 %; moderate thinning: 52.43 ± 3.45 %; Heavy thinning: 53.86 ± 6.43 %).

The CEC LMM has a negative relationship with dq_PS_t (-0.62) and %NQP_t (-0.07) with a small positive interaction among them (0.005). V had a positive relationship with G_QP_t (7.2), and small positive relationship with N_PS_t (0.02; p-value = 0.0635), and small negative interaction among them (-0.009).

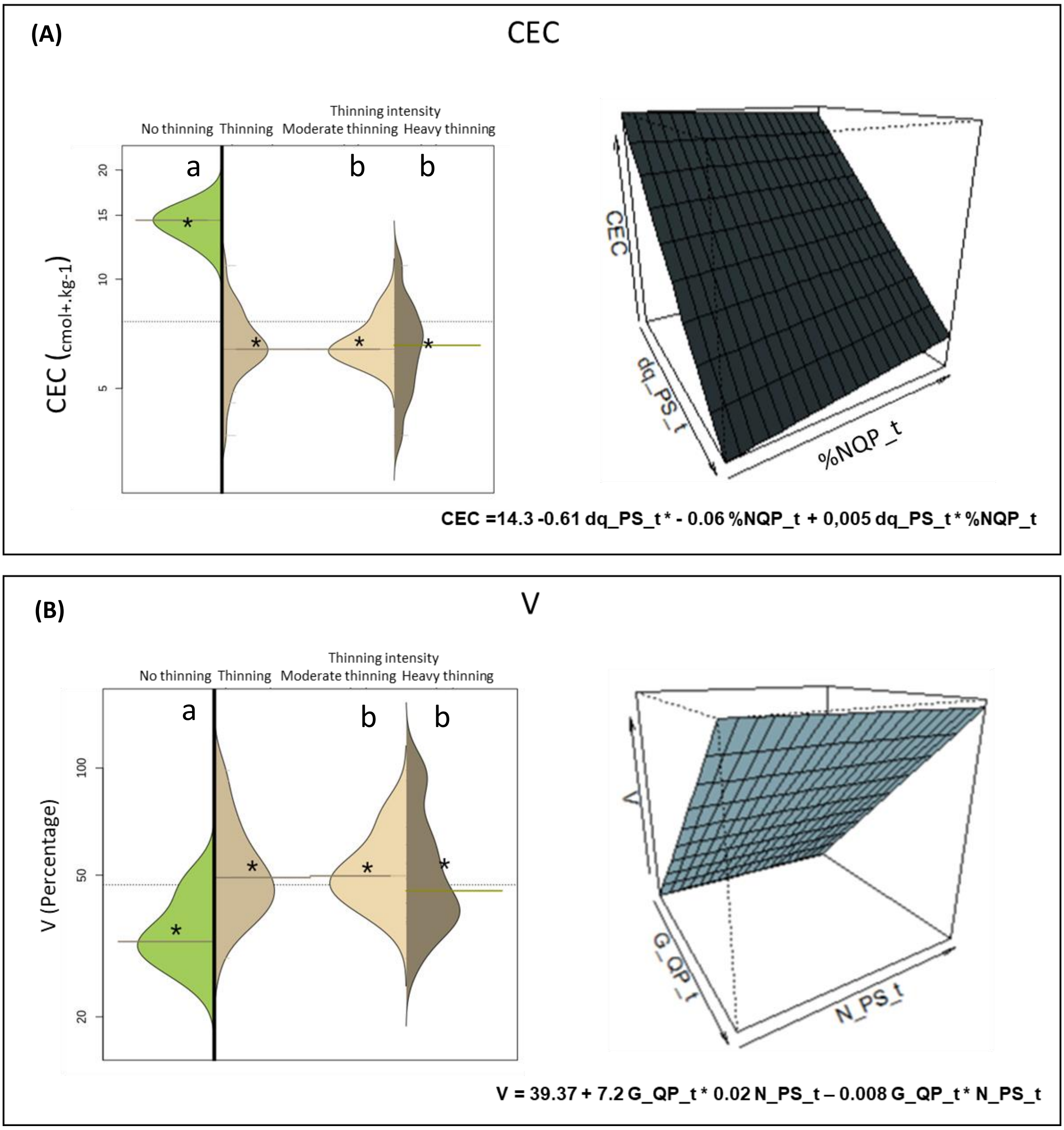


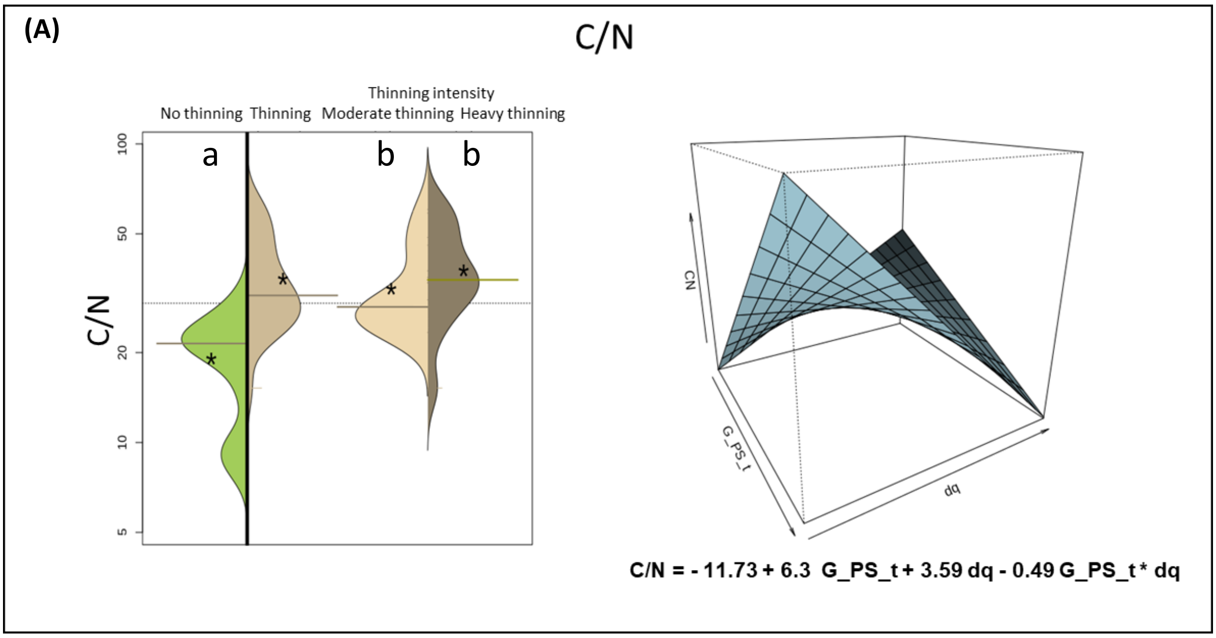
Figure 12. CEC (A) and V (B) bean-plots of no thinning vs thinning observations (green vs brown; left) and by thinning intensity (light brown and dark brown; right), and 3D-plot prediction of the LMM models selected by the new approach.

4.7 Ratios

The one-way ANOVA model revealed that C/N increase significatively by thinning (Fig. 10; p-value < 0.05; No thinning: 19.05 ± 0.35; Thinning: 35.19 ± 2.56; 3.30; Heavy thinning: 37.68 ± 3.91) but no differences were found between thinning intensities.

According to the LMM model C/N values have a positive relationship with G_PS_t (6.3) and dq (3.6), and a negative interaction effect (-0.49), that in subplots with high G_PS_t and dq leads to a C:N ratios like the values measured of subplots with low dq and no thinning.

Nevertheless, concerning the OxC/TOC ratio—one-way ANOVA model, significant differences by thinning were only found among the Non-thinning and the soft thinning treatments (p-value <0.05; No thinning: 72,46 ± 2,55; Thinning: 86,31 ± 3,78; moderate thinning: 89,22 ± 7,15; Heavy thinning: 83,40 ± 2,63).The oxC/TOC LMM the model with best fit is the null model and therefore, it does not include thinning variables as predictors, having only intercept.



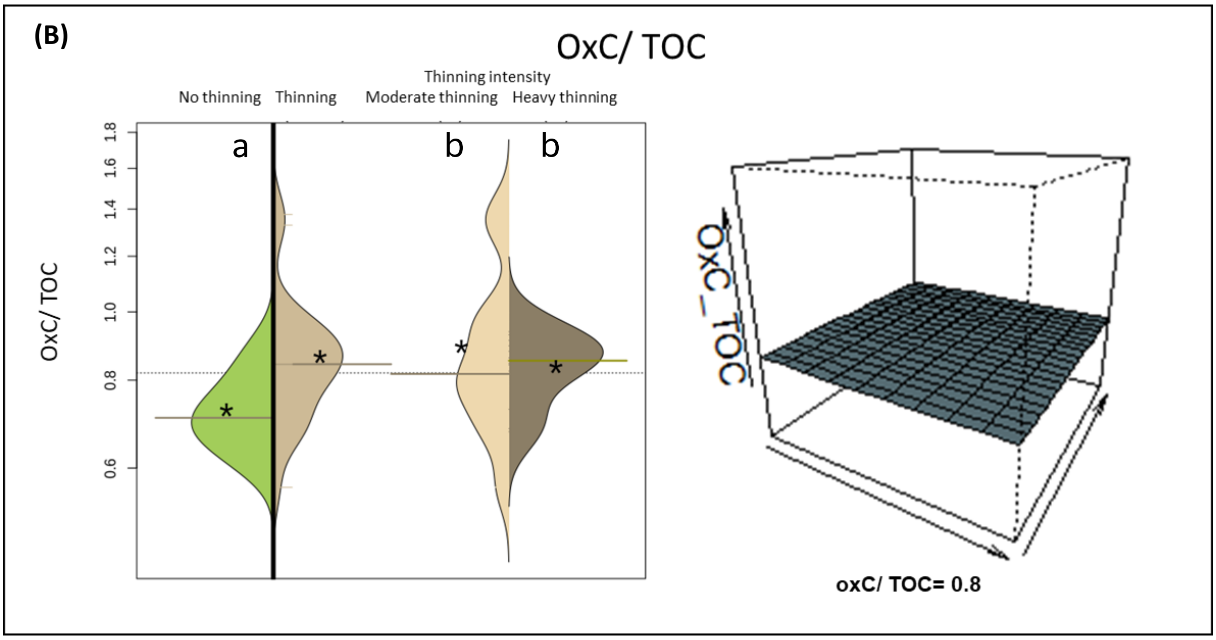


Figure 10. C/N (A) and OxC/TOC (B) bean-plots of no thinning vs thinning observations (green vs brown; left) and by thinning intensity (light brown and dark brown; right), and 3D-plot prediction LMM model selected by the new approach

4.8. Soil water properties

Regarding AW and WHC, the conventional one-way ANOVA and the a posteriori pairwise comparisons show (Fig. 5) their values increase significantly with the thinning intensity, both for AW (p-value = <0.05; No thinning: 4.44 ± 0.64 %; Thinning: 15.84 ± 1.51 %; moderate thinning: 11.85 ± 0.89 %; Heavy thinning: 19.84 ± 2.42 %) and WHC (p-value =<0.05; No thinning: 1.14 ± 0.19 g.cm^2; Thinning: 4.55 ± 0.40 g.cm^2; moderate thinning: 3.84 ± 0.37 g.cm^2; Heavy thinning: 5.26 ± 0.68 g.cm^2). This is consistent with the regression LMMs selected by the new approach above (Fig. 5), where for both AW and

WHC, the %G_t has a significant positive effect (0.23; $p<0.05$) (See model in annex), and in particular is the QP thinning the species selected that improve the soil water properties, either via %NQP_t (0.38; $p<0.05$) as in AW and or %GQP_t in WHC. However, both LMMs have a negative coefficient for the interaction with %G_t, which limits strongly the increase in AW and WHC.

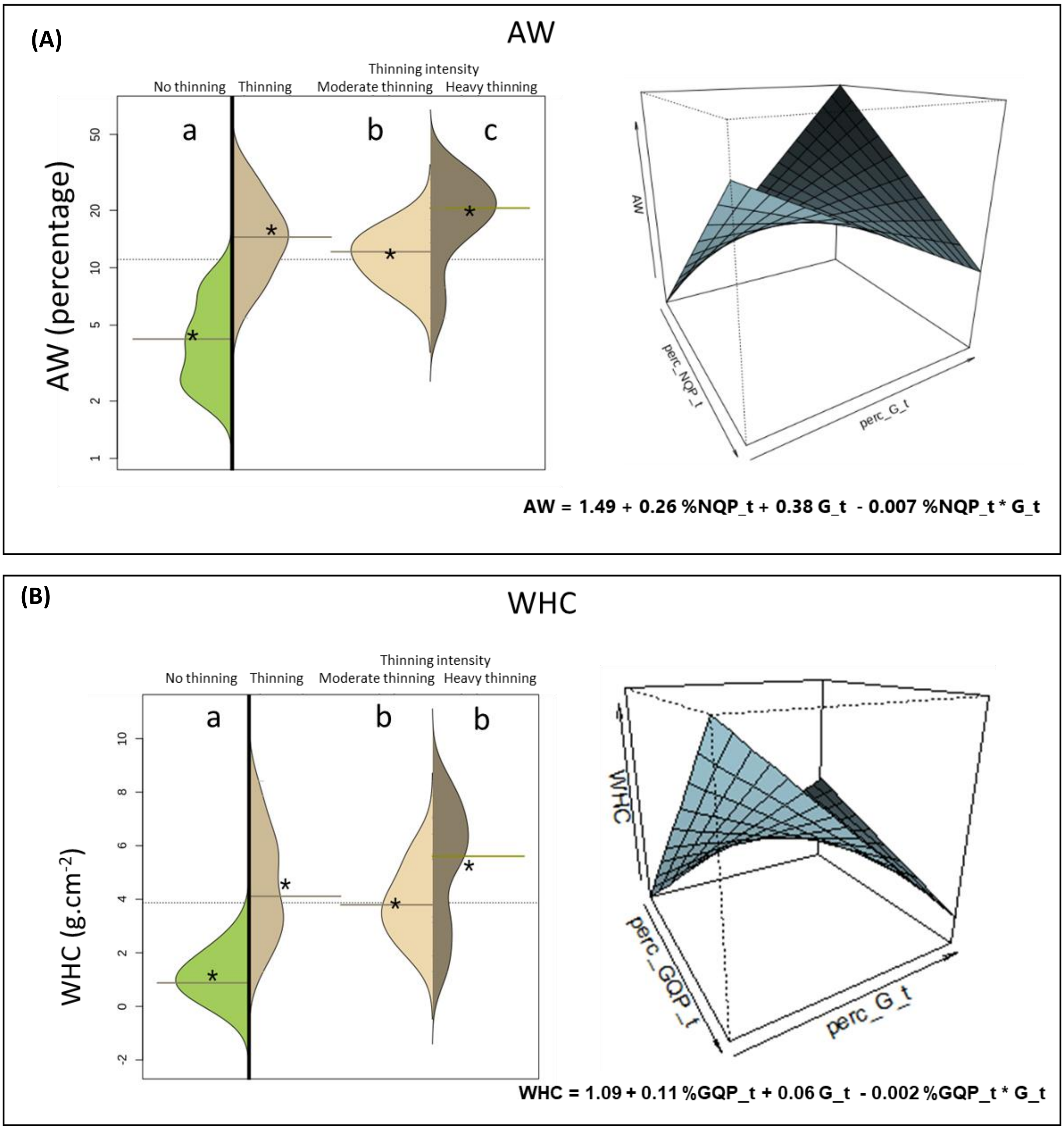


Figure 5. AW (A) and WHC (B) bean-plots of no thinning vs thinning observations (green vs brown; left) and by thinning intensity (light brown and dark brown; right), and 3D-plot prediction of the LMM models selected by the new approach for each soil water variable.

5. Discussion

Traditional modelling approaches often fall short when applied to datasets with many correlated variables, dependent observations, heteroscedastic and nonlinear relationships among response variables and predictors. Despite LMMs are able to cope with most of these issues (e.g., Pinheiro & Bates, 2000; Ciceu et al., 2020), the attempts to implement these methods with the available tools have been unsuccessful at the beginning, and the outcomes have been suboptimal because of the potential violations of certain assumptions and because the computational requirements exceed and the capabilities of the implementations for feature selection. In contrast, our proposed approach using a new algorithm not only addresses these limitations but also enhances the insights provided by conventional models, by fitting LMM. This is particularly relevant in scenarios involving complex systems, such as mixed stands, where short-term predictions are challenging to derive solely from standard treatments. Furthermore, through the application of LMM regressions, we can identify key predictors related to forest management and harvesting practices and generate specific predictions for each observation, as a function of the key predictor (e.g., as in Ciceu et al., 2020; 2022).

These results underline the complexity of interactions between forest management practices and soil nutrient dynamics in mixed forests. The differential response of different soil chemical variables to thinning intensity suggests the need for an adaptive management approach that considers the specific characteristics of the site and the species present (Bravo-Oviedo et al., 2014). Furthermore, these findings highlight the importance of considering the short-term effects of management practices on soil fertility and forest ecosystem sustainability.

5.1 pH and electrical conductivity

The one-way ANOVA model detected a pH decrease and an EC increase non-significant in the thinning plots respect of the control, and the regression LMMs, confirmed that pH and EC are influenced by thinning, mostly through Scots pine thinning, since the selected variables were the thinned basal area (G_t) and the percentage of Scots pine (%PS) suggesting that Scots pine fellling contributes soil acidification and increase slightly the EC. This can be attributed to several biological and chemical factors inherent to the species (Andivia et al., 2016). Decomposition of pine leaves can acidify the soil and cause changes in electrical conductivity since the coniferous litter is more acidic than deciduous litter (Burgess-Conforti et al., 2019).

Contrary, Pyrenean oak felling does not seem to have a strong effect on soil acidification and EC in the short term, some studies suggest that oak forests have a higher pH buffering capacity due to the higher presence of basic cations in litter and soil (Povilaitienė et al., 2022).

5.2 Soil carbon forms

The one-way ANOVA model shows that both studied carbon forms (i.e. oxC and TOC) decrease slightly, but not significantly, with thinning in the short term. One and a half years is likely not enough time to see clear/strong effects on soil carbon. Kim et al. (2016) also failed to detect changes in similar studies three years later thinning. However, the selected LMM also completes this information suggesting that soil carbon properties are slightly influenced by thinning, since soil carbon is function of the factor of thinning predictor (G_PS), but also by species mixture, since also select variables related to the mixture ratio (G_QP_before and %QP) are selected according to the fact that some studies mentioning mixed forests may have an enriched litter composition and higher litter decomposition rates, both of which affect the soil carbon cycle (Zhang et al., 2022; Getino-Álvarez et al., 2023).

5.3 Total nitrogen

The one-way ANOVA approach detected a nitrogen content decrease in the short term, after thinning but with no significant differences between treatments. According to that the LMM select only the negative effect of tree density with a low factor suggesting a good variable selection by the new approach. This relation to tree density could be respond to resources competition for resources such as water, light and nutrients, including nitrogen indicated Coulombe et al. (2017). Recent studies such as Kim´s et al. (2023) indicate that factors such as canopy cover and density can influence the quality and quantity of nutrients, including nitrogen, in the soil. Forest composition can modulate competition for nitrogen and other nutrients (Caihong et al., 2023a), but the LMM selected didn't include any predictor related with the mix/composition, likely because both the tree mix and the tree density depend on the spatial patterns of both species, which is the result of the past management.

5.4 Available phosphorous

The one-way ANOVA approach didn’t detect a significant decrease in available phosphorus in the short term after thinning, probably by the high thinned plots variability that is coherent with the regression LMM, where available phosphorus increases with the admixture of species and the amount of basal area cut during the thinning treatments and there is a negative interaction among both variables.

Recent studies in Spanish forests have shown that the effects of thinning on soil properties can be complex and sometimes counterintuitive. For instance, Blanco et al. (2009) found that moderate thinning in mixed Mediterranean forests can lead to short-term decreases in soil nutrient availability, particularly phosphorus, due to altered microbial activity and organic matter decomposition rates (Bravo-Oviedo et al., 2017) in a similar study but with a mixture of Pyrenean oak- Maritime pine observed those oak leaves showed faster decomposition rates than pine needles in unthinned plots but the thinning reduces the decay rate of oak leaves, that support the variables selection of our new approach, because select variables relate to the thinning (G_t) and to the admixture (Mix).

5.5 Exchangeable cations

The one-way ANOVA model shows how exchangeable cations decrease by thinning, but no differences were found in thinning intensity. This is consistent with the LMM models which select variables related to thinning of Scots pine for potassium (%GPS_t) and calcium (NPS_t) and to the mixture level post-thinning for magnesium (%QP) but also select for both predictor variables related to the stand situation previous the thinning treatment (G_Before for potassium and magnesium, G_QP_Before for calcium). In all cases the value of the estimated coefficient of predictor is low. The LMM of Na^{+} didn't include any predictor, and therefore the best fit is provided by the null model. These results reveal complex patterns in the response of soil cations to thinning treatments in mixed forests mostly in the short term. However, although it is generally known that tree density reduction treatments could increase nutrient availability by decreasing competition (Bosco Imbert et al., 2004), it is also known that forestry practices can significantly alter the litterfall process and thus the return of nutrients to the soil (Imbert et al., 2004), so it is possible to find a decrease in nutrients in the soil after a thinning/cutting treatment. In addition, since the amount of nutrients transferred by the litterfall depends on plant biomass and species, differences according to the species are expected: the average amounts of magnesium are higher in deciduous trees, while those of calcium are higher in evergreen trees.

5.6 Cation exchange capacity and base saturation

According to the one-way ANOVA model, CEC decreases, and V increases after thinning and does not vary between plots with different cutting intensities. The LMM model completes this information by showing for both variables a relationship with the thinning of both species, since the interaction between the variables is detected in both CEC and V. This suggests a complex soil dynamic, where a higher proportion of non-productive trees as QP can contribute to soil organic matter and, consequently, to CEC. This finding is in line with previous studies that have demonstrated the importance of structural diversity in the nutrient dynamics of forest soil (Grüneberg et al., 2019).

In this case, there is no relationship with the stand situation before the thinning treatment, as in the case of exchangeable cations. It is possible that, after the thinning treatment, the changes in the soil matrix related to available negative charges in soil particles surface, it means the changes in CEC, are faster and therefore, in the short term, a change in the cation exchange capacity is detected, which is weaker for the case of nutrients that will be positioned in these negative charges, as is the case of exchangeable cations.

5.7 Ratios

The one-way ANOVA model found that C/N values increase significatively by thinning and the LMM model select the thinned basal area of Scots pine as a predictor since the litter according to conifer litter contains more recalcitrant constituents than broadleaf litter does (Andivia et al., 2016; Getino-Álvarez et al., 2023) and the species with more sclerophyllous foliage have higher lignin content and higher C/N ratio (Augusto et al., 2015).

Nevertheless, neither the one-way ANOVA model nor LMM model for OxC/TOC found differences and predictors to explain the found variability, probably by the lack of differences in the behavior of the original variables (ie. OxC and TOC).

5.8 Soil water properties

The one-way ANOVA model shows that water properties increase with thinning, finding differences between thinning intensities only for AW. In this regard, Chen et al., (2014) found that thinning induced increased water storage in mixed pine-oak forests.

The LMM approach completes this information since it selects in both LMMs the thinned basal area and a variable related to the proportion of QP thinned, showing in both soil water properties a negative interaction between the selected variables. It seems that what increases the variables related to water in the soil is the QP thinning. Since there are differences in the diameter classes of both species cut (Annex 2; QP: smallest diameter; PS: largest diameter) and the LMM model selects the proportion of QP thinned, it seems that they are related to higher values of soil water properties in the thinning of small trees, in fact has already describe the thinning treatments reduce stress caused by competition for water (Aldea et al., 2023).

5.9 Management implications

The implications for forest management derived from this study are significant and multifaceted. Thinning emerges as a potential tool for climate change mitigation, particularly in preventing the impact of drought in mixed *Pinus sylvestris* and *Quercus* *pyrenaica* forests. This practice (tree felling) increases soil water availability, which can be crucial in regions prone to water scarcity (Aldea et al., 2017).

Species composition management proves to be a key factor in influencing specific soil properties (Pretzsch et al., 2017). For example, species mixing can favour water retention and improve soil dynamics, contributing to ecosystem resilience.

A holistic approach to planning forestry interventions is essential. Both thinning intensity and species composition should be carefully considered to improve soil properties and overall ecosystem health (Blanco et al., 2009). Research shows that thinning effects vary by species; for example, *Pinus sylvestris* logging has a more pronounced impact on soil acidification than *Quercus pyrenaica* logging.

The study emphasises that the removal of plant biomass alters water infiltration and retention patterns, which contributes to increased water availability. However, the relationship between thinning intensity and nutrient dynamics is complex and requires careful management(Caihong et al., 2023b). The results underline the importance of considering multiple factors in forest management, as there is no ‘one size fits all’ solution.

Tree density proves to be a crucial factor in improving soil fertility in these mixed ecosystems. However, the complexity of the interactions observed indicates that there is no universal solution (del Río et al., 2016). Management practices must be adapted to the specific conditions of each site, considering not only thinning intensity, but also species composition, canopy structure and soil properties.

Future studies should address the mechanisms underlying these complex interactions, including the role of soil microbiota and organic matter decomposition processes in post-thinning nutrient dynamics (Baldrian, 2016). This will allow a deeper understanding of how to optimise forest management practices to maintain the long-term health and productivity of mixed forest ecosystems.

The research on the early effects of thinning in Scots Pine-Pyrenean Oak mixed stands highlights the critical role of forest management in enhancing soil health and ecosystem resilience. By employing advanced computational tools, the study effectively demonstrates how varying levels of thinning interact with species diversity to influence topsoil properties (Collalti et al., 2020). The findings indicate that a well-planned thinning strategy can improve soil conditions, thereby fostering greater biodiversity and promoting sustainable forest management practices.

As global environmental challenges intensify, the integration of data science in forestry emerges as a vital approach for optimizing forest management. The ability to analyze complex interactions between tree species and soil characteristics not only aids in understanding forest dynamics but also informs strategies that enhance carbon sequestration and mitigate climate change impacts (Jactel et al., 2017). This research underscores the importance of mixed forest systems as a means to achieve ecological stability and productivity, paving the way for future studies aimed at refining management practices in diverse forest ecosystems. Ultimately, the insights gained from this study contribute to the broader goal of sustainable forest management, balancing economic needs with ecological preservation.

6. Conclusion

Soil pH showed a significant decrease by with thinning according to traditional ANOVA being the Scots pine thinned selected variable by the new LMM approach as a responsible o this decrease. Soil electrical conductivity show the contrary trend whiteout ANOVA differences.

No differences attributed to the treatment were found by traditional ANOVA for soil carbon forms but in both variables the new LMM approach select an interaction between abundance after thinning and Pyrenean oak proportion as a responsible of variability.

Contrary to total nitrogen, no differences attributed to the treatment were detected by traditional ANOVA for available phosphorus. Nevertheless, the new LMM approach pointed to tree density to explain the total nitrogen variability and an interaction between thinning and mixture level to explain the available phosphorus variability

The exchangeable cations show a significant decrease by thinning according to traditional ANOVA. The new LMM approach select different variables by different cations, but also select variables related to the stand situation previous the thinning treatment.

Cation exchangeable capacity and base saturation show a significant response by thinning according to traditional ANOVA. The new LMM approach select the interaction of both species thinning as responsible of this response.

Carbon nitrogen ratio show a significant increase by thinning according to traditional ANOVA that the new LMM approach relate to the thinning of Scots pine.

No differences are detected by traditional ANOVA and no selected variables for the new LMM approach in the oxidizable carbon to total organic carbon ration.

Soil water properties show a significant increase by thinning according to traditional ANOVA that the new LMM approach relate to Pyrenean oak thinned.

7. Acknowledgements

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Annex 1. Soil profile data

Table 2. General information of pit soil description Site, overstory and understory description, and pictures of the plot and the pit soil profile

Site description		
Author		Daphne López Marcos and Luis Alfonso Ramos Calvo
Date		10/06/2017
Weather		Sunny / Rain in the last 24 hours
Soil climate	**Moisture regime**	Xeric
	Temperature regime	Mesic
Location	**Province**	León
	Town	Palacios de Valdellorma
	Place	Los Corrales
	Coordinates	42º 45´40´´N 5º 12´41´´ W
	Altitude	1075 m
	Stepness	0 º
	Orientation	NE
Soil	**Parent material**	Gravels. sands. clays and silts. Alluvial.
	Geologic age	Holocene Cenozoic
	Soil type	Typic Dystroxerept
Vegetation	**Potential**	*Holco mollis- Querceto pyrenaicae* S.
	Current	*Pinus sylvestris* L. and *Quercus pyrenaica* Willd.

Pictures

Plot	**Pit soil profile**
	

Table 3. Pit description: mineral horizon description according to (FAO, 2009).

Horizons	Thickness (cm)	Colour: Wet	Colour: Dry	Description
Ah	0-20	5YR4/1	10YR5/3	Water status: slightly moist. Mottle: non-existent. Rock Fragments: few fine gravelly. Shape-spherical. Soil Texture: Loam. Soil Structure: moderate. granular. Consistence: friable. Slightly sticky and slightly plastic. Pores: common. fine and interstitial. No anthropic activity apparent. Roots: common fine roots and few coarse roots. No soil crusts. Horizon boundary: smooth and gradual.
AB	20-60	7.5YR5/4	5YR4/3	Water status: slightly moist. Mottle: non-existent. Rock Fragments: few fine gravelly. Shape-spherical. Soil Texture: Clay- loam. Soil Structure: moderate. granular. Consistence: friable. Slightly sticky and slightly plastic. Pores: common. fine and interstitial. No anthropic activity apparent. Roots: common fine roots and few coarse roots. No soil crusts.
Bw	60-100+	2.5YR5/6	7.5YR5/6	Water status: slightly moist. Mottle: existent 1mm x 2mm colour 10YR7/8. Rock Fragments: few fine gravelly. Shape-spherical. Soil Texture: Clay. Soil Structure: moderate. granular. Consistence: friable. sticky and plastic. Pores: common. fine and interstitial. No anthropic activity apparent. Roots: common fine roots and common coarse roots. No soil crusts.

Table 4. Pit description: analytic data of the mineral horizons. **

Analytic data							
Physycal properties							
Horizons	**Texture (%)**			**Stones**	**Density (g cm^{-3})**		**Porosity**
	Sand	**Silt**	**Clay**	**(%)**	**Bulk**	**Real**	**(%)**
Ah	39.6	34.64	25.67	26.8	0.83	2.4	65.48
AB	37.09	34.11	28.14	29.1	0.97	2.67	63.73
Bw	29.46	25.26	44.52	11.1	1.06	2.24	52.73
Chemical properties							
Horizons	**pH (H_2O)**	**EC (dS m^{-1})**	**Pav (mg kg^{-1})**	**TN (mg g^{-1})**	**TOC (mg g^{-1})**	**oxC (mg g^{-1})**	**CEC (Cmol$_+$ kg^{-1})**
Ah	5.3	80.45	5.59	1.55	33.21	21.8	3.16
AB	4.6	118.5	2.23	0.52	4.78	9.33	2.62
Bw	4.6	125.5	1.73	0	3.02	2.32	4.64
Water properties							
Horizons	**FC (%)**	**PWP (%)**	**AW (%)**				
Ah	37.46	26.82	10.65				
AB	21.96	13.51	8.45				
Bw	20.42	13.74	6.68				

**Texture (sand/silt/clay: % of sand. silt and clay) determined by the pipette method (MAPA, 1994) according to (Soil-Survey-Staff, 2014); Stones: coarse soil material (> 2 mm); bulk and real density. pH (H2O) and EC (electrical conductivity) according to (MAPA, 1994); Pav (available phosphorus) according to (Olsen and Sommers, 1982);TN (total nitrogen) and TOC (total carbon) analyzed with a LECO-CHN 2000 elemental analyzer; oxC (easily oxidizable carbon) according to (Walkley, 1947); CEC (cation exchange capacity) according to (Mehlich, 1953); FC (field capacity);

PWP (permanent wilting point) and AW (available water) according to (MAPA, 1994) and WHC (water holding capacity) according to (D. López-Marcos et al., 2019).

Annex 2. Thining data

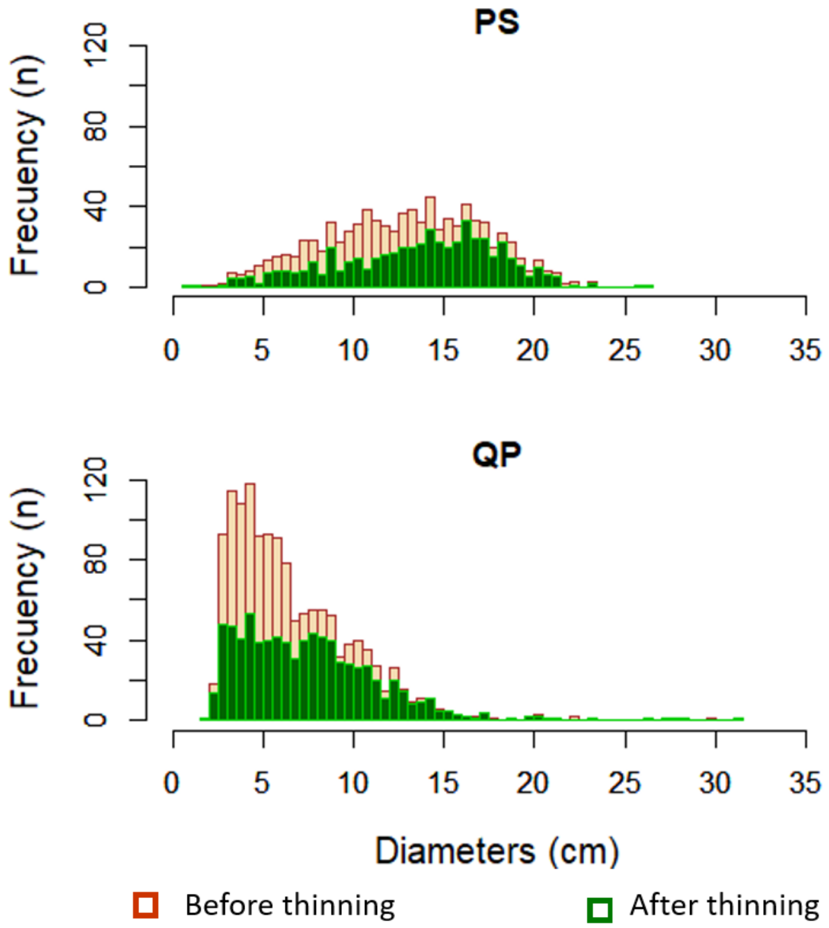


Figure 13. Frequency (n) of diameters (cm) thinned (brown) and unthinned (green) by species (PS-*Pinus sylvestris* L.; QP-*Quercus pyrenaica* Wild.)

Annex 4. Impact of this study on the 2030 Agenda´s SDGs (Sustainable Development Goals)

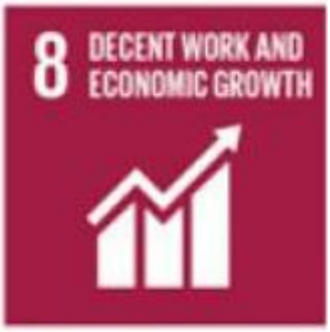
El Real Decreto 822/2021, de 28 de septiembre, por el que se establece la organización de las enseñanzas universitarias y del procedimiento de aseguramiento de su calidad, establece en su artículo cuarto, apartado 2, que los planes de estudio deben ser referente de valores democráticos, como la igualdad, y estar alineados con los Objetivos de Desarrollo Sostenible de la Agenda 2023 de Organización de las Naciones Unidas.

Siguiendo la recomendación del Vicerrectorado de Ordenación Académica, que considera que la asignatura más transversal del plan de estudios es el Trabajo Fin de Carrera (TFG/TFM), se redacta este anexo que recoge una breve reflexión sobre la relevancia del trabajo en diferentes dimensiones de los objetivos de desarrollo sostenible (ODS).

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future.

At its heart are the Sustainable Development Goals (SDGs), which are an urgent call for action that recognizes that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth, all while tackling climate change and working to preserve our oceans and forests.

The research “Small-scale early effects of thinning on the topsoil in Scots Pine-Pyrenean Oak mixed stands approached through new computational tools.” is directly related to some of these goals:



It contributes to the sustainable exploitation the forest economic resources while providing work for managers with a high level of technical specialization and workers in a rural environment with a high rate of depopulation.

It contributes to the mitigation of climate change as it helps to design more efficient soil carbon sequestration strategies.

It contributes to the conservation of endangered terrestrial ecosystems such as forests of Pyrenean-oak since allows the development of their earlier stages in mixed pine-oak forests allowing also the biodiversity conservation of their understory by the sustainable forest management of complex forests.