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Climate Change and Silvopasture: The Potential of the Tree and Weather to Modify Soil Carbon Balance

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Abstract: Silvopastoral systems play an important role in climate change mitigation, considering their effect on soil carbon sequestration. In silvopastoral systems, sewage sludge can be used as fertiliser, which is promoted by the Circular Economy Package of the European Commission. This study evaluates the soil chemical properties (pH, carbon), tree growth (top height, canopy cover), and their interactions from 1998 to 2012 in a *Pinus radiata* D. Don silvopastoral system in northwest Spain. Nine fertilisation treatments were applied: three doses of sewage sludge (160, 320, and 480 kg total N ha^{-1}) or no fertilisation, all with or without liming, and mineral fertiliser with no liming. Soil pH decreased over time due to cations extraction by trees and pine needles deposited in the understory. Tree growth increased light interception, decreasing soil carbon incorporation. The interannual variation of carbon also depended on weather conditions. Initially, fertilisation increased soil pH and carbon, but without compensating cations extraction over time. Therefore, it is advisable to apply amendments in the middle years of the plantation. Tree management is also needed to decrease competitiveness and enhance carbon incorporation. Moreover, control plots should be linked to the next CAP 2023–2027 eco-schemes accounting for soil carbon levels.

Keywords: agroforestry; sewage sludge; fertilisation; circular economy; policy; CAP

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Citation: Ferreiro-Domínguez, N.; Rodríguez-Rigueiro, F.J.; Rigueiro-Rodríguez, A.; González-Hernández, M.P.; Mosquera-Losada, M.R. Climate Change and Silvopasture: The Potential of the Tree and Weather to Modify Soil Carbon Balance. *Sustainability* **2022**, *14*, 4270. https://doi.org/10.3390/su14074270

Academic Editor: Pablo Peri

Received: 21 January 2022
Accepted: 31 March 2022
Published: 4 April 2022

1. Introduction

Agroforestry is defined as the deliberate integration of woody vegetation with a lower story agricultural production [1]. Agroforestry, and therefore silvopasture, is intended to be one of the most useful tools to achieve the upgrading of the rural areas throughout economic, environmental, and social improvements [2]. Several studies have shown that agroforestry improves the use of the existing resources (ecointensification) which increases the biomass production and, as a consequence, the amount of soil organic matter (OM), being OM the largest carbon (C) reservoir (81%) in the terrestrial ecosystems [1,3]. For this reason, agroforestry has been recognized as a tool for mitigating climate change [1] by the "4 per 1000" initiative [4], but also by several international organizations such as the United Nations (UN) in the Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD) [5]. Therefore, agroforestry is expanding across Europe, despite the lack of technical knowledge transfer and adequate policies promoting agroforestry practices at the field level [1].

P. radiata D. Don is the most used conifer in afforestation in Galicia (northwest Spain), covering a total area of around 96.177 ha according to the data offered by the IV National Forest Inventory [6]. In 2016, this conifer represented 15.20% of the Spanish total forest logging, being one of the most important productive species in this country [7]. Moreover, *P. radiata* has been widely used as tree species in the establishment of silvopastoral systems in Galicia, as well as in other regions of Europe [8,9] and the world [10,11]. In this type of agroforestry system, *P. radiata* favours C sequestration due to its high growth rate compared to other conifer and broadleaved species [12–14]. However, the soil C sequestration potential and other soil properties such as the pH depend on multiple factors such as weather conditions or tree and soil management [15]. The influence of tree management on soil carbon sequestration has recently gained importance due to an increasing concern about climate change [16]. Several studies have shown that tree management plays an outstanding role in the tree-understory-soil interaction that affects soil properties such as pH or OM [14,17,18]. However, experiments such as this study, with more than 10 years of experimentation in the field, are scarce and necessary to evaluate in the medium and long term the tree–understory–soil interaction and its influence on climate change mitigation.

Galician soils usually tend to be acidic, limiting both pasture production and tree growth [19]. High acidic soils are associated with several toxicities such as those derived from aluminium, deficiencies (calcium), and other plant restricting conditions [20]. In Galicia, liming and mineral fertilisation are the main practices to increase agricultural production. Sewage sludge (SS) could be used as organic fertiliser due to its high OM, macronutrients, and micronutrients content [21]. Moreover, recent studies have shown that the partial or total substitution of mineral fertilisers by organic fertilisers such as SS could be a viable alternative to adopt the Circular Economy Package of the European Commission in the farms [22]. When SS is used as fertiliser, N should be considered the main indicator to set the different doses of SS to be applied to the soil [23]. However, it is also important to take into account that heavy metals concentration in the SS is usually higher than in the soil [24]. In Europe, the Directive 86/278/CEE [25], and in Spain the Royal Decree 1310/1990 [26] regulate the use of SS as fertiliser to diminish the inherent risk of heavy metals toxicity to the soil, plants, and humans.

This study hypothesizes that in silvopastoral systems the fertilisation with SS as well as mineral fertilisation and liming increases the tree growth and therefore assumes that soil chemical properties such as the pH or the carbon are modified in the long term. The main goal of this study was to establish a relationship between silvopasture and soil chemical properties to determine the potential of this agroforestry practice on the mitigation and adaptation to climate change in Galicia. Therefore, specific objectives of this study were: (i) to evaluate changes in soil chemical properties (pH and carbon), (ii) to quantify the tree growth (top height and canopy cover), and (iii) to establish relationships between the variation of soil chemical properties and the tree growth during the period 1998–2012 in a silvopastoral system established on an acidic forest soil under *P. radiata* fertilized with SS in 1998, 1999, and 2000.

2. Materials and Methods

2.1. Characteristics of the Study Site

The experiment was carried out in Pol (Lugo, Galicia, north-western Spain, European Atlantic Biogeographic Region), at an altitude of 530 m above sea level. Galicia is a transition zone between the Atlantic and Mediterranean climates with mild winters and warm summers. This region is characterised by high rainfall levels, with more than 1000 mm per year across almost the entire region, and dry summer months, often resulting in moderate drought conditions.

The experiment was carried out on an afforested land settled on quartzite as parent rock material, with a loam-clay-sandy texture (62.9% sand, 26.4% clay, and 10.7% silt), classified as Umbrisol [27] and whose depth is above 50 cm. Before establishing the study, composite soil samples were collected in the area to ascertain the initial characteristics of the soil. The soil was acid (soil pH of 4.97) with an OM concentration of 12.3%. The total N concentration was high (0.52%), but the total concentration of P (0.03%) was low, as well as the concentrations of K, Ca, Mg, and Na extracted with $BaCl_2$ (cmol(+) kg^{-1}) (K: 0.13; Ca: 1.35; Mg: 0.41; and Na: 0.49), indicating a low Cation Exchange Capacity and a high Al saturation percentage (55.13%), which usually implies toxicity for plants. Moreover, the heavy metals concentrations in the soil were low and far below the limit allowed by law regarding the application of SS as fertiliser in agriculture set by the European Union Directive 86/278/CEE [25] and Spanish Royal Decree 1310/1990 regarding soils with pH lower than 7 [13,26]. Over time, the different fertilisation treatments established in this study increased the soil pH and reduced the saturated Al percentage in the interchange complex, which increased the pasture production in the system [13].

2.2. Experimental Design

The study was established in a five-year-old *P. radiata* plantation in 1997. Before the experiment, tree density was 1667 trees ha^{-1} and the mean height and diameter of the trees were 2.15 m and 5.19 cm, respectively, (height standard error was 0.12 m and diameter standard error was 0.29 cm). In October 1997, the existing scrub in the understory of the tree plantation was cleared with a rotary brush cutter, and later the soil was ploughed before the establishment of the plots. Twenty-seven plots were established with an area of 96 m^2 each, delimited by plantation lines, with each plot including a total of 25 trees presented within each 5 × 5 trees square.

In autumn 1997, the plots were fertilised with 120 kg P_2O_5 ha^{-1} and 200 kg K_2O ha^{-1} and sown with a mixture of 25 kg ha^{-1} of *Lolium perenne* L. cv "Brigantia", 10 kg ha^{-1} of *Dactylis glomerata* L. cv "Artabro" and 4 kg ha^{-1} of *Trifolium repens* L. cv "Huia". The experiment was settled as a randomised block design with three replicates and nine treatments. The nine tested treatments were a no fertilisation (NF) treatment and three SS doses based on its N addition to soil (S1: 160 kg total N ha^{-1}; S2: 320 kg total N ha^{-1}; and S3: 480 kg total N ha^{-1}) with or without liming (2.5 t $CaCO_3$ ha^{-1}). In the no-limed plots, a control mineral treatment (MIN) was also included in which 500 kg of 8% N—24% P_2O_5—16% K_2O ha^{-1} complex fertiliser was applied from 1998 to 2006 following the traditional fertilisation usually carried out in the Galician grasslands. The mineral treatment was not included in the limed plots because the combination of lime with mineral fertiliser is not a conventional practice in the area. Sewage sludge was applied by hand in March 1998, 1999, and 2000. Moreover, to evaluate the residual effect of the SS and to incorporate some sludge patches found in the plots previously fertilised with SS (mainly in high doses) into the soils, mineral fertiliser was applied in all plots fertilised with SS from 2001 (last application of SS was in 2000) to 2006 when the last application of mineral was carried out in the plots with the mineral treatment.

2.3. Sewage Sludge

The anaerobically digested SS came from the wastewater treatment plant managed by the company Gestagua S.A. in the city of Lugo (northwest Spain). The sewage sludge properties used in this study were previously described by Mosquera-Losada et al. [13]. The SS doses were based on the percentage of total N and dry matter of the SS and taking into account that around 25% of the total N from anaerobically digested SS is available in the first year after application [28]. Furthermore, the concentration of heavy metals in the SS was far below the legal maximum limit regarding SS addition to soils with a pH under 7, as indicated in the Spanish Royal Decree 1310/1990 [26].

2.4. Weather

Ombrothermic diagrams were carried out with the mean monthly temperatures and precipitation for the 1998–2002 and 2006–2012 periods in comparison with the mean values over the last 30 years (1981–2010). Temperature and precipitation data were collected from the closest regional weather station from the Galician Meteorological Service Network. The data of November and December 2001 were not available for the mean monthly temperatures and precipitation due to technical issues at the weather station.

The dry season index (Precipitation < 2*Temperature) was also estimated [29].

2.5. Field Samplings and Laboratory Analyses

During the periods 1998–2002 and 2006–2012 composite soil samples were collected each year in each plot in December at a soil depth of 25 cm as required in the Royal Decree 1310/1990 [26]. Soil samples were air-dried and sieved at 2 mm and ground with an agate mortar. The pH determination was carried out in water with a 1:2.5 soil-water ratio [30]. In 1998, 1999, 2000, 2006, 2007, 2008, and 2009 the soil carbon (SC) was estimated by oxidation of the total OM with potassium dichromate and sulphuric acid. The excess of dichromate was assessed with Mohr salt [31]. However, in 2001, 2002, 2010, 2011, and 2012 the SC was determined with a LECO CNS-2000 analyser [32]. The comparability of the C data obtained with the two estimation methods was possible due to the establishment of regressions, which did not show significant differences between both methods. Moreover, it is important to be aware that, in the Galician soils, carbonates (inorganic carbon) are rapidly dissolved and therefore the humic forms (organic carbon) are the dominant ones in the soils [33].

The total height of the nine central trees of each plot was measured in 1998, 1999, 2000, 2004, 2006, 2007, 2009, 2011, and 2012. The mean top height was calculated as the mean height of 20% of the nine thickest trees in the plot [34]. Tree height was measured with a telescopic pole when trees were below 8 m and with a vertex when trees exceeded it. Moreover, the crown diameter of the nine central trees of each plot was also measured in 1998, 2004, and 2006 to determine the percentage of tree canopy cover. A tape measure and a vertex were used for measuring these variables. Pruning labours were carried out in 2002 to improve wood quality.

The percentage of pine needles in the understory, regarding the total biomass, was determined by randomly collecting two biomass samples in each plot. The samples were cut with an electric hand clipper at a height of 2.5 cm (0.3 m $\times$ 0.3 m) in July during the periods 1998–2002 and 2006–2012. The biomass in the unsampled plot area was also cut and removed to allow for even regrowth in all plots. At the laboratory, samples were separated by hand according to the different species, senescent material, and pine needles, and then dried (72 h at 60 °C) to determine their composition on a dry weight basis. Pine needles accumulated in the understory were removed from the soil of the total area of plots after biomass sampling every year to know the annual biomass of accumulated needles in the understory.

2.6. Statistical Analysis

The data obtained for each variable in all years were analysed with repeated ANOVA measures (proc glm procedure), and Mauchly's criterion was used to test for sphericity. If the sphericity assumption was met, then the univariate approach output was used. Otherwise, multivariate output (taking into account Wilks' Lambda test) was used. The statistical model used was $Y_{ijk} = \mu + A_i + T_j + B_k + AT_{ij} + AB_{ik} + TB_{jk} + \varepsilon_{ijk}$, with Y_{ijk} being the variable, μ the mean of the variable, A_i the year i, T_j the treatment j, B_k the block k, AT_{ij} the year–treatment interaction, AB_{ik} the year–block interaction, TB_{jk} the treatment–block interaction, and ε_{ijk} the error.

The data obtained for each variable in each year were also treated by using an ANOVA (proc glm), but with this other statistical model $Y_{ik} = \mu + T_i + B_k + TB_{ik} + \varepsilon_{ik}$, with Y_{ik} being the variable, μ the mean of the variable, T_i the treatment i, B_k the block k, TB_{ik} the treatment–block interaction, and ε_{ik} the error.

The least-significant difference (LSD) test was used for subsequent pairwise comparisons ($p < 0.05$; a = 0.05) if the ANOVA was significant.

Linear regressions were calculated to estimate the relationship between the variation of soil chemical properties and tree growth.

The statistical software package SAS (2001) was used for all statistical analyses [35].

3. Results

3.1. Weather

Figure 1 shows that in 1999 (1233.3 mm), 2000 (1340.7 mm), 2008 (1222.3 mm), 2009 (1208.6 mm), and 2010 (1303.9 mm) the annual precipitation was higher than the mean precipitation over the last 30 years (1071.5 mm). However, 2007 (734.4 mm), 2011 (903.3 mm), and 2012 (781.8 mm) had lower annual precipitation than the annual 30 years mean for the study area. The annual mean temperatures during the studied period were warmer compared to the mean temperature over the last 30 years (11.6 °C), especially in 2006 (12.8 °C) and 2011 (13 °C), when the mean annual temperature raised to more than 1 °C in comparison with the historical data. The mean daily temperatures of the coldest (November, December, January, and February) and the warmest (June, July, August, and September) months during the studied period were 7.1 °C and 17.6 °C, respectively.

Finally, according to the dry season index, drought periods were observed in almost all years during the summer (July, August and September). Some particularities were observed in 1998 (two drought periods in June and August), 2000, 2001, and 2005 (earlier drought in May and June) but also in 2011 when it was found a lack of precipitation in winter and an early drought in June.

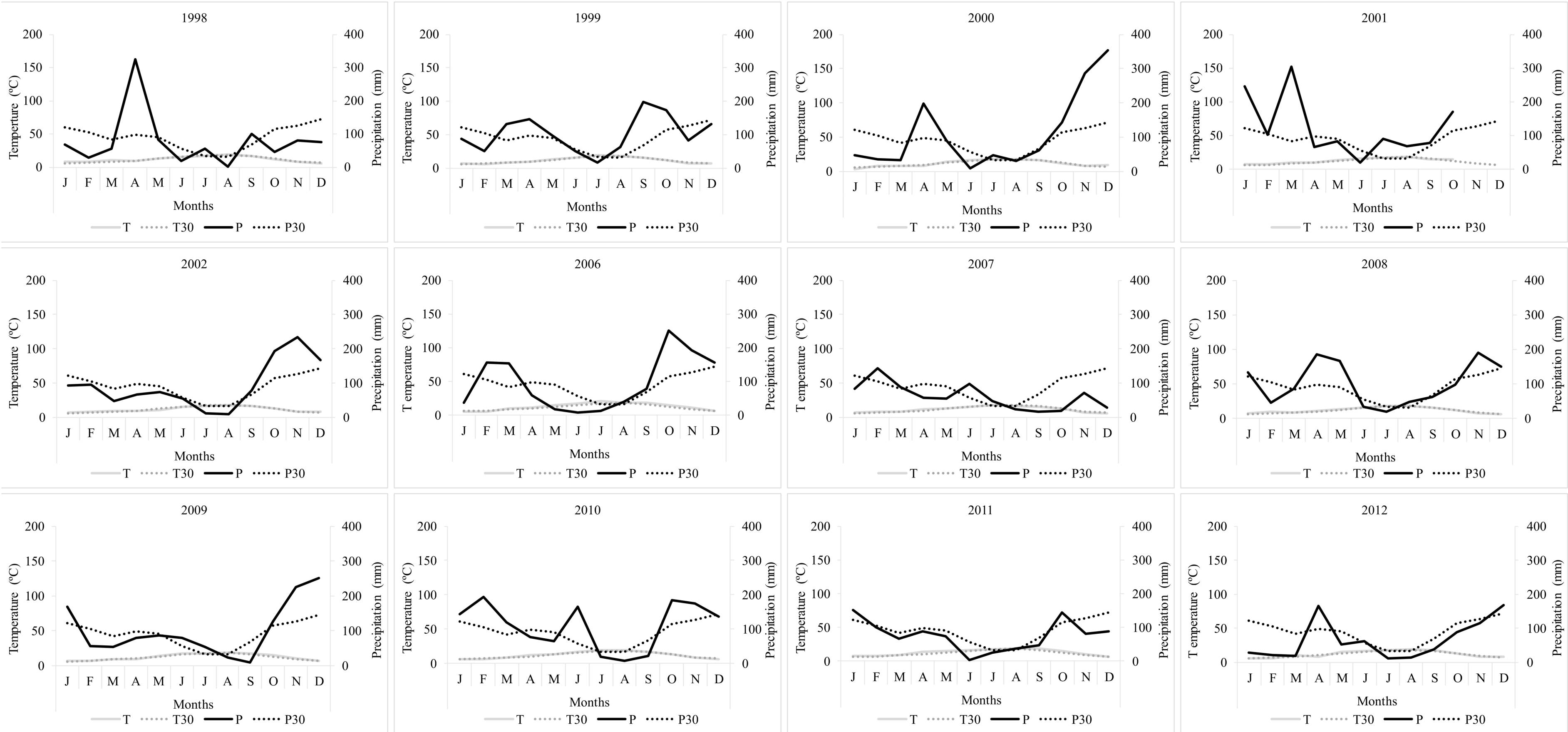

Figure 1. Monthly precipitation and mean temperatures for the study area from 1998 to 2012 and mean data for the last 30 years (1981–2010). T: mean monthly temperature (°C), T30: mean temperature over the last 30 years (°C), P: monthly precipitation (mm), and P30: mean precipitation over the last 30 years (mm). These curves are indicative of periods of droughts when the line of the precipitation is below the line of temperature on a 1:2 axis scale.

3.2. Soil

3.2.1. Soil pH

A significant effect of the year on soil pH was observed ($p < 0.001$). Soil pH was generally reduced from the beginning to the end of the experiment (Figure 2). The highest values of soil pH were found in 1998 and 2002, while the lowest values appeared in 2006 and 2010. Moreover, soil pH was modified by treatments in 1999 ($p < 0.01$), 2000 ($p < 0.001$), 2001 ($p < 0.05$), and 2009 ($p < 0.05$) (Figure 3). In this study, liming increased soil pH when the lime was combined with SS in 2000 (S1, S2, and S3) and 2001 (S1). Regarding SS addition to the soil, in limed plots, soil pH was higher in S2 and S3 compared to the NF treatment in 2000. On the contrary, in 2001, soil pH increased with S1 in comparison with S2 and S3 when lime was also applied. The positive effect of S1 on soil pH was also observed in the no limed plots in 2009 compared to S2 and NF treatment. Finally, MIN generally presented a lower soil pH value than the other treatments, except for the NF treatment without liming.

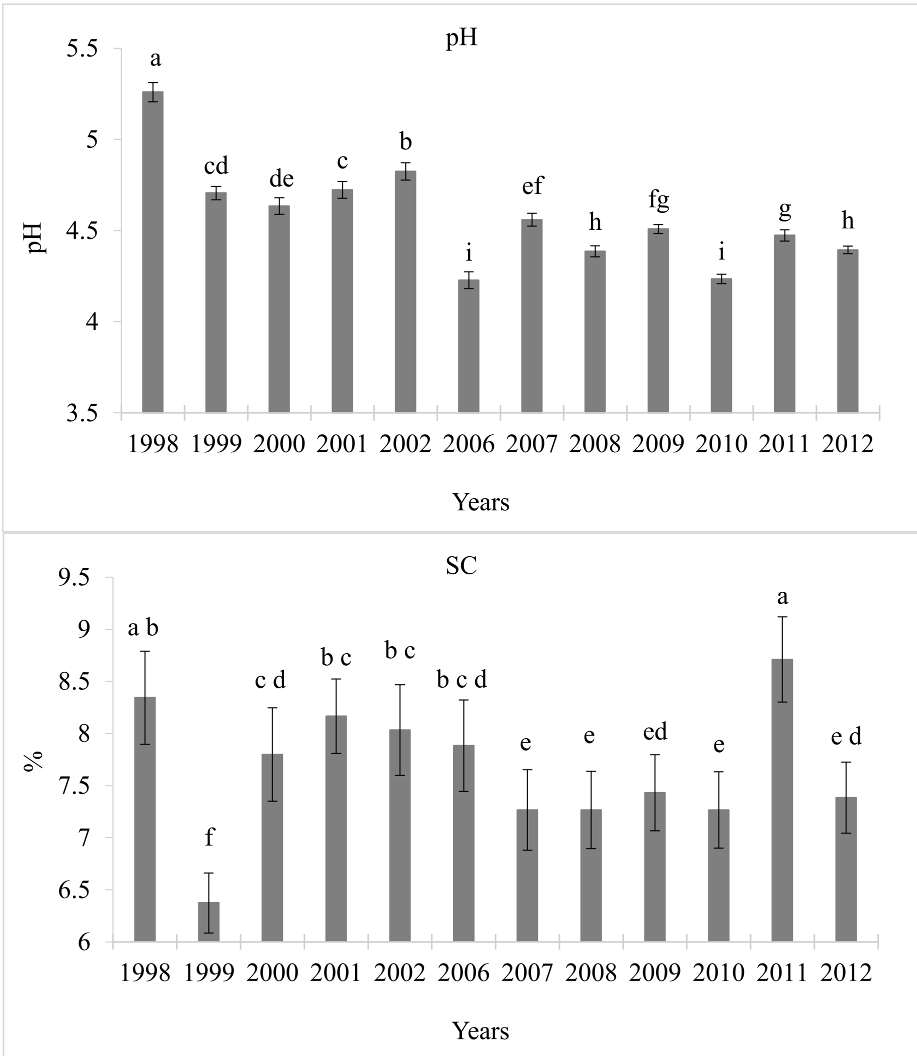

Figure 2. Mean soil pH and levels of soil carbon (SC) (%) through the studied period (1998–2012) for all experimental plots. Different lowercase letters indicate significant differences between the years. Bars in each column indicate the standard error of the mean.

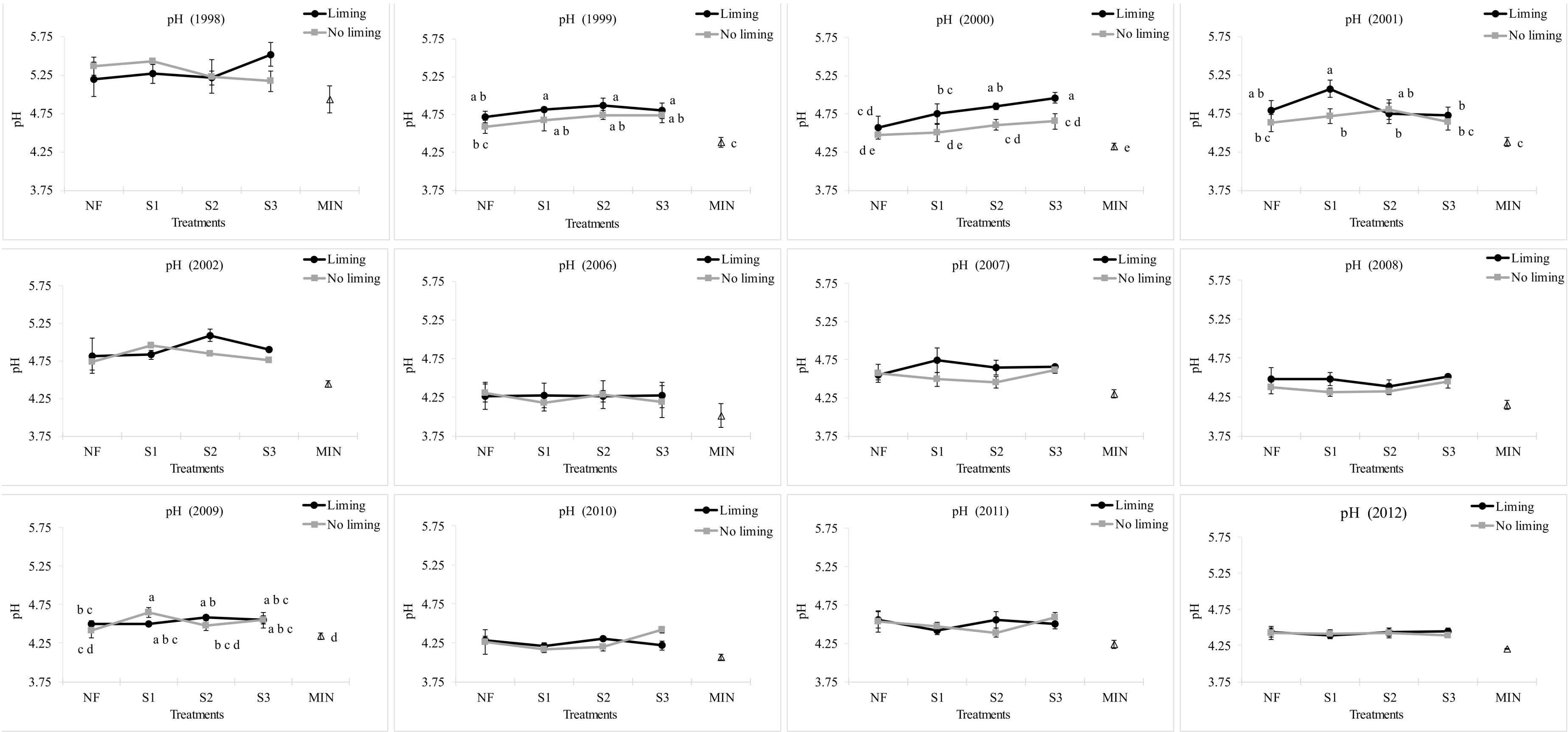

Figure 3. Soil pH under each treatment through the studied period (1998–2012), separated for each lime level. NF: no fertilisation; S1: low sewage sludge dose (160 kg N ha^{-1}); S2: medium sewage sludge dose (320 kg N ha^{-1}); S3: high sewage sludge dose (480 kg N ha^{-1}); and MIN: mineral fertilisation. Different lowercase letters indicate significant differences between the fertiliser treatments in each year. Bars indicate the standard error of the mean.

3.2.2. Soil Carbon

Soil carbon ranged between 6.37–8.71% (Figure 2), this soil variable being significantly modified by the interaction between year and treatment ($p < 0.001$). In this experiment, the SC generally decreased from 2006 to the end of the experiment, except for 2011. Figure 4 shows that, in 2009, lime added to the soil decreased the SC levels when the S3 dose was applied. Regarding SS effect on SC, in 1999, in the limed plots, the S3 dose increased the SC compared to S1. Moreover, in 2009, in the limed plots, it was also observed that the SC was lower in the NF treatment than in S1 and S2. A negative effect of the NF treatment on the SC levels was also observed in the plots without lime compared to S3 in 2006 and 2007 and S1 in 2008 and 2010. Finally, in the no-limed plots, the MIN treatment decreased more the SC than S3 in 1999 and all fertilisation treatments in 2009 (S1, S2, and S3).

3.3. Tree

3.3.1. Tree Top Height

Tree top height grew steadily during the study period until it finally reached a mean of 18.78 ± 0.40 m in 2012 (Figure 5). Tree top height was significantly modified by the treatments established in 2000, 2006, 2009, 2011, and 2012 ($p < 0.05$). A positive effect of liming on the top height of the trees was found under the NF treatment from the beginning to the end of the study (years 2000, 2006, 2009, and 2011). Sewage sludge applications (S1, S2, and S3) combined with liming and no liming increased tree top height compared to the NF treatment without lime in 2006, 2009, 2011, and 2012. Similarly, MIN increased the tree top height when compared to the treatment that did neither receive lime nor sludge (no limed—NF) in 2000, 2006, 2009, 2011, and 2012 while liming S1 treatment showed a higher tree top height than limed—NF treatment just in 2011.

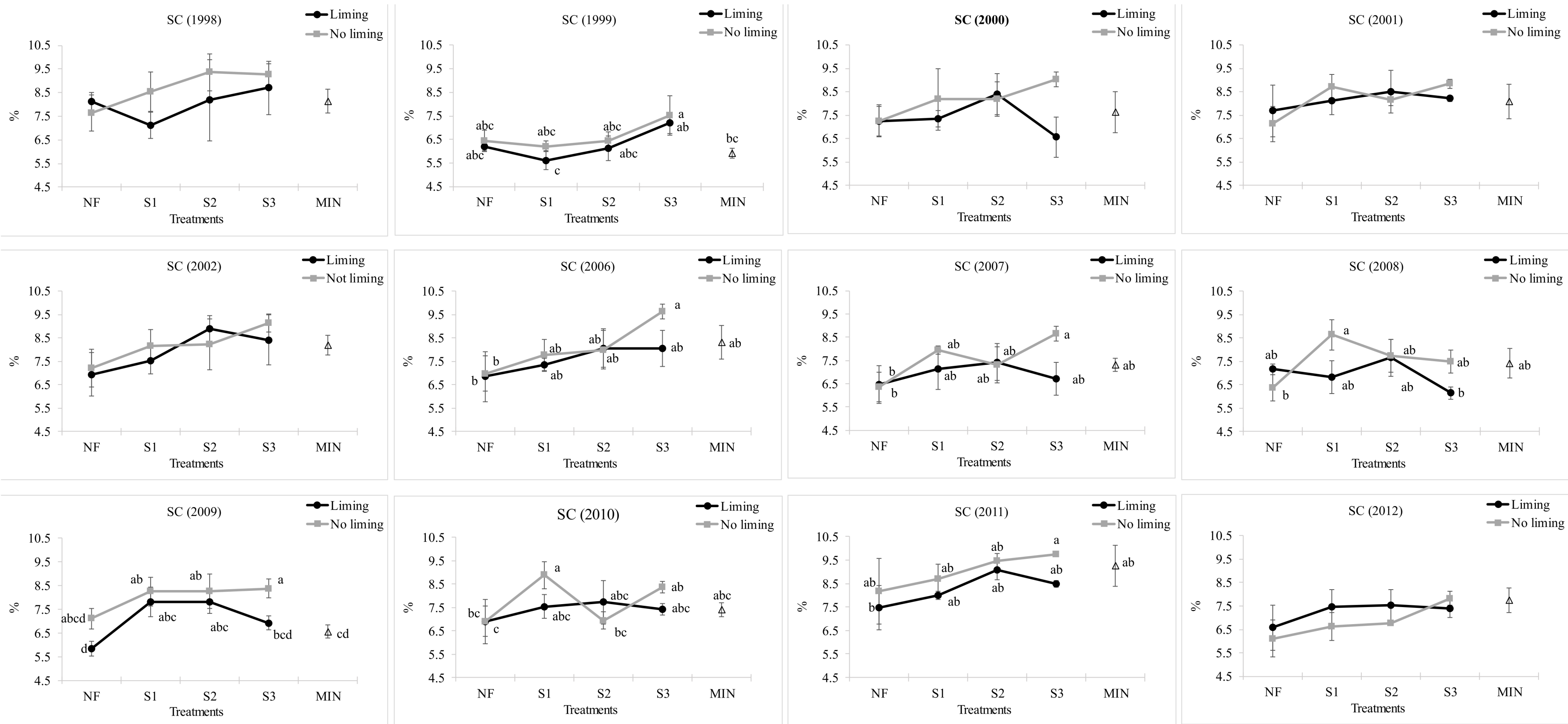

Figure 4. Soil carbon (SC) (%) values under each treatment through the studied period (1998–2012), separated for each lime level. NF: no fertilisation; S1: low sewage sludge dose (160 kg N ha^{-1}); S2: medium sewage sludge dose (320 kg N ha^{-1}); S3: high sewage sludge dose (480 kg N ha^{-1}); and MIN: mineral fertilisation. Different lowercase letters indicate significant differences between the fertiliser treatments in each year. Bars indicate the standard error of the mean.

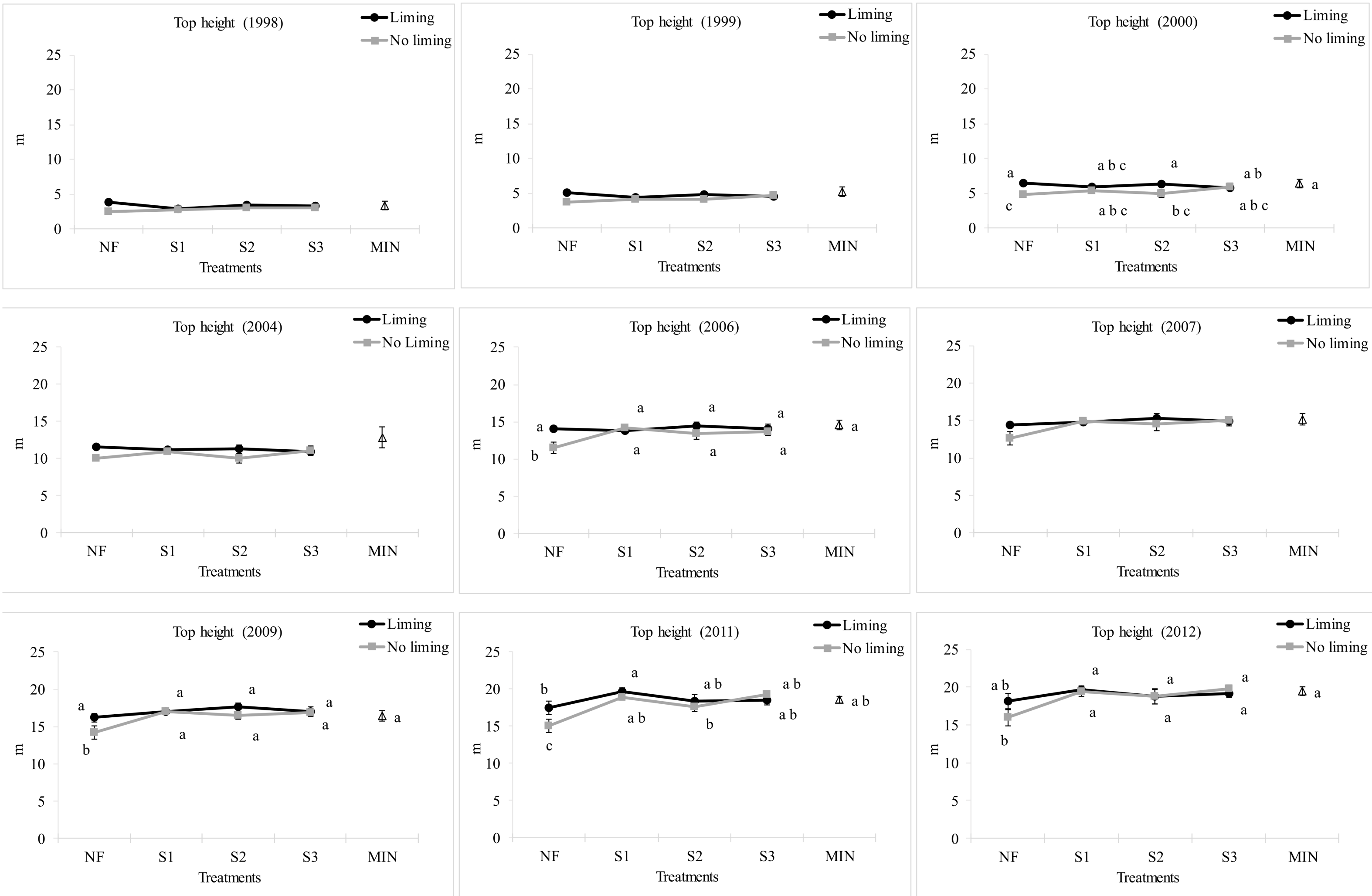

Figure 5. Top height values (m) under each treatment through the studied period (1998–2012), separated for each lime level. NF: no fertilisation; S1: low sewage sludge dose (160 kg N ha^{-1}); S2: medium sewage sludge dose (320 kg N ha^{-1}); S3: high sewage sludge dose (480 kg N ha^{-1}); and MIN: mineral fertilisation. Different lowercase letters indicate significant differences between the fertiliser treatments in each year. Bars indicate the standard error of the mean.

3.3.2. Tree Canopy Cover

Canopy cover was not affected by treatments (Figure 6). However, a tendency related to liming favouring canopy cover development when NF or S2 were applied in 1998 and 2004 can be observed. Canopy cover response to the SS and MIN fertilisation was not clear in any of the years of study, but both treatments seem to favour a sooner canopy cover closure, as observed for S2, S3, and MIN in 2006.

3.3.3. Pine Needles in the Understory

The year had a significant effect on the percentage of pine needles in the understory regarding the total biomass ($p < 0.001$). Figure 7 shows that the percentage of pine needles in the understory increased over time, mainly from 2006. However, a lower percentage of pine needles in the understory was observed in 2011 compared to the three previous years and the last year of the study.

3.4. Soil and Tree Relationships

Significant linear regressions were found pairing tree top height–soil pH and tree canopy cover–soil carbon to determine how forest cover affects soil parameters. Regression between tree top height and soil pH provided the equation pH = $-0.04 \times$ top height + 5.06 with an $R^2 = 0.62$ ($p < 0.001$) (Figure 8). Therefore, an inversely proportional relationship between the soil pH and the tree top height was observed, in which an increase in tree top height implied a reduction in soil pH.

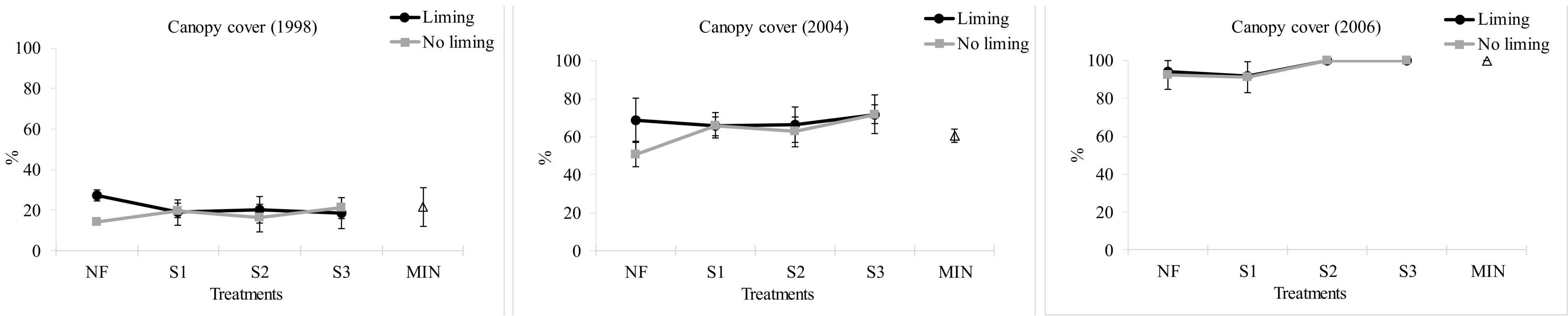

Figure 6. Tree canopy cover (%) under each treatment through the studied period (1998–2012), separated for each lime level. NF: no fertilisation; S1: low sewage sludge dose (160 kg N ha^{-1}); S2: medium sewage sludge dose (320 kg N ha^{-1}); S3: high sewage sludge dose (480 kg N ha^{-1}); and MIN: mineral fertilisation. Bars indicate the standard error of the mean.

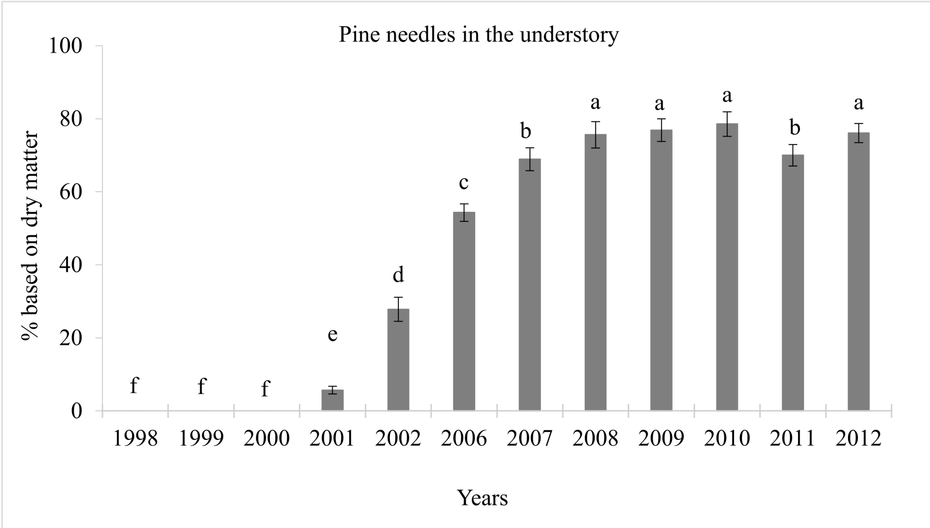

Figure 7. Pine needles in the understory (%) as based on dry-matter regarding the total biomass through the studied period (1998–2012). Different lowercase letters indicate significant differences between the years. Bars in each column indicate the standard error of the mean.

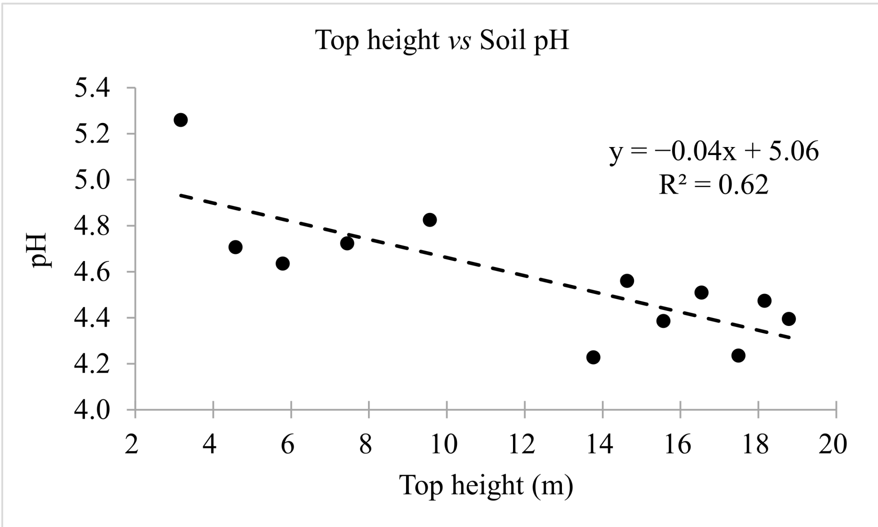

Figure 8. Relation and linear regression between tree top height (m) and soil pH during the studied period (1998–2012).

Paired tree canopy cover and soil SC regression spawned the equation SC = −0.01 × canopy cover + 8.43 with an R^2 = 0.73 (p < 0.001) (Figure 9). Tree canopy cover highest values seem to affect negatively SC values in the way that more canopy cover is associated with less SC.

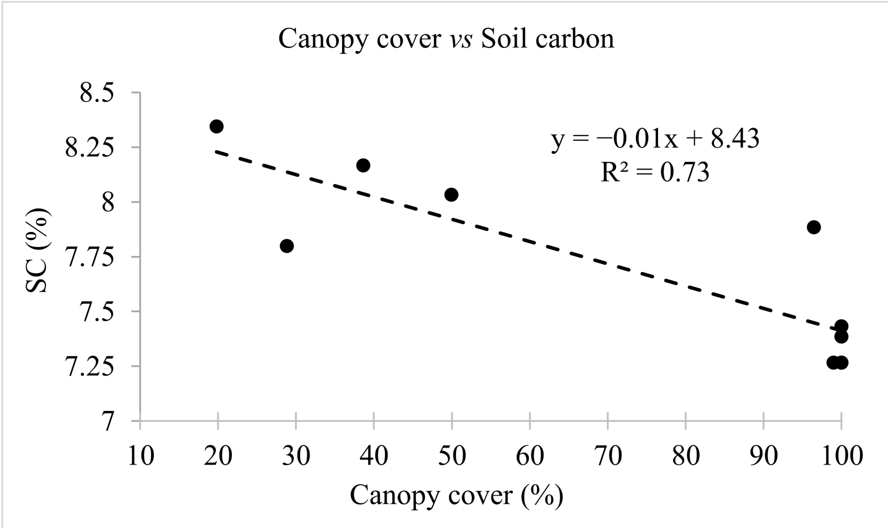

Figure 9. Relation and linear regression between tree canopy cover (%) and soil carbon (SC) (%) during the studied period (1998–2012).

4. Discussion

Tree top height observed in the last year of this experiment (15.95–19.82 m) was within the range established by Sánchez-Rodríguez et al. [36] in Galicia for an age of 20 years in the II (15–19 m) and III (19–23 m) site-quality classes, which indicate the capacity of forested land to grow wood. Moreover, in this study, a positive effect of lime and organic and inorganic fertilisers on the tree top height was observed in the long term compared to the lack of fertilisation treatment. Similar results were previously observed by numerous authors who described that management practices, such as liming and fertilisation, enhance the chemical and physical soil properties and therefore the tree growth, mainly after the establishment of the plantation, which can have a long term effect on the tree development [13,14,37]. Despite the positive effect of liming and organic and inorganic fertilisation on tree growth, these management practices are not generally linked to tree management, probably due to costs. However, in regions such as Galicia, where soil acidity can limit plant growth, the use of SS as fertiliser in silvopastoral systems could be a good alternative to implement the bioeconomy [38] and circular economy [39] objectives of the European Commission through recycling of nutrients and OM from SS. In the case of the canopy cover, a significant effect of the treatments on this tree variable was not found, probably because the canopy closure occurred at an early stage, this factor being similar for all treatments due to the previous competition among trees.

Therefore, in this study, tree growth depended on the soil fertility and a clear influence of the tree growth and the subsequent canopy closure was also observed on the variation of the soil pH and the SC over time. Regarding the soil pH, the top values of soil pH barely are up to 5.3, which indicate that this experiment was established in a very acidic soil [40]. The soil acidity could mainly be explained by the parent rock material generating sandy soils, the acidification usually caused by conifers, and the Galician rainfall regime [41]. The adequate profile of precipitation and temperature generally reduces soil pH because it favours cations extraction. On one hand, these climate conditions increase biomass that takes more nutrients from the soil and, on the other hand, because it facilitates the cations leaching through the soil profile, as probably occurred in this study in 2010 when the annual precipitation (1303.9 mm) was higher than the mean precipitation over the last 30 years (1071.5 mm) [42]. In this experiment, the significant relationship found between soil pH and tree top height allows us to assume that the uptake of soil cations by trees was the predominant process, over lime and SS addition, which decreased the soil pH over time, mainly from 2006 when the fertilisation ceased, as previously described by other authors [43]. Moreover, in this study, both the liming and the fertilisation with SS probably improved the N mineralisation due to the reduction in the C/N relationship [44] which made the uptake of cations by the trees and the understory vegetation more relevant than the beneficial effect of liming and SS on the soil pH [45]. In addition, it should be noted that the beneficial effect of lime on the soil pH decreased in the medium and long term. However, the beneficial effect of the SS on soil pH was maintained throughout the study [13], mainly when the high doses of SS (S3) were applied in comparison with the mineral and the no fertilisation treatments, but without compensating cations extractions by plants. The positive effect of the fertilisation with SS on soil pH could be explained by the Ca input into the soil [46]. Thereby, although the low SS doses (S1) implied a lower total input of Ca (S1: 230 kg $CaCO_3$ ha^{-1}) into the soil than the other doses (S2: 461.4 kg $CaCO_3$ ha^{-1} and S3: 692.4 kg $CaCO_3$ ha^{-1}), S1 increased more the soil pH than S2 and S3 in 2001 and S2 in 2009. The negative effect of S2 and S3 on soil pH compared to S1 could be due to the higher pasture production obtained when the soil was fertilised with S2 and S3 compared to S1, in which the soil conditions remained very poor, as happened in 2001 [13]. The higher soil pH and lower pasture production associated with S1 at the beginning of the study [13] probably had an early positive effect on tree top height, which was maintained until the end of the study. Moreover, the MIN fertilisation, applied in all the experimental plots from 2001 to 2006, could have also increased cations extraction from the soil by the understory vegetation, but mainly by tree roots due to their potential to explore a large soil volume and deeper soil layers in comparison with the understory vegetation roots [47]. Therefore, in this experiment, it seems that to maintain an adequate range of soil pH, the application of additional amendments with higher pH than the soil (lime, SS) is advisable in the middle years of the tree plantation, which may compensate the extractions of the different cations by the trees. Finally, the soil pH could also have been reduced in the long term due to the deposit of acidifying materials from the trees such as pine needles, mainly from 2006 when tree canopy reached the closure [48].

In the case of the SC, the values found in this experiment were similar to those described in previous studies developed in the same area (>12.08%) in which more than seven thousand soil samples were analysed under different land uses in the area [49]. The high SC characterizing Galician soils is mainly due to the enormous inputs of OM from the vegetation associated with warm temperatures and adequate water availability throughout the year, which makes Galicia the region of Europe with the highest forest growth rates. The high OM inputs, together with the low soil pH limiting the soil mineralization mechanisms, causes a higher soil OM compared to other Spanish soils where weather limits the biomass incorporation as the main C source in terrestrial ecosystems, and the high pH favours the incorporation and mineralization of the OM in the soil [50]. As in the case of the soil pH, in this experiment, the variation of the SC over time depended on the tree age and the subsequent canopy closure, but also the weather conditions. Thereby, at the beginning of the study, when the influence of the tree canopy was low and the inputs of OM to the soil from trees and pasture were also low, a negative effect of liming and fertilisation with SS was observed on the levels of SC. Thus, in 1999, the liming and the application of SS probably decreased the SC compared to 1998, because these management practices generally increase the mineralization rate of the soil OM [51–53]. Moreover, the larger annual rainfalls registered in 1999 (1233 mm) compared to the mean of the last 30 years (1071.5 mm) probably also increased the mineralization rate of the soil OM, because soil moisture is a key factor in the mineralisation process [28]. From 1999 to 2006, the SC increased, which could be due to the pasture establishment as a major soil OM source from fine roots and senescent material. In general, fine roots are characterised by rapid turnover rates, which significantly influences soil carbon cycling [54]. The application of SS to the soil, mainly the high doses (S3), probably also increased the soil OM due to the high OM content in the SS [28], but also due to the higher inputs of OM (needles) into the soil compared to the no fertilisation treatment, as tree growth was better in the SS treatments [13]. However, from 2006, when the tree canopy reached the closure (>96%), the SC generally decreased to the end of the experiment, despite the pine needles falling down. This result could be explained because the conditions of temperature, humidity, and aeration in the understory were probably negatively affected by the tree canopy growth which reduced the soil biota activity and, therefore, the incorporation of the fallen pine needles into the soil [55]. Moreover, from 2006, the understory vegetation was replaced by the fallen pine needles into the soil, which accumulated at the soil surface without being incorporated into the soil because pine needles break down at a slow rate compared to the leaves of broadleaf species [56]. The significant relationship found in this study between SC and tree canopy cover indicates that the tree canopy cover development influenced SC by modifying crucial processes such as the incorporation and mineralization of the needles' (OM) soil inputs [57,58]. Therefore, in this study, it seems highly advisable to carry out management activities on the plantation (pruning, clearing, or thinning) to improve soil biota activity and to increase the incorporation of the OM into the soil, which could favour the recycling of nutrients in the system as well as the soil C sequestration [59]. These recommendations are in line with the IPCC [16] to enhance mitigation efforts against climate change. Finally, it is also important to be aware that, in 2011, an atypical top SC value was found compared to the previous years. This result could be due to an unusual mean temperature in 2011 (13 °C) compared to the mean temperature over the last 30 years (11.6 °C), which probably fostered pine needles' incorporation into the soil in that year by triggering its decomposition by soil microorganisms [60]. In other experiments established in Galicia, it was also observed that SC depended on, among other factors, the mean temperature of the months before soil sampling [54]. Therefore, in rainy regions such as those in this experiment, small variations of the mean temperature can explain the high interannual variation of SC, as it causes a significant effect on soil microbiota and therefore on the processes they cause. In this context, the next Common Agricultural Policy (CAP) 2023–2027 will include the eco-schemes, which are mandatory schemes for Member States and voluntary for farmers to maximise environmental and climate benefits such as the SC sequestration with direct payments from Pillar 1 of the CAP [61]. In this study, it was found that the levels of SC depended of the weather conditions of a given year. For this reason, control plots should be established to check if the managed plots by the farmers increase the SC compared to the unmanaged plots, regardless of the weather conditions. Eco-schemes offer a new possibility to care for the environment and climate, thus supporting the transition towards more sustainable farming systems and contributing to the net-zero emissions in the agriculture sector in 2050 [62].

5. Conclusions

Tree growth increased cations extraction from soil and modified the understory microclimate, which decreased the levels of soil pH and SC over time. The interannual variation of SC also depended on the weather conditions, because the increase in temperature favoured the incorporation of organic matter into the soil. Moreover, a positive effect of the initial fertilisation with SS on soil pH and SC was observed, mainly in the case of the high doses of SS, which did not compensate for the cations extraction from the soil by the trees in long term. Therefore, the results obtained in this study show that it is advisable to apply additional amendments with higher pH than the soil (lime, sewage sludge) in the middle years of the tree plantation to maintain adequate ranges of soil pH and SC. Tree management is also needed to decrease competitiveness and enhance tree growth and carbon incorporation into the soil at the same time, as climate change mitigation may be increased. Moreover, control plots should be linked to the eco-schemes of the next Common Agricultural Policy (CAP) 2023–2027 to account for the SC levels for future policies.

Author Contributions: Supervision, M.R.M.-L.; Writing—Original draft, N.F.-D.; Writing—Review and editing, F.J.R.-R., A.R.-R., M.P.G.-H. and M.R.M.-L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Xunta de Galicia, Consellería de Educación, Universidade e Formación Profesional through the Consolidation funds 2019–2022. N.F.-D. was funded by Xunta de Galicia, Consellería de Educación, Universidade e Formación Profesional through the Programa de axudas á etapa posdoutoral modalide B (DOG nº 213, 08/11/2019 p. 48018, exp: ED481D 2019/009) and the Pilot Program of the University of Santiago de Compostela (USC) for the hiring of distinguished research staff—call 2021, funded under the collaboration agreement between USC and Banco Santander, for the years 2021–2024. F.J.R.-R. was funded by the Spanish Government through the Margarita Salas Grants funded by the NexGenerationEU programme (Spanish R.D 289/2021).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Divina Vázquez-Varela, Pablo Fernández-Paradela, Teresa Piñeiro-López, and Manuel Cotado-Rodríguez for their help with field and laboratory work.

Conflicts of Interest: The authors declare no conflict of interest.

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