land

MDPI

Article

Soil's Physical, Chemical, and Biological Responses to Different Post-Harvest Management of *Pinus elliottii* in Santa Catarina, Brazil

Ana Carolina de Mattos e Avila [1], Gunnar Kirchhof [2,*], Marlise Nara Ciotta [3], Sandra Denise Camargo Mendes [3], João Frederico Mangrich dos Passos [3], Marieli do Nascimento [4] and Jackson Adriano Albuquerque [4]

[1] Tasmanian Institute of Agriculture, University of Tasmania, Hobart 7005, Australia; ana.avila@utas.edu.au
[2] School of Agriculture and Food Sustainability, The University of Queensland, Brisbane 4067, Australia
[3] Agricultural Research and Rural Extension Company of Santa Catarina, Lages 88502-970, SC, Brazil; marlise@epagri.sc.gov.br (M.N.C.); mendes@epagri.sc.gov.br (S.D.C.M.); joaopassos@epagri.sc.gov.br (J.F.M.d.P.)
[4] Department of Soil and Natural Resources, Santa Catarina State University, Florianopolis 88520-000, SC, Brazil; marieli.nascimento@edu.udesc.br (M.d.N.); jackson.albuquerque@udesc.br (J.A.A.)
* Correspondence: g.kirchhof1@uq.edu.au

Abstract

Post-harvest forest residue management and liming practices can significantly affect soil quality. This study evaluated the impacts of burnt pine harvest residues and lime application methods (surface-applied vs. incorporated) on the chemical and physical properties of a Dystric Cambisol in Southern Brazil. Soil samples were collected at two depths (0–10 cm and 10–20 cm) and analyzed for pH, exchangeable acidity, organic carbon, cation exchange capacity, macroporosity, microporosity, and bulk density. The results showed that changes were more pronounced in the 0–10 cm layer and mainly affected chemical attributes. Incorporated lime increased pH from 4.7 to 5.1, increased base saturation from 17% to 36%, and reduced Al saturation from 45% to 13% in the 0–10 cm layer. Burnt residues alone did not significantly alter soil properties, whereas lime incorporation led to improved chemical conditions and enhanced soil structure, especially in the surface layer. The treatments that maintained pine residues on the surface favored biological processes in the topsoil, while the burning of these residues had variable impacts on soil structure and nutrient availability. These findings highlight the importance of incorporating lime to optimize soil rehabilitation following pine harvesting in subtropical forest systems.

Keywords: limestone; burning; pasture; soil science; chemical attributes; physical attributes; management

check for updates

Academic Editors: Angela Maffia and Adele Muscolo

Received: 14 October 2025
Revised: 19 November 2025
Accepted: 22 November 2025
Published: 27 November 2025

Citation: de Mattos e Avila, A.C.; Kirchhof, G.; Nara Ciotta, M.; Camargo Mendes, S.D.; Mangrich dos Passos, J.F.; do Nascimento, M.; Adriano Albuquerque, J. Soil's Physical, Chemical, and Biological Responses to Different Post-Harvest Management of *Pinus elliottii* in Santa Catarina, Brazil. *Land* **2025**, *14*, 2331. https://doi.org/10.3390/land14122331

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Approximately 25% of the Brazilian native grasslands have been converted to agriculture or plantation forestry in the past three decades [1]. At present, many of these plantation forestry areas are being harvested and progressively changed to pasture, and in some cases, also to produce grain crops such as beans, corn, and soybeans.

In Southern Brazil, *Pinus elliottii* is typically grown for about 20 years before harvest for timber production. Another study in Southern Brazil [2] concluded that pine residue management and the maintenance of residues on the soil surface affect sustainable forest

production. This is considered an effective and recommended practice to ensure that nutrients present in this biomass are returned to the soil through cycling to meet part of the nutritional demand for the next crop cycle. However, some farmers and companies remove residues, usually for energy generation and/or the production of other materials, as illustrated in [3]. For the forest phase, several studies have assessed changes in soil chemical composition [4,5], typically reporting on soil fertility decline and soil acidification [6–9]. The impact on soil's physical attributes, primarily the soil's structure, is generally related to the intensity of forestry operations during tree harvesting, use of harvesting machines, tree transportation to roadsides, and delimbing and wood cutting [10–13]. These studies highlighted the effect on soil's physical properties, largely through compaction [14–17], and its impact on growth and distribution of roots during the forest phase, which then impacts the pasture phase following land-use change. This is understandable when the shallow rooting depth of pastures and crops is considered.

The severity of the effects is largely determined by soil organic matter content and soil texture [18], as these impact attributes such as soil compaction, soil water retention, and the amount of residual wood biomass extracted [15,19]. Area management is also decisive depending on traffic intensity [20], axle load [21], and the types of tires [22] used in agricultural operations.

Due to economic constraints in recent years, there has been a shift in land use from plantation forestry to pasture. Some farmers are shifting their land-use system from reforestation with pine to forage for dairy or beef cattle grazing. This has been more frequent during the past 10 years and is associated with return on investment from forest operations compared to pasture. This is attributed to the long period of 20 years in plantation forestry compared to the shorter cycles of pasture or crop systems, which can yield higher cumulative returns over time despite potentially lower annual returns. Consequently, land-use change is primary driven by economic reasons to increase return on investment over shorter periods of time [23].

Harvesting trees results in considerable soil disturbance due to heavy machinery traffic. This impacts the composition of remaining plant species, successional species, and soil regeneration after tree harvesting [24].

The transition to pasture requires harvesting and removing trees and then managing the tree residue that remains on site. A common practice is burning the residues to facilitate pasture establishment, which will further impact the soil's physical, chemical, and biological attributes. This transition to pasture has a profound impact on soil's physical and chemical attributes, as well as biodiversity, nutrient cycling, the soil's physical attributes, and the hydrological cycle [25].

The management practice entails burning post-harvest residues of pines for area cleaning. This practice causes nutrient losses via runoff during heavy rain and the leaching of basic cations. Additionally, C and N can easily be lost through volatilization influenced by factors such as the type of plant residues, burning conditions, and residue moisture [26].

Maintaining pine residues partially increases nutrient recycling and protects against erosion through maintenance of ground cover [27,28]. The impact of harvest management is also affected by the type of forest, such as legumes (e.g., acacia) or, more commonly, pine plantations. For example, ref. [29] analyzed the influence of black acacia residues on water and soil losses through erosion. Based on their results, they recommended maintaining residues on the soil surface to reduce water and soil losses through water erosion. As a more general recommendation, ref. [30] reported that water and soil losses are higher in agricultural systems with a lower biomass of residues covering the soil.

Following conversion of forests to pasture or grain crops, many farmers correct soil acidity through liming, and nutrient decline through application of mineral fertilizers. The

efficiency of liming depends on the application method, whether by surface broadcast or incorporation. To facilitate pasture establishment on the disturbed sites, soil amelioration is generally limited to chemical soil improvement, such as liming or fertilizer application, with little attention being paid to soil's physical attributes [24]. So, the conversion to pasture necessitates changes in management practices, such as acidity correction and fertilizer application [17].

The action of fire directly or indirectly leads to physical, chemical, and biological modifications in the soil. These effects can be either localized or permanent [31]. A frequently reported effect is the impact of burning on soil organic matter, in particular the more reactive particulate fraction that not only affects physical and chemical attributes, but also biological soil attributes [32–34].

According to [35], burning reduces soil microbial biomass because it disrupts the interplay between soil organic matter and microbial communities; it also decreases the Shannon's microbial diversity [36] and changes the microbial community composition [36,37] and function [36,38,39].

Thus, sustainable soil management practices for the transition from forestry to productive pasture or cropping systems require a thorough understanding of their impact on soil's physical and chemical attributes [40].

We hypothesized that (1) burning pine residues would decrease soil organic matter and microbial activity, consequently reducing soil aggregate stability, nutrient retention, and overall soil fertility; and (2) lime incorporation would enhance cation exchange capacity, porosity, and soil structure by neutralizing soil acidity and promoting aggregation of soil particles.

This study specifically investigates how the burning or retention of *Pinus* residues, combined with different lime application methods (incorporated vs. surface-applied), affects soil fertility, acidity, and structural properties in a Cambisol. We aimed to identify the management strategy that most effectively promotes soil recovery and long-term sustainability during the transition from forestry to pasture.

2. Materials and Methods

2.1. Experimental Site

The study area was in the municipality of Lages, Santa Catarina State, Brazil (Figure 1), at the experimental area of the Experimental Station (27°48′13.5″ S, 50°20′03.5″ W) of the Agricultural Research and Rural Extension Company of Santa Catarina (EPAGRI). The soil was classified as Dystric Cambisol (Loamy Humic).

The landscape is slightly to moderately undulating, with a height above sea level of 900 m. The predominant native vegetation in the region is *Araucaria* (*Araucaria angustifolia*) Forest. The climate is humid mesothermal with mild summers, categorized as Cfb according to the Köppen classification. The annual average precipitation is 1650 mm, with most falling in spring and summer seasons, with the average temperature being 15.9 °C, ranging from 20.1 °C in summer to 11.6 °C in winter [41].

2.2. Site Preparation and Treatment Applications

The native vegetation was cleared 25 years ago and replaced with a plantation of *Pinus elliottii*. The forest stand was harvested after 20 years in December 2018. Standard timber harvesting machines were used, followed by tree trunk removal using logging machines and trucks to transport the trunks off site. Smaller branches, less than 10 cm in diameter, and leaves were left on the ground as pine residue.



Figure 1. Lages location on Brazil's map.

The experiment commenced in May 2019 with the following treatments:

Control: Natural regeneration and regrowth from on-site plant species.

LimeInc + Burn: Fescue seeding after lime incorporation and burning of forest residue.

LimeInc + Res: Fescue seeding after lime incorporating with pine residue left on the soil surface.

LimeSur + Burn: Fescue seeding after burning pine residue and surface liming.

LimeSur + Res: Fescue seeding with surface liming and pine residue left on the soil surface.

The forage species festuca (*Festuca arundinacea*) was sown at a rate of 30 kg ha^{-1}.

Burning was integrated with the liming treatments to reflect common field practices adopted by farmers during land-use conversion, in which residue burning is typically followed by soil acidity correction through lime application.

The experimental design was a complete randomized block, with nine repetitions and a plot size of 5 × 8 m (40 m^2). Lime was applied at a rate of 12 Mg ha^{-1} based on the recommendation of [42]. For the treatments with incorporation (LimeInc), a scarifier set to a depth of 10 cm was used to overcome residue blockage. Burning treatments (Burn) were applied after lime application.

The forage species festuca (30 kg ha^{-1}) was sown in June 2019. Thirty days after sowing, urea was hand-broadcast at a rate of 150 kg N ha^{-1}. When the pasture reached a height of 25 cm, it was cut to a height of 12 cm to simulate animal grazing. Nitrogen fertilization in the form of urea was further applied annually.

2.3. Soil Sampling and Soil Analysis

The soil was collected for physical, chemical, and biological analysis at the end of the summer and winter seasons, with the first sampling (E1) being on 18 March 2022, and the second (E2) on 29 September 2022.

In each plot, undisturbed samples were collected using rings that were 6 cm in diameter and 5 cm in length. These samples were used to measure bulk density and soil water release curves. Disturbed samples were collected to analyze stability of the aggregates and the chemical composition of the soil. Soil was sampled at depths of 0–10 and 10–20 cm.

Soil water release at tensions between 0, 10, 60, and 100 mbar was determined in a sand column [43], and soil water release at tensions between 1, 3, 5, 10, and 15 bar was determined in the Richards Chamber [44]. With the soil water release curve, the volumes of total pores, biopores, macropores, and micropores, as well as field capacity, permanent wilting point, and available water, were calculated. Biopores were defined as pores larger than 300 µm formed by biological activity (e.g., roots and soil fauna); macropores were defined as pores with diameters between 50 and 300 µm that allow the passage of water and air, facilitating infiltration, drainage, and aeration; and micropores were defined as the smallest pores, with diameters below 50 µm, responsible for water holding capacity. Plant available water was calculated as the difference between volumetric water content at field capacity and permanent wilting point [45]. Saturated hydraulic conductivity analysis was measured using a falling head method, as described by [46].

Disturbed samples were used to determine aggregate stability in water using the method of Kemper and Rosenau [47]. Soil granulometry was assessed following the procedure using the pipette method described by [48] and modified by [49]. For chemical analysis, samples were air-dried and sieved to 2.0 mm for pH (H_2O) and content of total phosphorus (P), potassium (K), organic carbon (OC), aluminum (Al), calcium (Ca), magnesium (Mg), and hydrogen plus aluminum (H + Al) [50]. Cation exchange capacity (CECef), sum of bases (SB), base saturation (BS), and aluminum saturation (M) were calculated.

The activities of enzymes involved in the N and P cycles—β-1,4-glycosidase (BG), β-1,4-N-acetyl-glycosaminidase (NAG), acid phosphatase (AP), and arylsulfatase (ARS)—were determined using a fluorescence-based method, as described by [51], and expressed in units of µmol h^{-1} g^{-1}. Dehydrogenase activity (DHA) was determined as a measure of aerobic microbial oxidation of the soil, using water-soluble iodonitrotetrazolium chloride (INT) as an artificial electron acceptor [52]. The lnBG:lnNAG ratio, used as an indicator of potential C:N acquisition activity, and the lnBG:lnAP ratio, an indicator of potential C:P acquisition activity, were calculated from the natural logarithm of the measurements made in this study [53]. The biological results were used to understand which different land management practices affect it, using principal component analysis (PCA).

2.4. Statistical Procedures

The first step for statistical analysis was to evaluate normality using the Shapiro–Wilk test and homogeneity of residual variance using the Bartlett test (significance level of 5%). For response variables not normally distributed, the Box–Cox transformation was applied using logarithmic or square transformation. Once the assumptions of normality and homogeneity were met, analysis of variance was performed for physical and chemical variables via two-way factor analysis, using treatment and time as the factors, to determine if there were significant differences also between samplings. For the attributes that showed significant differences between treatments, means were compared using the following orthogonal contrasts: (1) control vs. other treatments; (2) treatments with burnt pine residues vs. without burnt residues; and (3) incorporated limestone vs. limestone applied to the surface (Figure 1). Multivariate analysis was used to analyze which soil attributes differed between treatments and to separate treatments that differ from each other into groups. For this, principal component analysis (PCA) and dendrograms were performed using the R environment version 2025 [54].

3. Results and Discussion

Immediately after the pine trees were felled, before the experiment, the soil had the following chemical characteristics, as recorded in Table 1, from 0 to 10 cm in depth. According to the CQFS [42] guidelines, the Cambisol initially showed low fertility and strong acidity, with a pH of 4.5, base saturation of 15%, and Al saturation of 45%, indicating potential aluminum toxicity. Calcium, magnesium, and phosphorus levels were low, while potassium was within the intermediate adequate. Overall, the soil was dystrophic, requiring liming and nutrient correction to support crop or pasture establishment.

Table 1. Initial chemical properties of the Cambisol in the experimental area before treatment implementation (post-harvest condition).

Physical–Chemical Attributes	Unit	Value
Organic Matter	$g \cdot kg^{-1}$	39
pH H_2O		4.5
Phosphorus	mg kg^{-1}	6.5
Potassium	mg kg^{-1}	127
Calcium	cmolc dm^{-3}	2.6
Magnesium	cmolc dm^{-3}	1.3
Aluminum	cmolc dm^{-3}	3.4
CECpH7	cmolc dm^{-3}	28.6
Base saturation	%	15
Al saturation	%	45

Figure analysis treatment effects using Tables 2–4 for soil's physical, chemical and biological attributes, respectively, revealed several key points. Our results partially supported the first hypothesis, as burning did not cause significant changes in most soil properties during the evaluation period. However, the second hypothesis was confirmed, with lime incorporation improving both chemical and structural soil attributes.

Tables 2–4 show how much the values are different between samplings, and the overall statistical summary for the properties. Also, the changes in soil attributes were generally more pronounced in the 0–10 cm layer compared to the 10–20 cm layer, as can be seen in the analysis of variance. All the results were analyzed for each layer separately, with the exception of the biological samples that were collected only for the superficial layer (0–10 cm).

The ANOVA results were assessed according to treatment factor, time factor, and interaction treatment–time factor. Physical properties: No effects of interaction treatment–time were observed for any physical properties. There was a time effect on microporosity, macroporosity, biopores, available water, field capacity, and mean weighted diameter in one or both soil layers. Effect of the treatment was observed for macroporosity, biopores, and field capacity only in the 0–10 cm soil layer. Chemicals properties: The effects of the treatment and time were significant for more attributes. Effect of time was observed for phosphorus, potassium, organic matter, aluminum, calcium, magnesium, sum bases, base saturation, and Al saturation—in one or both layers. Effect of treatments were observed for pH, potassium, aluminum, calcium, magnesium, H + Al, effective cation exchange, sum bases, base, and Al saturation—in one or both layers. The biological analyses showed the effect of the treatment–time interaction for NAG, AP, DHA, ARS, and LnNAG:LnAP. The effect of time was observed only for BG and LnGB:LnAP. The effect of treatment was shown for all the biological variables, NAG, AP, BG, DHA, ARS, LnNAG:LnAP, and LnGB:LnAP.

Dendrogram analysis of treatment effects (Figure 2) revealed distinct clustering patterns. All treatments segregated from the control group, indicating significant post-treatment changes in the measured parameters. Notably, the forage seeding treatments

further separated based on the mode of limestone application. Treatments with incorporated limestone (LimeInc + Burn and LimeInc + Res) clustered distinctly from those with surface-applied limestone (LimeSur + Burn and LimeSur + Res). This suggests that the incorporation of limestone exerted a stronger influence on soil attributes compared to burning or retaining pine residues on the surface.

Table 2. Soil's physical attributes under different post-harvest management treatments at two sampling periods (E1 = first sampling; E2 = second sampling) and analysis of variance (ANOVA) by treatment and time, and by their interaction, for the 0–10 and 10–20 cm soil layers.

Sampling	**E1**	**E2**	**E1**	**E2**	**E1**	**E2**	**E1**	**E2**	**E1**	**E2**	**ANOVA**		
(0–10 cm)	Control		LimeInc + Burn		LimeInc + Res		LimeSur + Burn		LimeSur + Res		Factor treatment	Factor time	Factor Treatment–Time
Bulk density	1.34	1.34	1.25	1.21	1.27	1.27	1.31	1.28	1.28	1.36	ns	ns	ns
Total porosity	0.52	0.52	0.54	0.57	0.51	0.56	0.54	0.54	0.55	0.52	ns	ns	ns
Microporosity	0.42	0.43	0.40	0.43	0.36	0.43	0.41	0.43	0.41	0.44	ns	*	ns
Macroporosity	0.10	0.09	0.14	0.14	0.15	0.13	0.13	0.11	0.13	0.08	*	*	ns
Biopores	0.06	0.05	0.08	0.08	0.08	0.07	0.07	0.06	0.08	0.04	*	ns	ns
Field capacity	0.40	0.41	0.37	0.41	0.33	0.40	0.38	0.40	0.39	0.42	*	*	ns
Permanent wilting point	0.31	0.32	0.27	0.29	0.24	0.30	0.29	0.29	0.30	0.32	ns	ns	ns
Available water	0.10	0.11	0.12	0.14	0.11	0.12	0.11	0.13	0.11	0.11	ns	*	ns
MWD	5.6	6.0	5.7	5.9	5.8	6.1	5.6	6.1	5.8	6.0	ns	*	ns
SHC	2.0	1.9	2.2	2.5	2.4	2.3	2.1	2.3	2.3	1.7	ns	ns	ns
(10–20 cm)													
Bulk density	1.29	1.34	1.29	1.28	1.26	1.30	1.29	1.32	1.28	1.30	ns	ns	ns
Total porosity	0.54	0.52	0.55	0.54	0.54	0.54	0.52	0.53	0.52	0.54	ns	ns	ns
Microporosity	0.43	0.44	0.42	0.44	0.40	0.43	0.41	0.43	0.40	0.44	ns	*	ns
Macroporosity	0.11	0.08	0.13	0.11	0.15	0.10	0.11	0.09	0.12	0.10	ns	*	ns
Biopores	0.07	0.05	0.07	0.06	0.07	0.05	0.06	0.05	0.06	0.05	ns	*	ns
Field capacity	0.40	0.41	0.39	0.41	0.37	0.40	0.38	0.41	0.37	0.41	ns	*	ns
Permanent wilting point	0.30	0.33	0.30	0.31	0.28	0.31	0.29	0.31	0.29	0.31	ns	ns	ns
Available water	0.12	0.10	0.11	0.12	0.12	0.12	0.11	0.12	0.10	0.12	ns	ns	ns
MWD	5.6	6.1	5.4	6.0	5.8	6.0	5.6	6.0	5.8	5.9	ns	*	ns
SHC	1.7	2.2	2.1	2.3	2.3	2.3	1.9	1.9	2.3	2.5	ns	ns	ns

Where BD is bulk density (Mg m^{-3}); TP is total porosity, bio is biopores, macro is macropores, micro is micropores (m^3 m^{-3}), FC is field capacity (m^3 m^{-3}), PWP is permanent wilting point (m^3 m^{-3}), AW is plant available water (m^3 m^{-3}); MWD is mean weighted diameter (mm); SHC is saturated hydraulic conductivity (cm h^{-1}). Asterisk (*) and ns indicate, respectively, significant and non-significant difference between treatments by test F (ANOVA—analysis of variance).

Table 3. Soil chemical attributes under different post-harvest management treatments at two sampling periods (E1 = first sampling; E2 = second sampling) and analysis of variance (ANOVA) by treatment and time, and their interaction, for the 0–10 and 10–20 cm soil layers.

Sampling	**E1**	**E2**	**E1**	**E2**	**E1**	**E2**	**E1**	**E2**	**E1**	**E2**	**ANOVA**		
(0–10 cm)	Control		LimeInc + Burn		LimeInc + Res		LimeSur + Burn		LimeSur + Res		Factor Treatment	Factor Time	Factor Treatment–Time
Clay dispersion	16	17	18	19	20	21	15	16	15	14	ns	ns	ns
pH	4.7	4.8	5.0	5.1	5.1	5.1	4.9	5.0	5.0	5.1	*	ns	ns
P	4.3	5.7	4.4	6.5	4.6	5.1	4.2	6.0	5.7	5.3	ns	*	ns
K	117	110	96	68	86	69	89	68	98	82	*	*	ns
Organic matter	4.2	4.0	4.3	3.9	4.6	4.2	4.1	3.9	4.1	3.8	ns	*	ns
Al	2.8	3.6	1.2	1.2	1.3	1.1	2.1	2.6	1.7	2.1	*	ns	ns
Ca	3.5	2.7	5.1	4.5	5	4.7	3.7	3	4.2	3.4	*	*	ns
Mg	1.3	1.3	2.4	3.1	2.3	3.2	1.7	2	2	2.4	*	*	ns
H + Al	21.1	21.2	14.2	14.8	15.5	14.5	18.8	18.5	16.9	16.5	*	ns	ns
CECef	8.0	7.9	9.0	9.0	8.9	9.3	7.9	7.9	8.2	8.3	*	ns	ns
CECpH7	26	25	22	22	23	22	24	23	23	22	*	ns	ns
Sum bases	5.1	4.3	7.8	7.8	7.6	8.1	5.7	5.2	6.5	6.1	*	ns	ns
Base saturation	20	17	36	34	34	36	24	22	28	27	*	ns	ns
Al saturation	35	45	14	13	15	13	27	34	21	26	*	ns	ns

Table 3. *Cont.*

Sampling	E1	E2	E1	E2	E1	E2	E1	E2	E1	E2	ANOVA		
(10–20 cm)													
Clay dispersion	14	14	19	18	18	18	14	15	12	11	ns	ns	ns
pH	4.7	4.8	4.8	4.9	4.9	4.8	4.8	4.7	4.8	4.9	ns	ns	ns
P	3.3	4.7	4.8	5.2	4.7	4.1	4.5	4.1	3.7	3.9	ns	ns	ns
K	98	91	83	66	86	66	86	68	89	71	*	*	ns
Organic matter	3.4	3.4	3.6	3.4	3.8	3.4	3.6	3.2	3.4	3.6	ns	ns	ns
Al	3.4	4.3	2.8	3.3	2.4	2.9	2.9	3.9	2.8	3.6	*	*	ns
Ca	2.6	2.0	3.1	2.6	3.6	2.7	2.9	2.0	3.0	2.2	*	*	ns
Mg	0.9	1.0	1.3	1.8	1.7	1.8	1.3	1.4	1.4	1.5	*	ns	ns
H + Al	23.0	22.7	19.5	22.1	19.5	20.3	17.9	22.5	20.4	22.0	ns	ns	ns
CECef	7.3	7.6	7.5	7.9	8.0	7.7	7.4	7.5	7.4	7.5	ns	ns	ns
CECpH7	26.9	26.1	24.3	26.7	25.1	25.1	22.3	26.1	25.0	25.9	ns	ns	ns
Sum bases	3.8	3.3	4.7	4.5	5.6	4.7	4.4	3.6	4.6	3.9	*	*	ns
Base saturation	14	13	21	17	24	19	20	14	19	15	*	*	ns
Al saturation	47	56	37	42	32	38	40	51	38	48	*	*	ns

Where organic matter (g kg^{-1}); pH is potential of hydrogen; P is phosphorus, K is potassium (mg kg^{-1}); Ca is calcium, Mg is magnesium, Al is aluminum, H is hydrogen, Al is aluminum, SB is sum of bases, CECef is effective cation exchange capacity (cmolc kg^{-1}); CECpH7 is effective cation exchange capacity pH7 (cmolc kg^{-1}); BS is base saturation; M is aluminum saturation, %. Asterisk (*) and ns indicate, respectively, significant and non-significant difference between treatments by test F (ANOVA—analysis of variance).

Table 4. Soil biological attributes under different post-harvest management treatments at two sampling periods (E1 = first sampling; E2 = second sampling) and analysis of variance (ANOVA) by treatment and time, and their interaction, for the 0–10 cm soil layer.

Sampling	E1	E2	E1	E2	E1	E2	E1	E2	E1	E2	ANOVA		
(0–10 cm)	Control		LimeInc + Burn		LimeInc + Res		LimeSur + Burn		LimeSur + Res		Factor Treatment	Factor Time	Factor Treatment–Time
NAG	9	14	18	11	24	19	22	5	21	27	*	ns	*
AP	70	53	68	72	46	48	100	50	103	118	*	ns	*
BG	16	9	19	14	27	24	22	16	24	26	*	*	ns
DHA	40	27	33	54	31	63	39	42	29	24	*	ns	*
ARS	12	20	10	11	6	8	18	7	24	27	*	ns	*
LnNAG:LnAP	0.47	0.68	0.67	0.55	0.83	0.76	0.62	0.42	0.58	0.70	*	ns	*
LnBG:LnAP	0.67	0.56	0.69	0.61	0.86	0.80	0.66	0.69	0.68	0.68	*	*	ns

Where NAG is b-1,4-N-acetyl-glucosaminidase; AP is acid (alkaline) phosphatase; BG is b-1,4-glucosidase, and ARS is arylsulfatase. Asterisk (*) and ns indicate, respectively, significant and non-significant difference between treatments by test F (ANOVA—analysis of variance).

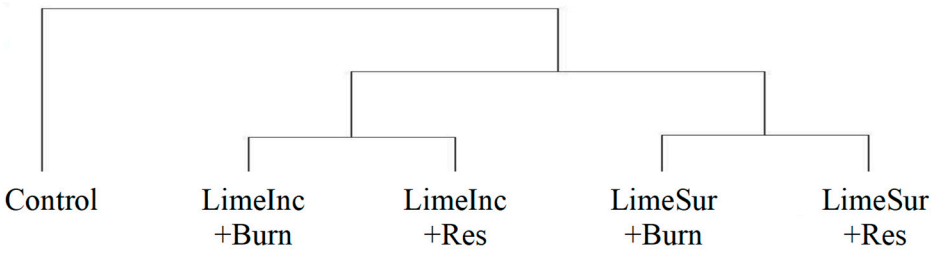


Figure 2. Dendrogram showing the clustering of soil chemical and physical properties (0–20 cm layer), as affected by lime incorporation or surface application combined with residue retention or burning.

Principal component analysis (PCA) biplots for the 0–10 and 10–20 cm soil layers (Figure 3) were constructed to visualize the relations between the measured soil properties and the applied treatments for the results when there were significant differences in ANOVA-factor treatment. These biplots corroborated the clustering patterns observed in the dendrogram analysis (Figure 1). The PCA analysis identified which soil properties were most closely associated with each treatment group, further supporting the notion that the

mode of limestone application (incorporated versus surface-applied) had a stronger influence on soil characteristics compared to burning or retaining pine residues on the surface.

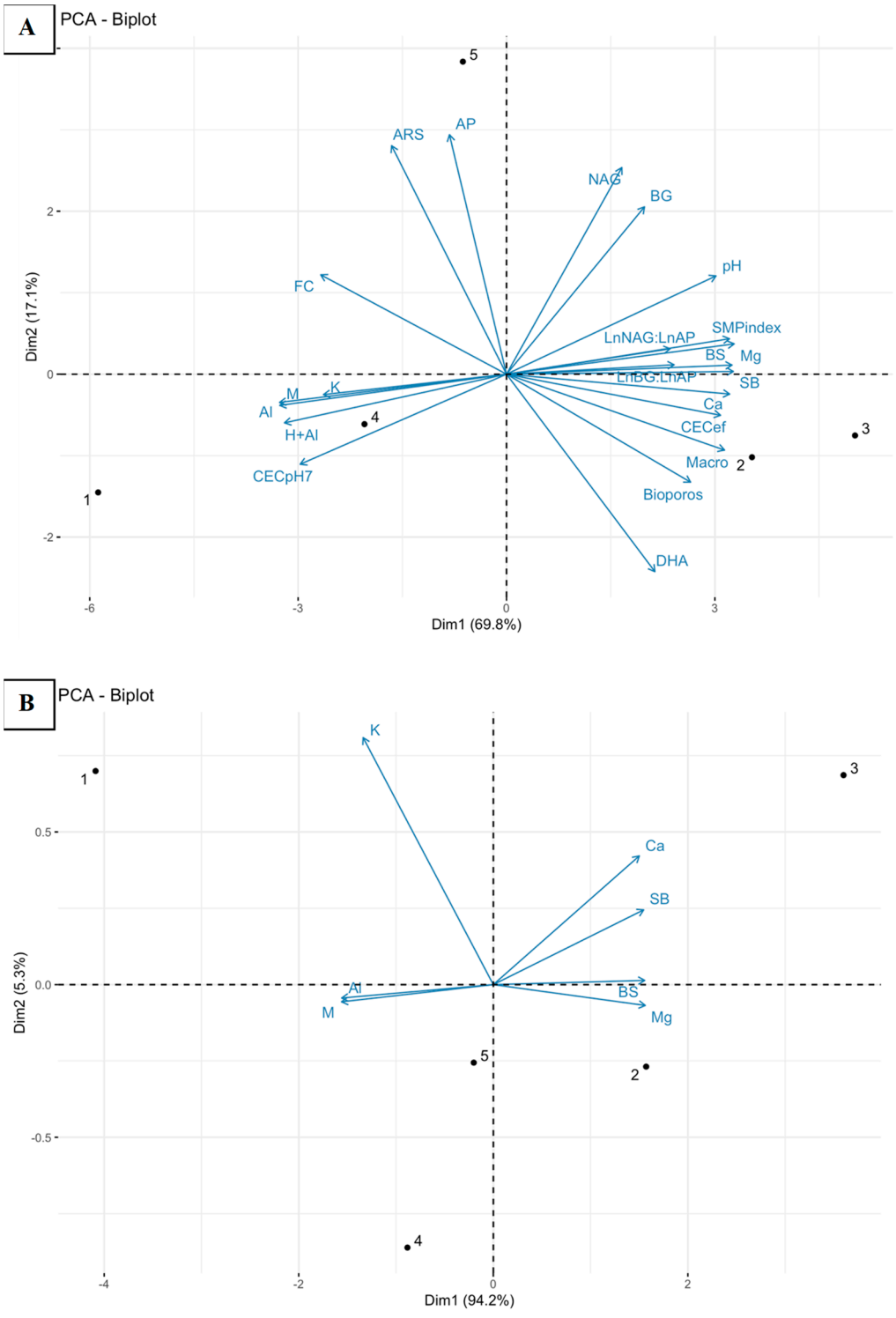


Figure 3. Principal component analysis (PCA) of soil's physical and chemical attributes in 0–10 cm layer (**A**) and 10–20 cm layer (**B**). The treatments are identified in the figures as follows: (1) control (natural regeneration and regrowth from on-site plant species); (2) LimeInc + Burn (Fescue seeding after lime incorporation and burning of forest residue); (3) LimeInc + Res (Fescue seeding after lime incorporating with pine residue left on the soil surface); (4) LimeSur + Burn (Fescue seeding after burning of pine residue and surface liming); and (5) LimeSur + Res (Fescue seeding with surface liming and pine residue left on the soil surface).

In the 0–10 cm layer, the first two principal components explain 86.9% of the total variability of the data (Dim1: 69.8%; Dim2: 17.1%). The variables most associated with the first component (Dim1) include pH, CECef, Ca, Mg, and SB, indicating a strong influence of liming on improving soil chemical conditions. Variables related to soil structure, such as macroporosity and biopores, are also correlated with Dim1. The second component (Dim2) primarily highlighted enzymatic activity, including ARS, AP, and BG, where biological processes played an important role in differentiating treatments in this layer.

The control treatment (1) indicated lower influence from chemical correction practices, with a strong association with Al, H + Al, M, and CECpH7 variables. The soil in the control treatment was more acidic and less fertile because no limestone was applied. The LimeInc + Burn (2) and LimeInc + Res (3) treatments were grouped together because they demonstrated improvements in soil chemical conditions due to lime incorporation. The LimeSur + Res (5) treatment had a greater influence on biological factors due to the presence of organic residues on the surface.

In the 10–20 cm layer, the principal components presented a different structure, with Dim1 explaining 94.2% of the total variation, and Dim2 only 5.3%. The chemical variables Ca, SB, Mg, and BS showed a strong correlation with Dim1, indicating that incorporated liming had a significant impact on the subsurface layer.

The distribution of treatments in the 10–20 cm layer confirmed that the control treatment (1) maintained distinct characteristics, with high acidity and low base availability. The LimeInc + Burn (2) and LimeInc + Res (3) treatments had a strong correlation with variables related to nutrient availability, showing that lime incorporation influenced even the deeper soil layer. On the other hand, the LimeSur + Burn (4) and LimeSur + Res (5) treatments had a lower effect on the subsurface, suggesting that surface liming had a limited impact beyond a 10 cm depth.

The treatments that maintained pine residues on the surface favored biological processes in the topsoil, while the burning of these residues had variable impacts on soil structure and nutrient availability.

The control treatment (1) showed a strong correlation with acidity indicators such as Al and H + Al, while treatments that received liming, especially LimeInc + Burn (2) and LimeInc + Res (3), had a strong relationship with pH, SB, Ca, and Mg, reflecting a significant improvement in soil fertility. The LimeSur + Res (5) treatment stood out for its higher correlation with biological variables, indicating that the presence of residues on the surface may have favored microbial activity and soil structure.

The results indicated that the choice of management practice has distinct effects on different soil layers, with incorporated liming being more effective in improving fertility at depth, while surface liming and the presence of pine residues positively influence biological activity and structure in the topsoil.

The positive correlation between Ca and Mg, and structural variables such as micropores and biopores supports the well-established mechanism by which divalent cations promote flocculation and aggregation through cation bridging and reduced electrostatic repulsion between clay particles. This structure improvement enhances aeration and water movement in the topsoil.

For the attributes that showed significant differences between treatments in the ANOVA, the means were compared using the following orthogonal contrasts: (1) control vs. other treatments; (2) treatments with burnt pine residues vs. without burnt residues; and (3) incorporated limestone vs. limestone applied to the surface (Figure 4).

Contrasting effects of soil improvement between the control and other treatments were evident in the analysis of soil properties (Table 5). In the 0–10 cm layer, significant differences were observed for macroporosity, and chemical properties like pH, potassium,

aluminum, calcium, magnesium, cation exchange capacity, base sum, base saturation, and aluminum saturation also exhibited significant changes compared to the control. Notably, the impact of treatments was less pronounced in the 10–20 cm layer, where only potassium, aluminum, magnesium, base sum, base saturation, and aluminum saturation showed significant differences. This suggests a stronger treatment influence on the surface soil (0–10 cm) and shows the effect of soil improvement.

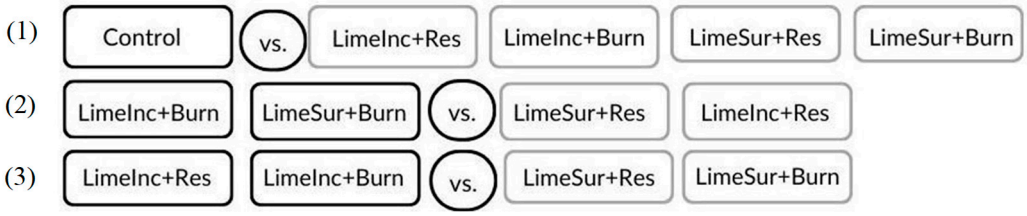


Figure 4. Orthogonal contrast analysis showing the effects of (**1**) control vs. other treatments; (**2**) burnt vs. retained pine residues; and (**3**) incorporated vs. surface-applied limestone on soil's physical and chemical properties.

Table 5. Orthogonal contrast results for soil's physical and chemical properties at 0–10 and 10–20 cm depths (see contrast design in Figure 4).

Contrast 1				
			Average Control	Others
Layer 0–10 cm	*	Macroporosity, $m^3\ m^{-3}$	0.10	0.13
	*	pH	4.8	5.0
	*	K, mg kg^{-1}	114	82
	*	Al, cmolc kg^{-1}	3.2	1.7
	*	Ca, cmolc kg^{-1}	3.1	4.2
	*	Mg, cmolc kg^{-1}	1.3	2.4
	*	H + Al, cmolc kg^{-1}	21.3	16.2
	*	CECef, cmolc kg^{-1}	8.0	8.6
	*	CECpH7, cmolc kg^{-1}	25.9	23.1
	*	SB, cmolc kg^{-1}	4.7	6.9
	*	BS, %	19	30
	*	M, %	41	21
	ns	BD, TP, micro, macro, FC, PWP AW, MWD, SHC, clay dispersion, P, OM.		
Layer 10–20 cm	*	K, mg kg^{-1}	95	77
	*	Al, cmolc kg^{-1}	3.8	3.1
	*	Mg, cmolc kg^{-1}	1.0	1.5
	*	SB, cmolc kg^{-1}	3.6	4.5
	*	BS, %	14	20
	*	M, %	52	41
	ns	BD, TP, micro, macro, biopores, AW FC, PWP, MWD, SHC, clay dispersion, pH, P, OM, Ca, H + Al, CECef, CECpH7.		
Contrast 2				
			Res (LimeInc or LimeSur)	Burn (LimeInc or LimeSur)
Layer 0–10 cm	ns	All variables		
Layer 10–20 cm	ns	All variables		

Table 5. *Cont.*

Contrast 3				
			Average LimeInc (Res or Burn)	LimeSur (Res or Burn)
Layer 0–10 cm	*	Macroporosity, $m^3\ m^{-3}$	0.14	0.11
	*	Biopores, $m^3\ m^{-3}$	0.08	0.06
	*	Field capacity, $m^3\ m^{-3}$	0.38	0.40
	*	Al, cmolc kg^{-1}	1.2	2.2
	*	Ca, cmolc kg^{-1}	4.8	3.6
	*	Mg, cmolc kg^{-1}	2.8	2.0
	*	H + Al, cmolc kg^{-1}	1.3	1.9
	*	CECef, cmolc kg^{-1}	9.1	8.1
	*	SB, cmolc kg^{-1}	7.8	5.9
	*	BS, %	35	25
	*	M, %	14	27
	ns	BD, TP, Micro, PWP, AW MWD, SHC, clay dispersion, pH, P, K, OM, CECpH7.		
Layer 10–20 cm	*	K, mg kg^{-1}	76	79
	*	Al, cmolc kg^{-1}	2.9	3.3
	*	Mg, cmolc kg^{-1}	1.6	1.4
	*	SB, cmolc kg^{-1}	4.9	4.1
	*	BS, %	20	17
	*	M, %	37	44
	ns	BD, TP, micro, macro, biopores, FC PWP, AW, MWD, SHC, clay dispersion, pH, P, K, OM, Al, H + Al, CECef, CECpH7.		

Where BD is bulk density, TP is total porosity, biopores, macro is macropores, micro is micropores, FC is field capacity, PWP is permanent wilting point, AW is plant available water, MWD is mean weighted diameter of aggregates, SHC is saturated hydraulic conductivity, OM is organic matter, ClayDisp is clay dispersion, pH is potential of hydrogen, P is phosphorus, K is potassium, Ca is calcium, Mg is magnesium, Al is aluminum, H + Al, SB is sum of bases, CECef is effective cation exchange capacity, BS is base saturation, and M is aluminum saturation. * Difference between orthogonal contrasts; ns denotes non-significant in the ANOVA. Contrasts 1, 2, and 3 are represented in Figure 4.

The control treatment did not receive acidity corrective, while the others received it. With this, a significant difference was observed in the attributes related to higher pH, CECef, Ca, Mg, SB, and BS content; and lower Al, H + Al, and M content. These effects were observed in both layers, but they were more pronounced in the surface layer.

Orthogonal contrast 2 (Figure 4) compared treatments where pine residues remained on the surface (LimeInc + Res and LimeSur + Res) with those where they were burned (LimeInc + Burn and LimeSur + Burn). Interestingly, this contrast revealed no significant differences in either the physical or chemical properties of the soil. This suggests that burning pine residues did not exert a major influence on soil characteristics within the timeframe of the study (39 months).

Orthogonal contrast 3 (Figure 4) was performed between the treatments that incorporated limestone (LimeInc + Res and LimeInc + Burn) versus those where limestone was applied on the surface (LimeSur + Res and LimeSur + Burn). In the 0–10 cm layer, microporosity, biopores, and field capacity were the physical variables that differed significantly between these groups. However, several chemical properties exhibited significant changes, including aluminum, calcium, magnesium, exchangeable acidity, effective cation exchange capacity, base sum, base saturation, and aluminum saturation. These findings highlight the importance of lime incorporation for influencing soil chemistry in the surface layer (0–10 cm).

For layer 10–20 cm, we had differences between these treatments for potassium, aluminum, magnesium, base sum, base saturation, and aluminum saturation. Lower pH in the control was expected, as limestone was not applied, consistent with the natural acidic conditions of many soils [55]. Also, the control treatment exhibited higher K content and Al saturation, indicative of natural nutrient cycling but also increased potential for toxicity in acid soils, different than the other treatment that had limestone applied [56]. Base saturation was significantly lower in the control, showing limited availability of exchangeable bases, typical for non-amended soils [57].

Further analysis of treatment effects using Tables 3 and 4 revealed several key points. First, the changes in soil properties were generally more pronounced in the 0–10 cm layer compared to the 10–20 cm layer. This suggests a stronger treatment influence on the surface soil. Second, chemical attributes appeared more affected by the treatments compared to physical attributes.

Burnt pine residues (treatments LimeInc + Burn and LimeSur + Burn compared to LimeSur + Res and LimeInc + Res) did not significantly affect soil chemical or physical properties (contrast 2—Figure 4). This was observed in both the surface layer (0–10 cm) and the deeper layer (10–20 cm). This suggests that burnt pine residues within this timeframe may not be a major driver of short-term changes in soil characteristics following harvest and treatment application.

In a study by [58], changes in the physical characteristics of an Oxisol subjected to six years of biannual fire treatments were evaluated. There were no marked variations in soil's physical characteristics (bulk density and soil water release) induced by fire, except for increased soil moisture in the non-burned area. However, ref. [59] did not observe significant differences in soil moisture between burned and unburned areas.

As plants only absorb mineralized nutrients, it is natural for them to grow more rapidly in areas that have been burned due to the rapid mineralization of nutrients in the burned vegetation [31]. However, these effects tend to disappear in the medium term due to nutrient leaching by rainfall, resulting in concentrations that may be even lower than those observed in soils that have not been affected by fire [60].

When the results of soil analyses do not show significant differences between different management practices in the area, it becomes possible to provide information to farmers about the best practices for the environment, for example.

It is worth noting that burning is allowed by law in agricultural areas, provided it is carried out in a controlled manner and in accordance with current legislation in each country, despite the environmental damage it may cause [61]. In general, the use of fire in agriculture can have negative impacts on soil health and contribute to climate change [31]. It is important to consider other alternatives to the use of fire, and their economic and environmental costs.

Contrasting treatments with versus without lime incorporation (Figure 3) revealed significant differences in soil properties, particularly in the 0–10 cm layer (Table 5). Furthermore, it increased effective cation exchange capacity (CECef), indicating a greater potential for the soil to retain essential cations. Notably, treatments with incorporated lime were more effective in reducing exchangeable aluminum content and saturation, as well as H + Al content, compared to surface application. This suggests a stronger ability to reduce soil acidity. Additionally, incorporated lime treatments exhibited higher levels of calcium, magnesium, sum of bases, and base saturation. These findings differ from those of [62], who observed effective improvement in Ca, Mg, and base saturation with surface application of limestone in an Oxisol under no-till conditions. It is important to highlight that the study by [62] was carried out over the long term. The authors suggest that incorporating lime increases its contact with soil acidity, potentially leading to a greater

reduction in pH. However, they highlight that this reduction depends on the soil's buffering capacity and the amount of lime applied. Our study suggests that under these specific conditions, incorporating lime was a more efficient strategy for improving soil chemical properties compared to surface application.

In a Dystrophic Grey Argisol, ref. [63] evaluated crop responses to limestone applied on the surface and incorporated into soil originally under native grassland. They observed that surface application of limestone at rates equal to or less than 1/2 SMP (half a dose of lime) to raise pH to 6.0 provided higher yields of corn and soybeans compared to limestone incorporation into the soil.

According to [64], crop yields and soil chemical attributes were evaluated following limestone reapplication in a no-till system established five years earlier in a Red Argisol. They concluded that surface limestone application in the no-till system, established five years earlier with limestone incorporation at the beginning of the system, did not increase yields of corn and soybeans. Limestone added to the soil surface in no-till increased pH, calcium, and magnesium levels, and decreased exchangeable aluminum only up to a depth of 5 cm, after 18 months of application.

The depth or layer sampled is crucial when limestone is applied to the surface. In the current study, sampling was performed in the 0–10 cm layer. In treatments with surface-applied limestone, it is possible that reactions are not yet complete, unlike incorporated limestone, where contact with the soil may have favored dissolution reactions, hydroxyl release, and increased Ca and Mg levels.

4. Conclusions

Multivariate analysis, through the dendrogram and principal component analysis (PCA), differentiated the treatments into three groups: control (native vegetation) × "LimeSur + Res and LimeSur + Burn" × "LimeInc + Res and LimeInc + Burn". Overall, treatments with limestone incorporation improved both the physical and chemical soil attributes.

Different post-harvest management practices increased macropores, pH, calcium, magnesium, CECef, SB, and base saturation levels compared to native vegetation. However, it decreased potassium, aluminum, H + Al, and aluminum saturation content in the surface layer (0–10 cm).

Burnt pine residues did not modify the soil's physical and chemical attributes, thus proving that, in the medium term (39 months), this Cambisol is resilient to change in regard to its chemical and physical attributes. The treatments that maintained pine residues on the surface favored biological processes in the topsoil, while the burning of these residues had variable impacts on soil structure and nutrient availability.

The incorporation of limestone increased macroporosity, biopores, calcium, magnesium, CECef, SB, and base saturation contents in the upper layer (0–10 cm), and decreased the aluminum, H + Al, and aluminum saturation content compared to the superficial application of limestone. However, it practically does not change the soil's physical attributes in the medium term.

5. Study Limitations and Future Directions

Although this study provides a comprehensive assessment of 39-month-term responses following pine harvest and land-use transition, it is limited to the 0–20 cm soil layer and does not include deeper horizons or monitoring of carbon dynamics. Future studies should address these aspects, as well as evaluate greenhouse gas fluxes, economic feasibility, and the integration of sustainable management practices at the farm scale.

Under the studied conditions, the combination of lime incorporation with residue retention (LimeInc + Res) is recommended as the most effective management practice for improving soil fertility and maintaining biological activity after pine harvest in Southern Brazil.

Author Contributions: Conceptualization, A.C.d.M.e.A., J.A.A., M.N.C., S.D.C.M. and J.F.M.d.P. methodology; A.C.d.M.e.A., J.A.A., M.N.C., S.D.C.M. and M.d.N.; software, A.C.d.M.e.A.; validation, A.C.d.M.e.A. and J.A.A.; formal analysis, A.C.d.M.e.A. and J.A.A.; writing—original draft preparation, A.C.d.M.e.A., J.A.A. and G.K.; writing—review and editing, A.C.d.M.e.A., J.A.A., G.K. and M.N.C.; supervision, J.A.A. and M.N.C.; project administration, M.N.C.; funding acquisition, M.N.C. and J.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CAPES Brazil, grant number 88881.846470/2023-01; and FAPESC, grant numbers 2021TR1405 and 2021TR1497.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Marlise Nara Ciotta, Sandra Denise Camargo Mendes, João Frederico Mangrich dos Passos were employed by the Agricultural Research and Rural Extension Company of Santa Catarina. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Henderson, K.A.; Reis, M.; Blanco, C.C.; Pillar, V.D.; Printes, R.C.; Bauch, C.T.; Anand, M. Landowner perceptions of the value of natural forest and natural grassland in a mosaic ecosystem in southern Brazil. *Sustain. Sci.* **2016**, *11*, 321–330. [CrossRef]
2. Schumacher, M.V.; Witschoreck, R.; Calil, F.N.; Lopes, V.G. Biomass and nutrients in a 27 years *Pinus taeda* L. clear cutting stand in Cambará do Sul, Rio Grande do Sul State. *Cienc. Florest.* **2013**, *22*, 321–332. [CrossRef]
3. Cunha, T.Q.G.; Barbosa, P.V.G.; Lima, P.A.F.; Pimentel, T.S.; Peixoto, L.L.S.; Junior, C.R.S. Characterization of MDF residue and its use in pellet production. *Nativa* **2018**, *6*, 300–304. [CrossRef]
4. Silva, L.B.; Dick, D.P.; Junior, A.V.I. Highland subtropical soils: Chemical attributes, content of organic matter and its resistance to chemical oxidation. *Cienc. Rural* **2008**, *38*, 1167–1171. [CrossRef]
5. Klug, I.; Mafra, A.L.; Friederichs, A.; Rech, C.; Neto, J.F. Soil chemical properties in forestry plantations replacing native vegetation in high-altitude grasslands. *Cienc. Florest.* **2020**, *30*, 279–290. [CrossRef]
6. Wiesmeier, M.; Dick, D.P.; Rumpel, C.; Dalmolin, R.S.D.; Hilscher, A.; Knicker, H. Depletion of soil organic carbon and nitrogen under pine plantations in southern Brazilian grasslands (Campos). *Eur. J. Soil Sci.* **2009**, *60*, 347–359. [CrossRef]
7. Dick, D.P.; Leite, S.B.; Dalmolin, R.S.D.; Almeida, H.C.; Knicker, H. Pine afforestation in South Brazilian highlands: Soil chemical attributes and organic matter composition. *Sci. Agric.* **2011**, *68*, 175–181. [CrossRef]
8. Tomasi, C.A.; Inda, A.V.; Dick, D.P. Humic substances in subtropical altitude Latosol under distinct uses and managements. *Cienc. Rural* **2012**, *42*, 2180–2184. [CrossRef]
9. Denardin, R.B.N.; Mattias, J.L.; Wildner, L.P.; Nesi, C.N.; Sordi, A. Carbon stock in soil under different forest formations, Chapecó, Santa Catarina State. *Cienc. Florest.* **2014**, *24*, 59–69. [CrossRef]
10. Braida, J.A.; Reichert, J.M.; Veiga, M.; Reinert, D.J. Mulch and soil organic carbon content and their relationship with the maximum soil density obtained in the proctor test. *Rev. Bras. Cienc. Solo* **2006**, *30*, 605–614. [CrossRef]
11. Szymczak, D.A.; Brun, E.J.; Reinert, D.J.; Frigotto, T.; Mazzalira, C.C.; Lucio, A.D.; Marafiga, J. Soil compaction caused by forest tractors in the *Pinus taeda* L. harvesting in the South-Western region of Paraná. *Rev. Árvore* **2014**, *38*, 641–648. [CrossRef]
12. Holthusen, D.; Brandt, A.A.; Reichert, J.M.; Horn, R. Soil porosity, permeability, and static and dynamic strength parameters under native forest/grassland compared to no-tillage cropping. *Soil Tillage Res.* **2018**, *177*, 113–124. [CrossRef]
13. Tonhato, L.; Lopes, E.S.; Rodrigues, C.K.; Sampietro, J.A.; Pelissari, A.L.; Silva, M.K.C. Soil structural quality after forest cutting by tire harvester and adapted hydraulic excavator. *Biofix Sci. J.* **2022**, *7*, 74–79. [CrossRef]
14. Pincelli, A.L.P.S.M.; Seixas, F.; Nunes, R. Compaction and soil fertility after eucalyptus harvest using feller buncher and skidder. *Cerne* **2014**, *20*, 191–198. [CrossRef]
15. Costa, A.; Albuquerque, J.A.; Costa, A.; Warmling, M.T.; Magro, B.A. Pine harvest impact on soil structure of a Dystric Cambisol (Humic). *Rev. Bras. Cienc. Solo* **2016**, *40*, e20140643. [CrossRef]

16. Andrade, M.L.C.; Tassinari, D.; Junior, M.S.D.; Martins, R.P.; Rocha, W.W.; Souza, Z.R. Soil compaction caused by harvest and logging operations in eucalyptus forests in coarse-textured soils from northeastern Brazil. *Cienc. Agrotec.* **2017**, *41*, 191–200. [CrossRef]
17. Andognini, J.; Albuquerque, J.A.; Warmling, M.I.; Teles, J.S.; Silva, G.B. Soil compaction effect on black oat yield in Santa Catarina, Brazil. *Rev. Bras. Cienc. Solo* **2020**, *44*, e20190157. [CrossRef]
18. Bonetti, J.A.; Anghinoni, I.; Moraes, M.T.; Fink, J.R. Resilience of soils with different texture, mineralogy and organic matter under long-term conservation systems. *Soil Tillage Res.* **2017**, *174*, 104–112. [CrossRef]
19. Reichert, J.M.; Cechin, N.F.; Reinert, D.J.; Rodrigues, M.F.; Suzuki, L.E.A.S. Ground-based harvesting operations of pine affects structure and pore functioning of clay and sandy clay soils. *Geoderma* **2018**, *331*, 38–49. [CrossRef]
20. Silva, S.R.; Barros, N.F.; Costa, L.M.; Leite, F.P. Soil compaction and eucalyptus growth in response to forwarder traffic intensity and load. *Rev. Bras. Cienc. Solo* **2008**, *32*, 921–932. [CrossRef]
21. Ansorge, D.; Godwin, R.J. The effect of tires and a rubber track at high axle loads on soil compaction–Part 2: Multi-axle machine studies. *Biosyst. Eng.* **2008**, *99*, 338–347. [CrossRef]
22. Grecenko, A.; Prikner, P. Tire rating based on soil compaction capacity. *J. Terramech.* **2014**, *52*, 77–92. [CrossRef]
23. Malinovski, R. Conversion of forest areas. *Forest* **2020**, *67*, 1–5.
24. Vasconcelos, W.L.F.; Rodrigues, D.M.; Silva, R.O.C.; Alfaia, S.S. Diversity and abundance of soil macrofauna in three land use systems in eastern Amazonia. *Rev. Bras. Cienc. Solo* **2020**, *44*, e0190136. [CrossRef]
25. Silva, L.L.; Ribon, A.A.; Backes, C.; Lopes, L.C.A.; Magalhaes, A.F. Atributos físicos do solo e produtividade da pastagem em sistema de manejo de integração lavoura-pecuária-floresta. *Sci. Electron. Arch.* **2021**, *14*, 88–102. [CrossRef]
26. Cassol, E.A.; Eltz, F.L.F.; Bazzano, M.G.P. Erosivity and hydrological characteristics of rainfalls in Rio Grande (RS, Brazil). *Rev. Bras. Cienc. Solo* **2010**, *34*, 235–244. [CrossRef]
27. Mroz, G.D.; Jurgensen, M.F.; Harvey, A.E.; Larsen, M.J. Effects of fire on nitrogen in forest floor horizons. *Soil Sci. Soc. Am. J.* **1980**, *44*, 235–242. [CrossRef]
28. Bertol, I.; Cogo, N.P.; Levien, R. Erosion in different soil preparations after corn and wheat harvests, in the presence and absence of crop residues. *Rev. Bras. Cienc. Solo* **1997**, *21*, 409–418. [CrossRef]
29. Silva, L.L.; Schneider, P.R.; Eltz, F.L.F. Influence of residues of harvesting of black wattle forest (*Acacia mearnsii de Wild*) on soil and water losses. *Cienc. Florest.* **1998**, *8*, 43–53. [CrossRef]
30. Fu, B.; Chen, L.; Huang, H.; Qu, P.; Wei, Z. Impacts of crop residues on soil health: A review. *Environ. Pollut. Bioavail.* **2021**, *33*, 163–174. [CrossRef]
31. Redin, M.; Santos, G.D.F.; Miguel, P.; Denega, G.L.; Lupatini, M.; Doneda, A.; Souza, E.L. Impacts of burning on chemical, physical, and biological attributes of soil. *Cienc. Florest.* **2011**, *21*, 381–392. [CrossRef]
32. DeBano, L.F.; Eberlein, G.E.; Dunn, P.H. Effects of burning on chaparral soils: I—Soil nitrogen. *Soil Sci. Soc. Am. J.* **1979**, *43*, 504–509. [CrossRef]
33. Heringer, I.; Jacques, A.V.A. Characteristics of a red Latosol under natural pasture subjected to prolonged fire action and alternative management practices. *Cienc. Rural* **2002**, *32*, 309–314. [CrossRef]
34. Rheinheimer, D.S.; Santos, J.C.P.; Fernandes, V.B.B.; Mafra, A.L.; Almeida, J.A. Changes of chemical attributes of a soil after burning its native permanent pasture. *Cienc. Rural* **2003**, *33*, 49–55. [CrossRef]
35. Pressler, Y.; Moore, J.C.; Cotrufo, M.F. Belowground community responses to fire: Meta-analysis reveals contrasting responses of soil microorganisms and mesofauna. *Oikos* **2019**, *128*, 309–327. [CrossRef]
36. Nelson, A.R.; Narrowe, A.B.; Rhoades, C.C.; Fegel, T.S.; Daly, R.A.; Roth, H.K.; Chu, R.K.; Amundson, K.K.; Young, R.B.; Steindorff, A.S.; et al. Wildfire-dependent changes in soil microbiome diversity and function. *Nat. Microbiol.* **2022**, *7*, 1419–1430. [CrossRef]
37. Caiafa, M.V.; Nelson, A.R.; Borch, T.; Roth, H.K.; Fegel, T.S.; Rhoades, C.C.; Wilkins, M.J.; Glassman, S.I. Distinct fungal and bacterial responses to fire severity and soil depth across a ten-year wildfire chronosequence in beetle-killed lodgepole pine forests. *For. Ecol. Manag.* **2023**, *544*, 121160. [CrossRef]
38. Whitman, T.; Whitman, E.; Woolet, J.; Flannigan, M.D.; Thompson, D.K.; Parisien, M. Soil bacterial and fungal response to wildfires in the Canadian boreal forest across a burn severity gradient. *Soil Biol. Biochem.* **2019**, *138*, 107571. [CrossRef]
39. Woolet, J.; Whitman, T. Pyrogenic organic matter effects on soil bacterial community composition. *Soil Biol. Biochem.* **2020**, *141*, 107678. [CrossRef]
40. Avila, A.C.M.; Albuquerque, J.A.; Kirchhof, G. Pinelands: Impacts of different long-term land uses on soil physical properties in Red Ferrosols. *Land* **2025**, *14*, 1471. [CrossRef]
41. Avila, A.C.M.; Albuquerque, J.A.; Campos, C.G.C. Climate change and its effect on the soil water balance of Lages, Santa Catarina. *Rev. Bras. Geogr. Fis.* **2022**, *15*, 2796–2809. [CrossRef]
42. CQFS RS/SC. *Manual de Calagem e Adubação para os Estados do Rio Grande do Sul e de Santa Catarina*; Sociedade Brasileira de Ciência do Solo—Núcleo Regional Sul: Porto Alegre, Brazil, 2016.

43. Gubiani, P.I.; Albuquerque, J.A.; Reinert, D.J.; Reichert, J.M. Water tension and extraction by suction table and sand suction column in two soils with high bulk density. *Cienc. Rural* **2009**, *39*, 2535–2538. [CrossRef]
44. Libardi, P.L. *Dynamics of Water in Soil*; EdUSP: Sao Paulo, Brazil, 2005.
45. Embrapa. *Manual de Métodos de Análise de Solo*; EMBRAPA: Brasília, Brazil, 2017.
46. Gubiani, P.I.; Reinert, D.J.; Reichert, J.M.; Gelain, N.S.; Minella, J.P.G. Falling head permeameter and software to determine the hydraulic conductivity of saturated soil. *Rev. Bras. Cienc. Solo* **2010**, *34*, 993–997. [CrossRef]
47. Kemper, W.D.; Rosenau, R.C. Aggregate stability and size distribution. In *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods*; American Society of Agronomy: Madison, WI, USA, 1986. [CrossRef]
48. Gee, G.W.; Bauder, J.W. Particle size analysis. In *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods*; American Society of Agronomy: Madison, WI, USA, 1986. [CrossRef]
49. Suzuki, L.E.A.S.; Reichert, J.M.; Albuquerque, J.A.; Reinert, D.J.; Kaiser, D.R. Dispersion and flocculation of Vertisols, Alfisols, and Oxisols in southern Brazil. *Geoderma Reg.* **2015**, *5*, 64–70. [CrossRef]
50. Tedesco, M.J. *Soil, Plant, and Other Material Analyses*; UFRGS: Porto Alegre, Brazil, 1995.
51. Jackson, C.R.; Tyler, H.L.; Millar, J.J. Determination of microbial extracellular enzyme activity in waters, soils, and sediments using high throughput microplate assays. *J. Vis. Exp.* **2013**, *80*. [CrossRef]
52. Ramirez, D.; Shaw, L.J.; Collins, C.D. Ecotoxicity of oil sludges and residuals from their washing with surfactants: Soil dehydrogenase and ryegrass germination tests. Environ. *Sci. Pollut. Res. Int.* **2021**, *28*, 13312–13322. [CrossRef]
53. Waring, B.G.; Weintraub, S.R.; Sinsabaugh, R.L. Ecoenzymatic stoichiometry of microbial nutrient acquisition in tropical soils. *Biogeochemistry* **2014**, *117*, 101–113. [CrossRef]
54. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2014.
55. Ejigu, W.; Selassie, Y.G.; Elias, E.; Molla, E. Effect of lime rates and method of application on soil properties of acidic Luvisols and wheat (*Triticum aestivum* L.) yields in northwest Ethiopia. *Heliyon* **2023**, *9*, e13988. [CrossRef]
56. Alvarez, E.; Fernandez-Marcos, M.L.; Monterroso, M.J.; Fernandez-Sanjurjo, M.J. Application of aluminium toxicity indices to soils under various forest species. *For. Ecol. Manag.* **2005**, *211*, 227–239. [CrossRef]
57. Gurmu, G.; Beyene, S.; Selassie, Y.; Kidanu, S. Lime requirement determination methods on acid neutralisation efficiency under selected acidic soils of the Ethiopian highlands. *Trop. Agric.* **2024**, *101*, 68–89.
58. Spera, S.T.; Reatto, A.; Correia, J.R.; Silva, J.C.S. Physical characteristics of a dark-red Latosol (Oxisol) of the Brazilian savannas (Cerrados) of Planaltina under fire action. Pesqui. *Agropecu. Bras.* **2000**, *35*, 1817–1824. [CrossRef]
59. Meirelles, M.L. Effect of fire on soil moisture in a Cerrado scrubland area. *Sci. Cult.* **1990**, *42*, 359–360.
60. Knicker, H. How does fire affect the nature and stability of soil organic nitrogen and carbon? A review. *Biogeochemistry* **2007**, *85*, 91–118. [CrossRef]
61. Sousa, C.T.C.; Bastos, A.T. Queimadas no Brasil e o direito ao meio ambiente ecologicamente equilibrado. *Rev. Cient. Intracienc.* **2020**, *1*, 1–10.
62. Ciotta, M.N.; Bayer, C.; Ernani, P.R.; Fontoura, S.M.V.; Wobeto, C.; Albuquerque, J.A. Liming management and its effect on acidity components of an Oxisol under no-tillage. *Rev. Bras. Cienc. Solo* **2004**, *28*, 317–326. [CrossRef]
63. Kaminski, J.; Rheinheimer, D.S.; Santos, E.J.S.; Gatiboni, L.C.; Bortoluzzi, E.C.; Xavier, F.M. Liming superficial and incorporated on soil under native sod and crops yield. *Cienc. Rural* **2000**, *30*, 605–609. [CrossRef]
64. Rheinheimer, D.S.; Santos, E.J.S.; Kaminski, J.; Xavier, F.M. Surface application of lime on no-tillage. *Cienc. Rural* **2000**, *30*, 263–268. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.