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Soil Quality Changes within a (*Nothofagus obliqua*) Forest Under Silvopastoral Management in the Andes Mountain Range, South Central Chile

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Received: 3 July 2020; Accepted: 4 August 2020; Published: 22 August 2020

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Abstract: In Chile, 49.1% of the national territory is affected by soil degradation (including erosion and loss of soil organic matter), whereby of the 51.7 Mha that have been historically associated with agricultural-livestock and forestry activities, only 35.5 Mha are being used at the present. Consequently, soil degradation has resulted in the release of about 11.8 Gg yr^{-1} of carbon (C) equivalent (CO_{2eq}) to the atmosphere. Silvopastoral systems (SPS), however, can increase soil organic C (SOC) through sequestration (C→SOC), improve ecosystem services, and have been internationally recommended for sustainable land use. Therefore, it was proposed to determine the effects of SPS on soils, over five years, in degraded sites that were located in the Ranchillo Alto (SPS-RA) (37°04′52″ S, 71°39′14″ W), Ñuble region. The sites were rated according to previous canopy disturbance levels (+) as follows: open (O_p)+++, semi open (SO_p)++, and semi closed (SC)+. The analysis was performed on different physical and chemical soil properties (0–5 and 5–20 cm depths), that were expressed as soil indicators (S_{IND}) for chemical and physical properties, which were used to calculate a soil quality (SQ) index (SQI). The results indicated overall SQI values of 37.6 (SC) > 29.8 (O_p) > 28.8 (SO_p), but there were no significant variations ($p < 0.05$) in physical SQ, whereas chemical SQ varied in all conditions, mostly at 0–5 cm in O_p and SO_p. Increases of SOC were also observed (2015–2018 period) of 22.5, 14.5, and 4.8 Mg ha^{-1} for SO_p, O_p, and SC, respectively, showing that SPS promote the reclamation of Ranchillo Alto soils.

Keywords: agroforestry systems; sustainable land management; C sequestration; Andisols

1. Introduction

At present, of the 10–12 Pg yr^{-1} of the world emissions of carbon equivalent (CO_{2eq}) (greenhouse gas emissions expressed as CO_2) [1,2], deforestation is the second largest anthropogenic source of CO_2 emissions [3]. Additionally, of the 4033 Mha that comprise the world forest areas, around 3.24% has been subjected to logging, which has resulted in the release of approximately 20% of the global soil organic C (SOC) depletion, mainly due to the expansion of agricultural frontiers [4]. Specifically, South America is the second leading region of the world for CO_{2eq} emissions from agricultural-forestry and livestock practices (40%) [5], resulting in losses of approximately 8.7% of the forest areas [4].

As a part of the international efforts addressing climatic change, silvopastoral systems (SPS), which are defined as predetermined associations of woody and herbaceous species and livestock and are a subtype of an agroforestry system (AFS), have remarkable carbon sequestration (C→SOC) potential, and are able to store around 1.8–6.1 Mg SOC yr^{-1} [6–8], which is critically relevant to natural pedologic processes, management practices, and environmental functions. In this regard, Karlen et al. [9], introduced the concept soil quality defined as, "Soil capacity under a determined management or ecosystem fringe to sustain biological productivity, preserve environmental functions, promoting plant and animal development and consequently human health". Soil quality (SQ) is measured through SQ indicators (S_{IND}), which directly or indirectly reflect soil functionality at different timescales [10,11]. According to [12–14], the selection criteria for soil indicators (S_{IND}) should include the following: (i) a correlation with ecosystem processes (e.g., C→SOC); (ii) integration with chemical physical and biological properties, (iii) easily measured, replicated, and verified; (iv) a sensitivity to seasonal or atmospheric variations and realistic management practices; (v) compatibility with previous data; and (vi) usefulness for different professionals.

Regarding the specific case of Chile, decades of overutilization of natural resources has resulted in 49.1% of the national territory being affected by soil degradation [15], which has caused yearly emissions of approximately 11.8 Gg CO_{2eq}, of which approximately 38% comes from agricultural soils [16]. Moreover, of the 51 Mha that have been historically used in agricultural-forestry and livestock production, only 35.5 Mha presently remain active [17], mostly because of a massive loss of forest biomass that has had a critical effect on optimal soil functionality (e.g., erosion) [18]. On that basis, different government and institutional initiatives have been implemented (e.g., National Forest Program), in order to mitigate soil degradation. However, SPS have achieved only a limited presence in the regulatory framework, a fact that has been documented by scientific researchers [19]. In Coyhaique, of the Chilean Patagonia, [20] an investigation compared SPS to an introduced plantation (both comprised of *Pinus ponderosa*), with results that showed C stocks of 224 Mg C ha^{-1}, 199 Mg C ha^{-1}, and a net C accumulation of 1.8 Mg yr^{-1} (800 trees) and 2.5 Mg yr^{-1} (400 trees) for the SPS and plantation, respectively. The authors concluded that trees in SPS use the site resources more efficiently (up to 30%).

Therefore, it was proposed to study the SPS within a native Roble (*Nothofagus obliqua*) forest in the Region of Ñuble (SPS-RA) having distinct levels of degradation, with the objective to determine the effect of SPS over the physical and chemical aspects of SQ, after five years of establishment. It was hypothesized that the SQ index (SQI) in the SPS-RA, would tend to increase at depths of 0–5 cm as a result of improved silvopastoral management, with annual net accumulation of SOC, regardless of the initial site condition, resulting in values above the minimal range reported in the literature for SPS (1.8 Mg SOC).

2. Materials and Methods

2.1. Description of the Study Site

The silvopastoral systems (SPS) are located in the Ranchillo Alto area which is a state-owned property in the Ñuble region (37°04′52″ S, 71°39′14″ W; 1200–2000 m.a.s.l) covering an area of about 635 ha and 120 km east of the City of Concepcion [19,21].

The silvopastoral systems located in the Ranchillo Alto area (SPS-RA) comprise 24 ha and were established mainly to recover the ecosystem value of the native forest along with the promotion among the community of sustainably oriented, rural economic practices. The woody element in the SPS-RA is Roble (*Nothofagus obliqua*), while the herbaceous component includes oats (*Avena sativa*), vetch (*Fabaceae purpurea*), clover (*Trifolium incarnatum*, *T. subterraneum* y *T. vesiculosum*), *Lolium multiflorum westerwoldicum*, *Phalaris acuatica*, *Lolium perenne*, *Festuca arundinacea*, *Dactylis glomerate)*, and the re-sprouting of Radal (*Lomatia hirsuta*), and Quila (*Chusquea quila*). According to USDA, 2014 [22], the soils are Andisols, "Santa Barbara" series (medial, amorphic, mesic Typic Haploxerands), and locally known as "trumaos".

Andisols in Chile are of major importance for agricultural production, corresponding to approximately 60% of national arable land (2.5 Mha) [23]. Moreover, Andisols constitute about 30–70% of the total surface in the Andean mountain range, which have critical relevance in terms of water cycling (e.g., preventing potential flooding downstream) [24,25]. However, previous conditions in the SPS-RA include over grazing and browsing and excessive logging, generating degradation processes evidenced by discontinuous soil cover, topsoil removal, formation of gullies, and massive losses of soil organic matter (SOM) [26].

To determine the SQI in the SPS-RA, the respective SQ indexes (S_{IND}) were examined and grouped as follows: (i) chemical parameters such as pH, %SOC, total N, NH_4^+, NO_3^-, P, K^+, Ca^{2+}, Mg^{2+}, Na^+, S, exchangeable Al (Al_{EXCH}), % of Al saturation (%Al_{SAT}) that are linked to soil fertility, and therefore to C→SOC and (ii) physical parameters such as particle density (PD), bulk density (BD), total porosity % (P_{OR}), % of water stable aggregates (WSA), infiltration velocity ($I_{NF}V$), water holding capacity (WHC) and penetration resistance ($P_{EN}R$) which couple soil particle arrangement and environmental services (e.g., water cycling).

2.2. Soil Sampling and Analysis

A total of thirty-six soil samples, randomly chosen, were collected in January 2019 from the depths of 0–5 and 5–20 cm for the three considered conditions (open (O_p), semi open (SO_p), and semi closed (SC)) (Table 1). Each sample (analyzed in triplicate), was air-dried, mixed, ground, and passed through a 2 mm sieve for determination of the respective S_{IND}. The work was carried out at the Agricultural Research Institute (INIA, Quilamapu) to determine most of the properties (except for SOC% and N%).

The chemical S_{IND} of SOC and total N were analyzed at the Soil and Natural Resources Laboratory (Faculty of Agronomy, University of Concepción), according to Wright and Bailey (2001) [27]. The temporal variation of SOC and N was determined by comparison of the current to previous data from the sites. The remaining indicators of $pH_{(water)}$, %SOM, [NH_4^+, NO_3^-, P, K^+, Ca^{2+}, Mg^{2+}, effective cation-exchange capacity (ECEC), Na^+, S, Al_{EXCH}] concentrations, and %Al_{SAT} were conducted using the methods proposed by Sadzawka et al. (2006) [28]. Regarding the physical S_{IND}, %WSA (water stable aggregates) was measured according to Kemper and Rosenau (1986) [29], where soil samples were placed in a 0.250 mm sieve and immersed within an aluminum chamber containing distilled water during 3 min, with a cycling of 1.3 cm (35 rep min^{-1}). The dispersed soil was placed in containers and dried at 105 °C, while the remaining soil was re-immersed into an aluminum chamber containing sodium hexametaphosphate (2 g L^{-1}) during 15 min with a cycling of 1.3 cm (35 rep min^{-1}). Once dried, samples from both procedures were weighed in order to determine each proportion within the total sample. The WHC (water holding capacity) was determined according to Zagal et al. (2003) [30]. A sample with a 1:2 soil water ratio was placed into a plastic cone sealed with adhesive tape at the bottom for about 12 h, after which the tape was carefully perforated to allow the water to drain which was collected into a plastic bottle, and then the subsequent liquid volume was measured. The $P_{EN}R$ determination was carried out by using a penetrometer model Soil Compaction Tester Dickey-John (Auburn, IL, USA); and determinations were made by following a transect over the 60 plots for each site condition in order to achieve a reliable representativity. Field measurements of unsaturated hydraulic conductivity (K) were performed using an infiltrometer model Mini Disk Infiltrometer S (Pullman, WA, USA). The methodology proposed by Zhang (1997) [31], was used to determine K (cm day^{-1}), based on the cumulative infiltration measurements. Bulk density (BD), was measured in soil that was sampled using cylindrical soil cores (211 cm^3), which were subsequently dried at 105 °C until reaching a constant weight, [32]. The soil particle density (PD) was evaluated through the pycnometer method [33], and net pore space (P)% was calculated from BD and particle density (PD) values, using the following equation:

$$P = [PD - BD/PD] \times 100 \quad (1)$$

Table 1. General information for each tree cover condition in the silvopastoral systems located in the Ranchillo Alto area (SPS-RA).

Cond	Location	Total Area (ha)	N° P and Area (ha)	Tree Density (Nº ha^{-1})	Forest Species	Tree Cover Description	Previous Degradation	Soil Sampling
O_p	37°14′51″ S, 72°26′30″ W 1250 m.s.n.m	4	3 × 1.33	60	Roble (*Nothofagus obliqua*)	Ground with 85–95% of external light (average area)	+++	2 depths (0–5 and 5–20 cm) × 6 sampling points
SO_p	37°14′50″ S, 72°26′30″ W 1250 m.s.n.m	4	3 × 1.33	134	Roble (*Nothofagus obliqua*)	Soil with 65–75% of external light (average area	++	2 depths (0–5 and 5–20 cm) × 6 sampling points
SC	37°14′49″ S, 72°26′30″ W 1250 m.s.n.m	4	3 × 1.33	258	Roble (*Nothofagus obliqua*)	Soil with/ 45–55% of external light (average area)	+	2 depths (0–5 and 5–20 cm) × 6 sampling points

* Cond, condition; Nº P, number of plots. A, area

2.3. Soil Quality Assessment

Soil quality estimation was performed by the selection of different S_{IND}, based on their relevance to the properties of the SPS-RA (e.g., soil fertility reclamation, C→SOC), and the previously stated selection criteria. Once a specific S_{IND} was analytically characterized (in the field or laboratory), a numerical point value (score) was, then, assigned to it, based on qualitative ranges (low, medium, and high) reported in the literature (e.g., Amacher et al. (2007) and Vidal (2007) [34,35]). Those ranges were related to different soil functionality levels, from critical to optimal, in which an individual S_{IND} can influence the overall status of soil quality SQI. However, in this study, the overall SQI was subdivided into chemical ($SQI_{CHEMICAL}$) and physical ($SQI_{PHYSICAL}$) and most of the ranges (low, medium, and high) for any single S_{IND} were taken from [34], although in some S_{IND}, the ranges were adjusted with the aim of improving their local representativity, based on the national scientific literature and the unique properties of Andisols. Additionally, another S_{IND} was included from the original proposal that was conducted by [34], in order to calculate the proposed global SQI (see Appendix A) for the specific purposes of this study. Accordingly, the chemical SQI was calculated as follows:

$$\begin{aligned} SQI_{CHEMICAL} = \Sigma\ [&pH + \%SOC + CEC + N + NH_4^+ + NO_3 \\ &+ C{:}N + P + K + Ca^{2+} + Mg^{2+} + Na + S + Al_{EXCH} + Al_{SAT}] \end{aligned} \quad (2)$$

where $SQI_{CHEMICAL}$ is the chemical soil quality index, %SOC is the percentage of SOC, ECEC is the effective cation-exchange capacity, N is total N, NH_4^+ is available ammonium, NO_3 is available nitrate, C/N is the C:N ratio, P is available phosphorus, K^+ is potassium content, Ca^{2+} is calcium content, Mg^{2+} is magnesium content, Na is sodium content, Al_{EXCH} is exchangeable aluminum, and Al_{SAT} is aluminum saturation (%).

Subsequently, physical SQI by S_{IND} was calculated as follows:

$$SQI_{PHYSICAL} = \Sigma\ [I_{NF}V + \%WSA + WHC + P_{EN}R + BD + PD + P_{OR}] \quad (3)$$

where $SQI_{PHYSICAL}$ is the physical soil quality index, $I_{NF}V$, is infiltration, %WSA is water stable aggregates %, WHC is water holding capacity, $P_{EN}R$ is penetration resistance, BD is bulk density, PD is particle density, and P_{OR} is total porosity.

Therefore, a global SQI was estimated using the means of both SQI types as follows:

$$SQI_{GLOBAL} = \Sigma\ [SQI_{CHEMICAL} + SQI_{PHYSICAL}]/2 \quad (4)$$

Finally, the % valuation for any site condition was calculated as:

$$\%\ SQ = [\text{number of } S_{IND} \text{ at critical level/number of } S_{IND} \text{ estimated}] \times 100 \quad (5)$$

* A list of abbreviations is provided in Appendix B (Table A3).

2.4. Statistical Analyses

The data were input, and calculations made for each S_{IND}, and the conversion to the SQI (Equations (2)–(5)), were performed using Microsoft Excel. All site conditions were analyzed in a completely randomized design that considered both the site conditions and soil depths. Statistical analyses were carried out using one-way ANOVA's; and when a source of variation showed a significant effect ($p \leq 0.05$), a means separation by Tukey's was performed in order to establish differences among the means of every S_{IND}. Additionally, a global Pearson's correlation was conducted in order to identify possible associations among the various S_{IND} ($r \geq \pm 0.7$). The data were analyzed using SPSS (statistical software V11.0, Inc, Chicago, IL, USA).

3. Results and Discussion

3.1. Soil Chemical Indicators

The evaluation of the means of the chemical S_{IND} showed that for each condition and soil depths there were adequate levels for pH, K, S, and Na [34] (Table 2, Table 3 and Appendix A).

Table 2. Soil chemical characterization results.

Cond/Depths	pH (H_2O)	SOC (%)	N (%)	C/N	P *	K *	Ca **	Mg **
O_p 0–5	5.63Aa	14.17Aa	0.61Aa	23.05Aa	2.98Aa	109.9Aa	1.6Aa	0.28Aa
O_p 5–20	5.59Ab	13.33Aa	0.61Aa	22.09Ab	2.08Ab	73.8Ab	0.46Ab	0.16Aa
SO_p 0–5	5.93Ba	12.57Ba	0.48Ba	26.31Ba	3.66Ba	87.6Ba	4.58Ba	0.58Ba
SO_p 5–20	5.59Bb	11.49Ba	0.45Ba	25.37Bb	2.13Bb	62.2Ba	1.37Bb	0.25Ba
SC 0–5	5.9Ca	10.82Ca	0.46Ba	22.37Aa	3.63Ba	113.7Aa	3.23Ba	0.32Ba
SC 5–20	5.85Cb	13.87Cb	0.53Ba	21.78Ab	2.15Bb	70.1Ab	3.33Ba	0.47Ba

* Cond, conditions; *n*:18; $p < 0.05$; * mg kg^{-1}; ** cmol (+) kg^{-1}. Distinct capital letters mean significant differences among conditions whereas lowercase letters refer to significant differences between depths.

Table 3. Soil chemical characterization results B. Continuation.

Cond/Depths	Na **	Al_{EXCH} **	ECEC	% Al_{SAT}	S *	NO_3^- *	NH_4^+ *
O_p 0–5	0.1Aa	0.34Aa	2.70Aa	12.74Aa	8.37Aa	16.78Aa	10.59Aa
O_p 5–20	0.1Ab	0.26Ab	1.16Ab	22.09Ab	9.23Ab	10.27Ab	9.07Aa
SO_p 0–5	0.05Ba	0.11Ba	5.55Ba	2.02Ba	9.26Ba	23.72Ba	18.92Ba
SO_p 5–20	0.07Bb	0.30Bb	2.15Bb	13.75Bb	10.73Bb	15.63Bb	13.43Ba
SC 0–5	0.08Aa	0.14Ca	4.06Ba	3.54Ca	13.20Ca	9.16Aa	12.85Ba
SC 5–20	0.13Ab	0.14Ab	4.25Bb	3.25Cb	11.93Cb	12.75Ab	15.68Ba

* Cond, conditions; *n*:18; $p < 0.05$; * mg kg^{-1}; ** cmol (+) kg^{-1}. Distinct capital letters mean significant differences among conditions whilst lowercase letters refer significant differences between depths. *n*:18; $p < 0.05$; * mg kg^{-1}; ** cmol (+) kg^{-1}. Distinct capital letters mean significant differences among conditions whilst lowercase letters refer significant differences between depths.

The mean values of soil pH were 5.6, 5.7, and 5.9 (±0.03) (O_p < SO_p < SC), with significant differences measured among the SPS conditions and soil depths. Lower values of pH were observed in the 0–5 cm horizon, which could be attributed to a higher acidic condition that was favored by a greater content of OM [36], however, in all cases the pH values were within desirable ranges for supporting plant grow [34].

Soil organic C% content values at the 0–20 cm depths were 13.5, 13.1, and 11.8% (±0.28) for O_p, SC, and SO_p, respectively (Table 4). The greatest SOC% occurred in the O_P, despite having the lowest tree cover, as well as being the more anthropogenically affected area. This contradiction could be related to the extensive history of agricultural burns for the potato crops (*Solanum tuberosum*), thereby generating pyrogenic C, as identified by the presence of charcoal fragments and intense black color in soil samples. Pyrogenic C, is highly resistant to oxidation due to its poly aromatic structure, and therefore could be a persistent fraction of total C. In forests of *Araucaria-Nothofagus spp*, of the Tolhuaca National Park, Chile (36°52′ S y 71°56′14″ O), [37] it has been estimated that pyrogenic C represented up to 5% of the total SOC. Concerning SOC storage (0–20 cm) in the present study, stocks of 150.5, 149.8, and 143.5 Mg ha^{-1} were estimated for SO_p, SC, and O_p, respectively (Figure 1).

Table 4. Variation of soil organic C (SOC) and total N in the period 2015–2018.

Conditions	* SOC_{2015}	SOC_{2018}	* N_{2015}	N_{2018}	* $C{:}N_{2015}$	$C{:}N_{2018}$
O_p 0–20	7.1	13.5	0.32	0.61	22.3	22.3
SO_p 0–20	7.1	11.8	0.38	0.46	19.2	25.6
SC 0–20	8.0.	13.1	0.42	0.52	19.5	22.0

SOC and N (%) * from Alfaro et al. (2018), weighted values * from [38].

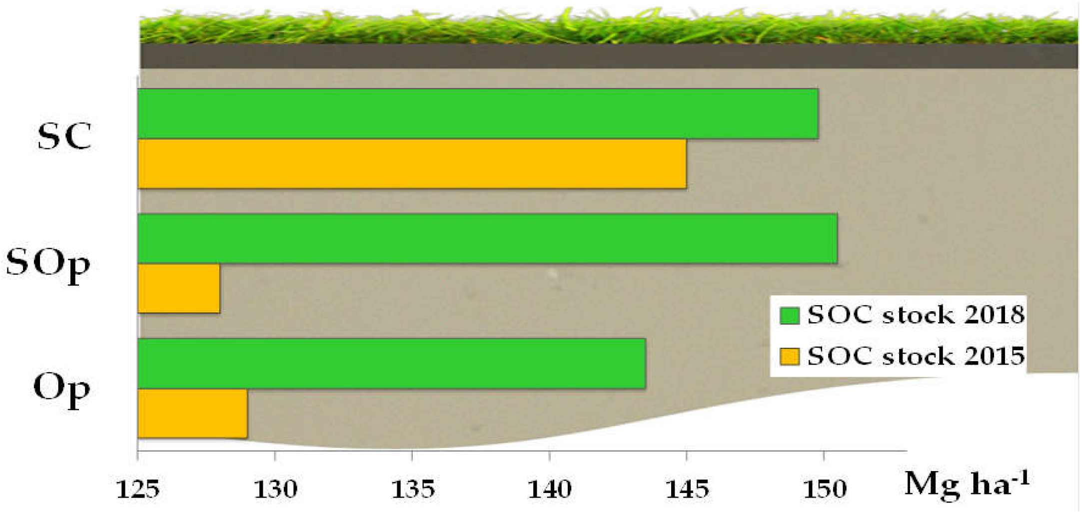

Figure 1. Temporal variations (2015–2018) of SOC stocks (0–20 cm) in the SPS-RA. O_P + 14.5 Mg C ha^{-1}; S_{OP} + 22.5 Mg C ha^{-1}; and 1.6 Mg of SOC for semi open (SO_P), open (O_P), and semi closed (SC), respectively.

The estimated carbon concentrations in the SPS-RA are significantly higher than those found in other soil conservation managements (e.g., conservation and no tillage cropping systems). In agriculturally managed Andisols, with wheat stubble incorporation from Yungay, Chile, Panichini (personal communication, May 2019), estimates indicate a mean SOC of 6.9% and a C stock of 130 Mg ha^{-1}. However, Muñoz et al. (2012) [39] determined SOC stocks that ranged from 33.1 to 35.5 Mg ha^{-1} C after 16 years of no-tillage in volcanic soils in south-central Chile.

In our study, the total N% (0–20 cm) ranged between 0.6 and 0.5 (±0.09), where O_p > SO_p = SC, and were within acceptable levels. However, the bioavailable N forms had averaged values for NO^{3-} that ranged from 17.7 to 11.9 mg kg^{-1} (SO_p > O_p = SC), whereas those for NH^{4+} were 15.0, 14.8, and 9.45 mg kg^{-1} (SC > SO_p > O_p, respectively), which were lower than the minimal requirements for most plants [34]. The N could be undergoing a net immobilization process in soil, or the low levels of NH^{4+} could be related to the high N demand by the herbaceous component, which preferentially uptakes this particular species because of its lower energetic cost to the plant as compared with NO^{3-}. Alternatively, the woody component favors NO^{3-} absorption because of the high soil exploratory capacity by roots as occurs in the SC condition [40,41]. Similarly, Alfaro et al. (2018) [38] found a nitrification rate pattern (NO^{3-}→NO_2^-) of SC > SO_p > O_p in the SPS-RA, which was 45% higher for SC as compared with SO_p.

Nonetheless, it is expected that the NH^{4+} levels will increase in soils, to eventually become the dominant bioavailable N species, due to the ongoing fecal depositions from the animal component within the system [42]. The temporal variation of SOC and total N are summarized in Table 4. The C/N ratio varied significantly at both ranges of depths (0–5 and 5–20 cm) as follows: O_p (23.1/22.1), SO_p (26.3/25.4), and SC (20.9/20.8). Ratios over 10 indicate a net immobilization of N, resulting in its incorporation into microbial biomass or by-products of microbial activity during the SOM cycling processes, consequently limiting its availability for plant growth [43].

In a previous investigation [19], the authors found a C/N ratio of 18.0 in the SPS-RA during 2014, showing a progressive increase over time of this S_{IND}, probably highlighting the bio constructive effects of SPS in soils. Phosphorous concentrations were 2.3–2.5 mg kg^{-1} (±0.07) and corresponded to typical values in volcanic soils 3–165 mg kg^{-1} [44], with a mean of 4.6 mg kg^{-1} *p* for native forests [45].

However, the *p* values found in the SPS-RA were significantly lower than previously observed [46] and ranged from 15.1 to 19.9 mg kg^{-1} P in volcanic soils under crop rotation of wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), subterranean clover (*Trifolium subterraneum* L.), canola (*Brassica napus* L.), and lentil (*Lens culinaris* L.) or natural grassland (6 mg kg^{-1} P).

Critical P levels in the SPS-RA could be related to P fixation mediated by P-OM associations and P-Al complexes in soil [47]. For other major nutrients, K concentrations at the 0–20 cm depths were O_p > SC > SO_p (82.8, 81.4, and 68.6 mg kg^{-1}, respectively) (±1.86), which was slightly limiting for plant growth; the S determinations showed that SC >SO_p > O_p (12.2, 10.4, and 9.0 mg kg^{-1}, respectively) (±0.27), and were adequate soil concentrations; there were moderate to low levels of Mg SC > SO_p > O_p with values of 50.5, 48.1, and 26.8 mg kg^{-1} (±5.53), respectively, similar to Ca where SC >SO_p > O_p (657.3, 596.2, and 215.5 mg kg^{-1}, respectively) (±63.1) were observed according to [34]. The measurement of soil ECEC at the 5–20 cm depths showed that SC > SO_p > O_p (4.2, 3.0, and 1.5 cmol kg^{-1}, respectively), which was an intermediate level (except for O_P 5–20 cm) with higher values in O_P and SO_P (0–5 cm) [48]. Regarding Al_{EXCH}, critical values were found of 0.3 and 0.1 cmol kg^{-1} (±0.02) (O_p = SO_p > SC), and the %Al_{SAT} with 19.8, 10.8, and 3.3 (±1.2) for O_p, SO_p, and SC, respectively. Both S_{IND} are typical for volcanic soils, but these still could lead to increased soil acidification, which would inhibit soil nutrient uptake (e.g., Ca and Mg) and restrict possible crop rotations that use Al sensitive species (e.g., barley and wheat) [49].

3.2. *Soil Physical Indicators*

In the physical S_{IND} analyses, the BD, PD, P_{OR}, and $P_{EN}R$ were estimated to be at optimal levels in all site conditions (Table 5 and Appendix A). Individually, BD showed representative values for Andisols with 0.50, 0.53, and 0.68 g cm^{-3} (±0.02) for SC, O_p, and SO_p respectively. The lowest mean was in O_p 5–20 cm (0.51 g cm^{-3}) and was possibly due to the presence of pyrogenic C [50], whereas higher means were observed in SO_p at the 5–20 cm depths (0.65 g cm^{-3}). Likewise, Panichini (personal communication, May 2019) determined a mean value of BD of 0.94 g cm^{-3} in volcanic soils of Yungay under stubble burning management. Moreover, PD varied from 1.95 to 2.1 g cm^{-3} (±0.05) with a mean value of 2.0 g cm^{-3}, which was within representative ranges of volcanic soils that are rich in OM, according to Nissen et al. (2005) [51].

The same authors determined similar PD values (1.92 g cm^{-3}) in forest soils (0–15 cm) of the Region of Osorno, Chile. Although there were no significant differences among %WSA (50.6–49.7 and 49.5%) (±0.65), there was a tendency for SC > O_p > SO_p, that could be related to previous site degradation. Gradual increases of %WSA are expected to occur though, and mediated by, emerging roots and hyphae associations [52,53]. The soil compaction test (measured through its $P_{EN}R$) revealed ranges of 100–200 psi that were suitable for root anchoring/exploration and plant growth [54,55]. It should be noted that there were scattered points within O_p with $P_{EN}R$ > 300 psi that had a visibly reduced coverage of vegetation.

Table 5. Soil physical results.

Condition/Depths	BD (g cm^{-3})	PD (g cm^{-3})	* P_{OR} Total (%)	WHC (%)	I_{NF}Vk (cm day^{-1})	WSA (%)	P_{EN}R (psi)
O_p 0–5	0.6Aa	1.9Aa	71.2Aa	60.8Aa	*	49.6Aa	100–200Aa
O_p 5–20	0.5Aa	2.0Aa	74.2Aa	58.9Aa	17Aa	49.7Aa	100–200Aa
SO_p 0–5	0.6Aa	1.9Aa	68.9Ba	59.2Aa	*	49.4Aa	100–200Aa
SO_p 5–20	0.7Aa	2.0Aa	68.3Ba	52.2Aa	18.3Aa	49.5Aa	100–200Aa
SC 0–5	0.5Aa	1.9Aa	73.6Aa	54.4Aa	*	51.2Aa	100–200Aa
SC 5–20	0.5Aa	2.0Aa	73.9Aa	62.9Aa	16.2Aa	50.4Aa	100–200Aa

n:18 and $p < 0.05$. Distinct capital letters mean significant differences among conditions, whereas lowercase letters refer significant differences between depths. * I_{NF}V values were considered for the total depth (0–20 cm) and * from the Equation (1). BD, bulk density, PD, particle density, P_{OR} Total, Total porosity, WHC water holding capacity, I_{NF}Vk, Infiltration velocity, WSA, % of water stable aggregates, P_{EN}R, Penetration resistance

In terms of hydraulic properties (0–20 cm), the P_{OR} presented optimal values in all conditions, with SC (73.8), O_p (73.5), and SO_p (68.5) that promote both water storage and root development. These results are consistent with [51], who found a P_{OR} of 73.9. The WHC (0–5 and 5–20 cm) was within a range of acceptable values that promote water storage and redistribution processes according to [35], and ranged as follows: O_p (60.8–58.9), SO_p (70.8–66), and SC (70.8–62.8) (±2.96); with the observed gradient probably corresponding directly with the previous disturbances of the sites, and additions of SOM (in SC and SO_P). In the case of soil with a high P_{OR} and low values of WHC (O_p), this could be due to hydrophobic conditions influenced by the possible presence of pyrogenic C.

The S_{IND} that relates to water infiltration and percolation in soil ($I_{NF}V$) 0–20 cm, showed an intermediate level with k values of 17, 18.3, and 16.2 cm day^{-1} with SO_p > O_p > SC [56].

However, for O_P, many attempts were necessary to carry out the measurements because of compacted surface soil and hydrophobicity which impeded the proper functioning of the infiltrometer.

3.3. Determination of SQI

After calculating the sub-indexes for all S_{IND}, distinctive trends were observed in both the chemical and physical indicators (Figure 2) which illustrated some of the native (or inherent) characteristics of soil quality in volcanic soils (e.g., P, BD, P_{OR}, Al_{EXCH}, and Al_{SAT}). Additionally, the results showed the possible direct effects of silvopastoralism over some of the S_{IND} sub-indexes (e.g., SOC). Chemical SQI was higher at SO_P at the 0–5 cm depths (probably reflecting the more favorable tree density that favors the beneficial SPS interactions) and SC at the 5–20 cm depths at the less disturbed site (Table 6). Nevertheless, SOC as the most important $S_{IND,}$ showed significant variations among all conditions, as evidenced in the O_P condition with a higher %C content (13.5) than the SO_P condition (11.8% SOC).

Table 6. Partial, global, and % soil quality index (SQI) scoring.

Condition/Depths	* $_{CHEMICAL}$SQI	** $_{PHYSICAL}$SQI (B)	*** $_{GLOBAL}$ SQI	**** SQI $_{\%}$
O_p 0–5	13	64.2	38.6	22.7
O_p 5–20	7.2	46.4	26.8	40.9
SO_p 0–5	24.6	46.4	35.5	22.7
SO_p 5–20	10.1	42.9	26.5	27.2
SC 0–5	10.1	50.0	30.1	22.7
SC 5–20	15.9	64.3	40.1	22.7

From the Equations * (2), ** (3), *** (4), and **** (5).

The Physical SQI showed less variation among the site conditions, with the highest scores in O_P at the 0–5 cm depths and SC at the 5–20 cm depths. The Global (physical plus chemical) SQI revealed less variation with scores of 26.5–40.1 from SO_P at the 5–20 cm depths and O_P at the 5–20 cm depths with the lowest scores in SC at the 5–20 cm depths and O_P at the 5–20 cm depths. The % "critical" SQI showed that the O_P at the 5–20 cm depths was the condition with the most S_{IND} that were at critical levels, likely as a result of the adverse impacts of logging, over grazing, over browsing among trees, cropping, and burning practices. In addition, historic logging and fire events, erosion, and percolation losses of nutrients (e.g., P, Ca^{2+}, and ECEC) via leaching have likely been the causes of the low fertility levels in O_P at the 5–20 cm depths [57,58].

An overall correlation analysis among the S_{IND} (Table 7) revealed some possible associations as follows: the %WSA was correlated with P_{OR} and $I_{NF}V$ (r ≥ 0.8) indicating the importance of soil aggregation on hydraulic conductivity; Al_{SAT} % and Al_{EXCH} were correlated with pH, ECEC, Ca^{2+}, and Mg^{2+} (r = −0.9) showing the inverse relationship between soil nutrients and Al forms; and SOC was correlated with N (r = 0.9), P (r = 0.7), K(r = 0.8), BD (r = 0.8), and P_{OR} (r = 0.7) which underlined the key role of SOM in soil quality.

Thus, this study demonstrated the importance of soil quality assessment in AFS, particularly SPS, and that the calculation of simple additive linear SQI is one of the most effective methods for detecting the impacts of management practices in soils [59]. In the future, it is expected that there will be an improvement in some of the S_{IND}, thereby increasing SQI in the SPS-RA in the medium to long term (10–20 y), probably by the continuous thickening of the organic duff on the soil surface (O_f horizon), and the widespread depositions of animal excrements, in addition to the positive effects of root and hyphae that promote the formation of stable aggregates >2.00 mm through root biomass and colonization mechanisms, which in turn creates greater SOC stabilization (e.g., C→SOC) [52,53].

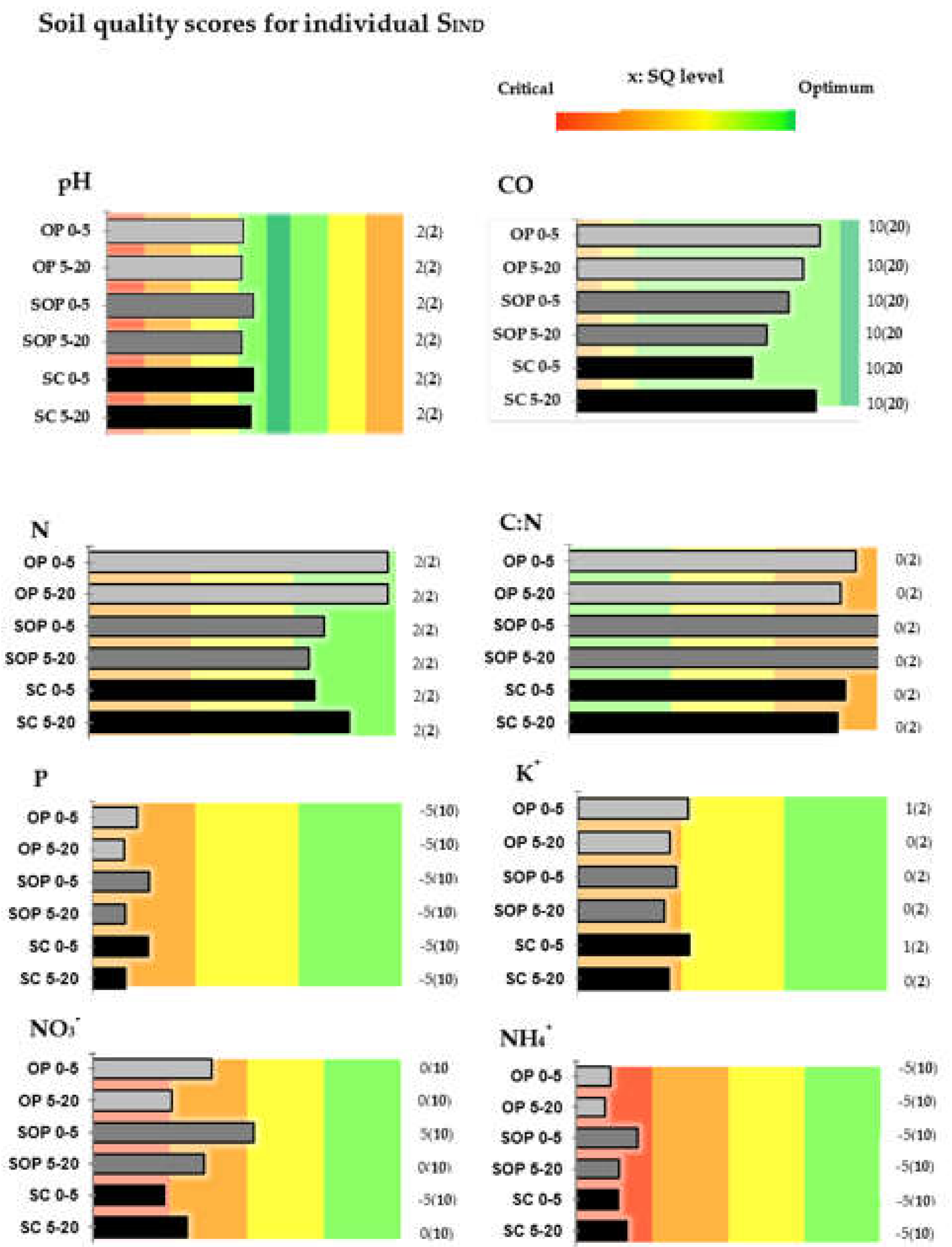

Figure 2. *Cont.*

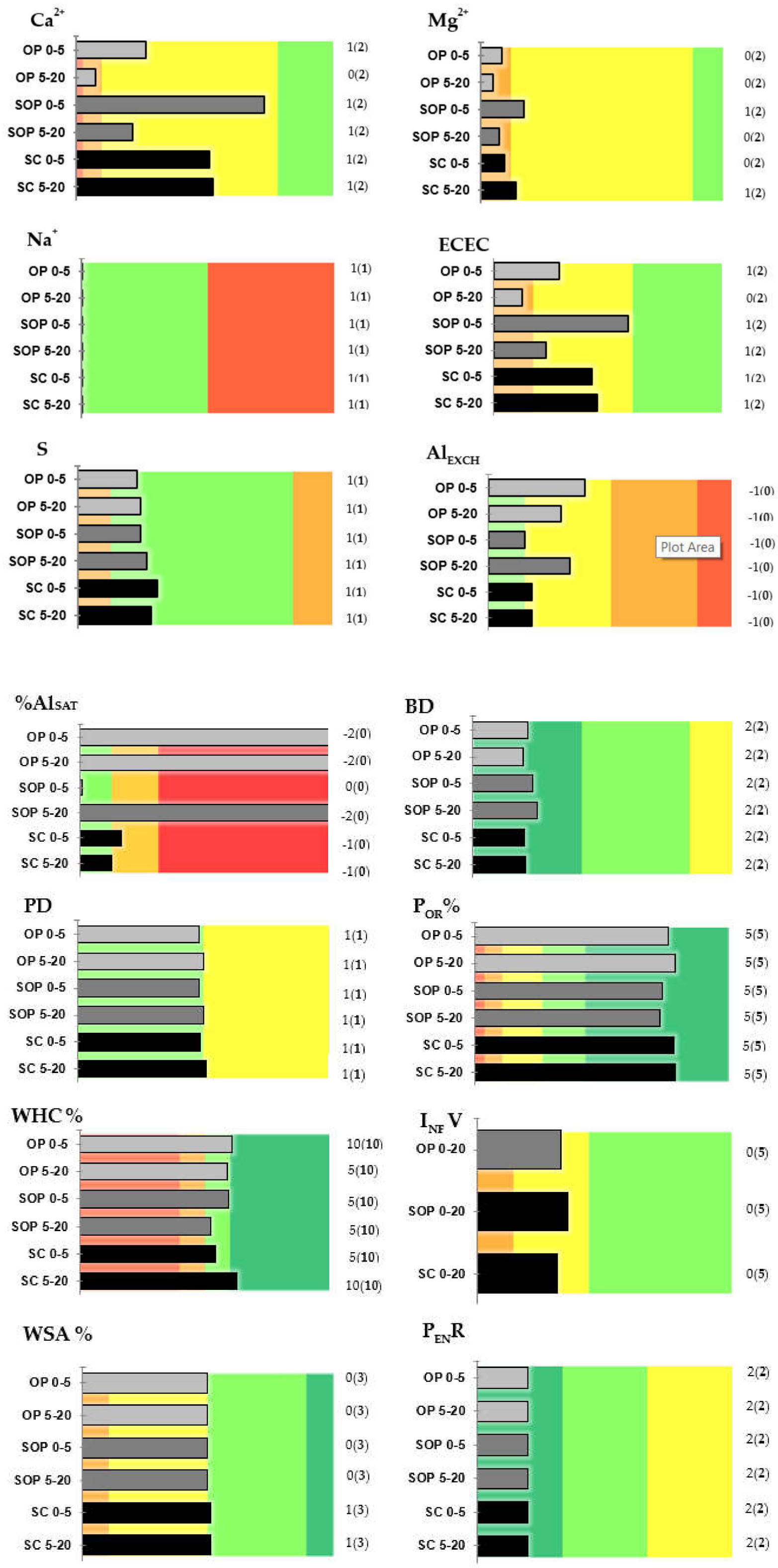

Figure 2. Integration of the different sub-indexes for all soil indicators (S_{IND}) considered. Each color corresponds to a different quality level, according to the ranges defined by Amacher et al. (2007) [34]. Greenish hues represent indexes from acceptable to optimal (differentiated from lower to greater color intensity respectively), reddish color symbolizes undesirable to critical levels; yellowish color indicates medium values of quality. Values in the columns on the right [x(**x**)], express x as the quality sub-index score, and (**x**) as the maximum possible sub-index value.

Table 7. Pearson's correlation coefficients for the distinct S_{IND} evaluated.

	pH	**SOC (%)**	**N (%)**	**C:N**	**P**	**K**	**Ca^{2+}**	**Mg^{2+}**	**Na**	**Al_{EXCH}**	**ECEC**	**Al_{SAT} %**	**S**	**NO_3^-**	**NH_4^+**	**BD**	**PD**	**P_{OR}**	**WHC%**	**$I_{NF}V$**	**WSA%**
pH	1	NS	NS	0.91	NS	NS	NS	NS	0.8	NS	NS	NS	NS	0.7	NS	0.8	0.7	NS	0.7	0.8	NS
SOC (%)	NS	1	0	0.91	0.7	0.9	NS	0.6	0.8	NS	NS	NS	NS	NS	NS	0.8	NS	0.7	NS	NS	NS
N (%)	NS	0.9	1	N	NS	0.8	NS	NS	N	NS	NS	NS	NS	0.8	NS	NS	NS	NS	NS	0.6	0.7
C:N	NS	NS	NS	1	NS	NS	NS	NS	N	0.9	NS	NS	NS	NS	NS	NS	NS	NS	0.6	NS	NS
P	NS	NS	NS	N	1	NS	NS	NS	N	NS	NS	NS	0.7	NS	NS	NS	NS	0.6	0.9	NS	0.7
K	NS	NS	NS	N	0.8	1	NS	0.9	0.6	NS	NS	NS	0.8	0.9	NS	NS	NS	0.6	0.9	NS	NS
Ca^{2+}	0.9	NS	NS	N	0.7	NS	1	NS	N	NS	NS	NS	NS	NS	NS	0.8	0.8	0.6	0.7	0.8	0.6
Mg^{2+}	0.8	NS	NS	N	NS	NS	0.9	1	N	NS	NS	NS	0.6	NS	NS	NS	0.8	NS	NS	0.8	0.9
Na	NS	NS	NS	−0.8	NS	NS	NS	NS	1	0.8	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.6
Al_{EXCH}	−1	NS	NS	N	NS	NS	−0.9	−0.8	N	1	NS	NS	NS	0.7	NS	0.8	0.7	NS	0.7	0.8	NS
ECEC	0.9	NS	NS	N	0.7	NS	1	0.9	N	−0.9	1	NS	NS	NS	NS	0.8	0.9	0.6	0.6	0.8	0.7
Al_{SAT} %	−0.9	NS	NS	N	−0.6	NS	−0.9	−0.9	N	0.9	−0.9	1	NS	NS	NS	0.9	0.7	0.8	0.8	0.7	NS
S	0.6	−0.6	NS	N	NS	NS	NS	NS	N	−0.6	NS	NS	1	NS	NS	0.6	NS	NS	NS	NS	NS
NO_3^-	NS	NS	NS	0.7	NS	NS	NS	0.6	N	NS	NS	NS	NS	1	NS	NS	0.7	NS	0.7	NS	NS
NH_4^+	0.8	NS	NS	N	NS	NS	0.9	0.9	N	−0.8	0.9	−0.8	NS	0.7	1	NS	0.7	NS	0.8	0.9	0.9
BD	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	NS	NS	1	0.6	0	NS	NS	0.7
PD	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	NS	NS	NS	1	NS	0.6	0.6	NS
P_{OR}	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	−0.6	NS	−0.7	NS	1	NS	0.7	0.9
WHC%	NS	0.6	0.6	N	NS	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	1	NS	0.9
$I_{NF}V$	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	NS	1	NS
WSA%	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	NS	NS	1

Among remarkable correlations are the following: pH-ECEC (r = 0.9), pH and the cations Ca^{2+} and Mg^{2+} (r = 0.9, 0.8), pH-Al_{EXCH} (r = −1), pH-Al_{SAT}% (r = −0.9), these last inverse correlations demonstrating the importance of Al in nutrient availability. Complementary correlations such as Al_{EXCH}, Ca^{2+} (r = −0.9), Mg^{2+} (r = −0.8), S (r = 0.7), as with Al_{SAT}% and ECEC, Ca^{2+}, and Mg^{2+} (r = −0.9) showed the dominance of this element in the interchange sites as long as pH values decrease, thus substituting these cations. SOC correlated with different nutrients, i.e., N (r = 0.9), P (r = 0.7), K (r = 0.8) as well as the physical S_{IND} BD (r = 0.8) and P_{OR} (r = 0.7), which highlighted its crucial role on nutrient supply and particle arrangement.

4. Conclusions

An overall chemical SQI was calculated that showed a large variability over all site conditions, with NH^{4+}, NO^{3-}, and P, being the most limiting chemical indicators (S_{IND}). Regarding the overall physical SQI, there were no significant differences between individual physical S_{IND} (except for P_{OR} in SO_p), presumably due to the timescale by which those properties underwent changes. The combined (chemical + physical) Global SQI (0–20 cm), showed the SC condition had the highest SQI (37.6), followed by O_P (29.8) and SO_P (28.8), demonstrating the importance of trees in preserving soil quality. However, the highest SQI was in SC at the 5–20 cm depths, reflecting its history of less disturbed management. There was an estimated increase of SOC stock of about 7.5, 4.8, and 1.6 Mg $ha^{-1}yr^{-1}$, in addition to the total N increase of 0.5, 2.0, and 1.2 kg ha^{-1} for SO_p, O_p, and SC, respectively. Nonetheless, NO_3^- and NH_4^+ availability is limited, which is strongly linked to the progressive increase of C/N ratios that was observed. These preliminary results confirm the importance of the SPS-RA in the C→SOC sequestration process, with results that were generally within the typically reported values in the literature (only occasionally exceeding them, e.g., SO_P) and showing that these systems promote nutrient cycling and soil restoration. Future seasonal and long-term research is now required in order to understand the role of biological activity in SOM transformations and determine the soil C balances in order to elucidate the possible C stabilization processes involved.

Author Contributions: Conceptualization, F.D. and J.O.; methodology, M.P., J.O., P.N., and F.D.; validation, F.D., J.O., E.Z., and N.B.S.; investigation, J.O. and P.N.; resources, M.P. and J.O.; formal analysis and data curation, J.O.·and M.P.; writing—original draft preparation, J.O. and P.N.; writing—review and editing, F.D., J.O., and N.B.S.; visualization, J.O.; supervision, F.D., N.B.S., M.P., E.Z., and P.A.M.-H.; project administration, F.D., J.O., and M.P.; funding acquisition, F.D. and M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Native Forest Research Fund of the National Forestry Corporation, Chile (FIBN-CONAF project No. 001–2014), VRID-UDEC Multidisciplinary project No. 219.142.040-M, Chile and the INIA Quilamapu agroecology lab.

Acknowledgments: We wish to express our sincere thanks to the Ranchillo Alto Research & Teaching Forest of the University of Concepción, and to INIA Quilamapu for full access to their agroecology lab.

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

Appendix A

Sub-index values for each S_{IND} considered.

Below are shown S_{IND} ranges or levels of soil quality and the correspondent sub-index values (modified from [34]).

Table A1. Soil quality levels and their associated sub-index values for physical S_{IND}.

Physical S_{IND}	Level	Interpretation	Subindex	Source
PD (g cm^{-3})	<2	Desirable	1	[51]
	>2	Without effect	0	
BD (g cm^{-3})	<1.10	Optimum	2	[60]
	1.10–1.47	Desirable	1	
	>1.47	Low	0	
P_{OR} (%)	<5	Critical	−5	[61]
	5–10	Restrictive	0	
	10–25	Acceptable	1	
	25–40	Desirable	2	
	>40	Optimum	5	

Table A1. *Cont.*

Physical S_{IND}	Level	Interpretation	Subindex	Source
WHC (%)	>60	Optimum	10	[35]
	51–60	Acceptable	5	
	41–50	Low	0	
	<40	Critical	−10	
$I_{NF}Vk$ (cm day^{-1})	<8.64	Undesirable	−5	[56]
	8.64–20	Acceptable	0	
	20–43.2	Optimum	5	
$P_{EN}R$ (psi)	>300	Undesirable	0	[54,55]
	200–300	Acceptable	1	
	100–200	Optimum	2	
WSA (%)	<50	Undesirable	0	[54]
	50–70	Medium	1	
	70–90	High	2	
	>90	Optimum	3	

Table A2. Soil quality levels and their associated sub-index values for chemical S_{IND}.

Chemical S_{IND}	Level	Interpretation	Sub-index	Source
pH	<3.0	Super critical	−1	[34]
	3.01–4.0	Critical	0	
	4.01–5.5	Limiting	1	
	5.51–6.8	Desirable	2	
	6.81–7.2	Optimum	2	
	7.21–7.5	Acceptable	1	
	7.51–8.5	Limiting	1	
	>8.5	Critical	0	
SOC (%)	>15	Excellent	20	[35]
	5–15	High	10	
	3–5	Moderate	1	
	<2	Low	−10	
N (%)	>0.5	Desirable	2	[34]
	0.1–0.5	Adequate	1	
	<0.1	Insufficient	0	
NO_3^- (mg kg^{-1})	<10	Critical	−5	[35]
	10–20.1	Insufficient	0	
	20.1–40	Adequate	5	
	>40	Desirable	10	
NH_4^+ (mg kg^{-1})	<25	Critical	−5	[35]
	25–50	Insufficient	0	
	51–75	Adequate	5	
	>75	Desirable	10	
	20–20	Moderate	1	
	>20	Insufficient	0	

Table A2. *Cont.*

Chemical S_{IND}	Level	Interpretation	Sub-index	Source
C:N ratio	1–10	Adequate	2	[34]
	10–20	Moderate	1	
	>20	Insufficient	0	
P (mg kg^{-1})	>16	Adequate	10	[48]
	5–15	Moderate	1	
	<5	Insufficient	−5	
K (mg kg^{-1})	>500	Adequate	2	[34]
	100–500	Moderate	1	
	<100	Insufficient	0	
S (mg kg^{-1})	>100	Insufficient	0	[34]
	1–100	Adequate	1	
	<1	Insufficient	0	
Ca (mg kg^{-1})	>1000	Desirable	2	[34]
	101–1000	Adequate	1	
	10–100	Insufficient	0	
	<10	Critical	−1	
Mg (mg kg^{-1})	>500	Adequate	2	[34]
	50–500	Moderate	1	
	<50	Insufficient	0	
ECEC(cmol kg^{-1})	>6.27	Adequate	2	[62]
	1.65–6.27	Moderate	1	
	<1.65	Insufficient	0	
Exchangeable % Na	<15	Critical	0	[34]
	≤15	Acceptable	1	
Al_{EXCH}(cmol kg^{-1})	<0.1	Adequate	0	[62]
	0.11–0.51	Moderate	−1	
	0.51–0.81	Undesirable	−2	
	>0.81	Critical	−3	
Sat Al (%)	1.1–3.1	Adequate	0	[62]
	3.2–6.1	Moderate	−1	
	6.2–12	High	−2	
	>12	Critical	−5	

Appendix B

Table A3. List of abbreviations.

Abbreviation	Description	Abbreviation	Description
Gg	Gigagrams	NO_3^-	Nitrate
Pg	Petagrams	P	Phosphorous
AFS	Agroforestry system	K^+	Potassium

Table A3. *Cont.*

Abbreviation	Description	Abbreviation	Description
SPS	Silvopastoral systems	Ca^{2+}	Calcium
SPS-RA	Silvopastoral systems Ranchillo Alto	Mg^{2+}	Magnesium
C	Carbon	Na^{+}	Sodium
CO_{2eq}	Carbon equivalent	S	Sulphur
SOM	Soil organic matter	Al_{EXCH}	Exchangeable Al
SOC	Soil organic carbon	$\%Al_{SAT}$	% of Al saturation
C→SOC	Carbon sequestration	ECEC	Effective cation-exchange capacity
SQ	Soil quality	pH	Soil reactivity
SQI	Soil quality index	PD	Particle density
S_{IND}	Soil quality indicator	BD	Bulk density
O_p	Open condition	% (POR)	Total porosity
S_{Op}	Semi-open condition	WSA	% of water stable aggregates
SC	Semi-closed condition	INFV	Infiltration velocity
N	Nitrogen	WHC	Water holding capacity
C/N	Carbon-to-nitrogen ratio	$P_{EN}R$	Penetration resistance
NH_4^+	Ammonium		

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