



Article

Intensification of Pasture-Based Animal Production System Has Little Short-Term Effect on Soil Carbon Stock in the Southern Brazilian Highland

Pedro Antonio Garzón Camacho ^{1,*}, Cassiano Eduardo Pinto ², Cássio Felipe Lopes ¹, Daniela Tomazelli ¹, Simone Silmara Werner ³, Fábio Cervo Garagorry ⁴, Tiago Celso Baldissera ², Janquiel Schirmann ³ and André Fischer Sbrissia ¹

¹ Department of Animal Production, Santa Catarina State University, Lages 88520-000, SC, Brazil; cassiolopes_@hotmail.com (C.F.L.); daniela.t@edu.udesc.br (D.T.); andre.sbrissia@udesc.br (A.F.S.)

² Company of Agricultural Research and Rural Extension of Santa Catarina, Lages 88502-970, SC, Brazil; cassiano@epagri.sc.gov.br (C.E.P.); tiagobaldissera@epagri.sc.gov.br (T.C.B.)

³ Department of Informatics and Statistics, Federal University of Santa Catarina, Florianópolis 88036-030, SC, Brazil; simone.werner@ufsc.br (S.S.W.); janquielis@gmail.com (J.S.)

⁴ Brazilian Agricultural Research Corporation—Southern Livestock Unit, Bagé 96401-970, RS, Brazil; fabio.garagorry@embrapa.br

* Correspondence: 10245773177@udesc.edu.br

Abstract: Pastures are of central importance in food production and provide multiple ecosystem services. The objective of this paper was to determine whether the intensification of pasture-based animal production systems, through practices such as fertilization and improved pasture species, has a higher capacity in the short-term (five years) to sequester carbon in the soil compared to (1) natural grassland without anthropogenic interactions, (2) natural grassland fertilized and overseeded with exotic species, and (3) annual pastures with frequent soil disturbance. The study assessed the organic carbon stock (OCS), total organic carbon (TOC), particle size, porosity, and density at different soil strata, as well as the root system and forage production. Forage dry matter (DM) production varied significantly with means ranging from 6615 to 13,000 kg ha⁻¹ year⁻¹ for natural grassland (NG) and permanent pasture (PP), respectively. Improved natural grassland (ING) and NG presented a higher density and root diameter than PP and annual pasture (AP). Forage systems significantly influenced soil porosity and density, with NG and ING showing lower soil densities and higher soil porosities. The OCS (0–100 cm) was similar between NG (270 Mg ha⁻¹), ING (255 Mg ha⁻¹), PP (274 Mg ha⁻¹), and AP systems (256 Mg ha⁻¹). Over a period of five years, the intensification of pasture-based animal production systems did not have a significant impact on OCS in the soils of a Brazilian subtropical highland.

Keywords: ecosystems services; grasslands; carbon sink; subtropical climate; Southern Brazil



Citation: Camacho, P.A.G.; Pinto, C.E.; Lopes, C.F.; Tomazelli, D.; Werner, S.S.; Garagorry, F.C.; Baldissera, T.C.; Schirmann, J.; Sbrissia, A.F. Intensification of Pasture-Based Animal Production System Has Little Short-Term Effect on Soil Carbon Stock in the Southern Brazilian Highland. *Agronomy* **2023**, *13*, 850. <https://doi.org/10.3390/agronomy13030850>

Academic Editor: Bing Gao

Received: 7 February 2023

Revised: 7 March 2023

Accepted: 8 March 2023

Published: 14 March 2023



Copyright: © 2023 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 one-third of the Earth's surface is covered by grasslands [1], which have a significant impact on food production and the provision of ecosystem services such as aquifer protection, biodiversity preservation, tourism, and the regulation of biogeochemical cycles including nitrogen and carbon [2–5]. The scientific community has taken a keen interest in grasslands due to their potential as an important sink of atmospheric carbon. However, this function seems to be heavily dependent on the management practices applied to them [6].

Soils globally contain more carbon than the atmosphere (4000 Pg C vs. 740 Pg C), making them a critical component of the global carbon cycle and climate. Changes in soil carbon storage can significantly impact global warming potential and are influenced by both anthropogenic and nonanthropogenic factors [7–10]. The capacity of pasture

soils to store carbon can be affected by soil management practices, fertilization, species diversity, the photosynthetic metabolism of plants, dry matter productivity, root systems, and defoliation regimes, among other anthropogenic factors. Nonanthropogenic factors, such as soil organic matter fractionation, altitude, and climate, also play a critical role in carbon sequestration [11,12].

The effective management of pasture environments can help mitigate global climate change. Intensifying animal production in pasture-based systems can lead to a favorable balance between emissions and soil carbon sequestration [6,7], since increasing soil pH [13] and applying fertilization [4] can enhance dry matter production, preserve soil structure, and result in a net positive balance between emissions and carbon sequestration [6,14].

This study hypothesized that the intensification of animal production systems based on permanent pastures has a greater potential, in the short-term, to increase carbon storage in the soil compared to natural pastures or those based on annual pastures. The objective was to determine whether the intensification of pasture-based animal production systems, through practices such as fertilization and improved pasture species, has a higher capacity in the short-term (five years) to sequester carbon in the soil compared to (1) natural grassland without anthropogenic interactions, (2) natural grassland fertilized and overseeded with exotic species, and (3) annual pastures with frequent soil disturbance.

2. Materials and Methods

The study was carried out between November 2019 and February 2021 at EPA-GRI/Experimental Station, Lages, SC, Brazil (50.18° W, 27.47° S; 920 m altitude). The region has a humid mesothermal climate (Cfb) (Álvares et al., 2013), and the soil of the experimental area is classified as a typic aluminic humic Cambisol [15]. Figure 1 presents the main climatic variables during the experimental period.

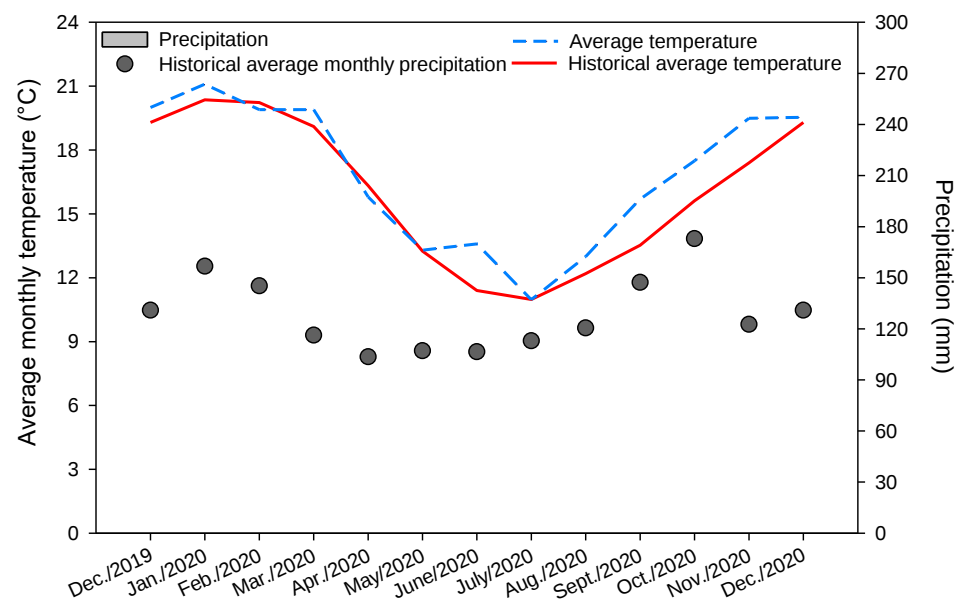


Figure 1. Temperature and precipitation during the experimental period and 58-year historical averages from the EPAGRI Experimental Station, Lages (Epagri/Ciram).

2.1. Experimental Treatments

The treatments consisted of four land use models for cattle farming (forage systems), each characterized by a progressive intensification process. Each forage system was replicated in four experimental units (EUs) ranging in size from 875 to 1800 m². The grassland systems studied represented a gradient of increasing soil management intensification, as follows: (1) Natural grassland (NG), with no tillage and no fertilization for at least 40 years. The predominant species is *Andropogon lateralis* [16]; (2) Improved natural grassland (ING), under a no-till system, where the natural grassland was overseeded with *Trifolium repens* L.,

Festuca arundinacea Schreb., *Lolium multiflorum* Lam., *Holcus lanatus* L., with fertilization of nitrogen, phosphorus, and potassium (NPK) 9–32–12; 300 kg ha^{−1} applied in the summer and 200 kg ha^{−1} in the winter. Nitrogen fertilization was applied (400 kg ha^{−1} of urea) at the grass tillering stage during winter; (3) Permanent cultivated pasture (PP), under a no-till system, with an intercropping of *Cynodon* spp. and *Trifolium repens* and overseeding of *Lolium multiflorum* in the winter. Nitrogen fertilization of 400 kg ha^{−1} of urea was applied twice a year, NPK 9–32–12; 300 kg ha^{−1} in the summer and 200 kg ha^{−1} in the winter; (4) Annual-cultivated pasture (AP), in a conventional land-use system, with tillage before summer and winter sowing, where *Pennisetum glaucum* (L.) was seeded during the summer and *L. multiflorum* in the winter, with nitrogen fertilization (400 kg ha^{−1} of urea) applied twice a year, NPK 9–32–12; 300 kg ha^{−1} applied in the summer and 200 kg ha^{−1} in the winter.

The ING, PP, and AP systems were implemented in 2015, when the soil pH was corrected using dolomitic limestone to reach a base saturation of 70%. In the AP, one plowing, consisting of the turnover of the topsoil layer, and two harrowing practices were performed for every pasture sowing. Fertilization was performed on the same day, for the three managed systems (ING, PP, and AP), in each season. The grazing management in all pasture systems occurred similarly as described by [16,17].

2.2. Soil Assessment

Soil chemical attributes were evaluated at a depth of 0–10 cm and samples were collected on 17 January 2020 and 27 July 2020 (Table 1).

Table 1. Soil chemical attributes under the evaluated systems: natural grassland (NG), improved natural grassland (ING), permanent pasture (PP), and annual pasture (AP).

System	pH-H ₂ O	H + Al	Base Sat- uration (%)	Ca/Mg	P Mehlich ^{−1} (mg dm ^{−3})	K Mehlich ^{−1} (mg dm ^{−3})	Ca (cmol _c dm ^{−3})	Mg (cmol _c dm ^{−3})	Al ³⁺ (cmol _c dm ^{−3})	CEC (cmol _c dm ^{−3})
NG	5.29	11.39	14.76	0.68	10	0.33	0.66	0.92	1.42	3.33
ING	6.20	2.72	85.30	1.34	18	0.38	9.01	6.80	0.00	16.18
PP	6.13	2.58	83.12	1.67	16	0.31	7.85	4.77	0.00	12.93
AP	6.16	3.16	81.53	1.49	16	0.31	8.13	5.64	0.00	14.08

On 18 September 2020, trenches were dug to a depth of 100 cm to collect soil samples to analyze organic carbon content, density, porosity, and particle size. Two samples were taken from each system at depths in ranges of 0–5, 5–10, 10–20, 20–40, 40–60, and 60–100 cm per EU. The soil samples were prepared by dehydrating them in an oven at 60 °C, followed by grinding, sifting (using a 2 mm sieve), and removing any fragments of stems, stalks, and roots. The particle size composition was then determined using the pipette method, with a dispersion of 1 mol L^{−1} NaOH [18].

Soil samples were collected in duplicate at the center of each soil layer using steel rings with a height of 5 cm and an internal diameter of 6 cm [18]. Total porosity and microporosity were measured using the tension table method [18], while soil density was determined using the volumetric ring method [19]. Soil samples were prepared following the same methodology as the particle size analysis. The total organic carbon (TOC) content of three replicates of each soil layer was evaluated using acid digestion [20]. The total organic carbon stock (OCS) was then calculated by summing the carbon stocks per layer, computed as the equivalent soil mass, according to [21], with the soil mass of NG serving as a reference.

2.3. Pasture Assessments

For root evaluations, two 20 × 20 × 20 cm soil monoliths were taken per EU. The roots were separated from the soil by washing and then weighed and dried at room temperature

in paper bags to determine the root weight (g m^{-2}). Root length, diameter and volume were determined using a flatbed scanner specifically modified for root scanning (Epson Expression 10000 XL; Seiko Epson Corporation [SEKEY], Japan) and WinRhizo software (Regent Instruments Inc., Québec City, QC, Canada). The forage mass (FM) of each forage system was evaluated from 8 December 2019 to 7 December 2020 and was estimated in the same way in all systems using double sampling [22] from the systematic visual estimation of 20 samples per EU in both pre- and post-grazing systems. The FM was extrapolated to hectare (kg DM ha^{-1}), calculated based on the dry matter of the cut of four samples paired using EUs during pre- and post-grazing. The cuts were performed above ground level by allocating 0.25 m^2 frames, using scissors and a clipper machine. The samples were dried in a forced-air oven at 55°C for 72 h to determine the dry matter. Regression equations of the estimated forage mass were constructed as a function of the forage mass obtained from the forage mass cuts (kg DM ha^{-1}) to calibrate the visual estimations [16].

To determine the annual forage accumulation rates, we added the summer and winter production of the systems. Summer production was measured from the first summer grazing on 12 July 2019 to the post-grazing period of the last grazing in the subsequent autumn on 29 April 2020. Winter production was measured from the first winter grazing on 17 July 2020 to the post-grazing period of the last spring grazing on 9 December 2020. We calculated the forage accumulation (FA) for each season by subtracting the post-grazing forage mass of the previous grazing from the actual pre-grazing forage mass.

2.4. Statistical Analysis

Data were analyzed using R statistical software (R Core Team, 2021, Vienna, Austria) [23]. Before proceeding with the analysis of variance, homogeneity of variances and normality of residuals were tested. Since the systems' spatial distribution was in adjacent areas and did not allow for complete randomization, we used a statistical model with repetitions nested in each system. Statistical analysis in the vertical soil profile was analyzed for each layer separately. In the analysis of TOC and OCS, clay was used as a co-variable since particle size directly relates to these parameters. Means were compared by using Tukey's test ($p < 0.05$).

3. Results

3.1. Soil

In the top layer (0–5 cm), middle layer (10–20 cm), and deepest layer (60–100 cm) (Figure 2), the TOC concentration varied significantly among pasture production systems ($p < 0.05$). The superficial layers had higher TOC concentrations than the deeper ones. For the 0–5 cm and 10–20 cm layers, ING had the highest TOC concentrations, followed by AP, NG, and PP (Figure 2). In the deepest layer (60–100 cm), NG had the highest concentration, followed by PP, ING, and AP. The soil OCS parameter showed a statistically significant difference ($p < 0.05$) in the same layers as TOC (Figure 2). However, there were no significant differences ($p > 0.05$) between the pasture production systems for the TOC stocks from 0 to 100 cm (Figure 2).

We observed a significant difference in density and soil porosity across all soil layers, except for the depths of 40–60 cm for density and 20–40 and 40–60 cm for soil porosity (Figure 3). In general, PP had the highest density in the surface layers compared to NG but did not differ from the other systems. The soil density in NG increased in the deepest layers. ING had the highest total porosity overall, and PP had the lowest. The NG and AP systems had intermediate values for this variable.

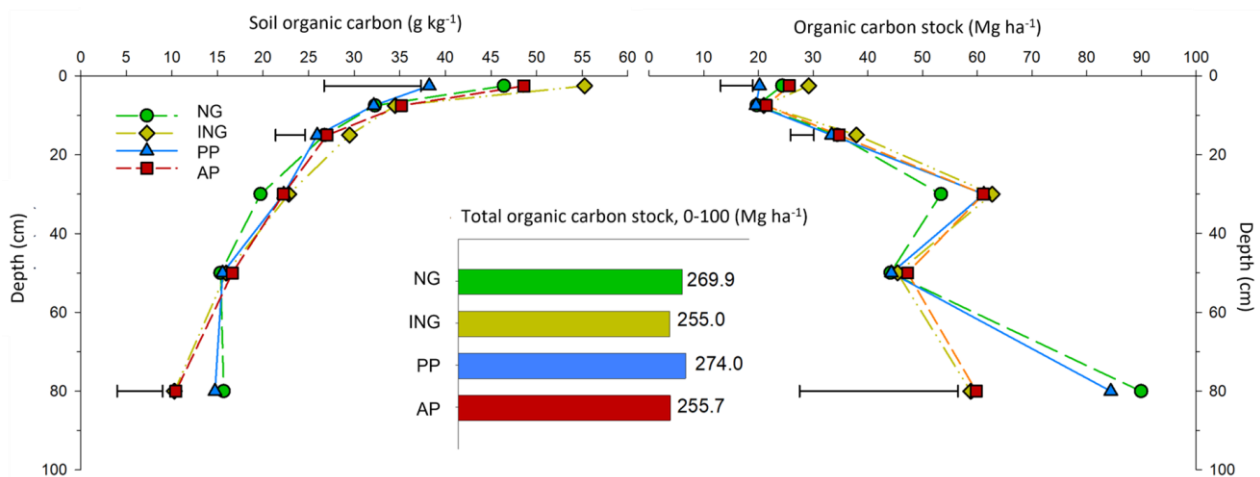


Figure 2. Total organic carbon (TOC) (g kg^{-1}) and organic carbon soil OCS (Mg ha^{-1}) contents in the soil profile in different cattle pasture-based exploitation models. Natural grassland (NG); improved natural grassland (ING); permanent pasture (PP), and annual pasture (AP). Bars represent the minimum significant difference according to Tukey's test ($p < 0.05$).

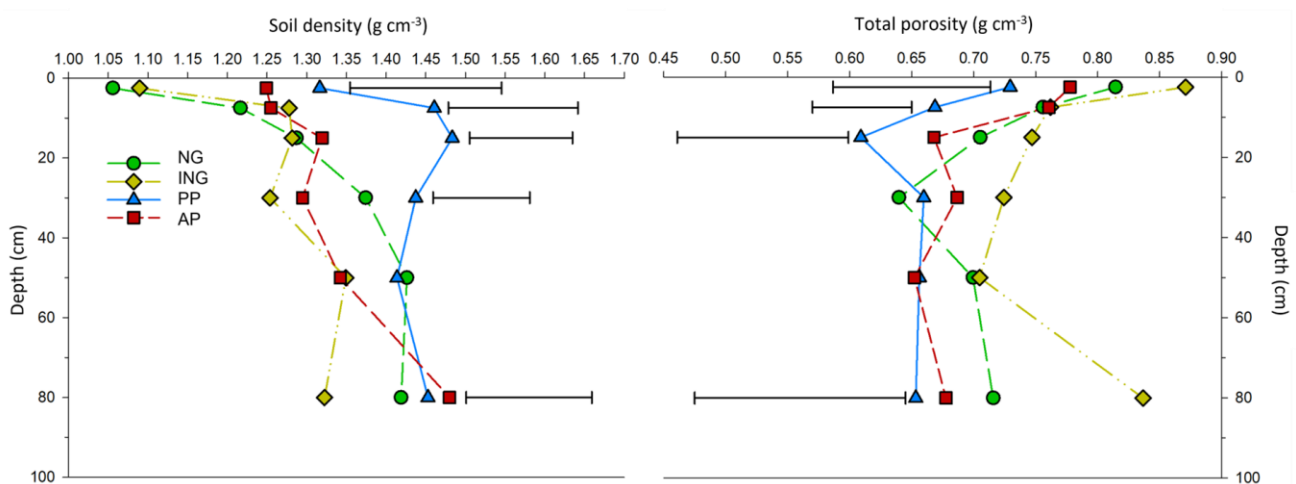


Figure 3. Soil density (g cm^{-3}) and porosity ($\text{cm}^3 \text{ cm}^{-3}$) down the soil profile in an improved natural grassland (ING), permanent pasture (PP), and annual pasture (AP) after five years of cultivation and a natural grassland (NG) with no anthropic management for 40 years. Bars represent the minimum significant difference according to Tukey's test ($p < 0.05$).

The soil texture analysis revealed no significant differences ($p < 0.05$) between the systems, except for the silt content at a depth of 20–40 cm (refer to Table 2). The permanent pasture exhibited the lowest content among NG and ING in this layer, although it was not significantly different from AP.

3.2. Pasture

The highest root dry matter density (g m^{-3}) was observed in NG, followed by PP and ING, while AP showed the lowest density. The mean root volume (cm^3) significantly differed between the two groups, with AP and NG having greater root volumes than PP and ING. The forage production differed between systems, with PP producing the highest, followed by AP and ING, which were not significantly different from each other, and NG having the lowest yield (Table 3).

Table 2. Percentages of sand, silt, and clay (%) in natural grassland (NG) without anthropic action for 40 years, improved natural grassland (ING), permanent pasture (PP), and annual pasture (AP) after five years of management. The means of the treatments followed by different letters indicate a statistically significant difference from each other based on Tukey's test ($p < 0.05$).

System	Sand	Silt %	Clay
		0–10 cm layer	
NG	34.96 ± 2.50	28.38 ± 5.89	36.65 ± 4.37
ING	29.46 ± 7.43	36.03 ± 4.48	34.50 ± 3.18
PP	42.90 ± 6.47	31.06 ± 7.37	26.04 ± 1.16
AP	32.82 ± 8.96	33.08 ± 5.87	34.10 ± 5.68
		10–20 cm layer	
NG	33.02 ± 7.03	36.67 ± 1.97	30.31 ± 7.02
ING	35.14 ± 10.83	35.83 ± 11.03	29.03 ± 5.99
PP	43.34 ± 1.73	33.03 ± 1.18	23.63 ± 2.35
AP	29.21 ± 8.55	38.59 ± 7.89	32.20 ± 1.24
		20–40 cm layer	
NG	31.26 ± 4.56	34.53 ± 6.23 a	34.21 ± 5.91
ING	28.02 ± 7.28	37.00 ± 5.05 a	34.98 ± 4.58
PP	38.21 ± 11.20	25.09 ± 4.32 b	36.67 ± 7.20
AP	33.89 ± 7.29	29.08 ± 4.86 ab	37.03 ± 2.60
		40–60 cm layer	
NG	30.91 ± 5.91	34.81 ± 6.23	34.28 ± 5.91
ING	33.13 ± 9.32	35.35 ± 4.09	31.52 ± 5.09
PP	40.10 ± 11.71	34.01 ± 6.21	25.89 ± 6.65
AP	28.68 ± 9.25	34.43 ± 6.62	36.89 ± 3.41
		60–100 cm layer	
NG	29.89 ± 5.91	34.59 ± 5.29	35.52 ± 1.46
ING	27.28 ± 8.82	39.27 ± 6.06	33.45 ± 3.94
PP	36.86 ± 10.07	28.30 ± 4.71	34.84 ± 7.70
AP	31.74 ± 7.24	27.90 ± 4.07	40.36 ± 3.60

Table 3. Forage production (kg DM ha^{−1} year), root volume (cm³), and average root dry matter density (g m^{−2}) in an improved natural grassland (ING), permanent pasture (PP), and annual pasture (AP) after five years of cultivation and a natural grassland (NG) without anthropic management for 40 years. The means of treatments followed by the same letter indicate no significant difference from each other according to Tukey's test ($p < 0.05$). Lowercase letters are used to explain variation between systems.

Parameter	NG	ING	PP	AP
			Roots	
Volume (cm ³)	2.899.22 ± 649.08 a	1.476.61 ± 522.59 b	1.522.58 ± 534.58 b	3.416.10 ± 989.65 a
Dry matter density (g/m ²)	292.44 ± 51.63 a	134.34 ± 57.76 b	162.08 ± 70.39 b	65.27 ± 19.89 c
			Shoot	
Forage accumulation (kg MS·ha ^{−1} ·year)	6.615 ± 1468 c	9.552 ± 563 b	13.044 ± 450 a	9.771 ± 805 b

4. Discussion

Variations in SOC content often occur gradually, and the residence time of carbon in soils under pastures can range from one to one thousand years [4]. Substantial changes in SOC content were found by [24] after 30 years of studies comparing conventional and no-tillage systems. However, ref. [25] found no significant differences in a 12-year experiment, which they attributed to data variability and the residual effect of past land management practices. Moreover, ref. [26] evaluated changes in carbon stocks in an Ultisol of permanent pastures established for 2, 9, and 18 years and found no statistically significant

variations compared to the original grassland. Similarly, ref. [27] observed no significant variation in SOC under natural grassland systems in the Argentinian Pampa during a 12-year trial, indicating that the studied soils were not sequestering carbon. In contrast, ref. [28] evaluated the effect of converting native grassland to cultivated pastures on soil carbon sequestration after 3 and 19 years of management and found a significant difference only after the longest implementation period (19 years). Hence, it is evident that the ability to change soil carbon storage is a result of the interaction between factors such as climate, time, and the cattle exploitation model [6,11,12].

In our experiment, nonanthropogenic factors may be primarily responsible for the lack of difference in soil organic carbon (SOC) among the soils studied. Climate is one of the most critical elements that affect the maintenance and storage of carbon in the soil [10,29] and the experiment was conducted in a humid mesothermal temperate climate [30] at an altitude higher than 900 m above sea level. Soils in this region are known for their high capacity for organic matter accumulation, which is converted into high carbon stocks due to the high precipitation and cold temperatures found at this altitude environment [31,32] and ref. [33] reported that the studied region's soils have the largest carbon storage capacity in Brazil. It is possible that the local climate reduced the mineralization of soil organic matter, thereby maintaining similar carbon stocks between treatments, despite the seasonal soil disturbance in the AP treatment. Low temperatures limit microbial activity [31] which, in turn, affects the transformation or decomposition of organic matter into energy for microbes. This energy is released as CO₂ through respiration, which is one of the primary drivers of soil carbon loss [34,35].

The lack of difference in SOC among the treatments may also be related to soil texture. Soil in the experimental area, specifically in the 0–20 cm layer, is composed of approximately 65% silt and clay (Table 2). Soils with a higher percentage of silt and clay provide chemical and physical protection to SOC, preventing microbial attack [31]. Due to the stability of the clay fraction, lower responses to soil management practices are observed in clayey soils with respect to carbon stocks [36].

As previously mentioned, changes in soil OCS occur slowly, even when the quantity is reduced or increased [9,10]. Therefore, fertilizers and liming and the use of permanent plant species can increase forage yields (see Table 3) and improve the productivity of shoots and roots [6,37], which may theoretically enhance soil carbon storage over a long period of time [13]. This improvement could be attributed to the higher carbon influx in these types of pasture systems (as shown in Table 3), providing a greater amount of high-quality carbon without soil disturbance. This, in turn, favors the formation of macroaggregates, leading to an increase in C stocks if mineralization is not increased.

The density of the soil is one of the factors used to calculate carbon stock. The difference in density observed in our study up to a depth of 40 cm may be attributed to the establishment methods of the production systems, particularly the mechanical pressures exerted by agricultural implements during soil tillage and sowing [38] and cattle trampling [39]. Cultivated permanent pastures presented the highest density, possibly due to machine traffic and a higher stocking rate due to greater forage productivity observed in this forage system (see Table 3) [39]. Although there was a significant difference at a depth of 60–100 cm, we cannot conclude that the management of productive systems had an influence on the density in this layer. The effects of agricultural mechanization on the soil are expressed in deeper layers than the effect of animal trampling; however, both are evident and increase over time [26,40]. Higher density values in deeper soil layers can also be explained by a reduction in organic matter or TOC contents [11,41], which is also observed in our data (see Figures 2 and 3). In contrast, soil total porosity is inversely proportional to soil density [32], which is significantly modified by animal trampling and agricultural machinery. Importantly, the reported values exceed 0.06 m³ m^{−3}, which is generally considered to be the threshold at which biological activity, gas exchanges, and the root growth of most crops are compromised [14,41]. Despite the slightly different results between exploitation models (especially PP), the density and porosity values were

not significant enough to affect the global soil carbon stock among the different practices studied over the period.

5. Conclusions

Over a period of five years, the intensification of pasture-based animal production systems did not have a significant impact on OCS in soils of a Brazilian subtropical highland.

Author Contributions: Conceptualization, P.A.G.C., A.F.S., T.C.B., C.E.P. and F.C.G.; methodology, T.C.B., J.S. and C.E.P.; formal analysis, S.S.W.; investigation, P.A.G.C., C.F.L. and D.T.; resources, T.C.B., C.E.P. and F.C.G.; data curation, P.A.G.C. and S.S.W.; writing—original draft preparation, P.A.G.C.; writing—review and editing, P.A.G.C., A.F.S., C.E.P., T.C.B., F.C.G. and J.S.; supervision, A.F.S., J.S., C.E.P., T.C.B. and F.C.G.; project administration, T.C.B., C.E.P., F.C.G. and J.S.; funding acquisition, T.C.B., C.E.P. and A.F.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FAPESC, grants number 2021 TR 1417, TR 813 and TR 543.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

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

References

1. Lemaire, G.; Hodgson, J.; Chabbi, A. *Grassland Productivity and Ecosystem Services*; CABI: Wallingford, UK; Oxfordshire, UK, 2011; ISBN 978-1-84593-900-7.
2. Zhao, Y.; Liu, Z.; Wu, J. Grassland Ecosystem Services: A Systematic Review of Research Advances and Future Directions. *Landsc. Ecol.* **2020**, *35*, 793–814. [\[CrossRef\]](#)
3. Bellarby, J.; Tirado, R.; Leip, A.; Weiss, F.; Lesschen, J.P.; Smith, P. Livestock Greenhouse Gas Emissions and Mitigation Potential in Europe. *Glob. Chang. Biol.* **2013**, *19*, 3–18. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Soussana, J.-F.; Lemaire, G. Coupling Carbon and Nitrogen Cycles for Environmentally Sustainable Intensification of Grasslands and Crop-Livestock Systems. *Agric. Ecosyst. Environ.* **2014**, *190*, 9–17. [\[CrossRef\]](#)
5. Bengtsson, J.; Bullock, J.M.; Egoh, B.; Everson, C.; Everson, T.; O'Connor, T.; O'Farrell, P.J.; Smith, H.G.; Lindborg, R. Grasslands—More Important for Ecosystem Services than You Might Think. *Ecosphere* **2019**, *10*, e02582. [\[CrossRef\]](#)
6. Conant, R.T.; Cerri, C.E.P.; Osborne, B.B.; Paustian, K. Grassland Management Impacts on Soil Carbon Stocks: A New Synthesis. *Ecol. Appl.* **2017**, *27*, 662–668. [\[CrossRef\]](#)
7. Viglizzo, E.F.; Ricard, M.F.; Taboada, M.A.; Vázquez-Amábile, G. Reassessing the Role of Grazing Lands in Carbon-Balance Estimations: Meta-Analysis and Review. *Sci. Total Environ.* **2019**, *661*, 531–542. [\[CrossRef\]](#)
8. Lal, R. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science* **2004**, *304*, 1623–1627. [\[CrossRef\]](#)
9. Chabbi, A.; Rumpel, C.; Hagedorn, F.; Schrumpp, M.; Baveye, P.C. Editorial: Carbon Storage in Agricultural and Forest Soils. *Front. Environ. Sci.* **2022**, *10*, 848572. [\[CrossRef\]](#)
10. Conant, R.T.; Paustian, K.; Elliott, E.T. Grassland Management and Conversion into Grassland: Effects on Soil Carbon. *Ecol. Appl.* **2001**, *11*, 343–355. [\[CrossRef\]](#)
11. Wang, J.; Li, Y.; Bork, E.W.; Richter, G.M.; Chen, C.; Hussain Shah, S.H.; Mezbahuddin, S. Effects of Grazing Management on Spatio-Temporal Heterogeneity of Soil Carbon and Greenhouse Gas Emissions of Grasslands and Rangelands: Monitoring, Assessment and Scaling-Up. *J. Clean. Prod.* **2021**, *288*, 125737. [\[CrossRef\]](#)
12. Lin, D.; McCulley, R.L.; Nelson, J.A.; Jacobsen, K.L.; Zhang, D. Time in Pasture Rotation Alters Soil Microbial Community Composition and Function and Increases Carbon Sequestration Potential in a Temperate Agroecosystem. *Sci. Total Environ.* **2020**, *698*, 134233. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Lange, M.; Eisenhauer, N.; Sierra, C.A.; Bessler, H.; Engels, C.; Griffiths, R.I.; Mellado-Vázquez, P.G.; Malik, A.A.; Roy, J.; Scheu, S.; et al. Plant Diversity Increases Soil Microbial Activity and Soil Carbon Storage. *Nat. Commun.* **2015**, *6*, 6707. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Neal, A.L.; Bacq-Labreuil, A.; Zhang, X.; Clark, I.M.; Coleman, K.; Mooney, S.J.; Ritz, K.; Crawford, J.W. Soil as an Extended Composite Phenotype of the Microbial Metagenome. *Sci. Rep.* **2020**, *10*, 10649. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Santos, H.G. *Dos Sistema Brasileiro de Classificação de Solos*, 5th ed.; Embrapa: Brasília, Brazil, 2018; ISBN 978-85-7035-800-4.
16. Zanella, P.G.; Junior, L.H.P.D.G.; Pinto, C.E.; Baldissera, T.C.; Werner, S.S.; Garagorry, F.C.; Jaurena, M.; Lattanzi, F.A.; Sbrissia, A.F. Grazing Intensity Drives Plant Diversity but Does Not Affect Forage Production in a Natural Grassland Dominated by the Tussock-Forming Grass *Andropogon Lateralis* Nees. *Sci. Rep.* **2021**, *11*, 16744. [\[CrossRef\]](#)

17. Giustina Junior, L.H.P.D.; Zanella, P.G.; Baldissera, T.C.; Pinto, C.E.; Garagorry, F.C.; Sbrissia, A.F. Grazing Height Management Does Not Change the Persistence Pathway of *Andropogon Lateralis* in a Natural Pasture. *Pesqui. Agropecu. Bras.* **2019**, *54*, e00405. [CrossRef]
18. Gee, G.W.; Bauder, J.W. Particle-Size Analysis. In *Methods of Soil Analysis Part 1*, 5th ed.; Klute, A., Ed.; American Society of Agronomy, Inc.: Madison, WI, USA, 1986; pp. 383–411.
19. Almeida, B.G.; Viana, J.H.M.; Teixeira, W.G.; Donagemma, G.K. Densidade do Solo. In *Manual de Métodos de Análise de Solo*; Teixeira, P.C., Donagemma, G.K., Fontana, A., Teixeira, W.G., Eds.; EMBRAPA: Brasília, Brazil, 2017; pp. 65–75.
20. Yeomans, J.C.; Bremner, J.M. A Rapid and Precise Method for Routine Determination of Organic Carbon in Soil. *Commun. Soil Sci. Plant Anal.* **1988**, *19*, 1467–1476. [CrossRef]
21. Ellert, B.H.; Bettany, J.R. Calculation of Organic Matter and Nutrients Stored in Soils under Contrasting Management Regimes. *Can. J. Soil Sci.* **1995**, *75*, 529–538. [CrossRef]
22. Haydock, K.; Shaw, N. The Comparative Yield Method for Estimating Dry Matter Yield of Pasture. *Aust. J. Exp. Agric.* **1975**, *15*, 663. [CrossRef]
23. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2021; Available online: <https://www.R-project.org/> (accessed on 7 February 2023).
24. Veloso, M.G.; Angers, D.A.; Tiecher, T.; Giacomini, S.; Dieckow, J.; Bayer, C. High Carbon Storage in a Previously Degraded Subtropical Soil under No-Tillage with Legume Cover Crops. *Agric. Ecosyst. Environ.* **2018**, *268*, 15–23. [CrossRef]
25. Franzluebbers, A.J.; Stuedemann, J.A. Soil-Profile Organic Carbon and Total Nitrogen during 12 Years of Pasture Management in the Southern Piedmont USA. *Agric. Ecosyst. Environ.* **2009**, *129*, 28–36. [CrossRef]
26. Conte, O.; Flores JP, C.; Cassol, L.C.; Anghinoni, I.; Carvalho PC, D.F.; Levien, R.; Wesp CD, L. Evolução de Atributos Físicos de Solo Em Sistema de Integração Lavoura-Pecuária. *Pesqui. Agropecuária Bras.* **2011**, *46*, 1301–1309. [CrossRef]
27. Alvarez, R.; Berhongaray, G.; Gimenez, A. Are Grassland Soils of the Pampas Sequestering Carbon? *Sci. Total Environ.* **2021**, *763*, 142978. [CrossRef] [PubMed]
28. Cardoso, E.L.; Silva, M.L.N.; Silva, C.A.; Curi, N.; Freitas, D.A.F. de Estoques de Carbono e Nitrogênio Em Solo Sob Florestas Nativas e Pastagens No Bioma Pantanal. *Pesqui. Agropecuária Bras.* **2010**, *45*, 1028–1035. [CrossRef]
29. Fidalgo EC, C.; Benites VD, M.; Machado PD, A.; Madari, B.E.; Coelho, M.R.; de Moura, I.B.; de Lima, C.X. Estoque de Carbono nos Solos do Brasil. *Bol. Pesqui. E Desenvol.* **2007**, *121*, 1–26.
30. Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; de Moraes Gonçalves, J.L.; Sparovek, G. Köppen's Climate Classification Map for Brazil. *Meteorol. Z* **2013**, *22*, 711–728. [CrossRef] [PubMed]
31. Lupatini, M.; Suleiman, A.K.A.; Jacques, R.J.S.; Lemos, L.N.; Pylro, V.S.; Van Veen, J.A.; Kuramae, E.E.; Roesch, L.F.W. Moisture Is More Important than Temperature for Assembly of Both Potentially Active and Whole Prokaryotic Communities in Subtropical Grassland. *Microb. Ecol.* **2019**, *77*, 460–470. [CrossRef] [PubMed]
32. Reichert, J.M. Mecânica do Solo. In *Física do Solo*; Van Lier, Q.J.: Viçosa, Brazil, 2016; pp. 29–102.
33. Hewins, D.B.; Lyseng, M.P.; Schoderbek, D.F.; Alexander, M.; Willms, W.D.; Carlyle, C.N.; Chang, S.X.; Bork, E.W. Grazing and Climate Effects on Soil Organic Carbon Concentration and Particle-Size Association in Northern Grasslands. *Sci. Rep.* **2018**, *8*, 1336. [CrossRef]
34. Lal, R.; Bruce, J.P. The Potential of World Cropland Soils to Sequester C and Mitigate the Greenhouse Effect. *Environ. Sci. Policy* **1999**, *2*, 177–185. [CrossRef]
35. Chivenge, P.; Murwira, H.; Giller, K.; Mapfumo, P.; Six, J. Long-Term Impact of Reduced Tillage and Residue Management on Soil Carbon Stabilization: Implications for Conservation Agriculture on Contrasting Soils. *Soil Tillage Res.* **2007**, *94*, 328–337. [CrossRef]
36. da Silva, S.C.; Sbrissia, A.F.; Pereira, L.E.T. Ecophysiology of C4 Forage Grasses—Understanding Plant Growth for Optimising Their Use and Management. *Agriculture* **2015**, *5*, 598–625. [CrossRef]
37. Greenwood, K.L.; McKenzie, B.M. Grazing Effects on Soil Physical Properties and the Consequences for Pastures: A Review. *Aust. J. Exp. Agric.* **2001**, *41*, 1231. [CrossRef]
38. Evrendilek, F.; Celik, I.; Kilic, S. Changes in Soil Organic Carbon and Other Physical Soil Properties along Adjacent Mediterranean Forest, Grassland, and Cropland Ecosystems in Turkey. *J. Arid Environ.* **2004**, *59*, 743–752. [CrossRef]
39. Greenwood, K.L.; MacLeod, D.A.; Hutchinson, K.J. Long-Term Stocking Rate Effects on Soil Physical Properties. *Aust. J. Exp. Agric.* **1997**, *37*, 413. [CrossRef]
40. Ribeiro, R.H.; Ibarr, M.A.; Besen, M.R.; Bayer, C.; Piva, J.T. Managing Grazing Intensity to Reduce the Global Warming Potential in Integrated Crop-Livestock Systems under No-till Agriculture. *Eur. J. Soil Sci.* **2019**, *71*, 1120–1131. [CrossRef]
41. Rauber, L.R.; Sequinatto, L.; Kaiser, D.R.; Bertol, I.; Baldissera, T.C.; Garagorry, F.C.; Sbrissia, A.F.; Pereira, G.E.; Pinto, C.E. Soil Physical Properties in a Natural Highland Grassland in Southern Brazil Subjected to a Range of Grazing Heights. *Agric. Ecosyst. Environ.* **2021**, *319*, 107515. [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.