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Carbon sequestration potential of pastures in Southern Brazil: A systematic review

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ABSTRACT: Since the industrial revolution, human activities have emitted approximately 2,500 Gt of CO_2, increasing the concentration of atmospheric CO_2 by 50 % compared to pre-industrial levels. To better understand the potential for mitigating greenhouse gas (GHG) emissions through proper management of degraded pasture areas, we conducted a systematic literature review and identified 23 publications reporting carbon sequestration values for pastures managed under different conditions in the south and southeast regions of Brazil. From this dataset, 17 publications considered to be in line with the research premises were selected to estimate the potential for soil carbon sequestration (SEQ) through pasture recovery in the southern region of Brazil, using conservative and regenerative agricultural management practices. Results show that managed pastures can sustain carbon sequestration rates of around 2.50 Mg C ha^{-1} yr^{-1} over approximately 20 years. However, due to the numerous variables influencing SEQ rates, the limited number of publications, and the lack of data for some variables among them, a more extensive analysis of publications and data is needed to establish causal and preponderance relationships regarding the effect of each variable on the found SEQ rates. Under current pasture occupation conditions in Brazil's south region, it is estimated these areas could sequester between 0.433 and 1.273 Gt CO_2 at the end of 20 years if managed under appropriate practices. These numbers are not representative to reduce atmospheric CO_2 concentration from legacy emissions and significantly mitigate physical impacts of climate change, reinforcing the importance of prioritizing the reduction of global GHG emissions as the primary mitigation strategy. On the other hand, from the perspective of mitigating the national agricultural sector's annual GHG emissions, this potential cannot be considered negligible. Carbon sequestration by soils under agricultural management can play a vital role in mitigating climate change, integrating the set of necessary solutions and actions for a Paris Agreement goals compatible trajectory of limiting global warming to between 1.5 and 2 °C by the end of the century.

Keywords: climate change, soil texture, degradation level, Atlantic Forest Biome, Pampas Biome.

INTRODUCTION

There has been a growing concern about how the environmental impacts of human activity affect the planet. In face of society's exponential growth rate and demand for resources under the current economic development model, the scientific understanding is that this dynamic constitutes a threat to civilization itself and life on Earth as we know it, as we are breaking planetary boundaries crucial for the stability and maintenance of the planet's support capacities, essential for our survival (Rockström et al., 2009; Steffen et al., 2015; IPCC, 2021).

There is broad scientific consensus that the planet's observed warming trend and intensification of related extreme events are a consequence of anthropogenic emissions of greenhouse gases (GHG), primarily from burning fossil fuels followed by land-use changes. The sixth and most recent assessment report by the Intergovernmental Panel on Climate Change (IPCC), the leading authority on the state-of-the-art in climate science, unequivocally confirms human influence in warming the atmosphere, oceans, and continental territories through anthropogenic GHG emissions (IPCC, 2021). The reports also highlight the urgent need for action to avoid irreversible consequences for humanity and the planet (IPCC, 2022).

Agriculture and conversions from native ecosystems to agrosystems contribute, worldwide, to approximately 24 % of global CO_2 emissions, 55 % of CH_4 emissions, and 85 % of total N_2O emissions into the atmosphere (IPCC, 2007), placing Brazil as the 4th largest historical CO_2 emitter (Evans, 2021), and currently responsible for around 4.4 % of global GHG emissions (Our World in Data, 2023; SEEG, 2023). Around 75 % of the country's gross emissions (tCO_2e) come from the agricultural and land-use sectors, with 24.8 and 49 %, respectively, in 2021 (SEEG, 2023), while the aggregate Gross Domestic Product (GDP) of agribusiness represented around 27.5 % of the national GDP (CEPEA, 2022). The country's total emissions for the 2000 to 2020 period are at similar levels as today, with land-use changes and agriculture accounting for approximately 52 and 24 %, respectively (SEEG, 2023).

Deducting carbon removals promoted by vegetation and land-use, in 2021, agricultural activity accounted for a total of 34.2 % of net national GHG emissions, of which 63.7 % came from enteric fermentation alone, accounting for around 16 % of gross national emissions and 22 % of the country's net emissions. In the same year, Brazil had between 95 and 100 million hectares of degraded pastures, representing almost two-thirds of the country's total pasture area (LAPIG, 2023; MapBiomas, 2023). Under the Paris Agreement, in addition to becoming Net Zero by 2050, Brazil has also voluntarily committed to reducing national GHG emissions by 43 % and restoring 15 million hectares of degraded pastures by 2030 (CDP, 2023).

Pasture degradation is an evolutionary process involving the loss of vitality, productivity, and the ability to sustain the production levels and quality required by animals. It also encompasses overcoming the harmful effects of pests, diseases, and invasive plants, ultimately leading to advanced degradation due to inadequate management (Townsend et al., 2012). Degradation is directly linked to soil quality (SQ), which comprises the set of functions and characteristics allowing it to accept, store, and recycle water, nutrients, and energy, sustaining productivity and promoting the health of plants and animals (Doran, 1997; Carter, 2001). This way, degradation can also be understood as the loss or decrease at some level of these properties, ensuring the soil ability to fulfill its functions in nature.

In the land-use context, the definition of management is related to the way human intervention occurs in a landscape through the set of practices adopted. Since degradation involves the loss of SQ and, consequently, its productive capacities and functional properties, appropriate or conservationist management of a productive system can prevent or reverse degradation characteristics, or from the opposite perspective, it can sustain or recover SQ. Different types of agricultural management in a crop, forestry and pasture areas directly influence SQ, particularly regarding soil aggregation and carbon content (Braida et al., 2007; Vezzani and Mielniczuk, 2009). Adopted management can contribute to observing better or worse conditions for these indicators. Practices without soil disturbance, such as plowing and harrowing, and the constant presence of plants, preferably of varied species, are some practices that favor the maintenance and improvement of carbon stocks (CS) and SQ (Fayad et al., 2019).

Certain agricultural systems and management conditions can mitigate GHG emissions into the atmosphere by maximizing the effects of soil and vegetation carbon sequestration (SEQ) (Carvalho et al., 2010a; Quintão et al., 2021). Regarding pasture management, different studies have highlighted the potential and capacity of systems such as Voisin Rational Grazing (VRG), Adaptive Multi-Paddock Grazing (AMP) and Holistic Grazing Management (HGM) to contribute to increases in soil CS, surpassing levels achieved by conventional management systems (Seó et al., 2017; Stanley et al., 2018; Mosier et al., 2021). This capacity arises from these systems favoring a reduction in erosion due to overgrazing, a greater supply of nutrients from animal excreta, maintenance of soil cover, and an ideal fallow period for sustaining the root zone and recomposing the aerial part of the vegetation (Machado, 2004; Machado Filho et al., 2021), aspects not controlled in extensive management systems. On the other hand, intensive confinement areas are generally associated with erosion and consequent soil carbon loss (Izaurralde et al., 2007; Olson et al., 2016).

In addition to management practices, CS levels and rates of soil SEQ vary depending on different factors, such as source material, pedogenetic processes, soil texture, amount of organic matter (OM) cycling and input, and climatic conditions, with higher CS generally being achieved in conditions of lower temperatures and higher rainfall (Jenny, 1941; Hengl et al., 2015; Gomes et al., 2019). At least 50 years of soil maintenance are required to achieve the maximum possible CS, but the rate of increase will not necessarily be constant throughout this period (Lal et al., 1998).

Numerous studies and authors have explored the carbon fluxes dynamics in soils managed under pasture in Brazil, primarily concentrated in the Amazon and Cerrado biomes (Moraes et al., 1996; Neill et al., 1997; Bernoux et al., 1998; Cerri et al., 2003; Bustamante et al., 2006; Segnini et al., 2007; Carvalho et al., 2010b; Oliveira et al., 2021). Despite the established knowledge about this potential and the existing mechanisms for valuing the environmental service of atmospheric carbon sequestration, significant degradation rates persist in the national territory, specially in the South Region, highlighting potential barriers to reversing this scenario.

Considering the economic and climatic importance of agriculture and land-use in the Brazilian context; the potential for reducing GHG emissions and promoting carbon removals in these sectors through GHG mitigation practices; and the limited visibility of studies focused on SEQ in Brazil's southern region pastures; this research aimed to identify soil SEQ potential in these managed systems through a systematic literature review. We hypothesize that the environmental service of carbon sequestration, potentially promoted by the recovery of these areas, represents a significant contribution to the global context of climate change, given the current conditions of pasture areas in this geographical region. Our goal was to investigate the potential magnitude of this environmental service for the described area, verifying its relevance and discussing opportunities and challenges associated with the transition to sustainable agricultural practices on a large scale.

MATERIALS AND METHODS

The delimited area for studies surveying by the systematic review was the South Region of Brazil, according to geopolitical division, characterized by the predominant climate typologies of humid subtropical (Cfa) and oceanic (Cfb) Köppen climate classification system. This region includes the Atlantic Forest and Pampa biomes. Pampa biome also extends into Argentina and Uruguay; however, no studies have been performed in these regions, as the research was exclusively conducted in Brazil's territory. Due to the limited volume of articles found, publications on the Atlantic Forest biome in the southeast region were also included in the research to enhance the representativeness of the analysis. The representation of the study area is depicted in figure 1.

In addition to the reference values found from the literature review, other data used to conduct the analyses included the mapping of Brazilian pasture degradation classes for the year 2021, provided by the Image Processing and Geoprocessing Laboratory of the Federal University of Goiás (LAPIG/UFG), and the grouping of soil classes from the Brazilian Soil Classification System (SiBCS) by Bernoux et al. (2002) provided by MCTI (2020). Data used are summarized in table 1; and figure 2 provides a visual representation of the two georeferenced products used in the analyses.

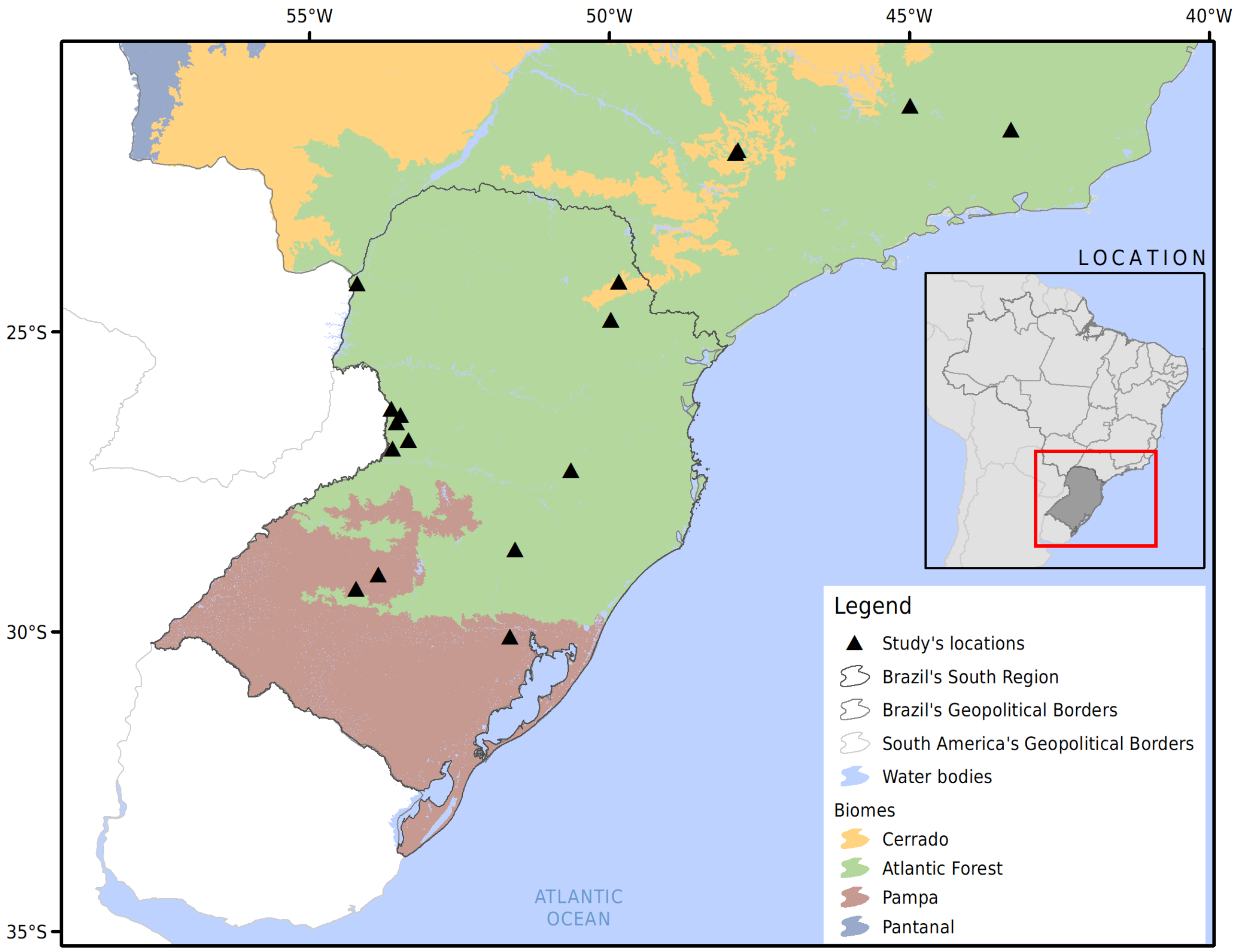

Figure 1. Location map of the study area. Source: Elaborated by the author with data provided by IBGE (2019).

Table 1. Variables used to conduct the analysis

Variablet	Source	Year	Nature
Pasture degradation classes (2021)	Image Processing and Geoprocessing Laboratory, Federal University of Goiás (LAPIG/UFG)	2023	Georeferenced, semi-quantitative
Grouping of soil classes from the Brazilian Soil Classification System (SiBCS)	Bernoux et al. (2002), made available by MCTI (2020)	2002	Georeferenced, qualitative
CO_2 emission and removal factors for managed pastures	Systematic literature review (*Scopus*)	-	Quantitative, referenced by attributes

Defining pasture carbon sequestration factors

The initial step in the methodological course of activities involved conducting a systematic literature review for mapping and summarizing the volume of soil carbon sequestration data available for Brazil's south region. This survey was performed by searching the Scopus platform in March 2023, using the combination of keywords (*Pasture* OR *Grassland* OR *Grazing*) & *Carbon* & *Soil* & (*Sequestration* OR *Removal* OR *Addition* OR *Accumulation*). Subsequently, the articles were sequentially filtered based on the criteria described in the following steps.

i. Sample universe: All articles returned by the combined keyword search (5,718 articles), filtered for Brazil region (336 articles).

ii. Bank of articles for analysis: Articles with quantitative data on soil organic carbon (SOC) located in the Atlantic Forest biome or the South Region (67 articles).

iii. Data tabulation: Articles that presented reference values for variation rates of soil CS in managed pastures, or for which it was possible to infer this variation from other data presented, such as experiment time and CS of a reference area (23 articles).

iv. Sample set selected: Articles with experiments located in the south or southeast region, whose soil CS variation rates resulted in carbon sequestration by pasture management (17 articles). For studies with values reported for different layers, we sought to adopt the value of the deepest layer up to the 0.40 m limit.

For each publication, all the available information on aspects influencing the observed SEQ rates was tabulated, which encompasses from geophysical data such as geographical location, altitude, biome, climatic characteristics and soil textural class; to the system's characteristics such as cultivated species, type of land-use, management type, grazing pressure (grazing height and/or animal stocking), forage productivity, animal productivity, adoption of soil turning and fertilization practices. Other relevant information for the analysis of found CS and SEQ rates included the year of native vegetation conversion, the area previous use before system implementation, the experiment duration, the layer depth, and the comparative basis of the CS adopted to determine the observed SEQ rates. Based on the values found, maximum, average, and minimum SEQ values were established for different soil textural class conditions as a prerequisite for the subsequent calculation stage (Table 2).

Considering the hierarchy $SEQ_{clayey} > SEQ_{clay\text{-}sandy} > SEQ_{sandy}$ indicated in the literature for the same climatic and management conditions, and the representativeness and characteristics of data returned by the systematic literature review, as a conservative

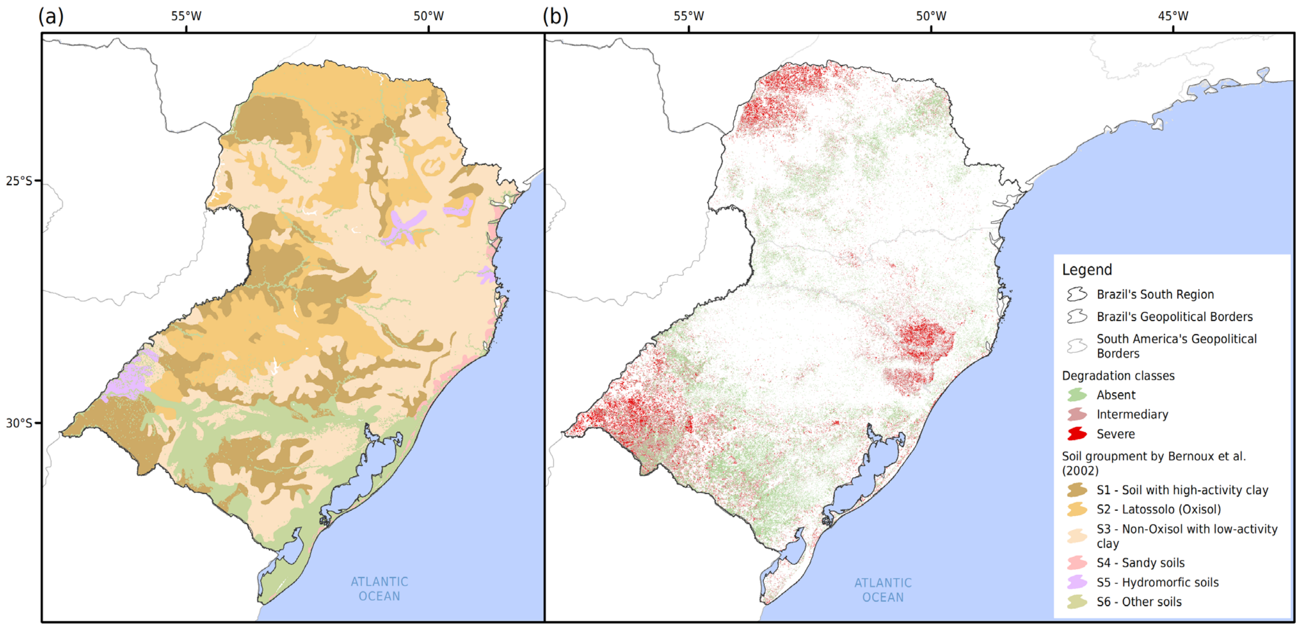

Figure 2. Illustration of the georeferenced data used to conduct the analysis. Grouping of soil classes from the Brazilian Soil Classification System by Bernoux et al. (2002) (a); Pasture degradation classes in 2021 (b). Source: Author elaborated on this with data provided by LAPIG (2023) and MCTI (2020).

approach, the range of maximum, average, and minimum SEQ values was attributively defined for the clayey textural class and unfolded for the others. To do this, based on the observed data from Stanley et al. (2018), correction factors of 80 % were applied to transpose the SEQ values found for clayey soils to clay-sandy soils, and 40 to 50 % to transpose the values from clayey soils to sandy soils. Since reference values for SEQ are typically expressed in publications in terms of Mg C ha^{-1} yr^{-1}, atmospheric CO_2 removal calculations were conducted by converting these values to Mg CO_2 ha^{-1} yr^{-1}, using the CO_2-C stoichiometry of 44/12 (CO_2 molar mass / C molar mass) as a basis.

Carbon sequestration potential through pasture recovery and management

To determine the SEQ factors to be applied in each pasture polygon, georeferenced data on the current degradation class and soil type grouping from the SiBCS produced by Bernoux et al. (2002) were cross-referenced. The following assumptions were made for this stage:

- CO_2 removal factors presented in the literature for well-managed and recovering pastures can be transposed to calculate the potential for increased CS in other pasture areas;
- Level of pasture degradation directly influences the amount of carbon stored in a given plot of soil;
- Recovery and proper management of pastures promote removals of atmospheric CO_2 continuously for 20 to 50 years until the SOC stock stabilizes (IPCC, 2019; Lal et al., 1998).

Considering that SOC contents tend to be higher in areas with a lower degradation index, maximum sequestration rates were assigned to areas with greater degradation and vice versa. Data provided by Bernoux et al. (2002) was used as a proxy to determine the soil textural class under each pasture polygon, assigning the correspondences shown in table 3.

Table 2. Conceptual distribution of carbon sequestration factors (SEQ) to be used in calculations of estimated SEQ potential by pastures

Parameter	Soil textural class		
	Clayey (clay)	Clay-sandy (clsa)	Sandy (sand)
SEQmax (Mg C ha^{-1} yr^{-1})	SEQmax-clay	SEQmax-clsa	SEQmax-sand
SEQavg (Mg C ha^{-1} yr^{-1})	SEQavg-clay	SEQavg-clsa	SEQavg-sand
SEQmin (Mg C ha^{-1} yr^{-1})	SEQmin-clay	SEQmin-clsa	SEQmin-sand

Source: Elaborated by the author. SEQmax: Maximum sequestration rate; SEQavg: Average sequestration rate; SEQmin: Minimum sequestration rate.

Georeferenced pasture quality data (LAPIG, 2023) was cross-referenced with the SiBCS soil class grouping data (Bernoux et al., 2002), thereby determining the soil textural class under each pasture polygon. Subsequently, acknowledging the high uncertainty associated with the likely SEQ values resulting from pasture management, three different scenarios were formulated for calculating the potential carbon sequestration in these areas, as shown in table 4.

Thus, based on the textural class characterization obtained for each pasture polygon and the corresponding assignment of SEQ factors, as shown in table 4, carbon sequestration potential in these areas was calculated for each scenario over a 20-year horizon. Once the potential carbon sequestration values were calculated, an assessment was conducted on their significance in terms of mitigating atmospheric CO_2 concentration. This assessment considered the equivalence of 7.8 Mg CO_2 for 1 ppm of atmospheric CO_2 (CDIAC, 1990). Subsequently, a discussion and critical analysis of the results obtained was undertaken, considering the challenges and prospects associated with the feasibility and scalability of carbon sequestration practices through land-use and management.

RESULTS

Definition of pasture carbon sequestration factors

The systematic review identified 5,718 articles, with 336 classified as located in Brazil. From these, 67 articles were selected for analysis, resulting in 23 publications for data tabulation. Out of these, 22 were obtained through the Scopus platform search, and one additional reference identified in one of these articles was incorporated. For two publications, the tabulation of qualitative data was complemented by references cited by the studies, one for each. Finally, 17 studies were selected to define the SEQ factors applied to estimate soil carbon sequestration potential in Brazil's south region pastures. Results show a broad variability of SEQ rate values found among different publications, ranging from 7.43 to 0.15 Mg C ha^{-1} yr^{-1} with a series of intermediate values between these extremes (Table 5).

Table 3. Deriving textural classes from soil groupings

Soil grouping according to Bernoux et al. (2002)	Textural class considered
S1 – Soil with high-activity clay	Clayey
S2 – *Latossolo* (Oxisol)	
S5 – Hydromorphic soils	
S3 – Non-Oxisol with low-activity clay	Clay-sandy
S4 – Sandy soils	Sandy
S6 – Other soils	

Source: Elaborated by the author based on Bernoux et al. (2002).

Table 4. Scenarios considered and respective carbon sequestration factors application

Level of pasture degradation	Scenario 1	Scenario 2	Scenario 3
Severe	SEQmax	SEQmax	SEQavg
Intermediary	SEQmax	SEQavg	SEQavg
Absent	SEQavg	SEQmin	-

Based on the list of carbon sequestration factors for managed pastures identified by the systematic literature review, the conceptual distribution table of SEQ factors for the estimate calculations of pastures carbon sequestration potential was populated with reference values. This was done through judgment and critical analysis of the results found in the literature. Thus, the maximum, average and minimum SEQ factors for clayey texture were defined as 2.50; 1.25; and 0.50 Mg C ha^{-1} yr^{-1}, respectively. These values were then proportionally adjusted for other textural classes according to the ratios derived from Stanley et al. (2018), as described in the methodology. This resulted in the values 2.00; 1.00; and 0.40 Mg C ha^{-1} yr^{-1} for clay-sandy texture, and 1.25; 0.50; and 0.25 Mg C ha^{-1} yr^{-1} for sandy texture, as shown in table 6.

Carbon sequestration potential from pasture recovery and management

Results for carbon sequestration potential of pasture areas found in the calculations range from 0.433 to 1.273 Gt CO_2 for the different scenarios considered (Table 7). These findings indicate the capacity to mitigate climate change effects through carbon sequestration in these pasture areas is not very significant. The balance of removals over a 20-year period in the most optimistic scenario is approximately 6.5 times less than the amount of CO_2 removal needed to reduce the concentration of the gas in the atmosphere by 1 ppm.

DISCUSSION

Due to the numerous variables influencing the observed and reported carbon sequestration values, and the limited number of available publications, it is not possible to make an assertive inference about the reasons explaining this variability, which is a limitation of this research. Counterintuitive results for experiments with different characteristics are also observed, such as SEQ values in pasture areas shortly after the conversion of native forest (Santos et al., 2019) being higher than values observed in pastures converted from other previous non-conservative uses (Tarré et al., 2001; Piva et al., 2020). This highlights the presence of a wide range of variables in pasture management influencing soil ability to sequester carbon.

Among the variables influencing the observed SEQ rates are the comparative basis adopted, layer depth sampled, soil texture, experiment duration, management system type, grazing pressure, sward height, adoption or non-adoption of soil tillage, fertilization, crops used and climatic conditions (Pinto et al., 2014; Cardozo Jr et al., 2016; Seó et al., 2017; Santos et al., 2019; Segnini et al., 2019), with emphasis on the first five mentioned aspects. Due to the complexity resulting from the combination of these different variables related to carbon sequestration, the characteristics and volume of data available make it impossible to conduct a conclusive statistical or empirical analysis of each variable preponderance on the sequestration values found, based on the sample set obtained by this research.

However, one observation that can be made is that longer observation times tend to show a reduction in the observed SEQ values, as evident in the analysis of publications reporting different values for the same experiment (Pinto et al., 2014; Oliveira et al., 2020a). This indicates that greater carbon accumulations tend to occur in the initial years and are amortized over time. A comparison between different publications cannot be

Table 5. Summary of the results found for carbon sequestration in pastures from the systematic literature review

Reference	Biome	Region	Soil texture	Soil use	Management system	Comparative basis	Duration	Layer	SEQ
							yr	m	Mg C ha^{-1} yr^{-1}
Pinto et al. (2014)	Atlantic Forest	Southeast	Clayey	Pasture	Continuous	CS in conventional corn farming	3	0.40	7.43
							3	0.40	7.27
							20	0.40	2.54
Seó et al. (2017)	Atlantic Forest	South	Sandy-clay	Pasture	Rotational	CS in direct planting system farming	5	0.40	5.28(1)
							8	0.40	4.53(1)
							17	0.40	1,.89(1)
			Clayey				14	0.40	1.61(2)
							30	0.40	0.62(1)
							9	0.40	0.40(1)
Resende et al. (2020)	Atlantic Forest	Southeast	Clayey	CLFi	N/I	Initial CS in the experiment area	8	N/I	3.84
							8	N/I	3.50
							8	N/I	3.21
							8	N/I	2.59
Bieluczyk et al. (2020)	Atlantic Forest	Southeast	Sandy-clay	Pasture	Extensive	Initial CS in the experiment area	6	0.40	1.96
							6	0.40	1.74
							6	0.40	1.68
Oliveira et al. (2020a)(1)	Atlantic Forest	Southeast	Clayey	Pasture	Rotational	Native vegetation CS	9	1	1.92
							15	1	1.80
Souza et al. (2009)	Pampa	South	Clayey	CLi	Continuous	Initial CS in the experimente area	6	0.20	1.40
							6	0.20	1.20
							6	0.20	0.60
Ribeiro et al. (2020)	Atlantic Forest	South	Clayey	CLi	Continuous	Initial CS in the experimente area	3.5	1	1.14
							3.5	1	0.28
Assman et al. (2014)	Pampa	South	Clayey	CLi	Continuous	Initial CS in the experimente area	9	0.20	0.96
Oliveira et al. (2017)	Atlantic Forest	South	Clayey	Pasture	N/I	Native vegetation CS	20	0.40	0.95
Segnini et al. (2019)(1)	Atlantic Forest	Southeast	Clayey	Pasture	Rotational	Native vegetation CS	15	0.30	0.94
							9	0.30	0.47
Ramalho et al. (2020)	Atlantic Forest	South	Clayey	CLi	N/I	Control area with pasture conducted with plowing and harrowing	9	0.20	0.57
Alves et al. (2020)	Pampa	South	Sandy-clay	CLi	Rotational	CS of the treatment with the lowest accumulation	14	0.30	0.50
Santana et al. (2013)	Atlantic Forest	South	Clayey	Pasture	Hybrid	Native pasture without mowing and burned for 8 years	17	0.50	0.44

Continue

Continuation

Reference	Biome	Region	Soil texture	Soil use	Management system	Comparative basis	Duration	Layer	SEQ
Rosset et al. (2014)	Atlantic Forest	South	Clayey	Pasture	Extensive	Set of system without plowing and harrowing	38	0.40	0.34
Piva et al. (2020)	Atlantic Forest	South	Clayey	CLi	Rotational	Area under conventional cultivation	3.5	0.20	0.25
Piva et al. (2014)					Rotational	N/I	3.5	0.20	0.19
Nicoloso et al. (2008)	Atlantic Forest/ Pampa (transition)	South	Sandy-clay	CLi	Continuous	Initial CS in the experiment area	3.75	0.10	0.15

[1] To obtain these results, the author provided complementary data not present in the publication. [2] Value is a composite average for five properties evaluated in the article. [3] Both references deal with the same experiment. Different SEQ values within the same reference where different characteristics are not observed in the table are due to suppressed information. CLFi: Crop-Livestock-Forest integration. CLi: Crop-Livestock integration. N/I: Not informed.

made for the reasons mentioned above, given the heterogeneity of conditions identified for the aspects that influence the results found in the studies. On the other hand, it could be mistakenly stated that continuous management systems (Pinto et al., 2014) have higher carbon accumulation than rotational systems (Seó et al., 2017; Segnini et al., 2019; Oliveira et al., 2020a), which is not in line with the state-of-the-art knowledge on the dynamics of soil organic matter (SOM) accumulation and CS increase in these types of systems (Machado, 2004; Machado Filho et al., 2021; Mosier et al., 2021).

Although indications about the best management practices in terms of carbon sequestration can be obtained through studies that isolated some variables, other limitations persist due to the lack of representativeness of publications. For example, while authors who worked with sward height as a control variable reported higher soil carbon accumulations for higher sward heights (Cecagno et al., 2018), others found divergent values for different time horizons (Souza et al., 2009). Findings obtained by Cecagno et al. (2018) are reinforced by Souza et al. (2009) for an observed period of six years, but inverse results are reported for the first three years of the observation period.

Data heterogeneity reported by the publications is another relevant aspect in terms of either completeness or the adoption of different reference values and approaches. An example of this second aspect is the depth of the layer sampled, with sequestration values being reported between the different studies for layers varying between 0.05, 0.10, 0.20, 0.40 and 1.00 m (Table 5). Another example is the comparative basis used to estimate carbon sequestration through pasture management. While some publications use as a comparative basis the CS measured at a previous point in time in the experiment area (Nicoloso et al., 2008; Souza et al., 2009; Assman et al., 2014; Bieluczyk et al., 2020;

Table 6. Factors considered for calculating the estimated potential for soil carbon sequestration through appropriate management of pastures in southern Brazil

Parameter	Soil textural class		
	Clayey	Clay-sandy	Sandy
SEQmax (Mg C ha^{-1} yr^{-1})	2.50	2.00	1.25
SEQavg (Mg C ha^{-1} yr^{-1})	1.25	1.00	0.50
SEQmin (Mg C ha^{-1} yr^{-1})	0.50	0.40	0.25

SEQmax adapted from Pinto et al. (2014); SEQavg adapted from Seó et al. (2017); SEQmin adapted from Alves et al. (2020).

Table 7. Potential carbon sequestration calculated for the scenarios considered

	Scenario 1 – Optimistic	Scenario 2 – Moderate	Scenario 3 – Conservative
Sequestration potencial	1,273 Gt CO_2	0,719 Gt CO_2	0,433 Gt CO_2

Resende et al., 2020; Ribeiro et al., 2020) or in areas with the same crop type but with different management (Alves et al., 2020; Ramalho et al., 2020), others consider areas with varying types of crop (Pinto et al., 2014; Seó et al., 2017; Piva et al., 2020) or even native vegetation (Oliveira et al., 2017; Segnini et al., 2019; Oliveira et al., 2020b) as the CS reference. This is a limiting factor for comparing and grouping the results obtained into representative sets of average carbon sequestration values by soil type, textural class, land-use class, and management system.

A recommendation already highlighted in the literature for new studies involving sustainable and regenerative agricultural practices, in terms of choosing the comparative basis for assessing variations in CS as a result of land-use changes and employed management techniques is to adopt as a comparative baseline, CS values found in correlated systems that better represent the initial conditions of the area where the experiment is taking place or the common practices adopted in business-as-usual scenarios. In general, these have a lower capacity for sequestering, storing, and maintaining soil CS when compared to areas of native vegetation, for example, and can allow for a more assertive assessment of the benefits that appropriate management practices can bring when employed in these conditions. In this sense, a suggestion for estimating variations in CS promoted by the adoption of practices such as crop-livestock integration (CLi) and crop-livestock-forest integration (CLFi) is the adoption of CS values observed in monoculture or degraded pasture systems as a comparative basis (Oliveira et al., 2023). In these cases, the compatibility of other parameters related to the dynamics of SOC and CS between the two evaluated systems should also be observed, such as climatic conditions and soil textural class, for example.

Although positive carbon sequestration values have been reported when comparing the soil CS of managed pastures with that of areas under native vegetation, the opposite has also been found (Dalal et al., 2005; Wendling et al., 2011). In general, replacing forests with pastures leads to a loss in the total amount of carbon stored by the system (Oliveira et al., 2017), especially when considering other aspects such as aerial biomass. Using native vegetation soil CS values as a reference and comparative basis for estimating carbon sequestration or emissions promoted by managed systems implies limitations to interpreting these values. However, this characteristic is considered to provide a conservative approach to the estimates made under the assumptions of this research, as the baseline scenario is degraded pastures assuming further management through regenerative practices. Thus, it is expected an increasing trend for the CS values in these areas, excluding the potential forest carbon loss observed after native vegetation conversions for example.

Another important observation regarding the results obtained is, in some cases, sequestration values are directly presented by the studies (Souza et al., 2009; Bieluczyk et al., 2020; Oliveira et al., 2020b; Ramalho et al., 2020), while in other cases it is necessary to calculate them through the difference between two different CS values presented by the study (e.g., CS in pasture area and CS in native vegetation), divided by the time horizon since the conversion or implementation of the management system (Pinto et al., 2014; Seó et al., 2017; Segnini et al., 2019; Resende et al., 2020). This possibly reveals there is not always a concern in highlighting this information by part of the authors. Both positive (Table 5) and negative variations in CS are found in the literature (Nicoloso et al., 2008; Segnini et al., 2019; Oliveira et al., 2020a, 2020b; Piva et al., 2020), and the negative variations may be associated with different reasons, such as conversion of native vegetation areas and comparison with their original soil CS, or inadequate management practices from the point of view of organic matter accumulation.

Currently, the concentration of atmospheric CO_2 is approximately 140 ppm above pre-industrial levels, which reinforces the fact that the best measure to contain the worsening effects of climate change is to avoid new GHG emissions into the atmosphere. However, the capacity of soils to sequester and store carbon on a global level cannot be considered negligible. On the opposite, a study recently published by the United Nations Environment Programme (UNEP) reveals for soils under different types of agricultural occupation around the world, improving management practices could result in an annual removal balance of 31 Gt CO_2 (UNEP, 2022), enough to reduce atmospheric CO_2 concentration by approximately 4 ppm per year.

Although in the scenario definition of this research, a greater potential for increasing CS was considered for degraded areas, depending on their level of degradation and the practices to be employed, the time horizon required for carbon sequestration rates to reach satisfactory levels may vary. Due to degradation, at early recovery stages, these areas may have a lower biomass productivity potential and, consequently, a lower amount of organic matter availability to be incorporated into the soil, which is a key factor for sustaining carbon sequestration rates (Cecagno et al., 2018; Santos et al., 2019). Thus, lower carbon sequestration rates could be found in initial years for scenarios of greater degradation until they reach higher levels with the recovery of such areas' productive capacity. Despite this, significant carbon sequestration rates for short time horizons after intervention with management in pastures areas previously maintained under non-conservationist management are found (Pinto et al., 2014; Martins et al., 2017).

Another relevant aspect to be mentioned is that the premise of a greater sequestration potential in severely degraded areas, as previously supported in the literature (Szakács, 2003), is based on the understanding the previous loss in CS results in a greater SEQ capacity when recovering the area, due to the originated deficit. Although, the notion that there is a carbon saturation point in the soil representing a limitation for its SEQ capacity is questioned by some authors in the scientific literature (Mathieu et al., 2015; Fontaine et al., 2018).

Still, pasture recovery and management activities can result in increased GHG emissions when compared to a baseline scenario, either through enteric fermentation methane emissions led by increasing animal occupation, fossil fuels-powered machinery, or other reasons such as the use and displacement of raw materials. Therefore, the net carbon sequestration balance promoted by management and recovery interventions may be lower than the results found. However, activities such as intensification of pasture-based livestock with rotational management and livestock-forest integration can be developed to amortize this balance (Stanley et al., 2018; Machado Filho et al., 2021). This highlights the importance of taking a systemic and integrative approach to agricultural and landscape management practices into consideration when discussing public policies and market incentives, guiding the sector practices towards a decarbonization path aligned with the Paris Agreement's primary goal of limiting global warming between 1.5 and 2 °C by the end of the century.

In this sense, there is currently an early stage but growing movement, which brings together large corporations and agents to diffuse initiatives, seeking to develop solutions that directly or indirectly contribute to overcoming bottlenecks for the regeneration of landscapes and pastures at scale, with a powerful appeal over the perspective of these systems carbon sequestration capacity. These arrangements range from business models and/or product innovations (e.g., Inocas, Belterra, Agroforestry Carbon, InPlanet); new reforestation-focused ventures arising from the coalition of major players and/or agents with the capacity to raise large amounts of investment (e.g., Biomas, Mombak, Re. Green); technological and intelligence solutions to increase the integrity and scalability potential of carbon measurements techniques and projects (e.g., Pachama, Sylvera, Arable); and alternative, low-cost carbon certification models to increase the voluntary carbon market accessibility to small and medium-sized producers and landowners (e.g. Bluebell Index, Carbify, Regen.Network, ONCRA).

Finally, the public and private sectors must create the proper incentive and support conditions necessary for transitioning agricultural production systems through the adoption of conservative and regenerative practices, such as technical assistance and rural extension (TARE) and incentive programs and credit lines, designed to suit the specific needs of different actors that can play a contributing role in this context.

CONCLUSIONS

Managed pastures can sustain soil carbon sequestration rates above the average found in the literature, with values as high as 2.50 Mg C ha^{-1} yr^{-1} for prolonged periods of the order of 20 years. Due to the large number of variables that influence SEQ rates; the limited number of publications found; and the lack of data for some of these variables among different publications; a larger set of publications and data needs to be analyzed to establish causal and preponderance relationships on the effect of each of these variables on the reported SEQ rates through a multivariate analysis.

Although the carbon sequestration potential for the specific pasture areas restricted to the south region of Brazil is not representative for promoting a significant reduction in atmospheric CO_2 concentration, in terms of mitigating climate change, literature suggests carbon sequestration by soils under agricultural management can play a significant role for this purpose, integrating the necessary set of solutions and actions for a Paris Agreement's goal compatible trajectory, of limiting global warming to between 1.5 and 2 °C by the end of the century.

For this to happen, coordinated efforts and political and financial incentives are needed to match the scale and speed required to implement these measures. For carbon finance instruments to make a significant contribution to this scenario, it is necessary to accelerate the development and application of technologies that make it possible to measure changes in soil carbon stocks in a reliable, cost-effective, and periodic manner at a large scale.

SUPPLEMENTARY MATERIALS

Supplementary data to this article can be found online at https://drive.google.com/drive/folders/1X3xheV9A10KmY64SbYb4Ifb3qamt5Y8E.

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