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Pathways to low-carbon agriculture: soil management, carbon storage, and wheat productivity in Paraná, Brazil

Abstract – The objective of this work was to evaluate 12 wheat farms in the state of Paraná, Brazil, in order to identify structural and functional soil property patterns that explain wheat productivity and soil carbon stocks, aiming to support improvements in soil management and guide the transition to low-carbon agriculture. Soil samples were collected at the depths of 0–10, 10–20, and 20–30 cm on farms under no-tillage systems, of which 90% adopt crop rotation. On the studied farms, enhancing crop rotation is necessary to increase soil carbon sequestration, resulting in a greater resilience to extreme climate events. The factor analysis shows that fertility, acidity, and physical properties shape soil patterns across the 12 farms. The low predictive power of the regression models for productivity suggests that unmeasured factors, such as climate and phytosanitary conditions, influence yield, highlighting the need of integrated soil fertility management to support productivity and carbon sequestration. The subindices soil and water conservation, soil fertility chemistry, and soil structural quality exhibit the lowest performances and, therefore, require prioritization in improvement programs for wheat production systems in the studied region.

Index terms: farming systems, no-tillage, soil fertility, sustainable agriculture, wheat yield.

Caminhos para agricultura de baixo carbono: manejo do solo, armazenamento de carbono e produtividade de trigo no Paraná, Brasil

Resumo – O objetivo deste trabalho foi avaliar 12 fazendas de trigo no estado do Paraná, Brasil, para identificar padrões estruturais e funcionais de propriedades do solo que explicam a produtividade do trigo e os estoques de carbono no solo, e assim subsidiar melhorias no manejo de solo e orientar a transição para uma agricultura de baixo carbono. Amostras de solo foram coletadas nas profundidades de 0–10, 10–20 e 20–30 cm em 12 fazendas sob sistemas de plantio direto, das quais 90% adotam rotação de culturas. Nas fazendas estudadas, o aprimoramento da rotação de culturas é necessário para aumentar o sequestro de carbono no solo, o que resulta em maior resiliência a eventos climáticos extremos. A análise fatorial mostra que a fertilidade, a acidez e as propriedades físicas moldam os padrões do solo nas 12 fazendas. O baixo poder preditivo dos modelos de regressão para produtividade sugere que fatores não mensurados, como condições climáticas

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e fitossanitárias, influenciam o rendimento, o que ressalta a necessidade de um manejo integrado da fertilidade do solo para apoiar a produtividade e o sequestro de carbono. Os subíndices de conservação do solo e da água, de fertilidade química do solo e de qualidade estrutural do solo exibem os menores desempenhos e, portanto, exigem priorização nos programas de melhoria para os sistemas de produção de trigo na região estudada.

Termos para indexação: sistemas agrícolas, plantio direto, fertilidade do solo, agricultura sustentável, produtividade do trigo.

Introduction

Climate change poses a threat to food security, especially in regions that depend on rainfed agriculture and are more vulnerable to climatic stresses (Muluneh, 2021). Beyond the climatic risks, global socioeconomic and climate scenarios project a 35% to 62% increase in food demand by 2050. This forecast, which includes significant variations in the population at risk of hunger, underscores the uncertainty and complexity surrounding the future of global food security (Van Dijk et al., 2021).

Solutions focused on climate change mitigation, adaptation, and promotion of food security are central to low carbon agriculture. This approach emphasizes, for instance, land-use intensification (Popin et al., 2025) and soil fertility as a key regulator of soil carbon fluxes (Mota Neto et al., 2025). This is particularly important in regions with predominantly acidic soils, where carbon accumulation strongly depends on the mineral fraction composed of iron and aluminum, and it is associated with cation exchange capacity (Li et al., 2025).

The carbon stock in an environment is determined by factors that influence net above- and below-ground biomass production. As a result, cropping systems with high phytomass production offer greater potential for soil carbon sequestration (Ardenti et al., 2023). However, this potential is highly dependent on edaphoclimatic conditions, which leads to different management practices across Brazilian biomes (Freitas et al., 2024).

The no-tillage system is among the most promising solutions for soil carbon sequestration. According to Sá et al. (2025), this system has the potential to restore carbon stock to a level similar to remaining vegetation, within a period of 36 to 54 years, depending on the biome. The authors also estimated that approximately 1.00 ha under no-tillage can prevent the deforestation of another hectare for food production in the Cerrado, and 0.85 ha in the Atlantic Forest.

Carbon plays a central role in all processes related to agriculture, acting as a key factor in the quality of soil, air, and water (Lal, 2004b). Currently, anthropogenic climate change is the main challenge to be addressed, as it directly threatens the pillars of sustainability and jeopardizes global food security (IPCC, 2021), increasing the number of hungry people, which already exceeds 800 million globally (The state […], 2022). The climate change is attributed to the uncontrolled rise in atmospheric CO_2 emissions, primarily from fossil fuel combustion for energy production and, to a lesser extent, from land-use change (IPCC, 2021; ICOS, 2023).

In Brazil, land-use change, especially illegal deforestation, remains the primary source of CO_2 emissions, accounting for 66% of the country's total. Meanwhile, the agricultural sector contributes to greenhouse gas emissions, primarily through nitrous oxide (N_2O) and methane (CH_4) (Tsai et al., 2024). Within this sector, livestock alone accounts for 80% (503.5 $MtCO_2e$) of the emissions, while other agricultural activities contribute to 20% (127.6 $MtCO_2e$) (Tsai et al., 2024).

Despite agriculture's role in greenhouse gas emissions, sustainable farming practices can mitigate them. The implementation of conservation practices, such as no-tillage systems, crop rotation, rational fertilizer use, and cover crops are proven strategies to increase soil carbon sequestration and reduce greenhouse gas emissions (Lal, 2004b, 2021; Paustian et al., 2016). The adoption of such practices has led to increased soil carbon stocks, greater biodiversity, and enhanced resilience of agricultural systems to climate change (Lal et al., 2011; Smith et al., 2019; Sá et al., 2025).

The state of Paraná is recognized as one of Brazil's leading agricultural regions, distinguished by the diversity and intensity of its crop and livestock production. Soil management is predominantly carried out under no-tillage systems with crop rotation. Between 2018 and 2021, soybean [*Glycine max* (L.) Merr.] accounted for 91% of the summer cropping area, while wheat (*Triticum aestivum* L.) occupied between 75% and 80% of the winter cropping area (Possamai et al., 2022). These crops play a fundamental role in the regional economy, particularly in Campos Gerais, a region that encompasses virtually all the studied municipalities. In this region, soybean and wheat represent R$ 5.7 billion (11.7%) and R$ 0.44 billion (13.5%) of the gross production value (Paraná, 2023), respectively, in its 22 municipalities (Melo et al., 2014).

With an estimated 1.15 million ha cultivated (IBGE, 2025), wheat holds great economic and environmental relevance for the state. Its cultivation is essential for the establishment and maintenance of soil conservation systems, as no-tillage management significantly contributes to atmospheric CO_2 sequestration (Veeck et al., 2022).

The present study is aligned with previous research on the techno-economic characterization of wheat production (Acosta et al., 2025), and assessment of environmental impacts associated with wheat cultivation and flour production were conducted through Life Cycle Assessment (LCA) (Giongo et al., 2020). It also contributes to ongoing efforts to identify and apply plant and soil management protocols that support the development of Low Carbon Wheat (Debiasi et al., 2023; Dossa et al., 2023), a concept brand currently under development at Embrapa.

The objective of this work was to evaluate 12 wheat farms in the state of Paraná, Brazil, in order to identify structural and functional soil property patterns that explain wheat productivity and soil carbon stocks, aiming to support improvements in soil management and guide the transition to low-carbon agriculture.

Materials and Methods

This study was conducted between 2023 and 2024 in the state of Paraná, a region that excels in wheat production. The region has a temperate climate (Cfb) according to Köppen classification, characterized by mild summers and uniformly distributed rainfall with no defined dry season. The average temperature in the hottest month does not exceed 22°C (Alvares et al., 2013). Precipitation ranges from 1,100 to 2,000 mm, and altitude varies from 600 to 1,000 m. For the present study, 12 farms were selected to characterize their production models, soil fertility, carbon stocks, and wheat productivity.

The farms were selected using quota sampling (Mattar, 1998) through structured questionnaires applied in 2023 (Acosta et al., 2025). The selection process used a database of 632 wheat producers from a major regional center for grain reception and processing in the south-central Paraná. This database was created from the 2022 wheat harvest delivery records, allowing for the stratification of producers by delivery per municipality, weighted by total volume. The sample size was calculated for a finite universe, with 90% confidence and 10% sampling error, resulting in a sample of 61 producers, according to Equation 1: $n = [(Z^2 \times p \times q \times N)/(\varepsilon^2 \cdot (N-1) + Z^2 \times p \times q)] = [(1.645^2 \times 0.5 \times 0.5 \times 632)/(0.1^2 \cdot (632-1) + 1.645^2 \times 0.5 \times 0.5)] = 61$, where: n, sample size; Z = Z-score, representing a 90% confidence level; p, probability of presence; q, probability of absence (p and q set at 50% for the socioeconomic and cropping characteristics of the farms); N, sample universe, corresponding to 632 producers; ε, estimated error, defined as 10%.

For operational reasons, this study used a subset of 12 farms from the sample group. Invitations were sent to producers requesting expression of interest in participating in the research. From the respondents, 12 farms, identified as Farm 1 (F1) to Farm 12 (F12), were selected based on logistical convenience, considering the feasibility of accessing the areas and conducting field data collection. Regardless of the size of the farms, the areas studied ranged from 26.6 to 126.0 ha, with a mean of 67.8 ha and a median of 56.5 ha (Acosta et al., 2025; Giongo et al., 2020).

Geographically, the study locations are situated in two mesoregions in the state of Paraná, with wheat cultivated in Homogeneous Regions for Wheat Cultivar Adaptation 1 (HRWCA) (Figure 1 A, B and C, Supplementary Material) (Santi, 2025a), which are characterized by cold and humid climates, while two of them with moderately warm and humid climates (Cunha et al., 2011). The predominant soils are deep and well-developed with a medium to clayey texture, classified as Ferralsol, whose main limitation is low natural fertility. In some areas, Cambisols may occur, presenting drainage limitations (Table S1, Supplementary Material) (Santi, 2025a).

The soil sampling on the 12 farms was conducted in 2023, on which three trenches were opened within a 1-ha area, spaced 50 m apart. From each trench, samples were collected for chemical and physical soil evaluations at depths of 0–10, 10–20, and 20–30 cm. Data on wheat yield and crop rotations from 2020 to 2024 were obtained directly from participating farmers. The dry matter production of each crop was then estimated using data from relevant literature (Krenchinski et al., 2018; Gonçalves et al., 2019, 2025; Rodrigues et al., 2020; Bordin-Rodrigues et al., 2021; Inagaki et al., 2021; Pott et al., 2023; Guelere et al., 2024).

The soil physical characterization was performed using volumetric rings (5 cm diameter × 2.5 cm height) to preserve the structure of the samples. Soil bulk density (BD), as reported by Santi (2025a), was determined at the Soil Physics and Water Laboratory of the University of Passo Fundo (UPF) and used to calculate the total organic carbon (TOC) stock (Santi, 2025b). For the chemical analyses, soil samples were collected with a spatula from predefined 10-cm layers, identified, and stored. The chemical determinations were conducted at the Soil Analysis Laboratory of the Federal University of Santa Maria (UFSM), following the methodology of Tedesco et al. (1995). Total organic carbon contents were quantified using a Flash EA 1112 elemental analyzer (Thermo Fisher Scientific, Waltham, MA, USA) at the Carbon and Nitrogen Biotransformation Laboratory of UFSM.

The total organic carbon stock, in Mg ha^{-1}, was calculated by multiplying the BD by the volume of each soil layer (10 cm) and its corresponding carbon concentration (%C), according to the methodology by Teixeira et al. (2017). Data for soil chemical attributes are presented with their respective standard deviations and critical levels. For critical levels with a range, the upper value of the low classification was used, while for those without variation, the value defined as low (e.g., Ca and Mg) was applied, with all information for each element obtained from Manual […] (2016).

To identify common structural and functional soil patterns and to assess how soil variables at different depths (0–10, 10–20, and 20–30 cm) explain the variability in soil carbon stock and crop productivity, two multivariate analyses were performed: exploratory factor analysis (EFA) and multiple linear regression (MLR). Before the analysis, the assumptions of normality, homoscedasticity, linearity, and the presence of outliers were checked (Table S2, Supplementary Material) (Santi, 2025a). The Anderson-Darling's test was used for normality, the Bartlett's test for homoscedasticity, and an inspection of the residuals plot was performed for linearity and outliers. All variables were standardized using the Z-score transformation to eliminate scale-related bias (Jain et al., 2005). Multicollinearity was assessed using the variance inflation factor (VIF), and variables with a VIF value above 10 were excluded from the dataset using the car package in R (Fox et al., 2024). A high VIF indicates a strong correlation with other variables in the model.

To evaluate the suitability of the dataset for exploratory factor analysis, Bartlett's sphericity test and the Kaiser-Meyer-Olkin (KMO) index were applied. Bartlett's test assesses whether the correlation matrix is significantly different from the identity matrix, while the KMO index evaluates sampling adequacy based on the magnitude of correlations among variables (Shrestha et al., 2021). KMO values below 0.5 were considered inappropriate, as in factor analysis, the correlation matrix indicates the strongest relationships among variables that may load on the same factor (Cerny & Kaiser, 1977). The Varimax rotation method was applied to maximize the variance explained by each factor (Goldberg & Velicer, 2006).

Multiple linear regression analysis was performed separately for each soil depth (0–10, 10–20, and 20–30 cm). This approach was used to quantify the relationships between soil variables (independent variables) and carbon stocks and wheat yield (dependent variables), accounting for the natural variability in soil fertility across depths, which is accentuated under no-tillage systems. The stepwise method was applied to build predictive models by iteratively adding or removing predictor variables based on statistical criteria, using the MASS package version 7.3-65 (Ripley et al., 2025). All statistical analyses were conducted using R software version 4.5.0 (R Core Team, 2018).

To analyze the soil conservation management quality index (SCMQI) of the 12 farms studied, the index by Amaral et al. (2025) was used. This index comprises five subindices and 14 indicators. Subindex 1 is crop diversification (CD), which includes the indicators of diversification intensity (DI), presence of summer grass (SG), and presence of winter grass (WG). Subindex 2 is profitable land use (PLU) that encompasses indicators of cost control history (CCH) and income-generating crops in winter (IGC). Subindex 3 is Soil and water conservation (SWC), which comprises the indicators of contour sowing (CS), agricultural terraces (AT), soil compaction (SC), and frequency of furrow erosion (FE). Subindex 4 is soil fertility chemistry (SFC), composed of the indicators of pH-H_2O, as well as phosphorus and potassium content in the 0–10 and 10–20 cm soil depths. Subindex 5 is soil structural quality (SSQ) that includes indicators for thickness of the surface soil layer with granular structure (SSGL) and organic matter (OM) content in the 0–20 cm soil depth (Table S3, Supplementary Material) (Santi, 2025a).

Each subindex, from one to five, has both a critical value and a weighting factor. The equations for calculating the values of each subindex and each indicator, along with the definitions of critical and maximum values, can be found in Amaral et al. (2025). Weighting factors relativize the importance of each subindex. The soil conservation management quality index (SCMQI) is the sum of the values obtained for each subindex, as represented by the following equation: SCMQI = CD + PLU + SWC + SFC + SSQ.

The classification scale for farm plots based on the SCMQI uses the following quality scores: A for SCMQI equal to or greater than 9.00, with no indicator below the critical level; B for SCMQI from 8.00 to 8.99, allowing only one indicator below the critical level; C for SCMQI from 7.00 to 7.99, allowing up to two indicators below the critical level; D for SCMQI less than 7.00, which indicates the need for corrective actions and adjustments to improve soil conservation management.

The subindices to achieve a specific quality range of each farm were analyzed using the mean, standard deviation, and coefficient of variation.

Results and Discussion

An analysis of the cropping systems adopted by the 12 farms during the 2020/2021 to 2023/2024 growing seasons (Table S4, Supplementary Material) (Santi, 2025a) reveals a direct link between management strategies and dry matter production, which, in turn, influences soil carbon dynamics, greenhouse gas emissions, and ultimately a system's climate resilience.

Among the plots studied, 11 farms (F2 to F12) employed some type of crop rotation, while one plot (F1) had no cover crops (Table S4, Supplementary Material) (Santi, 2025a). In summer, soybean was predominant, whereas in winter, farmers mainly used cover crops, such as cover crop mixture or black oat (*Avena strigosa* Schreb.), and wheat. Crop rotation involves the planned alternation of species over time to improve soil health, break pest and disease cycles, and optimize nutrient use (Franchini et al., 2011). In contrast, crop succession focuses on the sequential cultivation of different crops in the same area, usually within the same agricultural year (Bortolini et al., 2000).

Overall, the crop rotations employed can be improved, as fallow periods, often lasting around 60 to 90 days, were observed during the autumn-winter season, or soybean-wheat sequence. These periods are a result of the time gap between the soybean harvest and the optimal wheat sowing window, defined by the Agricultural Zoning of Climate Risk (ZARC) and the crop cycle requirements. Furthermore, rotations could be enhanced by including wheat in areas where only cover crops are grown during the winter. In this regard, Giongo et al. (2020), assessing Life Cycle Assessment (LCA), emphasized the need to adopt cover crop mixtures that include legumes as a strategy to enhance the sustainability of production systems.

In wheat/soybean succession systems, (Table S4, Supplementary Material) (Santi, 2025a), the fallow period between crops can lead to significant losses of soil organic matter. While wheat cultivation promotes net soil carbon accumulation, the subsequent fallow periods may result in losses of up to 27% of the carbon accumulated throughout the year (Veeck et al., 2022). This has important environmental implications, given the role of soil organic carbon in mitigating greenhouse gas emissions and improving soil resilience under climate stress (Lal, 2004a). Sustainable production systems rely on diversified crop rotations that consistently add plant residues to the soil, minimizing the interval between harvest and sowing. This practice directly enhances soil organic matter content (Saha et al., 2024), reduces climate-related stress, particularly water deficit, and increases system resilience (Degani et al., 2019). Therefore, crop selection and rotation design are essential for adapting agriculture to climate change (Ewing et al., 2024).

Based on dry matter production data (Table 1), greater biomass is consistently observed in the summer than in the winter across the four evaluated years. Soybean, cultivated in 75% of summer seasons, produced higher dry matter quantities than most winter crops.

However, its residues decompose rapidly, resulting in near-zero net carbon accumulation in the soil (Veeck et al., 2022). A similar effect is expected for common bean (*Phaseolus vulgaris* L.). Rotations that include maize (*Zea mays* L.) tend to offset this effect, as the crop produces large amounts of slowly decomposing biomass due to its high carbon-to-nitrogen ratio. In winter, grass species are dominant. Wheat is the main cash crop, while black oat and cover crop mixtures are the most common non-commercial crops. White oat (*Avena sativa* L.) and barley (*Hordeum vulgare* L.) were also occasionally cultivated as commercial crops. The highest dry matter inputs were recorded in cover crop mixtures composed of black oat, ryegrass (*Lolium multiflorum* Lam.), forage radish (*Raphanus sativus* L. var. oleiferus Metzg.), and common vetch (*Vicia sativa* L.).

Cropping systems with greater crop diversity and higher land-use intensity, such as those on F2, F8, and F10, showed the highest dry matter accumulation over the study period, with totals of 60.62, 54.60, and 70.30 Mg ha^{-1}, respectively (Table 1). These values indicate a greater return of organic residue to the soil, enhancing total organic carbon accumulation and atmospheric carbon dioxide (CO_2) sequestration (Zanatta et al., 2019; Tiecher et al., 2020). The combination of high biomass production and frequent cover crop use, as seen on F2, F6, F8, and F10, is a key factor in increasing soil organic matter and reducing greenhouse gas emissions (Bayer et al., 2006).

In contrast, F4 and F12 had the lowest total dry matter input, with 31.33 and 35.28 Mg ha^{-1}, respectively (Table 1). These farms followed less diverse cropping systems, relying primarily on the soybean-wheat succession. This limited input of plant residues may hinder the formation of stable soil carbon and reduce system resilience to extreme weather events, such as droughts and high temperatures, which are becoming more frequent due to climate change (IPCC, 2021).

Therefore, these findings demonstrate that diversified cropping systems produce greater amounts of dry matter, offering higher potential for soil carbon accumulation, enhanced resilience to climate extremes, and more effective resource conservation.

The soil chemical analysis revealed both vertical and spatial variability in fertility attributes among the farms, which may reflect differences in soil type, climate, management strategies, and input use over the years (Figure 1). Soil pH varied significantly, indicating a need for liming in at least five locations, where the 0–10 cm soil depth had a pH below 5.5 (Figure 1). This low pH level corresponds with the presence of toxic aluminum, as observed in F2, F5, F10, and F12, where aluminum contents exceeded 1.0 cmol$_c$ dm^{-3}.

Table 1. Total estimated dry matter[(1)] production (Mg ha^{-1}) of the summer and winter crop harvests per crop season and for the entire four-year period, across the studied farms (F1 to F12), from 2020 to 2024.

Farm	Total dry matter												
	2020/2021			2021/2022			2022/2023			2023/2024			2020–2024
	Summer	Winter	Year	Summer	Winter	Year	Summer	Winter	Year	Summer	Winter	Year	
F1	4.07	3.68	7.75	3.62/10.87	3.68	18.17	4.07	3.68	7.75	4.07	3.68	7.75	41.42
F2	10.87/3.62	3.68	18.17	4.07	12.91	16.98	3.62	3.68	7.30	10.87/3.62	3.68	18.17	60.62
F3	4.07	3.68	7.75	4.07	4.01	8.08	4.07	3.68	7.75	10.87	3.68	14.55	38.13
F4	4.07	3.68	7.75	4.07	4.01	8.08	4.07	3.68	7.75	4.07	3.68	7.75	31.33
F5	4.07	3.68	7.75	4.07	5.11	9.18	4.07	3.68	7.75	10.87	3.68	14.55	39.23
F6	4.07	3.68	7.75	3.62	5.38	9.00	4.07	12.91/3.68	20.66	3.62	3.68	7.30	44.71
F7	4.07	12.91	16.98	4.07	3.68	7.75	3.62/4.07	3.68	11.37	4.07	3.68	7.75	43.85
F8	4.07	4.01/3.68	11.76	4.07	12.91	16.98	10.87	3.68	14.55	3.62	4.01/3.68	11.31	54.60
F9	10.87/3.62	3.68	18.17	4.07	12.91	16.98	4.07	3.68	7.75	3.62	3.68	7.30	50.20
F10	10.87/3.62	3.68	18.17	4.07	12.91	16.98	3.62/10.87	3.68	18.17	4.07	12.91	16.98	70.30
F11	4.07	4.01	8.08	3.62/4.07	3.68	11.37	4.07	3.68	7.75	3.62	3.68	7.30	34.50
F12	4.07	3.68	7.75	4.07	4.01	8.08	3.62/4.07	3.68	11.37	4.07	4.01	8.08	35.28

[(1)]Crop dry matter values were estimated using mean values from published literature. Dry matter of barley was derived from its harvest index. Consulted literature: soybean (Inagaki et al., 2021; Gonçalves et al., 2019); wheat (Gonçalves et al., 2019; Inagaki et al., 2021); bean (Bordin-Rodrigues et al., 2021); maize (Gonçalves et al., 2019; Guelere et al., 2024); crop mixtures (Gonçalves et al., 2025); white oat (Pott et al., 2023); barley (Rodrigues et al., 2020); and black oat (Krenchinski et al., 2018). The description of the crop species grown by the farmers can be found in Table S4 of the Supplementary Material (Santi, 2025a).

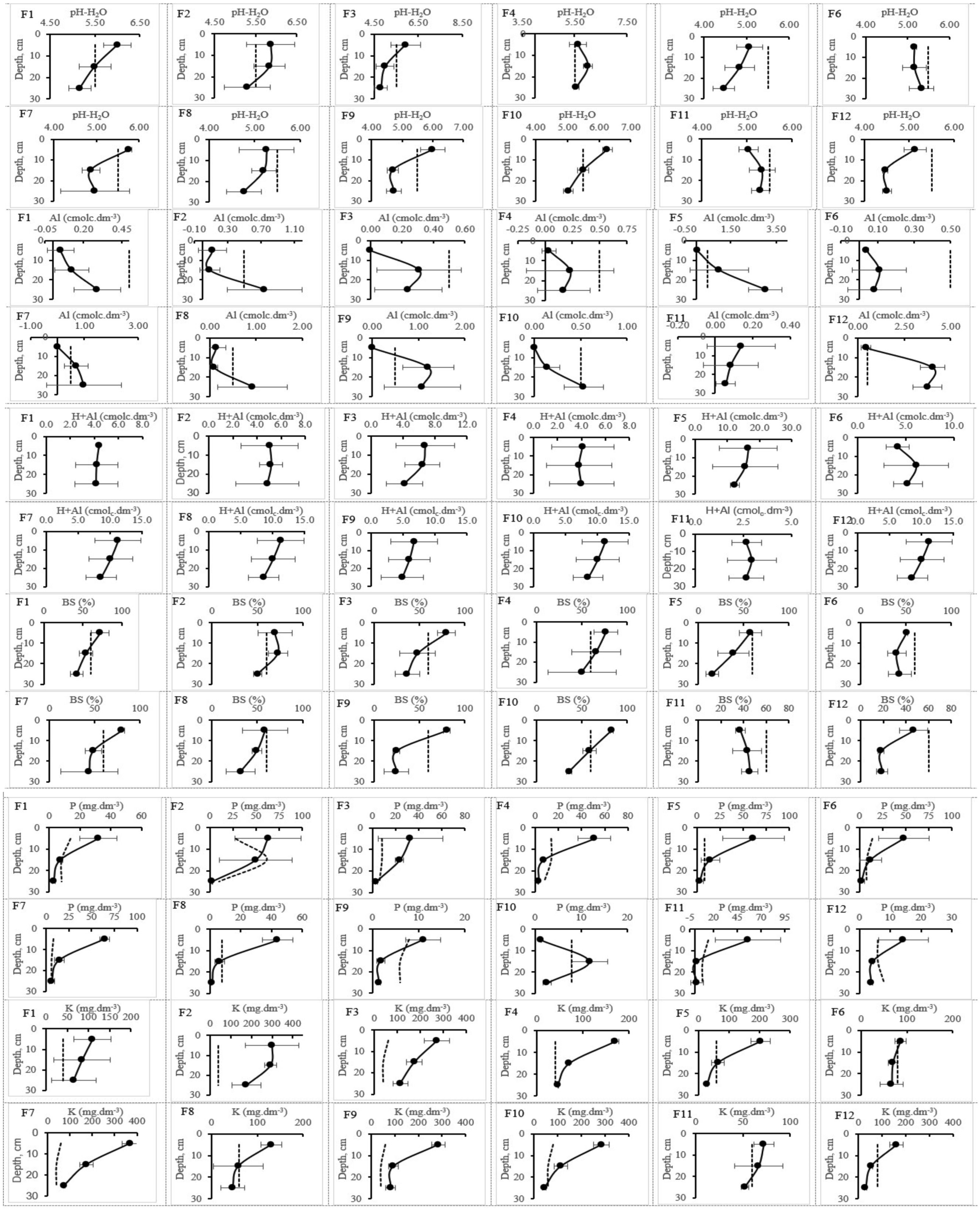
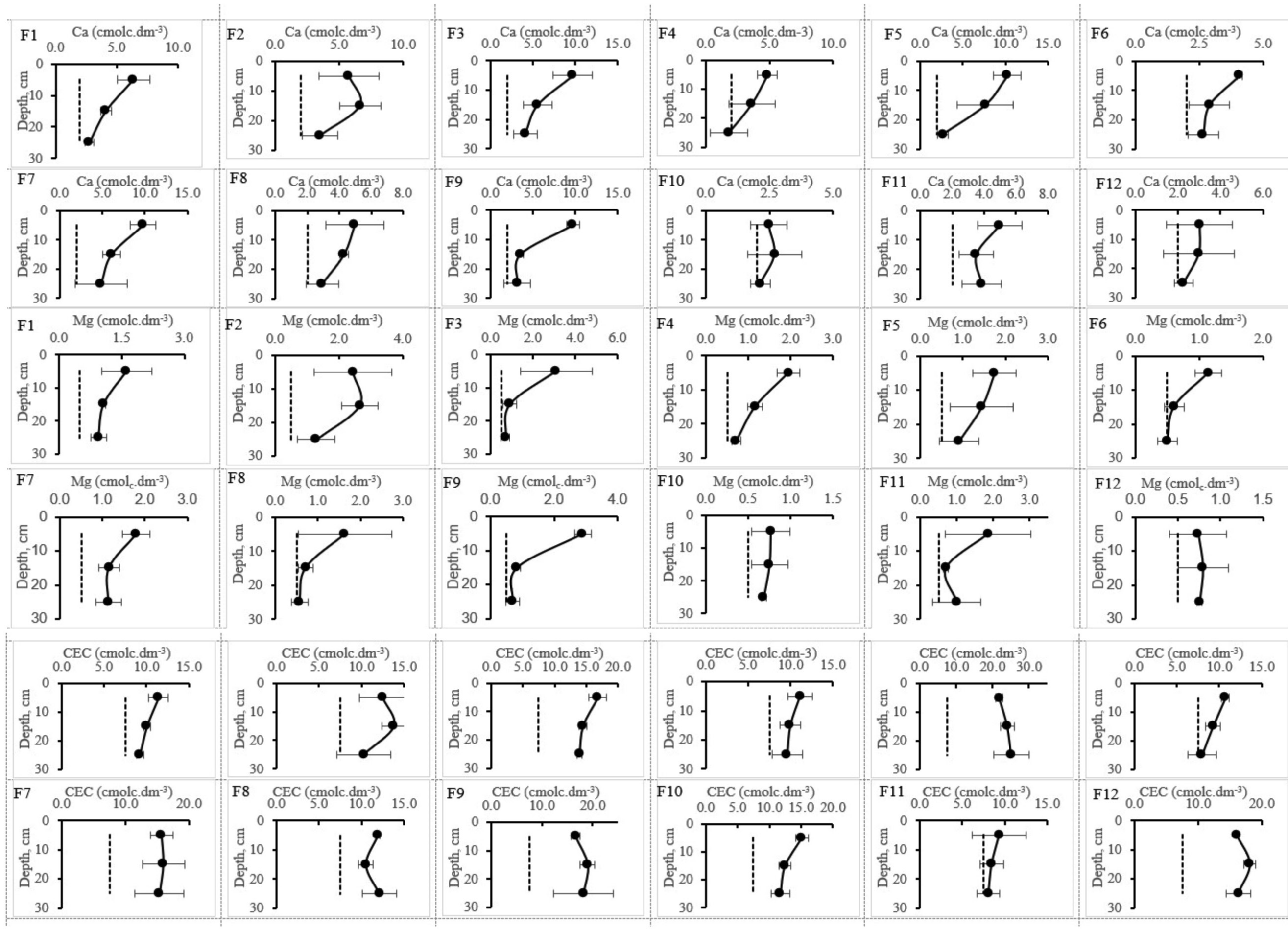


Figure 1. Soil chemical attributes evaluated at 0–10, 10–20, and 20–30 cm soil depths on the farms (F1 to F12), in 2023. (1)The critical value, represented by the dotted line, was established according to CQFS-RS/SC (Manual […], 2016). (continue)



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This can cause phytotoxicity in plants, reducing root growth and biomass production (Rahman et al., 2024), especially for sensitive crops like common bean and soybean, resulting in lower soil carbon accumulation. Furthermore, low pH directly increases nitrous oxide (N_2O) emissions, a potent greenhouse gas (Qiu et al., 2024) with a global warming potential 273 times greater than CO_2 (IPCC, 2021). While Al^{3+} levels were low in the surface soil (Figure 1), its presence in deeper layers may affect crop productivity.

Base saturation (BS%) is a key indicator of the chemical quality of the environment and is closely related to soil pH. In the studied farms, BS% was below the critical 60% threshold in half of the areas, aligning with pH values (Figure 1) and reinforcing the recommendation for soil acidity correction to improve crop yields. Low base saturation also negatively affects dry matter production, thereby reducing the system's ability to sequester atmospheric carbon and hinders climate change mitigation efforts (Bünemann et al., 2018).

Extractable acidity (H + Al) varied significantly throughout the soil profile in the analyzed farms, with lower values in the upper layer (0–10 cm) and higher values in the subsequent layers (Figure 1). The values of F6, F9, F10, and F12 exceeded 10 $cmol_c\ dm^{-3}$, which is considered high and may indicate low efficiency of surface-applied amendments. In these cases, the high potential acidity in deeper layers is a limiting factor for root growth, which can impair nutrient and water uptake, compromising plant growth, development, and crop yields (Zoca & Penn, 2017).

Phosphorus and potassium contents were above critical levels in almost all farms studied in the 0–10 cm layer, except for phosphorus in F10 (Figure 1), indicating surface accumulation, which is typical in areas under no-till systems. According to Khan et al. (2023), phosphorus directly influences crop yields by supporting root development and other functions, which results in greater dry matter production. Among many benefits to plants, potassium plays a key role in determining crop productivity and also influences dry matter production and soil carbon accumulation (Zörb et al., 2014).

Calcium and magnesium levels in the soil were above the critical threshold in all farms, especially up to 20 cm depth (Figure 1), which supports adequate plant nutrition and contributes to improved base saturation and biomass production. Principal Component Analysis (PCA) showed that these nutrients help explain soil total organic carbon stocks (Table 2). Additionally, cation exchange capacity (CEC) was also above the critical threshold in all farms (Figure 1), indicating

Table 2. Correlation matrix between wheat yield and soil variables at soil depths of 0–10, 10–20, and 20–30 cm, in the 12 farms studied. Strong correlations are highlighted.

Variable(1)	0–10 cm soil depth									
	Yield	TOC	Clay	pH	P	K	Al	Ca	Mg	SAW
Yield	1.00									
TOC	0.23	1.00								
Clay	0.42	-0.03	1.00							
pH	0.20	0.08	-0.32	1.00						
P	0.02	0.09	-0.08	-0.09	1.00					
K	**0.61**	0.49	0.34	0.40	0.10	1.00				
Al	-0.12	0.14	0.12	**-0.63**	-0.13	-0.23	1.00			
Ca	0.37	**0.75**	0.11	0.35	0.13	**0.67**	-0.29	1.00		
Mg	0.22	0.56	-0.22	**0.66**	0.08	0.52	-0.45	**0.62**	1.00	
SAW	-0.29	-0.24	-0.42	0.37	-0.35	-0.38	-0.06	-0.22	-0.01	1.00

Variable(2)	10–20 cm soil depth								
	Yield	Clay	pH	P	K	Al	Ca	Mg	SAW
Yield	1.00								
Clay	0.23	1.00							
pH	-0.09	**-0.61**	1.00						
P	0.23	-0.43	0.33	1.00					
K	0.36	-0.10	0.26	0.66	1.00				
Al	-0.10	0.51	**-0.67**	-0.24	-0.24	1.00			
Ca	0.33	-0.28	0.50	0.31	0.39	-0.32	1.00		
Mg	0.34	-0.28	0.45	**0.63**	**0.63**	-0.33	**0.66**	1.00	
SAW	-0.29	-0.30	0.29	-0.03	-0.29	-0.17	-0.18	-0.20	1.00

Variable(3)	20–30 cm soil depth							
	Yield	Clay	pH	K	Al	Ca	Mg	SAW
Yield	1.00							
Clay	0.41	1.00						
pH	-0.12	-0.47	1.00					
K	0.14	0.05	0.24	1.00				
Al	0.15	0.35	**-0.66**	-0.35	1.00			
Ca	0.13	-0.15	**0.78**	0.22	-0.38	1.00		
Mg	0.31	-0.02	0.41	0.40	-0.22	0.44	1.00	
SAW	-0.29	-0.39	0.28	-0.16	-0.29	-0.02	0.02	1.00

(1)Yield, wheat yield; TOC, total organic carbon stock; Clay, clay content; P, available phosphorus; K, exchangeable potassium; Ca, exchangeable calcium; Mg, exchangeable magnesium; Al, exchangeable aluminum; pH, soil pH; SAW, soil available water capacity. (2)The variable total organic carbon stock (TOC) was excluded because the KMO value was lower than 0.5. (3)The variables total organic carbon stock (TOC) and phosphorus (P) were excluded because their KMO values were lower than 0.5.

that the studied plots have good capacity to retain and supply nutrients. These elements, which define soil fertility, when maintained at adequate levels, support the development of sustainable production systems. It not only reflects sound management by farmers but also promotes greater carbon sequestration in the soil, an important factor for mitigating climate change (Lal, 2004a).

Total organic carbon stocks followed the same trend as the other analyzed nutrients, showing stratification with depth, with the highest values in the 0–10 cm layer (Figure 2).

F5 and F9 showed the highest total organic carbon stocks in the 0–10 cm layer (> 60 Mg ha^{-1}) and also maintained high amounts at deeper depths (Figure 2). Despite its low dry matter production (Table S5, Supplementary Material) (Santi, 2025a), the high total organic carbon on F5 can be attributed to its geographical location at a high elevation (close to 1,000 masl) (Table S1, Supplementary Material) (Santi, 2025a), which provides favorable conditions for maintaining soil total organic carbon, with carbon percentage in the 0–10 cm layer exceeding 6% (Santi, 2025a). F6, F8, and F11 had the lowest total organic carbon stocks throughout the soil profile, especially below 10 cm, which may be related to physical and chemical conditions. Physically, these soils have lower clay content (200 to 260 g kg^{-1}), which offers less protection to organic matter and leads to higher decomposition rates compared to more clayey soils. Chemically, low pH limits dry matter production (Rahman et al., 2024).

Although total organic carbon levels in the soil are satisfactory, low carbon stocks on some farms presents the necessity to improve soil management by restructuring crop rotations. Increasing organic matter input is essential for enhancing soil quality (Conceição et al., 2005), as it positively affects soil chemical, physical, and biological properties. Beyond being crucial for climate change mitigation, increasing soil total organic carbon stocks also leads to higher crop yields. According to Lal (2006), 1% increase in soil organic matter content results in yield increases of 20

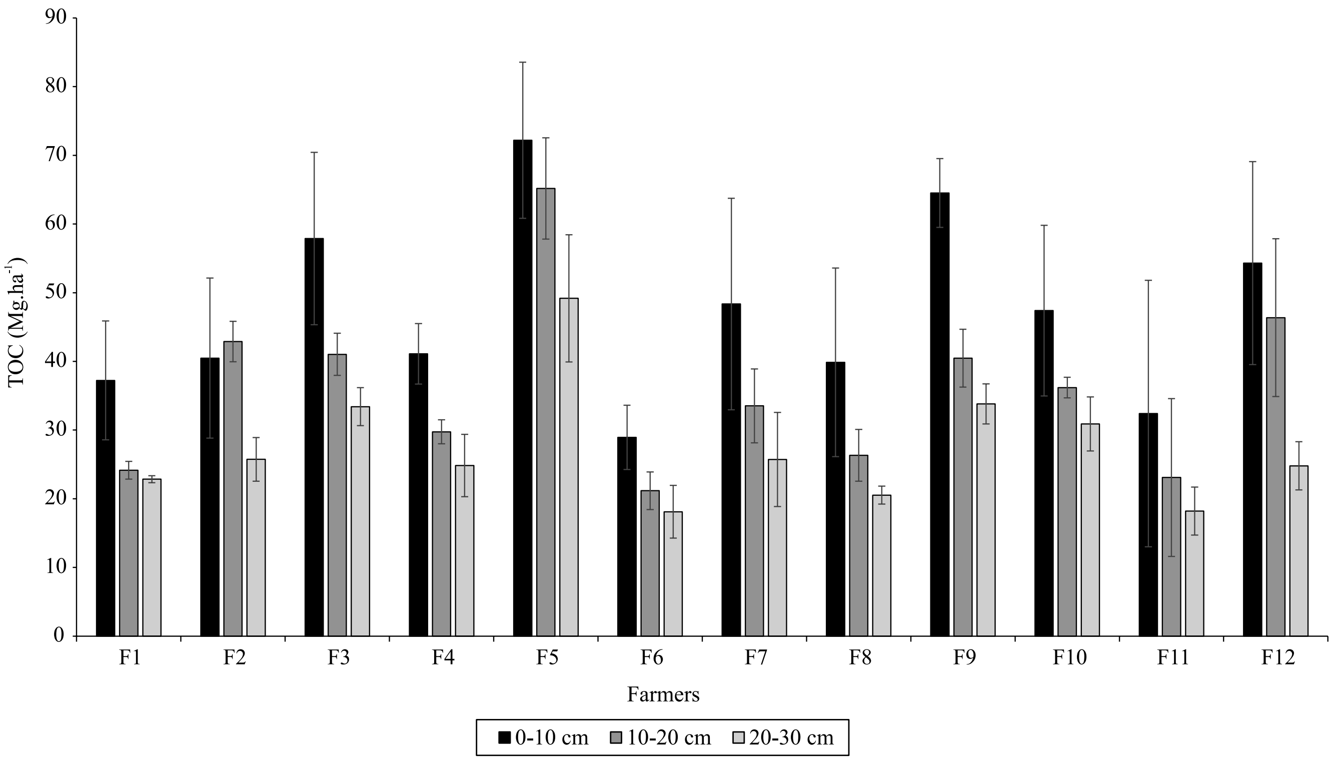

Figure 2. Total organic carbon (TOC) stocks, and respective standard deviation limits (on top of each bar), evaluated at 0–10 cm (1st bar), 10–20 cm (2nd bar), and 20–30 cm (3rd bar) soil depths, in the farms studied (F1 to F12), 2023.

to 70 kg ha^{-1} for wheat, and up to 300 kg ha^{-1} for maize, which is relevant information for the farm studied.

While the amount of produced dry matter is important, this study demonstrates that the effective soil carbon accumulation depends on a complex interaction of biomass production, residue quality, soil chemical and physical conditions, and management practices. Strategies such as species diversification and acidity correction throughout the soil profile are essential to increase carbon stocks and enhance the resilience of the production system in the face of climate change (Lal, 2004b; Conceição et al., 2005; Sá et al., 2025). Many of the production systems already have high soil carbon content, but further improvements in rotations, especially for those using fallow periods, are necessary to maximize soil carbon stocks, a key factor in combating climate change.

The 0–10 cm soil depth exhibited the most significant correlations among variables, with six correlations above 0.60 (Table 2). The strongest correlation was observed between soil total organic carbon stock and calcium content (r: 0.75). Both potassium and magnesium were significantly correlated with calcium. Soil pH exhibited a negative correlation with aluminum and a positive correlation with magnesium. In contrast, wheat yield was significantly correlated only with potassium in the surface layer (Table 2). At the 10–20 cm soil depth, pH continued to show a negative correlation with aluminum and clay. Magnesium was positively correlated with phosphorus, potassium, and calcium. In the 20–30 cm soil depth, pH maintained its negative correlation with aluminum and a positive correlation with calcium.

Exploratory factor analysis revealed that the factor structure of the soil differed across the analyzed depths, indicating that the structural and functional patterns of the soil vary with depth. In the 0–10 cm soil depth, where most chemical reactions occur due to the greater deposition of plant residues, application of fertilizers, and soil amendments, three factors were extracted, explaining 63% of the total data variance. The first factor, named carbon stock regulation, comprised total organic carbon stock, calcium, and magnesium. The second factor, labelled soil reaction, represented the antagonistic relationship between pH and aluminum. The third factor, called soil fertility, included positive relationships among yield, clay, phosphorus, and potassium, as well as a negative relationship with soil available water capacity.

In the 10–20 and 20–30 cm soil depths, two factors occurred, explaining 53% and 49% of the total data variance, respectively (Table 3). In the 10–20 cm soil depth, soil fertility was represented by the variables phosphorus, potassium, calcium, magnesium, and yield. The physical properties reflected soil reaction, which were represented by the relationships among pH, aluminum, and clay content. In the 20–30 cm soil depth, soil fertility continued to include potassium, calcium, and magnesium, but also included pH (Table 3). Soil physical properties grouped the variables for yield, clay content, and available water capacity.

In the factor analyses of the 10–20 and 20–30 cm soil depths, the explanatory power of soil fertility was greater in accounting for data variance and yield compared to the 0–10 cm soil depth. In these deeper layers, soil available water capacity played a lesser role within the fertility factor. Instead, it showed a higher loading in the soil physical properties in the 20–30 cm soil depth, where it was positively associated with yield.

Multiple regression analysis showed that soil pH had a significant negative effect on total organic carbon stock across all three soil layers analyzed, with the strongest effect observed in the 20–30 cm soil depth (Table 4). While aluminum and magnesium had a positive association with carbon stock in the upper two layers, calcium remained an explanatory variable across all depths. In contrast, clay had a specific effect, influencing carbon stock only in the 10–20 cm soil depth (Table 4).

Regression models for wheat productivity showed lower coefficients of determination (R^2) than those for total organic carbon stock, suggesting that additional variables, such as climatic, genetic, and phytosanitary factors may also influence yield (Bornhofen et al., 2018). Clay had a positive effect across all soil layers, while macronutrients influenced productivity in a depth-specific manner: potassium in the 0–10 cm soil depth, phosphorus in the 10–20 cm one, and magnesium in the 20–30 cm one. This highlights the importance of managing soil fertility in deeper layers. Aluminum, in turn, had a specific negative effect on productivity, but limited to the 10–20 cm soil depth.

The association between total organic carbon stock and calcium (Table 2) corroborates the results observed in the formation of carbon stock regulation (Table 2), as well as in the regression models, in which calcium explained total organic carbon stock in all layers (Table 3). This pattern suggests that exchangeable calcium may be related to carbon stabilization in soil aggregates, as discussed by Huang et al. (2024). Magnesium contributed to explaining total organic carbon stock in the 0–10 and 10–20 cm soil depths. This may be associated with greater shoot and root biomass production, given its role is a component of the chlorophyll molecule (Ferreira et al., 2023).

Among the factors related to soil acidity, pH regulates aluminum availability by making it less soluble under neutral conditions (Barrow & Hartemink, 2023). In the regression models, pH also had a negative impact on carbon, which may be

Table 3. Factor loading matrix after orthogonal rotation using Varimax method, results of the variance explained by each extracted factor, and the relationships between variables and the extracted factors at three soil depths, in the 12 farms studied, 2023. Highlighted values indicate the most significant relationship between a factor and a given variable.

Soil depth	0–10 cm				10–20 cm			20–30 cm		
Factor[(1)]/Variable[(2)]	CSR	SR	SF	Com	SF	SR	Com	SF	SP	Com
Yield	0.22	0.32	**0.56**	1.9	**0.51**	-0.20	1.3	0.24	**0.60**	1.3
SOC[(3)]	**0.98**	-0.17	0.11	1.1	*	*	n/a	*	*	n/a
Clay	-0.13	-0.09	**0.73**	1.1	-0.07	**-0.70**	1.0	-0.11	**0.70**	1.1
pH	0.27	**0.92**	-0.28	1.4	0.19	**0.90**	1.1	**0.84**	-0.53	1.7
P[(3)]	0.06	-0.06	**0.17**	1.5	**0.64**	0.27	1.4	*	*	n/a
K	0.51	0.47	**0.62**	2.8	**0.75**	0.12	1.1	**0.35**	0.11	1.2
Al	0.02	**-0.68**	0.04	1.0	-0.17	**-0.68**	1.1	-0.48	0.48	2.0
Ca	**0.78**	0.24	0.28	1.5	**0.59**	0.38	1.7	**0.86**	-0.09	1.0
Mg	**0.66**	0.51	-0.07	1.9	**0.82**	0.33	1.3	**0.56**	0.13	1.1
SAW	-0.13	0.24	**-0.67**	1.3	-0.41	0.41	2.0	-0.02	**-0.56**	1.0
Variance[(4)]										
Eigen	2.42	2.04	1.87		2.49	2.30		2.20	1.72	
Proportion	0.24	0.20	0.19		0.28	0.26		0.27	0.21	
Cumulative	0.24	0.44	0.63		0.28	0.53		0.27	0.49	
Explained	0.38	0.32	0.30		0.52	0.48		0.56	0.44	
Contribution	0.38	0.70	1.00		0.52	1.00		0.56	1.00	

[(1)]CSR, carbon stock regulation; SR, soil reaction; SF, soil fertility; SP, Soil physics; Com, communality, representing the proportion of each variable's variance explained by the extracted factors. [(2)]Yield, wheat yield; SOC, soil organic carbon stock; Clay, clay content; P, available phosphorus; K, exchangeable potassium; Ca, exchangeable calcium; Mg, exchangeable magnesium; Al, exchangeable aluminum; pH, soil pH; SAW, soil available water capacity. [(3)]* indicates variable excluded from the factor analysis due to KMO < 0.5. [(4)]Eigen, sum of squared loadings (eigenvalue) of each factor; Proportion, proportion of total variance explained by each factor; Cumulative, cumulative variance explained; Explained, contribution of each factor to total explained variance; Contribution, accumulated contribution of extracted factors.

Table 4. Multiple linear regression equations and the respective R^2 and Adjusted R^2 (p-value), with total organic carbon stock and wheat yield as dependent variables (Y), and soil variables as independent variables, for each of the three soil depths, in 12 farms studied, 2023.

Y	Soil depth (cm)	Regression equation[(1)]	R^2	Adjusted R^2
TOC	0–10	$Y = 3.48 \times 10^{-4} - 0.26 \bullet pH + 0.39 \bullet Al + 0.70 \bullet Ca + 0.44 \bullet Mg$	0.81	0.78 (< 0.001)
	10–20	$Y = -0.001 - 0.19 \bullet Clay - 0.42 \bullet pH + 0.66 \bullet Al + 0.61 \bullet Ca + 0.25 \bullet Mg$	0.80	0.77 (< 0.001)
	20–30	$Y = 3.96 \times 10^{-4} - 0.95 \bullet \mathrm{pH} + 0.87 \bullet Ca$	0.38	0.34 (< 0.001)
Yield	0–10	$Y = 9.22 \times 10^{-5} + 0.24 \bullet Clay + 0.53 \bullet K$	0.43	0.40 (< 0.001)
	10–20	$Y = 0.0007 + 0.48 \bullet TOC + 0.58 \bullet Clay + 0.28 \bullet P - 0.59 \bullet Al$	0.38	0.30 (0.004)
	20–30	$Y = 3.49 \times 10^{-4} + 0.42 \bullet Clay + 0.32 \bullet Mg$	0.27	0.23 (0.005)

[(1)]pH, soil pH; Al, exchangeable aluminum; Ca, exchangeable calcium; Mg, exchangeable magnesium; Clay, clay content; K, exchangeable potassium; TOC, total organic carbon stock; P, available phosphorus.

attributed to limited nutrient uptake in highly acidic or alkaline soils, affecting biomass production (Rahman et al., 2024). Furthermore, pH influences microbial activity and organic matter stabilization processes (Wang & Kuzyakov, 2024). Although aluminum is generally associated with toxicity, it was positively correlated with carbon stock in the two upper layers. Studies indicate that organic matter can form stable complexes with aluminum, promoting carbon sequestration (Vance et al., 2020). Nevertheless, high concentrations of aluminum remain detrimental to plant development and the deposition of organic residues in the soil.

Macronutrients exhibited distinct, depth-specific behaviors in both the factor analysis and regression models, explaining carbon stock and productivity in a non-uniform manner. Adequate availability and balance of phosphorus, potassium, calcium, and magnesium are essential for plant nutrition and optimal crop performance (Nadeem et al., 2018; Sharma et al., 2025). The observed variability in nutrient availability and their relationships with carbon and productivity reflects the different edaphoclimatic characteristics, management practices, and soil types across the 12 farms in this study.

The behavior of clay was relevant due to its negative effect on carbon stock in the 10–20 cm soil depth (Table 4). This contrasts with the general understanding that clay promotes the physical protection of organic matter from microbial decomposition through the formation of aggregates and organo-mineral complexes (Sarkar et al., 2018). However, at high concentrations, especially in poorly structured soils, clay may reduce aeration and water infiltration, limiting the biological activity required for the formation and stabilization of carbon in the soil (Cardoso et al., 2023). This effect contrasted with the productivity results, in which clay showed a positive association with grain yield across all soil layers.

The results from the 12 commercial farming areas provide insights into the technological level and real opportunities for increasing soil carbon stocks in Brazilian agriculture. These findings can support the development of protocols and the optimization of public policies for low-carbon agriculture, such as the Plan for Adaptation and Low Carbon Emission in Agriculture (ABC + Plan) (Brasil, 2021).

Despite its potential for high yields, wheat is subject to direct factors that limit its development, grain quality, and final productivity. Yield suppression

Table 5. Values of subindices soil conservation management quality index (SCMQI) estimations, and quality score for each farm studied (F1 to F12), for the crop seasons between 2020 and 2023, in the state of Paraná, Brazil. Results of descriptive statistics of the subindices and SCMQI.

Farm	Municipality	Subindice(1)					SCMQI	Score(2)
		CD	PLU	SWC	SFC	SSQ		
F1	Ipiranga	2.80	1.00	1.30	1.70	0.50	7.20	C
F2	Ipiranga	3.00	0.80	1.50	2.00	0.60	7.80	C
F3	Teixeira Soares	2.90	0.80	1.50	1.70	0.80	7.60	C
F4	Fernandes Pinheiro	1.90	0.80	1.50	1.30	0.50	6.00	D
F5	Irati	2.90	0.80	1.50	0.70	0.80	6.70	D
F6	Ponta Grossa	1.90	1.00	1.50	0.70	0.40	5.40	D
F7	Palmeira	1.90	0.80	1.50	1.70	0.50	6.40	D
F8	Palmeira	3.00	0.80	1.50	0.70	0.40	6.30	D
F9	Piraí do Sul	3.00	0.50	1.50	1.00	0.80	6.80	D
F10	Tibagi	3.00	0.80	1.50	1.30	0.40	7.00	C
F11	Imbituva	1.90	1.00	1.50	2.00	0.40	6.80	D
F12	Prudentópolis	1.90	1.00	1.50	0.70	0.60	5.60	D
Statistics	Mean	2.51	0.81	1.48	1.28	0.56	6.64	D
	Standard deviation	0.52	0.15	0.07	0.51	0.16	0.71	
	CV(%)	20.72	18.31	4.67	39.61	29.11	10.64	

(1)CD, crop diversification; PLU, profitable land use; SWC, soil and water conservation; SFC, soil fertility chemistry; SSQ, soil structural quality. (2)C, 7.0 ≤ SCMQI < 8.00, up to two indicators below critical level; and D, SCMQI < 7.0, requiring corrective actions and adjustments if the goal is to join or benefit from a potential soil conservation management improvement program.

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becomes more pronounced when the crop undergoes stress during critical development stages, often associated with abiotic factors, such as frost, excessive rainfall, and high relative humidity, as well as biotic factors, particularly fungal diseases (Cunha et al., 2009). Wheat yields on the evaluated farms showed significant variation (Table S6, Supplementary Material) (Santi, 2025a), with average yields ranging from 3,042 kg ha^{-1} (F4 and F12) to 4,620 kg ha^{-1} (F7). Factors such as excessive rainfall during the crop cycle, high temperatures during flowering, and disease incidence, especially Fusarium head blight (scab), were decisive in determining final yield and may have contributed to the lower yields observed, notably in 2023.

F1 demonstrated greater yield fluctuation, with a standard deviation of 604.8 kg ha^{-1}. Conversely, F9 showed the lowest variability (138.7 kg ha^{-1}) due to agronomic and environmental indicators identified in the factor analysis. These indicators, such as higher calcium and magnesium contents, improved pH balance favored associations between yield, potassium, phosphorus, and clay, suggesting a more stable and potentially sustainable production system.

Yield stability and the control of deleterious factors play a fundamental role in the context of climate change and the intensification of extreme climatic events in southern Brazil, such as excessive or insufficient rainfall and out-of-season frosts (IPCC, 2021). This study not only clarified the key drivers of wheat yield instability and supported the implementation of mitigation practices, but also advanced the understanding of soil carbon accumulation in relation to farm management practices. The findings offer insights that can be replicated with adaptations in similar agricultural contexts.

Eight out of the 12 farms analyzed were classified with a score D on the soil conservation management quality index (SCMQI). This result is mainly attributed to the subindices for soil and water conservation (SWC), soil fertility chemistry (SFC), and soil structural quality (SSQ), all of which presented values below the critical thresholds. The mean SWC subindex (n = 12) was 1.48, which represents roughly half of the maximum value (3.0) (Table 5). The primary factor for this low performance index of 49% (1.48/3.0) for SWC was the absence of mechanical practices to control surface runoff on crop fields, specifically the lack of agricultural terraces.

Despite the use of contour planting and the generally medium texture and moderate compaction of the soils, the absence of agricultural terraces on these farms increases the risk of water erosion during rainy years and reduces water retention and availability in the soil during drought years. Consequently, the resilience of agricultural activities under climate change scenarios is reduced.

Whereas the SFC subindex performance rose to 64%, chemical limitations persisted in the 0–20 cm soil depth, with pH values below 5.5 observed in either the 0–10 or 10–20 cm soil depth on five of the farms. The SFC subindex also showed the highest coefficient of variation, indicating that soil chemical fertility varies widely among the farms and needs to be corrected to enhance productivity.

The soil organic matter content was the factor that most affected the SSQ. These findings corroborate those of Amaral et al. (2025), who found similar subindices values for SWC, SFC, and SSQ in soils with aluminic characteristics. These soils were classified as Latossolos Vermelhos (Rhodic Ferralsols), Cambissolos Háplicos (Haplic Cambisols), and Nitossolos Vermelhos (Rhodic Nitisols), in the Serrana mesoregion of Santa Catarina state and the Campos de Cima da Serra region in Rio Grande do Sul state.

This study demonstrated that the wheat production systems on the 12 evaluated farms, located within a region that accounts for over 200,000 ha of wheat cultivation, exhibited considerable variability in soil fertility, structure, and acidity, which helps to explain differences in productivity and soil carbon stocks. Despite the adoption of conservation technologies, limitations persist in the composition of crop rotations and the overall quality of soil management, particularly in deeper layers where responses to interventions are more restricted. Therefore, enhancing crop diversification, correcting subsurface acidity, and improving fertility are essential steps to increase system resilience and promote soil carbon sequestration. The transition to low-carbon agriculture must be driven by integrated improvements in soil and crop management, with active farmer participation and support from public policies that promote the sustainable intensification of agricultural production systems.

Conclusions

1. On the studied farms, enhancing crop rotations is necessary to increase soil carbon sequestration, resulting in greater resilience to extreme climate events.

2. The factor analysis demonstrates that fertility, acidity, and physical properties shape soil patterns across the 12 farms.

3. The low predictive power of the regression models for productivity suggests that unmeasured factors, like climate and phytosanitary conditions, influence yield, highlighting the necessity of integrated soil fertility management to support productivity and carbon sequestration.

4. The subindices Soil and Water Conservation, Soil Fertility Chemistry, and Soil Structural Quality exhibit the lowest performances, thus they require prioritization in improvement programs for the wheat production systems in the studied region.

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Data available: research data are available in the Redape repository.

Declaration of use of AI technologies

No generative artificial intelligence (AI) was used in this study.

Conflict of interest statement

The authors declare no conflicts of interest.

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