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Limestone incorporation on the spatial variability of soil chemical attributes

Abstract – The objective of this work was to evaluate the spatial variability of soil chemical attributes at two depths, with and without limestone incorporation. The experiment was conducted in a banana orchard area in the municipality of Cristino Castro, in the state of Piauí, Brazil. The soil was classified as a Fluvisol. Samples were collected at the depths of 0.0–0.2 and 0.2–0.4 m at 21 georeferenced points both in the sites with and without limestone incorporation. The evaluated attributes were pH, phosphorus, potassium, calcium, magnesium, organic matter (OM), sum of bases (SB), cation exchange capacity (CEC), and base saturation (BS). A symmetric distribution of the chemical attributes was observed, with coefficients of variation greater than 30%, indicating a high spatial variability and reinforcing the need for site-specific soil management. Limestone incorporation influenced the semivariograms, evidencing spatial dependence at the two depths. The pH value ranged from 4.2 to 7.4 at the 0.2–0.4 m depth with limestone incorporation. Mechanical incorporation increased OM in the 0.0–0.2 m layer and elevated Ca^{2+}, Mg^{2+}, OM, SB, CEC and V% at both depths, improving soil fertility and promoting greater homogeneity of chemical attributes. In addition, K^+ distribution is heterogeneous, with a low availability in all treatments.

Index terms: geostatistics, soil depth, soil fertility.

Incorporação de calcário sobre a variabilidade espacial de atributos químicos do solo

Resumo – O objetivo deste trabalho foi avaliar a variabilidade espacial de atributos químicos do solo em duas profundidades, com e sem incorporação de calcário. O experimento foi conduzido em plantação de bananeira no município de Cristino Castro, no estado de Piauí, Brasil. O solo foi classificado como Neossolo Flúvico. As amostras foram coletadas a 0.00–0.20 e 0.20–0.40 m de profundidade em 21 pontos georeferenciados, tanto no local com incorporação de calcário como no sem. Os atributos avaliados foram pH, fósforo, potássio, cálcio, magnésio, matéria orgânica (OM), soma de bases (SB), capacidade de troca de cátions (CEC) e saturação por bases (V%). Observou-se distribuição simétrica dos atributos químicos, com coeficientes de variação superiores a 30%, o que indica elevada variabilidade espacial e reforça a necessidade de manejo específico do solo por local. A incorporação de calcário influenciou os semivariogramas, tendo evidenciado dependência espacial nas duas profundidades. O pH variou de 4.2 a 7.4 na profundidade de 0.2–0.4 m, com incorporação de calcário. A incorporação mecânica aumentou a OM na camada de 0.0–0.2 m e elevou os valores de Ca^{2+}, Mg^{2+}, OM, SB, CEC e V% em ambas as profundidades, tendo melhorado a fertilidade do solo e promovido maior homogeneidade dos atributos químicos. Além disso, a distribuição de K^+ é heterogênea, com baixa disponibilidade nos tratamentos.

Termos para indexação: geoestatística, profundidade do solo, fertilidade do solo.

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Introduction

The growing demand for food requires both higher crop yields and the space optimization of existing arable areas. High-fertility soils are essential for overcoming this challenge (Hemathilake & Gunathilake, 2022). Therefore, proper soil fertility management is crucial for achieving high yields, as it influences nutrient dynamics and availability (Al-Shammary et al., 2024).

Characterizing the spatial variability of soil chemical properties is a strategic tool for fertility management in agricultural systems, as it enables the identification of nutrient spatial distribution and the factors influencing their availability. Within precision agriculture, this approach supports the site-specific application of soil amendments and fertilizers, enhancing input-use efficiency, production system sustainability, and production cost rationalization (Santos Júnior et al., 2021; Plazas et al., 2025).

In this context, soil fertility maps have become essential tools for assessing spatial variability in soil attributes. This variability is influenced by several factors, among which the method of amendment application is prominent, as it directly affects nutrient distribution and availability (Oliveira et al., 2021; Matos et al., 2022).

Liming is a widely used practice to correct soil acidity, a primary factor limiting nutrient availability and crop development. The practice reduces aluminum and manganese toxicity alongside potential acidity (H+Al), increases base saturation (V%), and enhances the availability of nutrients such as calcium, magnesium, and phosphorus (Enesi et al., 2023; Klein et al., 2024). Consequently, it promotes root development, fertilizer use efficiency, and plant growth. These benefits tend to be more pronounced when lime is incorporated into the soil, as incorporation promotes a uniform distribution of the amendment throughout the soil profile, maximizing its effects and reducing spatial variability in fertility (Enesi et al., 2023).

Therefore, the efficiency of liming depends significantly on the method of application. While surface application without incorporation can result in corrections restricted to the topsoil, the incorporation tends to promote greater spatial homogeneity and improves soil nutrient availability, thereby providing better plant nutrition (Matos et al., 2025).

Despite advances in assessing the effects of liming on soil chemical properties, information regarding how limestone application influences the spatial variability of these attributes across different depths remains limited. Recent evidence indicates that limestone incorporation is more effective at correcting subsurface acidity, reducing chemical gradients throughout the soil profile and increasing productivity compared to surface application (Brum et al., 2026). However, further studies are needed to relate these changes to the spatial distribution of chemical attributes, thereby providing a basis for refining fertility management strategies in agricultural systems.

Understanding the spatial variability of soil chemical attributes, especially in areas with and without limestone incorporation, is crucial for helping farmers make assertive fertilization decisions. Adaptation to the specific needs of each area to address fertility limitations with greater precision ultimately enhances productivity and profitability (Barros et al., 2022).

The objective of this work was to evaluate the spatial variability of soil chemical attributes at two depths, with and without limestone incorporation.

Materials and Methods

The field study was conducted from 2016 to 2019 in a banana orchard located in the municipality of Cristino Castro, Piauí, Brazil (8°49'38"S latitude and 44°13'04"W at 223 m of altitude) (Figure 1). According to the Köppen classification, the local climate is Aw type, characterized by a dry winter and a hot, rainy summer, with a mean temperature of 27ºC and an average annual accumulated rainfall of 900 mm.

Soil sampling was conducted in an experimental area within a well-established banana (*Musa* spp.) orchard, composed of the Prata, Maçã, and Grand Naine cultivars. The soil in the area was classified as a Neossolo Flúvico, according to the Brazilian Soil Classification System (Santos et al., 2018), equivalent to a Fluvisol.

The 5 ha experimental area contained 42 georeferenced sampling points arranged in a 35×30 m regular grid, divided into two 2.5 ha subareas with 21 points each, that differed in the limestone application method performed in early 2016. Initially, the soil had 4.5 pH and 23% of bases saturation (V%). To correct acidity and raise V% to 60%, the liming requirement was calculated based on the V% criterion. In both subareas, a rate of 4 Mg ha^{-1} of

dolomitic limestone with a total relative neutralizing power of 92%, containing 24% CaO and 12% MgO, and a medium particle size of 0.30 to 0.84 mm was applied. In one subarea, limestone was surface-applied along planting rows without incorporation. In the other, limestone was mechanically incorporated at a depth of 0.30 m using a 32-inch disc harrow in a linear and uniform manner. As nutrient levels were below the crop requirements, fertilization followed the recommendations of Sousa & Lobato (2004), consisting of 0.2 kg of single superphosphate and 0.2 kg of monoammonium phosphate per planting hole at the time of planting, followed by monthly fertigation using a 20-00-20 formulation at 50 kg ha^{-1}.

In March 2019, when the orchard was three years old, soil samples were collected at the 21 georeferenced points in each subarea. At each point, five samples were collected at a distance of 0.50 m from the mother plant, and combined into a composite sample for depths of 0.00–0.20 and 0.20–0.40 m.

The samples were air-dried, sieved through a 2 mm mesh, and analyzed according to Teixeira et al. (2017). Evaluated attributes included: pH in water; P and K^+ extracted according to the Mehlich-1 method, and quantified by colorimetry and flame photometry, respectively; Ca^{2+} and Mg^{2+} extracted with 1 mol L^{-1} KCl and determined by atomic absorption spectrophotometry; and organic matter (OM) by the wet method. The sum of bases (SB), cation exchange capacity (CEC), and V% were calculated from K^+, Ca^{2+}, Mg^{2+}, and Al^{3+} concentrations.

The data were analyzed using descriptive statistics in Minitab software (Minitab LLC, State College, PA, USA), evaluating measures of central tendency and location, coefficient of variation (CV), asymmetry, kurtosis, maximum and minimum values, and amplitude. The Kolmogorov-Smirnov test was applied to verify the normality of the evaluated attributes. Additionally, Pearson's linear correlation analysis ($p<0.05$) was conducted following the classification proposed by Figueiredo Filho & Silva Júnior (2009).

To evaluate spatial dependence, semivariograms were fitted under the stationarity assumption of the intrinsic hypothesis. Theoretical models, specifically spherical, exponential, and Gaussian, were fitted using GS+ software to determine the optimal fit. Model selection was based on the sum of squared residuals, coefficient of determination (R^2), and correlation coefficient obtained through cross-validation (CVRC). Spatial variability of soil attributes was subsequently mapped using the kriging interpolation method according to the adjusted models, allowing the prediction of attribute values at unsampled locations using Surfer software (Golden Software, Colorado, USA).

The range and degree of spatial dependence (DSD) were determined using the nugget-to-sill ratio, and classified according to Cambardella et al. (1994). Additionally, principal component analysis (PCA) was performed to identify the main variation patterns

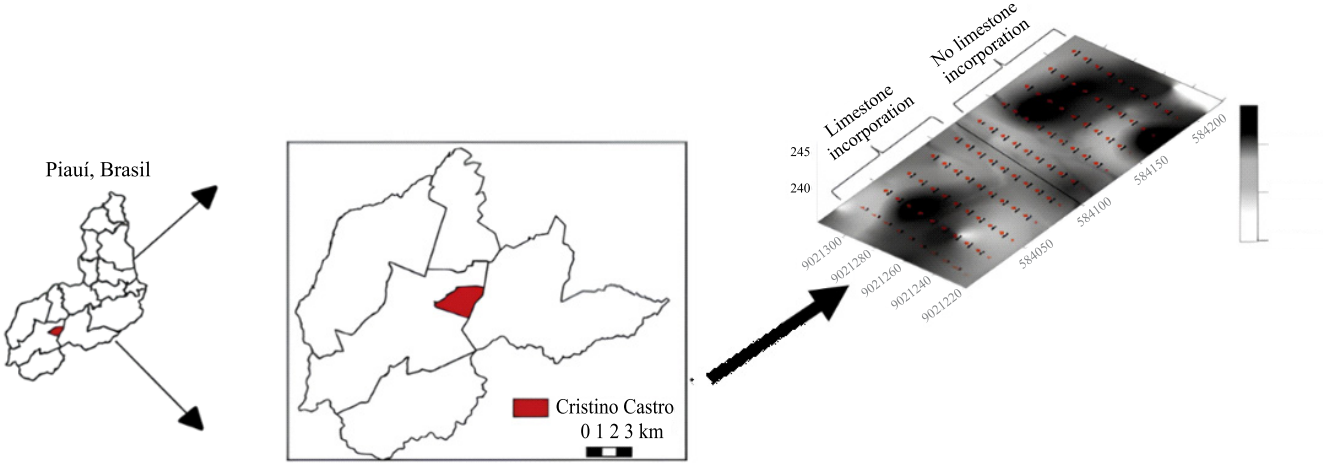

Figure 1. Location and geographical position of the study areas, in the municipality of Cristino Castro, in the state of Piauí, Brazil.

among soil chemical properties and to verify the association between limestone application methods and the joint distribution of the evaluated attributes. The analysis was conducted using PAST software, version 4.17 (Hammer et al., 2001).

Results and Discussion

Descriptive analysis of soil chemical attributes across both depths and limestone application methods revealed a predominantly symmetrical distribution, with values close to the mean and median. The symmetry of the data distribution, measured by asymmetry, indicated that positive asymmetry predominated in relation to the data normal distribution (Table 1).

Negative kurtosis prevailed among the evaluated chemical attributes, indicating that the data contained fewer extreme outliers than the normal distribution. For most variables, the values were below 3, confirming the presence of fewer outliers. According to Oliveira et al. (2021), while the ideal kurtosis value is zero, values ranging from +2 to -2 are still within the acceptable range.

With the incorporation of limestone, the kurtosis values departed further from the normal distribution for K^+, Ca^{2+} and SB at the 0.00–0.20 m depth, as well as P, K^+, Ca^{2+}, Mg^{2+} and SB at the 0.20–0.40 m depth. In the unincorporated area, the attributes furthest from normality were Ca^{2+} and SB at the 0.00–0.20 m depth, alongside P, Ca^{2+} and Mg^{2+} at 0.00–0.20 m depth (Table 1). Studies such as Borges et al. (2022) confirm that different forms of limestone application can effectively increase Ca^{2+} content, V% and other chemical variables of soil fertility, especially in the superficial layers of the soil.

Regardless of application method and soil depth, pH and Ca^{2+} consistently exhibited the lowest and highest CVs, respectively. At the 0.20–0.40 m depth, a CV value of 133.62% was observed for P with incorporated limestone, and 129.66% without incorporation, though neither exceed the CV value of 169.18% recorded for Mg^{2+} in the unincorporated treatment (Table1).

Except for pH, all soil chemical attributes showed coefficients of variation higher than 30% regardless of treatment factors. This high variability may be associated with various factors such as soil formation, type of management, topography and agricultural practices (Agegnehu et al., 2023). Thus, differences in soil amendment strategies likely served as a main driver of this variability.

Pearson's correlation indicated positive and significant interactions for most variables ($p<0.01$ and $p<0.05$) across both depths and limestone application methods. These significant interactions occurred more frequently when limestone was incorporated in the soil (Table 2).

With limestone incorporation, significant positive correlations were found at the 0.00–0.20 m depth were observed between P and pH; Ca^{2+} with pH, OM, P and K^+; SB with pH, OM, P, K^+, Ca^{2+} and Mg^{2+}; CEC with OM, Ca^{2+}, Mg^{2+} and SB; and V% with pH, P, Ca^{2+}, Mg^{2+} and SB. At the 0.20–0.40 m depth, significant positive correlations occurred between: Ca with OM and K; Mg^{2+} with OM and Ca; SB with OM, K^+, Ca^{2+} and Mg^{2+}; CEC with pH, OM, Ca^{2+}, Mg^{2+} and SB; and V% with K^+, Mg^{2+} and SB.

The incorporation of limestone to a depth of 0.20 m increased pH, Ca^{2+}, Mg^{2+} and SB, thereby increasing the V%. These results corroborate the findings of Reis et al. (2021) who assessed the chemical attributes of the soil under different management systems and observed that pH correlated with cations and SB, indicating interdependence among these chemical attributes.

At a depth of 0.40 meters, increased Ca^{2+} availability resulting from soil amendment application helped improve soil structure, thereby promoting microbiological activity, which in turn increased OM mineralization and the availability of other nutrients. Rowley et al. (2020) confirmed this dynamic in a study that linked calcium to soil organic carbon stock.

The results indicate that limestone incorporation significantly influenced the semivariogram variables of the soil chemical attributes at both depths, indicating that these variables exhibited spatial dependence (Table 3). Gaussian and spherical models were the best fits for most of the variables. The main exceptions were Ca^{2+} and V% at the 0.20–0.40 m depth under both treatments, in which the exponential model was the best fit.

According to Bernardi et al. (2016), Gaussian and spherical models best describe the behavior of soil chemical attributes. The Gaussian model indicates that the value distribution tends towards a normal distribution, with low variation. This premise was confirmed in Table 1, which indicated a normal

Table 1. Descriptive analysis of the soil chemical attributes at depths of 0.00–0.20 and 0.20–0.40 m in areas with (WI) and without (WOI) limestone incorporation, in the municipality of Cristino Castro, in the state of Piauí, Brazil.

Attribute[(1)]	Area	Mean	Median	Minimum	Maximum	Skewness	Kurtosis	CV (%)
Depth 0.00–0.20 m								
pH	WI	5.77	5.89	4.96	7.07	0.35	0.56	8.97
	WOI	5.13	5.04	4.35	6.44	0.98	0.64	10.05
OM	WI	5.60	5.25	1.55	11.42	0.72	-0.33	49.70
	WOI	4.39	4.55	1.73	7.37	0.43	1.36	29.10
P	WI	8.45	8.18	1.95	21.93	0.82	-0.41	72.54
	WOI	11.29	7.07	1.23	26.67	0.69	-1.15	77.07
K^+	WI	0.08	0.06	0.02	0.26	1.96	3.81	75.38
	WOI	0.12	0.11	0.05	0.31	1.41	1.30	57.01
Ca^{2+}	WI	1.67	1.25	0.41	7.04	2.72	9.19	86.74
	WOI	0.43	0.32	0.03	2.22	2.65	8.43	115.44
Mg^{2+}	WI	0.41	0.43	0.03	0.83	0.07	-0.76	55.78
	WOI	0.18	0.16	0.06	0.44	1.02	0.48	53.80
SB	WI	2.19	1.77	0.64	7.79	2.37	7.16	72.91
	WOI	0.75	0.63	0.27	2.51	2.22	6.36	68.03
CEC	WI	3.97	3.13	1.36	9.76	1.58	1.84	54.42
	WOI	2.96	2.82	1.96	5.19	1.01	0.82	29.57
V (%)	WI	53.34	50.66	25.23	92.38	0.53	0.49	29.56
	WOI	25.52	22.41	8.73	54.84	0.93	0.22	53.57
Depth 0.20–0.40 m								
pH	WI	5.82	5.93	4.39	7.46	0.04	0.86	12.41
	WOI	4.75	4.72	4.24	6.05	1.13	1.51	9.74
OM	WI	2.17	1.55	0.14	7.90	1.40	2.58	89.13
	WOI	2.79	2.43	1.02	5.43	0.67	-0.38	45.36
P	WI	4.85	2.27	0.91	27.51	2.60	7.17	133.62
	WOI	5.07	2.08	0.78	27.77	2.66	7.35	129.66
K^+	WI	0.06	0.05	0.01	0.31	2.92	9.32	103.88
	WOI	0.09	0.07	0.05	0.25	1.53	2.77	52.00
Ca^{2+}	WI	0.85	0.48	0.05	3.84	2.00	4.80	107.70
	WOI	0.25	0.15	0.01	1.07	1.79	3.06	109.87
Mg^{2+}	WI	0.20	0.13	0.00	0.68	1.24	1.11	85.77
	WOI	0.27	0.08	0.03	1.50	2.18	3.17	169.18
SB	WI	1.13	0.67	0.23	4.43	1.72	3.19	95.60
	WOI	0.63	0.36	0.20	1.85	1.25	0.04	87.53
CEC	WI	2.79	2.01	1.00	8.42	1.77	2.26	72.64
	WOI	2.93	3.09	1.49	4.77	-0.10	-0.55	30.24
V (%)	WI	37.48	34.97	9.95	87.33	0.91	0.78	51.31
	WOI	19.97	15.07	6.72	47.84	1.21	0.11	66.35

[(1)] WI, with limestone incorporation; WOI, no limestone incorporation; OM, organic matter; SB,sum of bases; CEC, cation exchange capacity; V%, base saturation; Max, maximum values; Min, minimum values; CV, coefficient of variation.

data distribution with moderate variation, that is, a smoothing of the values along the spatial distribution. Conversely, the spherical model indicates a more erratic distribution that is a more abrupt value distribution over a given distance.

Areas with limestone incorporation showed a lower nugget effect and higher sill, indicating reduced short-range spatial variability and higher total spatial variability. This suggests a uniform distribution of chemical attributes in areas where limestone was incorporated.

The adjusted semivariogram models exhibit varying DSD between the areas. Furthermore, the R^2 and CVRC analysis reveals that the models successfully explain the variability of the data, displaying higher

Table 2. Pearson linear correlation for the soil chemical attributes at depths of 0.0–0.20 and 0.20–0.40 m in areas with and without limestone incorporation, in the municipality of Cristino Castro, in the state of Piauí, Brazil.

Attribute	Area	Depth 0.00–0.20 m[(1)]							
		pH	OM	P	K^+	Ca^{2+}	Mg^{2+}	SB	CEC
OM	WI	-0.1							
	WOI	0.0							
P	WI	0.5*	0.02						
	WOI	0.2	-0.2						
K^+	WI	0.2	0.2	0.4					
	WOI	-0.1	0.2	-0.01					
Ca^{2+}	WI	0.4*	0.6**	0.5**	0.5*				
	WOI	0.3	0.2	0.09	-0.2				
Mg^{2+}	WI	0.2	0.4	0.09	-0.1	0.4			
	WOI	0.7**	0.3	0.3	0.2	0.1			
SB	WI	0.4*	0.6**	0.5**	0.5*	0.9**	0.5*		
	WOI	0.4	0.3	0.1	-0.2	0.9**	0.4		
CEC	WI	0.06	0.8*	0.1	0.2	0.8**	0.5**	0.8**	
	WOI	-0.3	0.5*	-0.2	0.1	0.5**	-0.07	0.5*	
V%	WI	0.7**	0.08	0.6**	0.3	0.6**	0.4*	0.6**	0.2
	WOI	0.8**	0.06	0.3	-0.1	0.7**	0.6*	0.7**	-0.02
		Depth 0.20–0.40 m							
		pH	OM	P	K^+	Ca^{2+}	Mg^{2+}	SB	CEC
OM	WI	-0.3							
	WOI	-0.1							
P	WI	0.08	-0.3						
	WOI	0.09	-0.05						
K^+	WI	0.3	0.1	0.3					
	WOI	-0.2	-0.03	0.01					
Ca^{2+}	WI	0.01	0.5*	-0.0	0.6**				
	WOI	0.06	0.2	0.5	0.3				
Mg^{2+}	WI	-0.4	0.4*	0.2	0.2	0.6**			
	WOI	-0.1	-0.3	-0.09	-0.07	0.04			
SB	WI	-0.04	0.5*	0.06	0.6**	0.9**	0.6**		
	WOI	-0.07	-0.1	0.1	0.1	0.5*	0.8**		
CEC	WI	-0.5**	0.8**	-0.1	0.2	0.7**	0.7**	0.7**	
	WOI	-0.5*	0.3	0.01	0.4	0.4*	0.4*	0.6**	
V%	WI	0.38	0.06	0.4	0.6**	0.7	0.4*	0.7**	0.2
	WOI	0.1	-0.2	0.1	0.1	0.5*	0.8**	0.9**	0.4*

[(1)]WI, with limestone incorporation, WOI, without limestone incorporation; OM, organic matter; SB, sum of bases; CEC, cation exchange capacity; V%, base saturation. * and ** Significant by the F test at $p<0.05$ and $p<0.01$, respectively.

Table 3. Models and semivariogram parameters of the chemical attributes at depths of 0.0–0.20 and 0.20–0.40 m in areas with and without limestone incorporation, in the municipality of Cristino Castro, in the state of Piauí, Brazil.

Attribute[(1)]	Area	Models	C_0	$C_0 + C_1$	DSD	Range (m)	R^2	CVRC	
								b	a
Depth 0.00–0.20 m									
pH	WI	Gaussian	0.0001	0.2052	0.05	74.47	0.72	1.35	-2.0
	WOI	Gaussian	0.001	0.364	0.27	92.49	0.93	-0.21	6.21
OM	WI	Gaussian	0.01	9.58	0.10	85.39	0.90	-7.33	43.88
	WOI	Spherical	0.111	0.667	16.64	93.6	0.90	1.09	-0.42
P	WI	Spherical	21.49	48.78	44.05	92.6	1.00	1.07	-1.12
	WOI	Gaussian	20.5	123.5	16.60	104.26	0.98	0.78	1.97
K^+	WI	Spherical	0.000001	0.0023	0.04	47.3	0.32	0.29	0.05
	WOI	Gaussian	0.00001	0.00336	0.30	55.94	0.66	-12.55	1.51
Ca^{2+}	WI	Gaussian	0.001	0.948	0.11	95.78	0.80	-4.34	7.9
	WOI	Gaussian	0.0001	0.053	0.19	85.9	0.83	-10.61	3.3
Mg^{2+}	WI	Gaussian	0.00001	0.0383	0.03	61.48	0.48	-8.41	3.42
	WOI	Gaussian	0.00001	0.00736	0.14	49.36	0.75	-5.84	1.18
SB	WI	Gaussian	0.001	1.217	0.08	83.65	0.69	-6.84	15.67
	WOI	Gaussian	0.0001	0.0899	0.11	69.97	0.69	-8.55	6.06
CEC	WI	Gaussian	0.01	7.815	0.13	97.51	0.96	-0.04	4.15
	WOI	Spherical	0.409	0.819	49.94	81.4	0.97	0.4	1.77
V%	WI	Gaussian	0.1	198.2	0.05	49.01	0.96	-12.53	704.17
	WOI	Gaussian	0.1	227.2	0.04	74.65	0.90	-7.27	204.83
Depth 0.20–0.40 m									
pH	WI	Spherical	0.001	0.552	0.18	82	0.88	0.99	0.03
	WOI	Spherical	0.0138	0.2096	6.58	77.4	0.99	0.86	0.65
OM	WI	Spherical	2.213	4.427	49.99	75	0.32	0.88	0.26
	WOI	Spherical	0.612	1.753	34.91	91.4	0.81	1.11	-0.27
P	WI	Gaussian	0.01	18.23	0.05	86.94	0.81	-14.56	62.04
	WOI	Spherical	2.74	6.912	39.64	87.9	0.54	0.58	1.34
K^+	WI	Gaussian	0.000001	0.000375	0.27	58.02	0.38	-10.32	0.5
	WOI	Gaussian	0.00001	0.001682	0.59	62	0.87	-6.09	0.66
Ca^{2+}	WI	Exponential	0.001	0.626	0.16	169.8	0.87	-0.62	1.08
	WOI	Gaussian	0.0001	0.05	0.20	65.99	0.82	-9.85	2.38
Mg^{2+}	WI	Gaussian	0.0001	0.0394	0.25	69.97	0.76	-3.89	1.08
	WOI	Gaussian	0.0001	0.0678	0.15	55.94	0.34	-16.41	2.91
SB	WI	Spherical	0.573	1.481	38.69	82.5	0.54	0.96	-0.03
	WOI	Spherical	0.0001	0.1252	0.08	47.8	0.49	2.9	-0.92
CEC	WI	Gaussian	0.01	5.426	0.18	65.29	0.92	-12.49	40.61
	WOI	Spherical	0.363	0.933	38.91	76.8	0.48	1.06	-0.23
V%	WI	Gaussian	0.1	252.5	0.04	52.13	0.59	-14.46	557.19
	WOI	Exponential	0.3	42.78	0.70	47.4	0.10	-16.39	251.98

[(1)] WI, with limestone incorporation, WOI, without limestone incorporation; OM, organic matter; SB,sum of bases; CEC, cation exchange capacity; V%, base saturation; C_0, nugget effect; C_0+C_1, sill; DSD, degree of spatial dependence; R^2, coefficient of determination of the model; CVRC, cross-validation regression coefficient; a, intercept; b, slope.

R^2 and CVRC varying according to the variable and soil depth.

Akpan et al. (2025) reported different DSD across different soil attributes, such as OM and pH. Semivariogram analyses reveal weak to strong levels of DSD, indicating the extent of spatial correlation within soil attributes. In addition, the choice of the semivariogram model is critical, as it influences the accuracy of spatial variability and mapping (Obroślak & Dorozhynskyy, 2017).

In limestone incorporated area, the range values at the 0.00–0.20 m depth varied from 47.3 m for potassium to 97.51 m for CEC, whereas at the 0.20–0.40 m depth the values were 58.2 m for potassium to 169.8 m for calcium. In the area without limestone incorporation, the values ranged from 49.36 m for Mg^{2+} to 104.26 m for P at 0.00–0.20 m depth, and from 47 m for SB and V% to 91.4 m for OM at 0.20-0.40 m depth. The spatial range represents the maximum distance in which sample points are spatially correlated; thus, a larger range indicates spatial continuity over greater distances (Vogado et al., 2020). Therefore, the results of this study show that when the corrective was incorporated, Ca^{2+} and SB were distributed more homogeneously, regardless of depth, but K^+ was distributed more heterogeneously.

The K^+ is a mobile nutrient in the soil; however, its movement can be influenced by several factors, including the way the soil amendment is incorporated into the soil texture (Liu et al., 2020). As demonstrated by the semivariograms and spatial distribution maps (Figures 2 and 3), if the soil amendment significantly alters soil pH, it can affect the solubility and adsorption of potassium, due to the variable binding to clay and OM (Liu et al., 2020), resulting in a less uniform distribution.

Soil pH ranged from 4.2 to 7.4 across all depths and limestone application methods. However, it can be observed that the incorporation of limestone led to a pH ranging from 5.0 to 5.8 at both depths. Acidity neutralization was greater at the 0.20-0.40 m depth layer under incorporation demonstrating the effectiveness of this practice in mitigating subsoil acidity. Azam & Gazey (2021) observed that the application of limestone in surface layers without incorporation delays pH increase in deeper layers of the soil, highlighting that the deep incorporation of limestone can have lasting and more significant effects on soil quality improvement, as it facilitates uniform distribution of limestone and accelerates acidity neutralization.

By raising soil pH, limestone creates a favorable environment for soil microbial activity, contributing to OM accumulation in incorporated areas. Although OM values decreased with depth, values at 0.00–0.20 m reached a maximum value of 9.5 g kg^{-1}, with values around 3.5 g kg^{-1} predominating in this area and at this depth. In addition, calcium carbonate supplied by liming can contribute to the accumulation of organic carbon in the soil, influencing the chemical structure and microbial communities, thereby promoting OM increase in the surface layers (Dou et al., 2023).

Unlike OM, P displayed contrasting depth-distribution trends between management practices. In the 0.00–0.20 m layer, availability was higher when the soil improver was not incorporated, whereas higher P levels occurred in the 0.20–0.40 m depth layer when limestone was incorporated. Following the interpretation of Ribeiro et al. (1999) P availability was categorized as very low at the 0.20–0.40 m depth, but reached a good status at the 0.00–0.20 m depth when limestone was applied without incorporation.

Despite phosphate fertilization carried out in the areas, the P semivariogram clearly demonstrate the low mobility of this nutrient in the soil, since its availability decreased from the depth of 0.00–0.20 m to 0.20–0.40 m. This reduction was most prominent under surface liming without incorporation, where P concentrations declined by nearly 70% from topsoil to the deeper soil horizon (Figure 2).

Limestone incorporation played a crucial role in increasing soil pH, which in turn reduced P fixation and increased its availability, as already observed in the research by Corbett et al. (2022), since the practice of liming reduces undesirable metal cations associated with P fixation, such as Al and Fe. In addition, other studies state that the type of limestone used influences the increase in P availability (Fan et al., 2022), whereas in the present study, dolomitic limestone was used. Notably, Fan et al. (2022) demonstrated that dolomitic limestone was more effective than $CaCO_3$ in increasing P availability, reducing fixation, and increasing the fraction of labile P in the soil.

K^+ exhibited a heterogeneous spatial distribution regardless of depth and application method. Furthermore, according to the soil fertility classification of Ribeiro et al. (1999), K^+ levels were

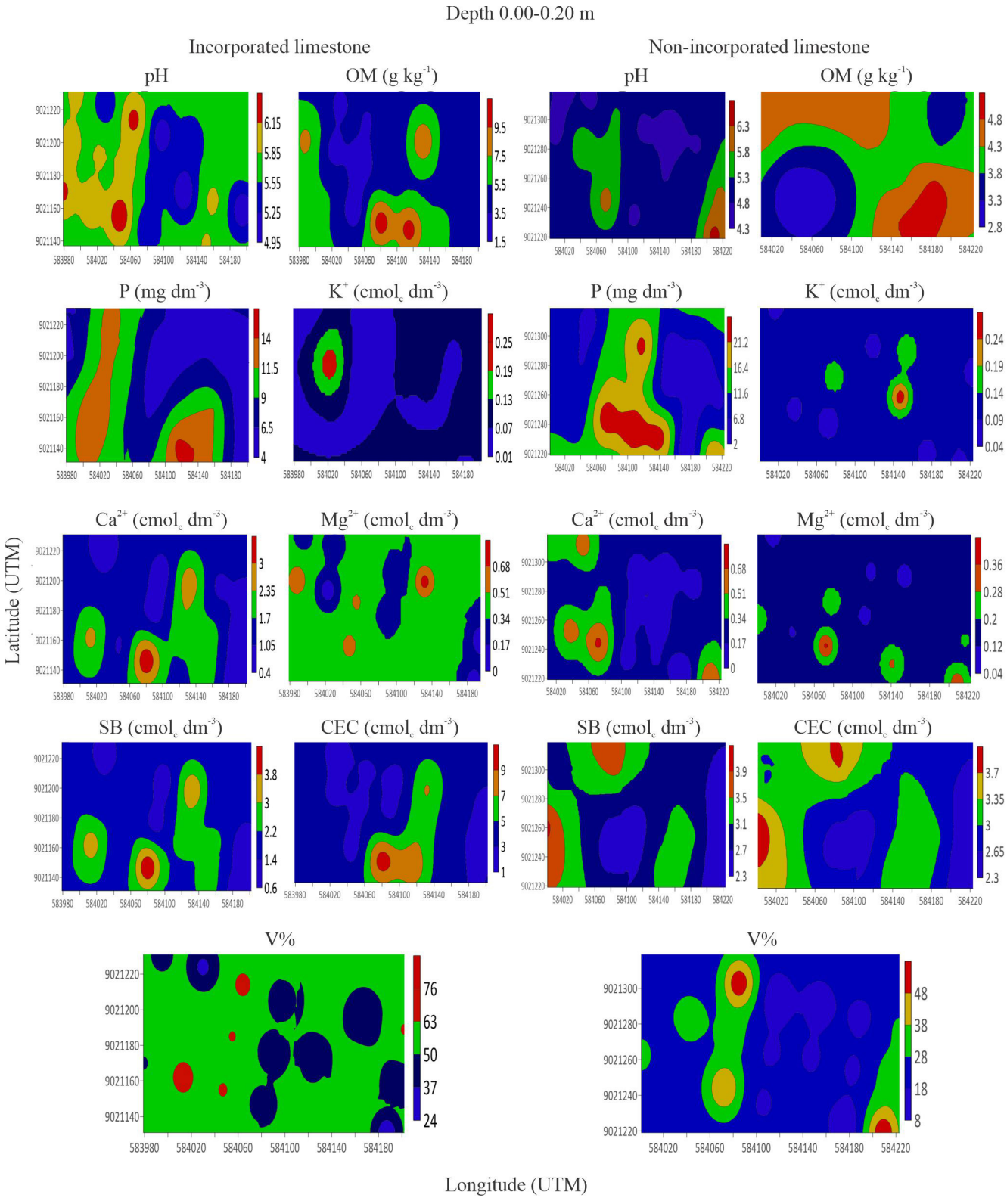

Figure 2. Spatial distribution of soil chemical attributes at a depth of 0.00–0.20 m in areas with and without limestone incorporation, in the municipality of Cristino Castro, in the state of Piauí, Brazil.

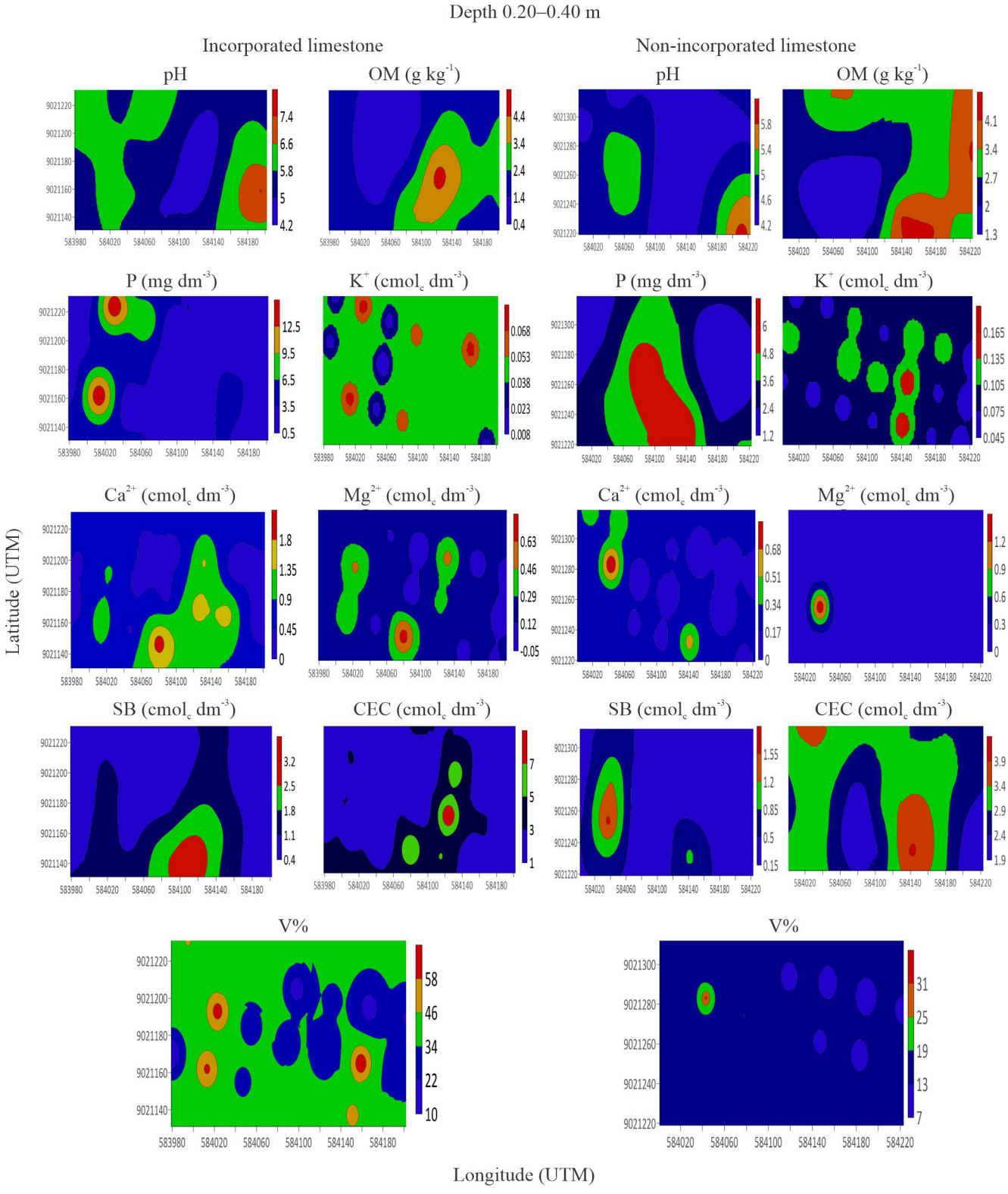

Figure 3. Spatial distribution of soil chemical attributes at a depth of 0.20–0.40 m in areas with and without limestone incorporation, in the municipality of Cristino Castro, in the state of Piauí, Brazil.

categorized as low, probably due to the soil sandy texture, which favors K^+ loss through leaching. These vertical variations align with findings by Khushboo et al. (2020), who demonstrated that soil K^+ content varies significantly at different depths and land uses, with distinct patterns at depths of 0.00–0.20 m and 0.20–0.40 m.

Limestone incorporation increased the levels of Ca^{2+} and Mg^{2+}, SB, CEC and V%, thereby improving soil fertility across both evaluated depths. This strategy favors nutrient retention and availability, providing suitable conditions for plant growth, as reported by Borges et al. (2022).

PCA explained 63.9% of the total data variability, with 45.9% attributed to PC1 and 18.31% to PC2 (Figure 4). Along PCA 1, the attributes pH, Ca^{2+}, Mg^{2+}, SB, CEC, and V% exhibited a strong positive correlation, being pronounced in samples from the limestone incorporated area. This result indicates that limestone incorporation contributes to greater homogeneity and nutrient availability, corroborating the findings of Matos et al. (2025), who highlighted the efficiency of the method in increasing the availability of essential nutrient availability for plant development.

PCA 2 was mainly associated with variations in P and K^+ contents, which showed greater availability in the area without limestone incorporation across both depths. The pH increase caused by limestone incorporation can reduce P availability by favoring the formation of less soluble calcium phosphates and altering P forms in acidic soils (Holland et al., 2024). Regarding K^+, surface application tends to concentrate the nutrient in the upper layer, where root activity is higher, whereas limestone incorporation redistributes K^+ along the soil profile, decreasing its surface availability (Han et al., 2023).

The proximity of the variables within the PCA quadrants reflects the correlations observed in the Pearson analysis (Table 2). This analysis confirms that limestone incorporation promoted greater uniformity and positive interactions among pH, Ca^{2+}, Mg^{2+}, SB, CEC, and V%, whereas surface application resulted in higher spatial variability and higher concentrations of P and K^+.

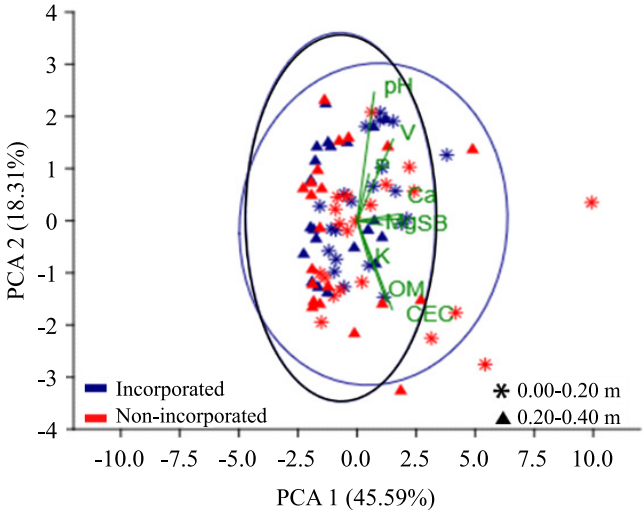

Figure 4. Biplot of Principal Component Analysis showing the relationship between soil chemical attributes and limestone application methods.

Conclusions

1. Limestone incorporation is more efficient than surface application for correcting soil acidity, promoting higher pH values and greater uniformity of chemical attributes, especially in the 0.20–0.40 m layer.
2. Limestone incorporation reduced the spatial variability of soil chemical attributes, promoting a more homogeneous distribution of nutrients and contributing to efficient fertility management.
3. Under the conditions of this study, limestone incorporation proved to be the most suitable strategy for improving soil chemical quality.

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

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The authors declare no conflicts of interest.

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