PAB Pesquisa Agropecuária Brasileira 60 years

Soil Science/ Original Article

ISSN 1678-3921

Journal homepage: www.embrapa.br/pab

For manuscript submission and journal contents, access: www.scielo.br/pab

Bioturbation as a promoter of limestone migration in soil

Abstract – The objective of this work was to evaluate the potential of roots and earthworms as bioturbation agents for the migration of limestone particles in soil under a confined pot system. The experiment was carried out in a greenhouse, using a completely randomized, two-factorial design with four replicates across the total of 24 experimental units. The factors comprised three depths (0-5 cm; 5-10 cm; 10-15 cm) and eight soil, limestone, and bioturbation agents combinations: autoclaved soil with limestone; natural soil; natural soil with limestone; natural soil with earthworms; natural soil with millet roots; natural soil with limestone and earthworms; natural soil with limestone and millet roots; natural soil with limestone, earthworms and millet roots. Soil bulk density, porosity, and total chemical and mineralogical analysis were performed to determine potential limestone particle migration in depth. Earthworm abundance and biomass as well as root density across layers were quantified. Pearl millet root development improved soil physical attributes by reducing bulk density and increasing total porosity, while earthworms promoted biogenic bioturbation through the active ingestion and deposition of applied calcite and dolomite.

Index terms: calcite, dolomite earthworms, fasciculated roots, mineralogy.

Bioturbação como promotor da migração de calcário no solo

Resumo – O objetivo deste trabalho foi avaliar o potencial das raízes e das minhocas como agentes de bioturbação para a movimentação de partículas de calcário no solo confinado em vasos. O experimento foi conduzido em casa de vegetação, em delineamento inteiramente casualizado, em esquema bifatorial, com quatro repetições e 24 tratamentos no total. Os fatores consideram três profundidades (0-5 cm; 5-10 cm; 10-15 cm) e oito combinações de solo, calcário e agentes de bioturbação: solo autoclavado com calcário; solo natural; solo natural com calcário; solo natural com minhocas; solo natural com raízes de milheto; solo natural com calcário e minhocas; solo natural com calcário e raízes de milheto; solo natural com calcário, minhocas e raízes de milheto. Foram realizadas análises de densidade do solo, porosidade, química total e análises mineralógicas para determinar a possível migração de partículas de calcário em profundidade. A abundância e a biomassa de minhocas, além da densidade de raízes em diferentes camadas do solo foram quantificadas. O desenvolvimento da raiz de milheto melhorou atributos físicos do solo por meio da redução da densidade e aumento da porosidade, enquanto as minhocas promoveram a bioturbação ao ingerirem e depositarem a calcita e dolomita aplicadas ao solo.

Termos para indexação: calcita, dolomita, minhocas, raízes fasciculadas, mineralogia.

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Received
November 07, 2025

Accepted
July 08, 2026

How to cite
CASSEL, J.L.; PETRY, C.; CHIOMENTO, J.L.T.; BORTOLUZZI, E.C. Bioturbation as a promoter of limestone migration in soil. **Pesquisa Agropecuária Brasileira**, v.61, e04304, 2026. DOI: https://doi.org/10.1590/S1678-3921.pab2026.v61.04304.

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Introduction

The efficiency of liming depends heavily on soil management. When soil is subjected to mechanical turnover, the deep distribution of the acidity corrective is facilitated. However, with the implementation of the no-tillage system (NTS), limestone began to be applied and maintained on the soil surface (Rheinheimer et al., 2024). Limestone is a material composed of calcite and dolomite (Bortoluzzi et al., 2022) characterized by low solubility and low migration in the soil profile (Borges et al., 2022; Rheinheimer et al., 2024). This limits acidity correction in depth, especially in areas featuring chemical stratification in the A horizon (Tiecher et al., 2016; Rheinheimer et al., 2024). Over the years, this scenario has created stratified layers of pH and other chemical properties within the soil profile (Borges et al., 2022). Therefore, the challenge in NTS is to implement management strategies that promote limestone migration through the soil profile.

Bioturbation refers to the capacity of biological agents to move and mix particles among soil layers through feeding, burrowing, and foraging (Jouquet et al., 2006; Aquino et al., 2017; Michel et al., 2022). The presence of earthworms, larvae, and other organisms can improve soil aggregate structure and stimulate the formation of macropores or biopores. Thus, soil biodiversity combined with crop rotation can promote both permanent biopore creation and active soil bioturbation (Dudas et al., 2023). The creation of these biopores — continuous and interconnected channels in the soil formed by plant roots and macrofauna, such as earthworms and insects — favors changes in the soil profile (Wang et al., 2024), that can facilitate the downward migration of limestone particles. In addition, the construction of biogenic structures, such as tunnels, channels, pores, aggregates, and coprolites, serves as a primary mechanism for particle movement along the surface horizon (Vidal et al., 2023).

Studies associating the combined effects of roots and earthworms on nutrient cycling and soil pH correction remain limited (Vidal et al., 2023). Generally, the activities of these organisms have effects on biogeochemical cycles, such as carbon cycling, with consequences on plant growth, soil structuring, and microbial interactions (Ratsiatosika et al., 2024). For example, when feeding on soil particles on the surface, earthworms can transport and deposit them at depth in the form of coprolites. This process facilitates the displacement of minerals, nutrients, and other particles (Pelosi et al., 2024), thereby promoting biological incorporation of surface-applied correctives. Furthermore, earthworm bioturbation is known to influence the movement of mycorrhizae, microplastics, biochar, and other minerals (Baskar et al., 2023; Pelosi et al., 2024). In addition, earthworms produce calcium carbonate granules, which have soil acidity correction properties (Vidal et al., 2023).

The earthworm species *Eisenia fetida*, an epigeic organism, is one of the best-known species due to its ease of cultivation in pots, especially for composting, and its broad utility as a test organism. Conversely, endogeic or anecic earthworms inhabit deeper soil horizons and create larger networks of macropores (Vidal et al., 2023). However, they are less suitable for cultivation in controlled environments due to spatial limitations in experimental pots.

The cultivation of cover crops aimed at mitigating soil degradation via the root system is a common practice in NTS, primarily to support conservation practices such as increasing organic matter, decompacting soil, and preventing erosion. Millet (*Pennisetum glaucum* R.Br.) is a grass species resistant to climatic adversities. Due to its robust root system, it is widely cultivated to provide soil cover and serve other purposes (Mukherjee et al., 2025). Ultimately, the pores produced by millet roots serve as a channel that facilitates particle migration between soil horizons.

The objective of this work was to evaluate the potential of roots and earthworms as bioturbation agents for the migration of limestone particles in soil under a confined pot system.

Materials and Methods

The experiment was conducted from December 2023 to June 2024, in the municipality of Passo Fundo, in the state of Rio Grande do Sul (RS), Brazil (28º15'46"S; 52º24'24"W). The study was carried out in a 90 m^2 greenhouse with a semicircular roof oriented in a northwest-southeast direction. The galvanized steel structure of the greenhouse was

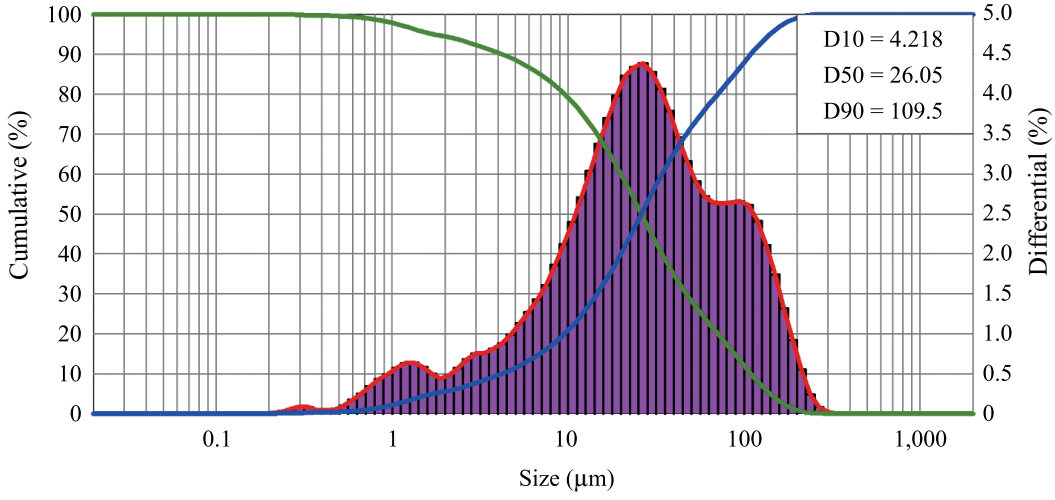
covered with a 150 µm low-density polyethylene film containing an anti-ultraviolet additive, while the sides were covered with anti-aphid mesh.

The soil used in the experiment was collected from the A horizon of a Latossolo Vermelho [Rhodic Ferralsol (IUSS Working Group WRB, 2022)]. The soil was analyzed to determine its active and potential acidity, which served as the basis for the subsequent limestone application recommendation (Tedesco et al., 1995).

The experiment was arranged in a two-factor completely randomized design with four replicates, evaluating a total of 24 treatments. The factors consisted of three soil depths: 0-5 cm; 5-10 cm; 10-15 cm, and eight distinct soil managements: natural soil (NS); autoclaved soil with limestone (AS + L); natural soil with limestone (NS + L); natural soil with limestone and earthworms (NS + L + E); natural soil with limestone and roots (NS + L + R); natural soil with limestone, roots, and earthworms (NS + L + R + E); natural soil with roots (NS + R); and natural soil with earthworms (NS + E). Each experimental unit consisted of a polypropylene pot, with dimensions of 25x20 cm and a 5 kg of soil capacity. These pots were maintained on metal benches, at a height of 1.2 m above the greenhouse floor. Environmental temperatures inside the greenhouse were monitored monthly throughout the experimental period: December – 12.90ºC, 24.16ºC, and 38.90ºC; January – 13.00ºC, 23.37ºC, and 35.30ºC; February – 18.10ºC, 24.78ºC, and 35.70ºC; March – 12.72ºC, 23.33ºC, and 36.17ºC; April – 8.70ºC, 21.94ºC, and 35.30ºC; May – 4.30ºC, 17.69ºC, and 33.90ºC; June – 1.90ºC, 17.48ºC, and 37.40ºC. For all units, sprinklers in a mechanized irrigation system were used with a 2 L min^{-1} flow rate. The irrigation regime consisted of activating the sprinklers six times per day, with a total wetness of 12 min, and the water depth supplied was 7.50 mm day^{-1}.

For the treatments containing earthworms or roots, eight *E. fetida* earthworms and five *P. glaucum* seeds were introduced to each pot during the implementation of the experiment. Following *P. glaucum* emergence, the seedlings were thinned to maintain two plants per pot. Three months after sowing, the aerial parts of the plants were cut close to the soil surface. For the autoclaved soil treatment, the soil was added into a plastic container, covered with a layer of aluminum foil, a second layer of kraft paper and sterilized in an autoclave at 120ºC for 1 hour.

For the treatments liming treatments, 23.2 g of dolomitic limestone with a relative neutralizing value of 89.38% were applied per experimental unit, corresponding to an application rate of 6.8 Mg ha^{-1}. The applied limestone was evaluated using a S2-WD Wet & Dry Laser Particle Size Analyzer (Bettersize, Liaoning, China) which revealed a D50 median particle size of 26.05 µm (Figure 1). Crop straw



Diam µm	Percent
1,000	2.16
2,000	5.53
5,000	11.41
10.00	20.83
20.00	40.10
45.00	68.78
75.00	81.31
100.0	87.96
200.0	99.11
300.0	100.00

Figure 1. Particle size distribution of the limestone used in the experiment.

was applied to the surface at a rate equivalent to 6 Mg ha^{-1} across all experimental units, except for the autoclaved soil treatment. Weeds were removed every two weeks, and 75 g of organic material were added in each pot to serve as a food source for the earthworms. This organic material was sourced from the vermicomposting of organic waste on a rural property located in the municipality of Passo Fundo, RS, Brazil, and exhibited the following chemical characteristics: N, 2.78%; P_2O_5, 3.53%; K_2O, 1.80%; Ca,= 4.70%; Mg, 0.67%; and pH, 7.52.

At the conclusion of the experiment, undisturbed soil samples were collected at 5 cm intervals, using soil core rings extracted with an Uhland-type core sampler. The physical attributes evaluated were particle density (PD), bulk density (BD), total porosity (TP), and volumetric moisture at field capacity (VMfc) (Teixeira et al., 2017).

At the conclusion of the assay, the earthworms were recounted and their biomass was quantified by weighing the recovered individuals to determine the survival (SU), reproduction (RE), and mortality (MO) rates, thereby verifying the effects of liming on these organisms. The collected earthworms were then oven-dried at 65ºC for 48 hours. X-ray diffraction (XRD) in disordered powder using a D2 Phaser (Bruker, Billerica, MA, USA) was used only on the samples of dry earthworm powder + coprolites; the diffractogram peaks were subsequently compared with reference values in the literature to detect calcite and dolomite (Mindat.org, 2024). For total chemical analysis, the samples were subjected to energy-dispersed X-ray fluorescence (XRF) using a S2 Ranger (Bruker, Billerica, MA, USA) performed in duplicate, with mean values used to express the total chemical composition (Bortoluzzi & Poleto, 2013; Sullasi et al., 2014).

The results were subjected to analysis of variance (ANOVA), and treatments means were compared using Scott-Knott's test at a 5% probability of error. All statistical analyses were performed using Sisvar software (Ferreira, 2011).

Results and Discussion

No significant interactive effects were observed between soil depth and management for PD, BD, TP, and VMfc. Statistical differences occurred independently for both the depth and management factors (Tables 1 and 2). The lowest particle and bulk densities, along with the highest total porosity, were detected in the 0-5 cm layer (Table 1). This result may be attributed to the surface deposition of organic material and the intensive exploration of the 0-5 cm layer by biological agents.

The AS + L treatment showed higher particle density, but did not significantly differ from the NS + E, NS + L + E, and NS + L + R + E treatments (Table 2). Because earthworms incorporate organic material into the soil (Vidal et al., 2023), their activity increases density to a level similar to autoclaved soil. These results are already described in the literature, where it has been reported that earthworm activity transitions both compacted and decompacted soil toward an intermediate state (Barré et al., 2009). Regarding the natural soil treatment, the presence of earthworms increased the particle density by approximately 7%, and directly increased the soil bulk density by 35% compared with the natural soil without

Table 1. Means and standard deviation of physical properties according to the depth of soil used in the experiment[(1)].

Depth (cm)	Particle density (PD, g cm^{-3})	Bulk density (BD, g cm^{-3})	Total porosity (TP, cm^3 cm^{-3})	VMfc[(2)] (cm^3 cm^{-3})
0-5	2.22 ± 0.13b	0.67 ± 0.11b	0.70 ± 0.05a	0.24 ± 0.07a
5-10	2.37 ± 0.10a	0.85 ± 0.15a	0.65 ± 0.06b	0.25 ± 0.09a
10-15	2.39 ± 0.09a	0.89 ± 0.14a	0.63 ± 0.05b	0.21 ± 0.06a
Significance	*	*	*	ns
CV[(3)] (%)	5.34	19.74	9.41	36.80

[(1)]Means followed by equal letters, in the columns, do not differ significantly by Scott-Knott's test at a 5% probability of error. [(2)]VMfc, volumetric moisture at field capacity. [(3)]CV, coefficient of variation. *Significant difference at 5% probability of error; and [ns]Nonsignificant.

liming, indicating the active incorporation of organic material.

Contrary to expectations, in this study, the earthworms promoted soil densification by increasing both particle and bulk densities, while reducing total soil porosity (Table 2). These findings can be attributed to species-specific behaviors, as *E. fetida* belongs to the epigeic group (Vidal et al., 2023). Consequently, it acts mainly within the surface layer and creates smaller pores, failing to promote bioturbation at depth. This parallel increase in bulk and particle densities is linked to the incorporation of organic material, since earthworms tend to select particles richer in organic carbon and associate them with the secreted mucus (Bartz et al., 2024), physically protecting them in compact coprolites, also known as biogenic aggregates (Steffen et al., 2013). These coprolites showed fine sand contents, a lower proportion of coarse sand, and higher values of clay, and silt. In addition to displaying high stability, they contained greater concentrations of organic carbon and exchangeable cations (Silva Neto et al., 2010), which may be related to the higher soil densities detected (Table 1).

Total porosity was higher in the NS + L + R treatment, though it did not significantly differ from the NS, NS + L, NS + R, and NS + L + R + E treatments (Table 2). Notably, the treatments featuring plant roots showed increased porosity, confirming root systems can be a valuable tool for bioturbation. Conversely, earthworm presence in the natural soil resulted in the lowest total porosity value. This treatment had a 13% reduction in total porosity relative to the natural soil without earthworms, indicating that earthworms can compact the soil through their movement and the localized incorporation of organic material (Barré et al., 2009; Vidal et al., 2023; Bartz et al., 2024).

The porosity formed by the root system of *P. glaucum* seems to be a viable mechanism to facilitate limestone translocation due to water flow. The particle migration process aligns with the findings of Bortoluzzi et al. (2008), who demonstrated that fine clay particles of up to 15 μm naturally migrated through the soil profile. Creating a soil profile with a continuous porosity and a diameter suitable for particle transport promotes the vertical displacement of calcite and dolomite, thereby improving acidity correction at depth.

The XRD performed on earthworm and coprolite samples indicated the presence of calcite in all treatments, whereas dolomite was detected exclusively in the treatments that received liming (Figure 2). Calcite was confirmed by the presence of peaks at d = 0.1674 nm, 0.2285 nm, and 0.2495 nm, while dolomite was confirmed by the presence of peaks at d = 0.1848, 0.2192, and 0.2540 nm. Identifying calcite and dolomite within the earthworm biomass and coprolites is important to determine whether

Table 2. Means and standard deviation of physical properties according to soil management practices used in the experiment[(1)].

Management[(2)]	Particle density (PD, g cm^{-3})	Bulk density (BD, g cm^{-3})	Total porosity (TP, cm^3 cm^{-3})	VMfc[(3)] (cm^3 cm^{-3})
NS	2.25 ± 0.12b	0.70 ± 0.13b	0.69 ± 0.05a	0.25 ± 0.0a
AS + L	2.44 ± 0.08a	0.94 ± 0.04a	0.61 ± 0.02b	0.25 ± 0.04a
NS + L	2.28 ± 0.14b	0.74 ± 0.19b	0.68 ± 0.06a	0.21 ± 0.06b
NS + L + E	2.36 ± 0.06a	0.86 ± 0.07a	0.63 ± 0.03b	0.17 ± 0.05b
NS + L + R	2.25 ± 0.14b	0.69 ± 0.17b	0.70 ± 0.06a	0.28 ± 0.11a
NS + L + R + E	2.43 ± 0.10a	0.83 ± 0.11a	0.66 ± 0.04a	0.28 ± 0.08a
NS + R	2.24 ± 0.19b	0.72 ± 0.18b	0.68 ± 0.08a	0.23 ± .011a
NS + E	2.37 ± 0.05a	0.94 ± 0.23a	0.60 ± 0.10b	0.17 ± 0.13b
Significance	*	*	*	*
CV (%)	5.34	19.74	9.41	36.80

[(1)]Means followed by equal letters, in the columns, do not differ significantly by Scott-Knott's test at a 5% probability of error. [(2)]NS, natural soil; AS, autoclaved soil; L, limestone; E, earthworms; R, roots; and CV, coefficient of variation. [(3)]VMfc, volumetric moisture at field capacity. *Significant difference at 5% probability of error.

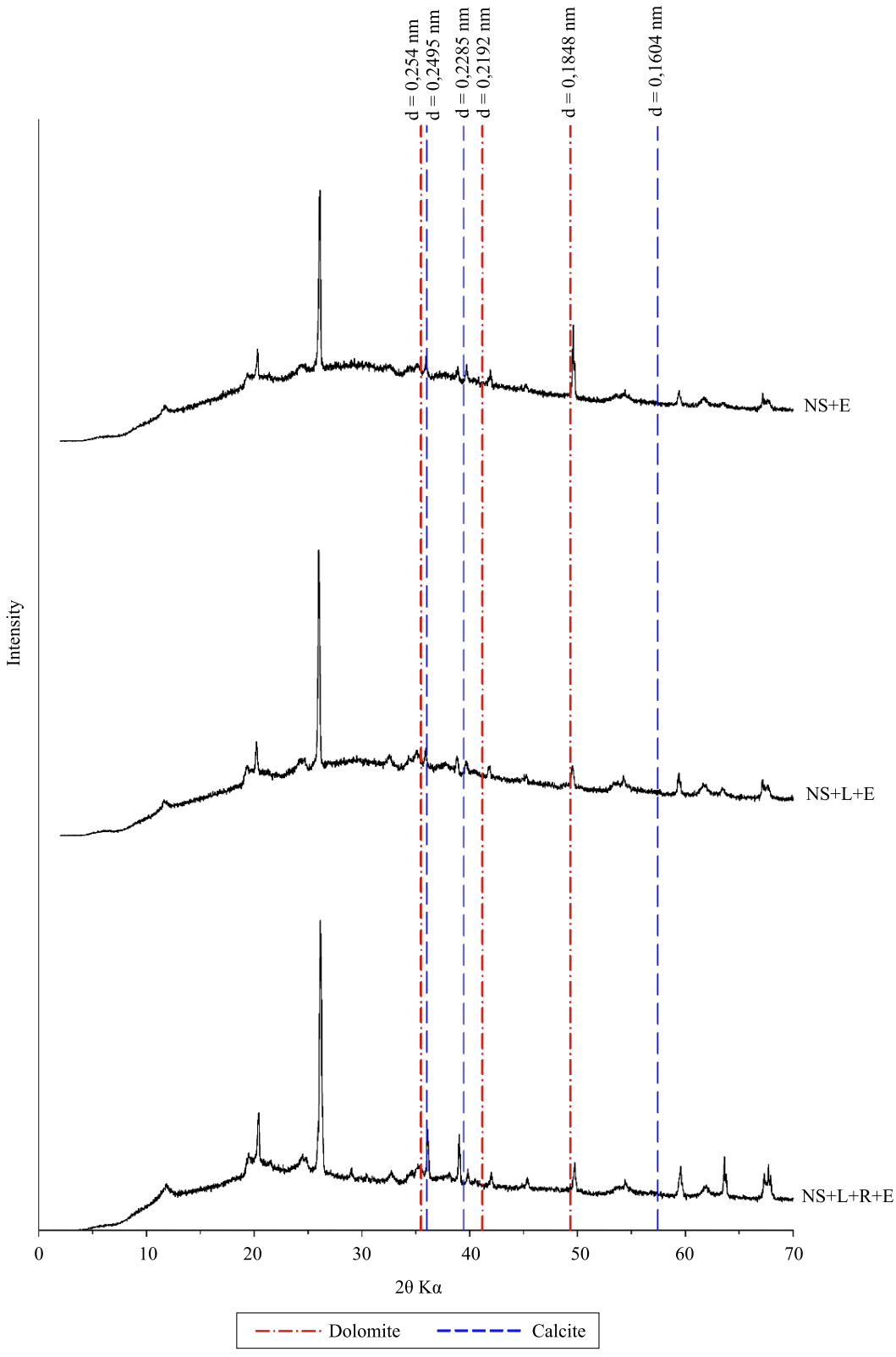


Figure 2. Presence of calcite and dolomite in earthworm diffractograms combined with their digestive contents, across liming system treatments with and without the presence of roots. NS + E: natural soil and earthworms; NS + L + E: natural soil with limestone and earthworms; NS + L + R + E: natural soil with limestone, roots, and earthworms.

these organisms ingest calcareous minerals and subsequently deposit them throughout the soil profile, thus characterizing bioturbation. Due to their behavior, earthworm-mediated bioturbation occurs through the active ingestion and deposition of calcareous minerals, mirroring documented bioturbation processes of other materials (Baskar et al., 2023; Vidal et al., 2023; Pelosi et al., 2024). Furthermore, the Ca and Mg surplus in the soil caused by lime dissolution can be recrystallized in new calcite and dolomite particles by earthworm activity. This mechanism also affects the overall soil aggregation (Bortoluzzi et al., 2010). Conversely, the roots create a less dense soil profile characterized by greater porosity, which may facilitate the percolation of limestone and water particles.

The total chemical composition of the earthworm + coprolite samples, determined by XRF, revealed the presence of calcium across all soil management treatments involving earthworms, with an increase of up to 150% where limestone was applied (Table 3). Magnesium was detected only in the NS + L + E and NS + L + R + E treatments, due to the application of dolomitic limestone. Other elemental constituents – including phosphorus; sulfur, which was detected specifically where limestone was applied; and silicon, aluminum, and iron, which represent the structural components of Latossolos Vermelhos (Rhodic Ferralsols) of basaltic origin – were consistently found in lower proportions in the natural soil treatments compared to those receiving liming. Therefore, it was shown that earthworms can ingest limestone particles and promote the bioturbation of calcite and dolomite, mirroring mechanisms previously documented for mycorrhizae, microplastics, biochar, and other minerals (Baskar et al., 2023; Pelosi et al., 2024).

Table 3. Chemical composition of earthworms and their digestive contents, under liming system treatments[(1)] with and without the presence of roots.

Element	NS + E (μg g^{-1})	NS + L + E (μg g^{-1})	NS + L + R + E (μg g^{-1})
Si	11,300	17,700	36,600
Al	3,100	5,900	8,100
Fe	2,500	6,900	9,000
Ca	1,500	2,000	3,800
Na	1,700	2,100	9,000
Ti	600	1,600	1,500
Mg	0	222	909
P	0	149	761
S	0	218	319
Mn	32	107	96

[(1)]Treatments: NS + E, natural soil and earthworms; NS + L + E, natural soil with limestone and earthworms; and NS + L + R + E, natural soil with limestone, roots, and earthworms.

In this study, two bioturbation mechanisms were highlighted: 1) the creation of a porous soil profile by *P. glaucum* roots, which facilitate the percolation of calcareous particles in depth; and 2) the ingestion and deposition of limestone throughout the soil profile by earthworms. Stratified chemical analyses remain necessary to confirm bioturbation of the alkalizing front and the dissolution of calcareous particles along the soil profile. Ultimately, these findings highlight a possibility for future research focused on correcting subsurface acidity through the biological mechanisms of limestone bioturbation.

Finally, this study provides evidence of limestone particle migration facilitated by the reduction in soil density achieved through *P. glaucum* root development, and the possibility of limestone bioturbation mediated by earthworms. However, direct agronomic validation of the efficiency of deep liming with root and earthworm driven bioturbation under field conditions is necessary, since the pot cultivation system is limiting for earthworm species and the growth of root systems, as well as using soils with previous disturbances.

Conclusions

1. Soil density and porosity were improved by the cultivation of *Pennisetum glaucum*, creating favorable conditions for the downward migration of particles, such as limestone, through the soil profile.

2. Earthworms ingest limestone particles and can promote bioturbation of calcite and dolomite applied to the soil.

References

AQUINO, T.; ROCHE, K.R.; AUBENEAU, A.; PACKMAN, A.I.; BOLSTER, D. A process-based model for bioturbation-induced mixing. **Scientific Reports**, v.7, art.14287, 2017. DOI: https://doi.org/10.1038/s41598-017-14705-1.

BARRÉ, P.; MCKENZIE, B.M.; HALLETT, P.D. Earthworms bring compacted and loose soil to a similar mechanical state. **Soil Biology & Biochemistry**, v.41, p.656-658, 2009. DOI: https://doi.org/10.1016/j.soilbio.2008.12.015.

BARTZ, M.L.C.; DUDAS, R.T.; DEMETRIO, W.C.; BROWN, G.G. Earthworms as soil health indicators in no-tillage agroecosystems. **European Journal of Soil Biology**, v.121, art.103605, 2024. DOI: https://doi.org/10.1016/j.ejsobi.2024.103605.

BASKAR, P.; SACHAN, K.; SINGH, B.V.; SAIKANTH, D.R.K.; HARISH KUMAR, R.K.M.; GAUTAM, R.; SINGH, O. Earthworm castings in ecosystem health through their elemental composition. **International Journal of Plant & Soil Science**, v.35, p.2076-2087, 2023. DOI: https://doi.org/10.9734/ijpss/2023/v35i183494.

BORGES, W.L.B.; HIPÓLITO, J.L.; SOUZA, I.M.D. de; JULIANO, P.H.G.; RODRIGUES, L.N.F.; ANDREOTTI, M. Methodologies for applying calcium compounds in agropastoral systems: changes in soil chemical attributes. **Agronomy Journal**, v.114, p.771-783, 2022. DOI: https://doi.org/10.1002/agj2.20926.

BORTOLUZZI, E.C.; GARIBOTTI, A.; TIECHER, T.; SANTOS, D.R. dos; MOTERLE, D.F.; FIORIN, J.E. Revisiting limestone quality for soil liming purpose. **Minerals**, v.12, art.1522, 2022. DOI: https://doi.org/10.3390/min12121522.

BORTOLUZZI, E.C.; PERNES, M.; TESSIER, D. Mineralogia de partículas envolvidas na formação de gradiente textural em um argissolo subtropical. **Revista Brasileira de Ciência do Solo**, v.32, p.997-1007, 2008. DOI: https://doi.org/10.1590/S0100-06832008000300009.

BORTOLUZZI, E.C.; POLETO, C. Metodologias para estudos de sedimentos: ênfase na proporção e na natureza mineralógica das partículas. In: POLETO, C.; MERTEN, G.H. (Ed.) **Qualidade dos sedimentos**. 2. ed. São Paulo: ABRH, 2013. p.1-60.

BORTOLUZZI, E.C.; POLETO, C.; BAGINSKI, A.J.; SILVA, V.R da. Aggregation of subtropical soil under liming: a study using laser diffraction. **Revista Brasileira de Ciência do Solo**, v.34, p.725-734, 2010. DOI: https://doi.org/10.1590/S0100-06832010000300014.

DUDAS, R.T.; DEMETRIO, W.C.; NADOLNY, H.S.; BROWN, G.G.; BARTZ, M.L.C. Earthworms in the state of Paraná, Brazil: state of the art. **Revista Brasileira de Ciência do Solo**, v.47, e0220159, 2023. DOI: https://doi.org/10.36783/18069657rbcs20220159.

FERREIRA, D.F. Sisvar: a computer statistical analysis system. **Ciência e Agrotecnologia**, v.35, p.1039-1042, 2011. DOI: https://doi.org/10.1590/S1413-70542011000600001.

IUSS WORKING GROUP WRB. **World Reference Base for Soil Resources**: international soil classification system for naming soils and creating legends for soil maps. 4th ed. Vienna: International Union of Soil Sciences, 2022. 236p.

JOUQUET, P.; DAUBER, J.; LAGERLÖF, J.; LAVELLE, P.; LEPAGE, M. Soil invertebrates as ecosystem engineers: intended and accidental effects on soil and feedback loops. **Applied Soil Ecology**, v.32, p.153-164, 2006. DOI: https://doi.org/10.1016/J.APSOIL.2005.07.004.

MICHEL, E.; NÉEL, M.-C.; CAPOWIEZ, Y.; SAMMARTINO, S.; LAFOLIE, F.; RENAULT, P.; PELOSI, C. Making waves: modeling bioturbation in soils – are we burrowing in the right direction? **Water Research**, v.216, art.118342, 2022. DOI: https://doi.org/10.1016/j.watres.2022.118342.

MINDAT.ORG. **[Database of minerals Mindat]**. 2024. Available at: <https://www.mindat.org/>. Accessed on: Feb. 25 2025.

MUKHERJEE, B.; JHA, R.K.; SATTAR, A.; DUTTA, S.; BHATTACHARYA, U.; SAMANTA, S.; HUIREN, B.; SINGH, S.K.; DAS, S.; BAL, S.K. Harnessing the potential of millets for climate-resilient and sustainable agriculture. **Frontiers in Plant Science**, v.16, art.1574699, 2025. DOI: https://doi.org/10.3389/fpls.2025.1574699.

PELOSI, C.; TASCHEN, E.; REDECKER, D.; BLOUIN, M. Earthworms as conveyors of mycorrhizal fungi in soils. **Soil Biology and Biochemistry**, v.189, art.109283, 2024. DOI: https://doi.org/10.1016/j.soilbio.2023.109283.

RATSIATOSIKA, O.; TRAP, J.; HERINASANDRATRA, V.; RAZAFIMBELO, T.; BERNARD, L.; BLANCHART, E. Earthworms enhance the performance of organic amendments in improving rice growth and nutrition in poor ferralsols. **Soil Biology and Biochemistry**, v.195, art.109477, 2024. DOI: https://doi.org/10.1016/j.soilbio.2024.109477.

RHEINHEIMER, D. dos S.; BORTOLUZZI, E.C.; MOTERLE, D.F.; LE GUET, T.; BASTOS, M.C.; COELHO, L.L.; MEOTTI, B.L.; SANTANA, A. de S.; TIECHER, T. Kinetics of soil re-acidification under no-tillage system. **Soil & Tillage Research**, v.242, art.106137, 2024. DOI: https://doi.org/10.1016/j.still.2024.106137.

SILVA NETO, L. de F. da; SILVA, I. de F. da; INDA, A.V.; NASCIMENTO, P.C. do; BORTOLON, L. Atributos físicos e químicos de agregados pedogênicos e de coprólitos de minhocas em diferentes classes de solos da Paraíba. **Ciência e Agrotecnologia,** v.34, p.1365-1371, 2010. DOI: https://doi.org/10.1590/S1413-70542010000600002.

STEFFEN, G.P.K.; ANTONIOLLI, Z.I.; STEFFEN, R.B.; JACQUES, R.J.S. Importância ecológica e ambiental das minhocas. **Revista de Ciências Agrárias**, v.36, p.137-147, 2013. DOI: https://doi.org/10.19084/rca.16291.

SULLASI, H.S.L.; OLIVEIRA JÚNIOR, J.P. de; CAMPOS, J.R. de O.; SOUZA, R.E. de; SANTOS, C.D.F. A técnica de fluorescência de raios X por dispersão de energia (EDFRX) e sua aplicação em amostras de moedas antigas. **Fumdhamentos**, v.11, p.114-128, 2014.

TEDESCO, M.J.; GIANELLO, C.; BISSANI, C.A.; BOHNEM, H.; VOLKWEISS, S.J. **Análise de solo, plantas e outros materiais**. 2.ed. rev. e ampl. Porto Alegre: Universidade Federal do Rio Grande do Sul, 1995. 174p. (UFRGS. Boletim técnico, 5).

TEIXEIRA, P.C.; DONAGEMMA, G.K.; FONTANA, A.; TEIXEIRA, W.G. **Manual de métodos de análise de solo**. 3.ed. rev. e ampl. Brasília: Embrapa, 2017.

TIECHER, T.; MARTINS, A.P.; PERETTO, E.J. da S.; FINK, J.R.; SANTOS, L. da S.; DENARDIN, L.G. de O.; TIECHER, T.L. **Evolução e estado da fertilidade do solo no Norte do Rio**

Grande do Sul e Sudoeste de Santa Catarina. Porto Alegre: UFRGS, 2016. 53p.

VIDAL, A.; BLOUIN, M.; LUBBERS, I.; CAPOWIEZ, Y.; SANCHEZ-HERNANDEZ, J.C.; CALOGIURI, T.; VAN GROENIGEN, J.W. The role of earthworms in agronomy: consensus, novel insights and remaining challenges. **Advances in Agronomy**, v.181, p.1-78, 2023. DOI: https://doi.org/10.1016/bs.agron.2023.05.001.

WANG, S.; GAN, L.; ZHANG, S.; LI, J.; CHANG, C.; ZHANG, Y.; ZHANG, H.; WEI, B. Soil biopores and non-biopores responses to different tillage treatments in sugarcane fields in Guangxi, China. **Agronomy**, v.14, art.1378, 2024. DOI: https://doi.org/10.3390/agronomy14071378.

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Chief editor: Edemar Corazza
Edited by: Mírian Baptista

Data availability statement

Data available upon request: research data are only available upon reasonable request to the corresponding author.

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.

Acknowledgments

To Universidade de Passo Fundo, for the support; to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), for financing, in part, this study (project number 302460/2022-5); and to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), for financing, in part, this study (Finance Code 001).

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