

Identifying and defining main changes in soil attributes to enhance environmental health and poverty alleviation in the Amazonian periphery

Kalyne Pereira Miranda Nascimento

Universidade Estadual do Maranhão

Edaciano Leandro Lösch

edacianoleandro@hotmail.com

Universidade Estadual do Maranhão

Katia Pereira Coelho

Universidade Estadual do Maranhão

Jéssica de Freitas Nunes

Universidade Estadual do Maranhão

Maria Karoline C. R. de Sousa

Universidade Estadual do Maranhão

Alana das Chagas Ferreira Aguiar

Federal University of Maranhão

Emanoel Gomes de Moura

Universidade Estadual do Maranhão

Research Article

Keywords: Soil fertility, Sustainability, Recommendation, Land reclamation, Tropical soil

Posted Date: September 9th, 2024

DOI: <https://doi.org/10.21203/rs.3.rs-4853575/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

In the humid tropics, ensuring food security through sustainable food production relies heavily on addressing infertile soil. Identifying and enhancing key soil attributes crucial for plant growth poses significant challenges for poverty alleviation. We identify the main soil attributes that can boost crop performance and serve as predictors of sustainability, offering practical and economic recommendations for immediate improvement. The experiment was carried out in five areas of alley cropping systems where the leguminous tree *Clitoria fairchildiana* and annual legumes including *Cajanus cajan*, *Crotalaria juncea*, or *Stylosanthes* and *Tithonia diversifolia* were planted to increase soil organic matter, all consociated with maize. Nine soil samples were collected at each of the 10 sampling points. P, pH ($H + Al^{3+}$), exchangeable K^+ , Ca^{2+} and Mg^{2+} were analyzed. We found that increased stabilised soil organic matter fraction, rather than P and K availability, is responsible for enhanced maize grain yield. This factor must be considered when assessing land and the environment, as well as implementing appropriate land management systems to avoid misallocation of limited resources. Input recommendations should align with the threshold values of 32 mmolc.dm⁻³ for Ca and 8 mmolc.dm⁻³ of Mg, aiming to achieve a combined level of 40 mmolc.dm⁻³ of Ca + Mg (Ca:Mg ratio of 4:1) and MAOC content around 14 g.kg⁻¹. Soil researchers should further explore the interactions between Ca + Mg and MAOC and biomass-derived compounds as innovative soil quality management tools.

Introduction

In the humid tropics, more than in other regions, environmental quality plays a critical role in ensuring food security, agricultural viability, and environmental income (Acevedo et al. 2018). Poor soil fertility, a key component of environmental health, directly correlates with low productivity, food insecurity, and rural poverty (Vysochyna et al. 2020). Moreover, many poor rural communities inhabit marginal lands that are inherently unsuitable for long-term sustainable agriculture, making them heavily reliant on agricultural or environmental improvements for their livelihoods (Azam-Ali et al. 2023). In these circumstances, the loss of soil quality, reduced productivity, and diminishing job and subsistence prospects create a distinct cycle of poverty (Heger et al. 2020). Therefore, since sustainable food production for ensuring food security highly relies on improvements in infertile soil, identifying and enhancing humid tropical soil attributes crucial for plant growth become primary challenges for researchers seeking to alleviate poverty (Dorward and Giller, 2022). Failure to address soil health issues prevents smallholder farmers from equitably benefiting from yield gains resulting from improved plant genetics and other associated agronomic practices, as highlighted in recent science advances (Shahane and Shivay, 2021).

In tropical soils under cultivation, inadequate practices and intense climate drivers can, within a few years, lead to degradation characterized by the leaching of basic cations and carbon loss (Sena et al. 2020). These interdependent factors are the main drivers of land degradation processes, rendering continuous soil use impractical and prompting many farmers to resort to shifting cultivation systems (Ramos et al. 2018). Due to rapid organic matter turnover and elevated rates of base leaching, shifting

cultivation contributes to a vicious cycle where poverty exacerbates environmental pressure, leading to further environmental degradation, thereby perpetuating poverty and associated hunger (Moura *et al.* 2021). Unlike in most tropical regions where soil quality is assessed using chemical indicators and recommendations typically include phosphate and lime applications to improve agricultural soil quality, such approaches are insufficient in sandy loam soils prone to cohesion in the humid tropics. In these soils, chemical management alone fails to adequately raise soil fertility and ensure high food production (Moura *et al.* 2021).

To evaluate environmental quality, soil analysis coupled with specific input response functions has been pivotal in generating evidence-based, efficient recommendations to ensure soil fertility and elicit positive crop responses (Asadi *et al.* 2017). Despite attempts to implement this model in some tropical regions, its adoption by smallholder farmers and the establishment of a self-sustaining business model have been limited. Consequently, barriers remain to be surmounted to achieve healthy and fertile soils, which are essential for fostering greater prosperity within rural communities. When farmers have limited resources for purchasing inputs, evaluations should be carefully targeted to identify basic indicators strongly correlated with the efficient utilisation of the costliest inputs (Bünemann *et al.* 2018). Additionally, it is crucial to implement complementary measures to enhance sustainability and improve crop performance.

Therefore, soil researchers face the challenge of moving beyond conventional soil analysis procedures and finding innovative soil quality assessment tools to boost regionally applicable knowledge directly benefiting end users' well-being. These innovative tools must emphasize the immediate need to reverse soil degradation processes before they become irreversible, given the impact of intense climate drivers on SOM loss, base leaching, and fertility depletion. We start from the assumption that in humid tropics soils, there is an opportunity to formulate a novel strategy for assessing soil quality, considering the interests of smallholder farmers and sustainability aspects beyond input recommendations for enhancing crop performance. In this scenario, this study aimed to identify the primary soil attributes whose improvement can drive crop performance and predict sustainability, facilitating the provision of immediate and cost-effective recommendations.

Material and Methods

Area characterization

The experiment was conducted in partnership with family farmers on the periphery of the Brazilian Amazon, in the county of Santa Rita (03°08'37" S; 44°19'33" W). Climatologically, the area experiences a rainy season from February to June and a dry season with a pronounced water deficit from July to December. The local soils exhibit hard-setting characteristics and are classified as Arenic Hapludults (Soil Survey Staff 2010; Moura *et al.* 2012). The chemical and physical properties of the soil were determined prior to establishing the experiment and are as follows: pH 4.0 (in CaCl₂); 20 g kg⁻¹ of organic-C; 15 mg dm⁻³ of P; 25 mmolc dm⁻³ of Al + H; 15 mmolc dm⁻³ of Ca; 9 mmolc dm⁻³ of Mg; 1

mmolc dm⁻³ of K; 50 mmolc dm⁻³ of CEC; percentage base saturation of 50.0%; 300 g kg⁻¹ of coarse sand; 545 g kg⁻¹ of fine sand; 61 g kg⁻¹ of silt; 90 g kg⁻¹ of clay.

Experimental design and conduction

The study took place in five areas of alley cropping systems, where leguminous trees (*Clitoria fairchildiana*; sombrero) were planted at a spacing of 0.5 m between plants and 3.0 m between rows. Additionally, some farmers incorporated annual legumes such as *Cajanus cajan* (pigeon pea), *Crotalaria juncea* or *Stylosanthes* sp.. These crops were consociated with maize (*Zea mays* L.) to increase soil organic matter.

In all the areas, from 2018 up to 2022, at the onset of the rainy season, three rows of maize cultivar Ag 7088 were sown between the legume rows. The maize rows were spaced 80 cm apart, with plants positioned 25 cm apart. Planting fertilisation included the application of 50 kg ha⁻¹ of N, 120 kg ha⁻¹ of P₂O₅, 100 kg ha⁻¹ of K₂O, and 5 kg ha⁻¹ of Zn. A total of 100 kg ha⁻¹ of N-supplied urea was applied at the V8 growth stage of maize each year. Legume branches were pruned to a height of 0.5 m above ground level, and their biomass was evenly distributed in the soil immediately after maize sowing. To measure soil parameters and assess maize productivity, 10 sampling points were delimited for each area within a uniform grid of 10 x 14 m. The coordinates of each sample point were recorded using a GPS device.

Fractionation of soil organic carbon analyses

In July 2022, nine samples were collected from the surface soil layer (0–15 cm) at each point with an auger to analyze the physical fractionation of soil organic matter. The soil organic matter was physically fractionated according to the methods of Cambardella and Elliott (1992). Air-dried soil samples weighing 20 g were sieved through a 2 mm mesh and placed in 250 ml polyethene cups, to which 80 ml of 5 g L⁻¹ of sodium hexametaphosphate was added. The mixture was shaken for 15 hours in a horizontal shaker at a rate of 130 oscillations min⁻¹. Subsequently, all the vial contents were transferred onto a 0.053 mm mesh sieve and rinsed with a gentle stream of distilled water until the clay was completely removed. The material retained on the sieve was defined as total particulate organic matter (> 53 µm) and then dried at 50°C. After drying, the sample was ground in a porcelain mortar. An aliquot was then collected, weighed, and analysed for its C content, representing the soil particulate organic carbon (POC) in particulate organic matter. An aliquot of the 2 mm sieved subsample was ground in a porcelain mortar, weighed, and analysed to determine soil total organic carbon (TOC) according to the Sparks et al. (1996) method. Soil mineral-associated carbon (MOC) was calculated as the difference between TOC and POC.

Soil chemical analyses and maize grain yield

The same soil samples were analysed for P, pH, (H + Al³⁺) and exchangeable K⁺, Ca²⁺, Mg²⁺. P, K, Ca, and Mg were measured using an exchangeable ion resin (Raij et al. 1986) with a Varian 720-ES ICP Optical Emission Matter Analysis Spectrometer. pH in CaCl₂ was determined following Peech (1965),

while ($H + Al^{3+}$) was measured via Solution SMP as described by Quaggio et al. (1985). The maize grain yield (MGY) was determined at physiological maturity in two 10m² areas within each 70 m² grid.

Statistical analyses

R-studio (ver. 4.1.3, 2023) was used to run one-way ANOVA tests, homogeneity (Lavene), normality (Shapiro-Wilk) and generate simple linear regressions at 5% probability. Principal component analysis (PCA) was constructed to evaluate the interaction of the dataset.

Results

Similarly, the regression equation of POC (Fig. 2a) with MGY indicated a narrow range of amplitude and negative correlation with MGY. In contrast, the amplitude of MAOC was broader, and the correlation between MAOC and MGY (Fig. 2b) was stronger compared to that between POC and MGY. The highest productivity (12 Mg.ha⁻¹) was achieved with MAOC levels around 14 g.kg⁻¹.

Regarding the influence of cations on MGY, regression equations indicated that when together, Ca and Mg explained 64% of MGY (Fig. 3c), while the effect of Ca (Fig. 3a) alone was lower (43%). However, the effect of Mg alone was greater than Ca and Ca + Mg (Fig. 3b). The highest MGY was achieved with a combined Ca + Mg around 41 mmolc.dcm⁻³.

Correlations between MAOC and basic cations were stronger when Ca (Fig. 3d) and Mg (Fig. 3e) were also considered together (Fig. 3f). The value of Ca + Mg required for good structure, as proposed by Johannes et al. (2017) (SOC:Clay ratio < 1:10), might exceed 40 mmolc.dm⁻³, which aligns closely with levels required for the highest MGY (Fig. 3f).

In the principal components analysis (Fig. 4) axis 1 (57.1%) and axis 2 (21.5%) together explained 78.6% of the variance and indicated that MAOC, Ca + Mg, Ca and Mg had a strong association and a tendency towards an increase MGY. That is, when the concentrations of these variables increased, the MGY tended to increase. The largest contribution observed in axis 1 was from the Ca + Mg variable (18.2%), while the smallest was from P (0.2%). For axis 2, the largest contribution was from TOC (68%), with Mg, Ca and Ca + Mg having the smallest contribution (< 1%).

Discussion

The weak correlations observed between P and K with MGY suggest that in structurally fragile tropical soils, a conventional strategy relying on analyses of P and K availability followed by chemical fertilisation may not be the most effective strategy to support family farmers. In soil with insufficient aggregator elements such as iron and soil organic carbon, reduced soil rootability leads to low nutrient use efficiency, rendering chemical nutrient application ineffective (Nunes et al. 2024). In the same soil, Moura et al. (2013) reported P recovery efficiency by maize as low as 6.2%. Such a low recovery rate is clearly insufficient to offset fertiliser costs and could contribute to farmers' reluctance to transition away from

shifting cultivation practices. These findings emphasize the necessity of implementing measures to improve soil rootability before fertilizer application (Sena et al. 2020).

In this regard, the intense climate acting and fast turnover characteristic of the humid tropics minimize the significance of substrate recalcitrance in C accumulation and soil improvement (Moura et al. 2023). Therefore, the light fraction of POC comprised of labile material was less important in contributing to MGY compared to MAOC, which accounted for 64% of maize productivity. Indeed, in cohesive soil with low content of mineral aggregator elements, increased MAOC seems to be the principal way of enhancing soil rootability and improving nutrient use efficiency (Silva et al. 2016). The reduction in soil impedance attributed to MAOC arises from a dilution effect resulting from its mixing with the denser mineral fraction of the soil (Maltas et al. 2018). Moreover, in soil prone to cohesion, aside from decreasing soil bulk density, increased soil rootability is observed due to aggregation promoted by MAOC, often resulting in an increase in total pore space. The amount of water molecules around soil particles with a high content of organic matter also contributes to reducing cohesion and soil penetration resistance (Locatelli et al. 2023).

The effect of Ca and Mg on MGY in this experiment extends beyond their ability to alleviate Al-induced toxicity (Gupta et al. 2023). They also help remove other toxic elements such as Mn from the root zone (Rahman et al. 2018) and play crucial roles in the regulatory mechanisms that plants use to adapt to adverse tropical environmental conditions like drought and heat (Saud et al. 2017; de Vries et al. 2020; Gupta et al. 2023). The primary factor driving the strong correlation between MGY and basic cations in this experiment was their capacity to reduce SOC bioavailability, consequently increasing the stabilised SOC fraction operationally defined as MAOC (Shabtai et al. 2023). Indeed, the correlations between MAOC and Ca + Mg were strong enough to explain 71% of the stabilised SOC fractions.

The conventional explanation for this relationship involves physicochemical associations between organic compounds and minerals, such as sorption, co-precipitation, and complexation (Shabtai et al. 2023). Recent studies have further supported this relationship, demonstrating positive correlations between polyvalent cations and soil organic carbon stability (Rowley et al. 2018, Song et al. 2018; Dlamini et al. 2019). Organo-mineral interactions are pivotal in stabilising SOC, as they facilitate interactions between cations and microbial biomass. Bonds formed between organic compounds and mineral surfaces minimise microbial degradation of organic compounds, contributing to SOC stabilisation (Porrás et al. 2018, Kleber et al. 2015, Schmidt et al. 2011).

Environmental and agricultural benefits from MAOC surpass those provided by other soil quality indicators in the humid tropics, as noted by Sena et al. (2020) and Nunes et al. (2024). In this experiment, the value of MAOC required for soil good structure, as proposed by Johannes et al. (2017) (SOC:Clay ratio < 1:10), was around 14 g.kg⁻¹. This level coincided with the highest MGY of 12 Mg.ha⁻¹. Notably, the Ca + Mg levels higher than 40 mmolc.dm⁻³ corresponding to that MAOC content are considered very good according to the Brazilian soil test interpretation guides. Therefore, according to our results, to support family farm systems, thresholds of 32 mmolc.dm⁻³ for Ca and 8 mmolc.dm⁻³ of Mg should be

adopted to maintain an adequate Ca:Mg ratio. These thresholds should be included in soil analyses and test interpretation guides to ensure confidence among farmers and other stakeholders in researchers and development agents. Importantly, the sustainability of the systems will be ensured only if soil management maintains these threshold levels. To overcome the intense climatic drivers that can accelerate the SOM decomposition rate, implementing a cation no-till system with continuous use of biomass is mandatory (Nunes et al. 2024).

Conclusions

Our findings showed that increased stabilised soil organic matter fraction, rather than P and K availability, is responsible for enhanced MGY. This must be considered for land and environment evaluation, as well as for an adequate soil management system to prevent waste of scarce resources. Conversely, the strong correlation between Ca + Mg and MAOC revealed that soil researchers must take advantage of interactions between these cations and biomass-derived compounds as innovative soil quality management tools.

In this regard, there is an opportunity to define a new strategy for assessing soil quality that considers the interest of smallholder farmers and the sustainability aspects of reversing soil degradation processes before it becomes unachievable. In this sense, input recommendations must be according to the threshold of 32 mmolc.dm⁻³ for Ca and 8 mmolc.dm⁻³ for Mg, achieving 40 mmolc.dm⁻³ of (Ca + Mg), a Ca:Mg ratio of 4:1, and MAOC content around 14 g.kg⁻¹. Additionally, to prevent shifting cultivation and subsequent environmental degradation, a complementary strategy involving the continuous addition of high-quality biomass must be adopted to maintain MAOC levels throughout all cultivation years.

Declarations

Author Contribution

KPMN: conceptualization, methodology, validation, formal analysis, investigation, writing - original draft, writing - review & editing. ELL: validation, formal analysis, writing - original draft, writing - review & editing. KPC: validation, writing - original draft. JFN: validation, investigation, writing - original draft. MKCRS: investigation, data curation. ACFA: resources, supervision. EGM: conceptualization, validation, writing - original draft, writing - review & editing, supervision.

Data Availability

The data that support this study will be shared upon reasonable request to the corresponding author.

References

1. Acevedo, M.F., Harvey, D.R., Palis, F.G. (2018). Food security and the environment: Interdisciplinary research to increase productivity while exercising environmental conservation. *Global Food Security*, 16, 127–132. doi.org/10.1016/j.gfs.2018.01.001
2. Asadi, S.S., Lahari, K., Madhulika, K.S. (2017). Analysis of Soil Quality for Environmental Impact Assessment-A Model Study. *International Journal of Civil Engineering and Technology*, 8(3) 798–805. iaeme.com/Home/article_id/IJCIET_08_03_080
3. Azam-Ali, S., Ahmadzai, H., Choudhury, D., Von Goh, E., Jahanshiri, E., Mabhaudhi, T., Meschinelli, A., Modi, A.T., Nhamo, N., Olutayo, A. (2023). Marginal Areas and Indigenous People Priorities for Research and Action. In: von Braun, J., Afsana, K., Fresco, L.O., Hassan, M.H.A. (eds) *Science and Innovations for Food Systems Transformation*, Springer, Cham. doi.org/10.1007/978-3-031-15703-5_14
4. Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., Deyn, G., Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., Groenigen, J.W. van., Lijbert, B. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, 120 105–125. doi.org/10.1016/j.soilbio.2018.01.030
5. Cambardella, C., Elliott, E. (1992). Particulate Soil Organic-Matter Changes across a Grassland Cultivation Sequence. *Soil Science Society of America Journal*, 56 777–783. doi.org/10.2136/sssaj1992.03615995005600030017x
6. de Vries, J., de Vries, S., Curtis, B.A., Zhou, H., Penny, S., Feussner, K., Pinto, D.M., Steinert, M., Cohen, A.M., von Schwartzenberg, K., Archibald, J.M. (2020). Heat stress response in the closest algal relatives of land plants reveals conserved stress signaling circuits. *Plant Journal*, 103(3). pp1025–1048. doi.org/10.1111/tpj.14782
7. Dlamini, P., Mbanjwa, V., Gxasheka, M., Tyasi, L., Sekhohola-Dlamini, L. (2019). Chemical stabilisation of carbon stocks by polyvalent cations in plinthic soil of a shrub-encroached savanna grassland, South Africa. *Catena*, 181. doi.org/10.1016/j.catena.2019.104088
8. Dorward, A., Giller, K.E. (2022). Change in the climate and other factors affecting agriculture, food or poverty: An opportunity, a threat or both? A personal perspective. *Global Food Security*, 33 100623. doi.org/10.1016/j.gfs.2022.100623
9. Gupta, S., Kaur, N., Kant, K., Jindal, P., Ali, A., Naeem, M. (2023). Calcium: A master regulator of stress tolerance in plants. *South African Journal of Botany*, 163. doi.org/10.1016/j.sajb.2023.10.047
10. Heger, M.P., Zens, G., Bangalore, M. (2020). Land and poverty: the role of soil fertility and vegetation quality in poverty reduction. *Environment and Development Economics*, 25(4):315–333. doi:10.1017/S1355770X20000066
11. Johannes, A., Matter, A., Schulin, R., Weisskopf, P., Baveye, P.C., Boivin, P. (2017). Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? *Geoderma*, 302.pp 14–21. doi.org/10.1016/j.geoderma.2017.04.021
12. Kleber, M., Eusterhues, K., Keiluweit, M., Mikutta, C., Mikutta, R., Nico, P.S. (2015). Mineral-organic associations: Formation, properties, and relevance in soil environments. *Advances in Agronomy*, 130 1–140. doi.org/10.1016/bs.agron.2014.10.005

13. Locatelli, J.L., de Lima, R.P., Santos, R.S., Cherubin, M.R., Creamer, R.E., Cerri, C.E.P. (2023). Soil Strength and Structural Stability Are Mediated by Soil Organic Matter Composition in Agricultural Expansion Areas of the Brazilian Cerrado Biome. *Agronomy*, 13(1):71. doi.org/10.3390/agronomy13010071
14. Maltas, A., Kebli, H., Oberholzer, H.R., Weisskopf, P., Sinaj, S. (2018). The effects of organic and mineral fertilizers on carbon sequestration, soil properties, and crop yields from a long-term field experiment under a Swiss conventional farming system. *Land Degradation & Development*, 29(4). doi.org/10.1002/ldr.2913
15. Moura, E.G. (2021). Entre a Agricultura e a Ecologia, uma interface por onde transita a emancipação dos agricultores do trópico úmido. São Luís: UEMA, cap. 6 e 7, p. 63–97.
16. Moura, E.G., Oliveira, A.K.C., Pinheiro, K.M., Aguiar, A.C.F. (2012). Management of a cohesive tropical soil to enhance rootability and increase the efficiency of nitrogen and potassium use. *Soil Use and Management*, 28 370–377. doi.org/10.1111/j.1475-2743.2012.00424.x
17. Moura, E.G., Sena, V.G.L., Correa, M.S., Aguiar, A.C.F. (2013). The Importance of an Alternative for Sustainability of Agriculture around the Periphery of the Amazon Rainforest. *Recent Patents on Food, Nutrition & Agriculture*, 5 (1). doi.org/10.2174/2212798411305010011
18. Moura, E.G., Vaconselos, C.S., Coelho, K.P., Nunes, J.F., Losch, E.L., Oliveira, L.G.S., Pereira, E.R.C., Aguiar, A.C.F. (2023). Refining the Use of Ecosystem Services to Increase Sustainability and Resilience in Tropical Agriculture. In: Gervasi, O., et al. *Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science*, 14106. pp 551–563. Springer, Cham. doi.org/10.1007/978-3-031-37111-0_38
19. Nunes, F.J., Campos, L.S., Aguiar, A.D.C.F., Mooney, S.J., Pimentel, K.A., Moura, E.G. (2024). Understanding how management can prevent degradation of the structurally fragile soils of the Amazonian periphery. *European Journal of Agronomy*, 153. doi.org/10.1016/j.eja.2023.127037
20. Peech, M. (1965). Hydrogen-ion activity. In C.A. Black et al., Eds. *Methods of Soil Analysis. Part 2. American Society of Agronomy*, Madison, WI, pp. 914–926.
21. Porras, J., Giannakis, S., Torres-Palma, R.A., Fernandez, J.J., Bensimon, M., Pulgarin, C. (2018). Fe and Cu in humic acid extracts modify bacterial inactivation pathways during solar disinfection and photo-Fenton processes in water. *Applied Catalysis B: Environmental*, 235. doi.org/10.1016/j.apcatb.2018.04.062
22. Quaggio, J.A., Raij, B. van, Malavolta, E. (1985a). Alternative use of the SMP-buffer solution to determine lime requirement of soils. *Communications in Soil Science and Plant Analysis*, 16(3), pp 245–260.
23. Rahman, M.A., Lee, S.H., Ji, H.C., Kabir, A.H., Jones, C.S., Lee, K.W. (2018). Importance of Mineral Nutrition for Mitigating Aluminum Toxicity in Plants on Acidic Soils: Current Status and Opportunities. *International Journal of Molecular Sciences*, 8 19(10). doi.org/10.3390/ijms19103073

24. Raij, B. van, Quaggio, J.A., Silva, N.M. (1986). Extraction of phosphorus, potassium, calcium and magnesium from soils by an ion-exchange resin procedure. *Communications in Soil Science and Plant Analysis*, 17(5) pp.544–566.
25. Ramos, F.T., Carvalho, D.E.F.G., Weber, O.L.S., Beber, D.C., Campelo Jr., J.H., Souza Maia, J.C. (2018). Soil organic matter doubles the cation exchange capacity of tropical soil under no-till farming in Brazil. *Journal of the Science of Food and Agriculture*, 98(9). doi.org/10.1002/jsfa.8881
26. Rowley, M.C., Grand, S., Verrecchia, É.P. (2018). Calcium-mediated stabilisation of soil organic carbon. *Biogeochemistry*, 137 (1–2). pp 27–49. doi.org/10.1007/s10533-017-0410-1
27. Saud, S., Fahad, S., Yajun, C., Ihsan, M.Z., Hammad, H.M., Nasim, W., Alharby, H. (2017). Effects of nitrogen supply on water stress and recovery mechanisms in Kentucky bluegrass plants. *Frontiers in Plant Science*, 8. doi.org/10.3389/fpls.2017.00983
28. Schmidt, M., Torn, M., Abiven, S. et al. (2011). Persistence of soil organic matter as an ecosystem property. *Nature*, 478. pp 49–56. doi.org/10.1038/nature10386
29. Sena, V.G., Moura, E.G., Macedo, V.R., Aguiar, A.C., Price, A.H., Mooney, S.J., Calonego, J.C. (2020). Ecosystem services for intensification of agriculture, with emphasis on increased nitrogen ecological use efficiency. *Ecospher*, 11(2). doi.org/10.1002/ecs2.3028
30. Shabtai, I.A., Wilhelm, R.C., Schweizer, S.A., Höschen, C., Buckley, D.H., Lehmann, J. (2023). Calcium promotes persistent soil organic matter by altering microbial transformation of plant litter. *Nature Commun*, 14 6609. https://doi.org/10.1038/s41467-023-42291-6
31. Shahane, A.A., Shivay, Y.S. (2021). Soil Health and Its Improvement Through Novel Agronomic and Innovative Approaches. *Frontiers in Agronomy*, 3. doi.org/10.3389/fagro.2021.680456
32. Silva, A.N., Figueiredo, C.C., Carvalho, A.M., Soares, D.S., Santos, D.C.R., Silva, V.G. (2016). Effects of cover crops on the physical protection of organic matter and soil aggregation. *Australian Journal of Crop Science*, 10. pp1623–1629. doi.org/10.21475/ajcs.2016.10.12.PNE164
33. Soil Survey Staff (2014). *Keys to Soil Taxonomy*. [S.l: s.n.].
34. Song, Z., Liu, C., Müller, K., Yang, X., Wu, Y., Wang, H. (2018). Silicon regulation of soil organic carbon stabilization and its potential to mitigate climate change. *Earth-Science Reviews*, 185. pp 463–475. doi.org/10.1016/j.earscirev.2018.06.020
35. Sparks, D.L., Paga, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Summer, M.E. (1996). *Methods of soil analysis: Chemical methods. Part 3. Madison, Soil Science Society of America*, pp.961–1010.
36. Vysochyna, A., Stoyanets, N., Mentel, G., Olejarz, T. (2020). Environmental Determinants of a Country's Food Security in Short-Term and Long-Term Perspectives. *Sustainability*, 12(10):4090. doi.org/10.3390/su12104090

Figures

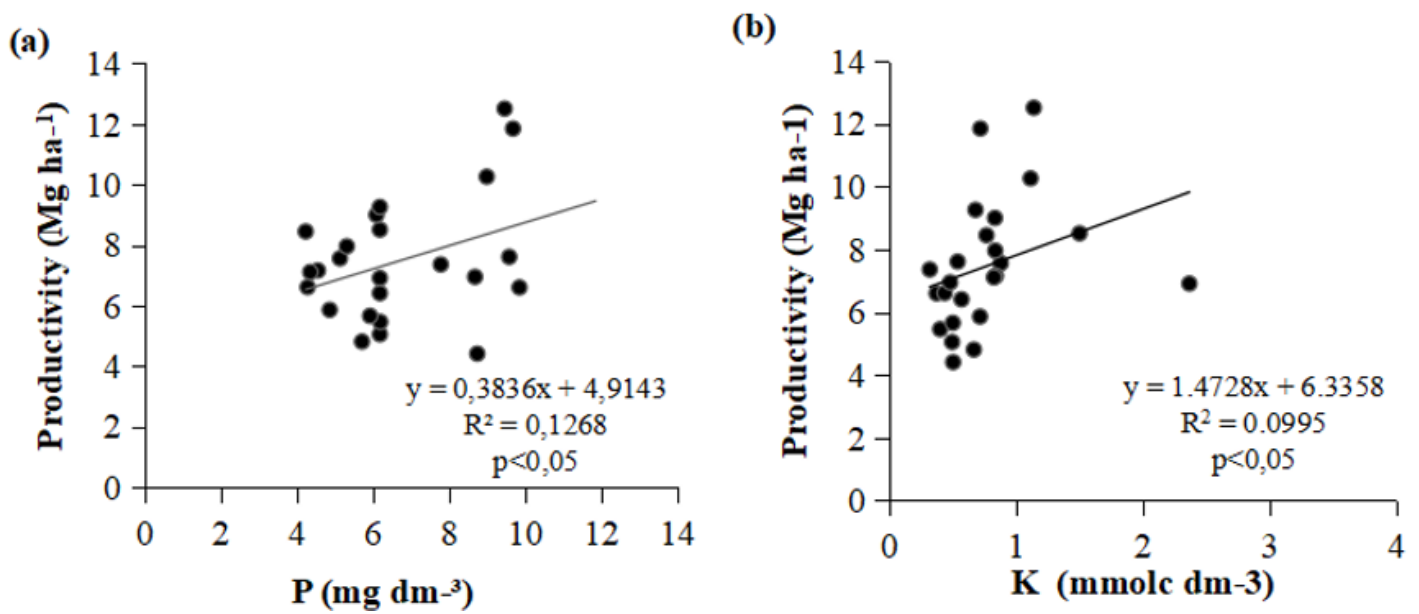


Figure 1

Linear regression analysis of soil phosphorus (a) and potassium (b) content versus maize grain yield

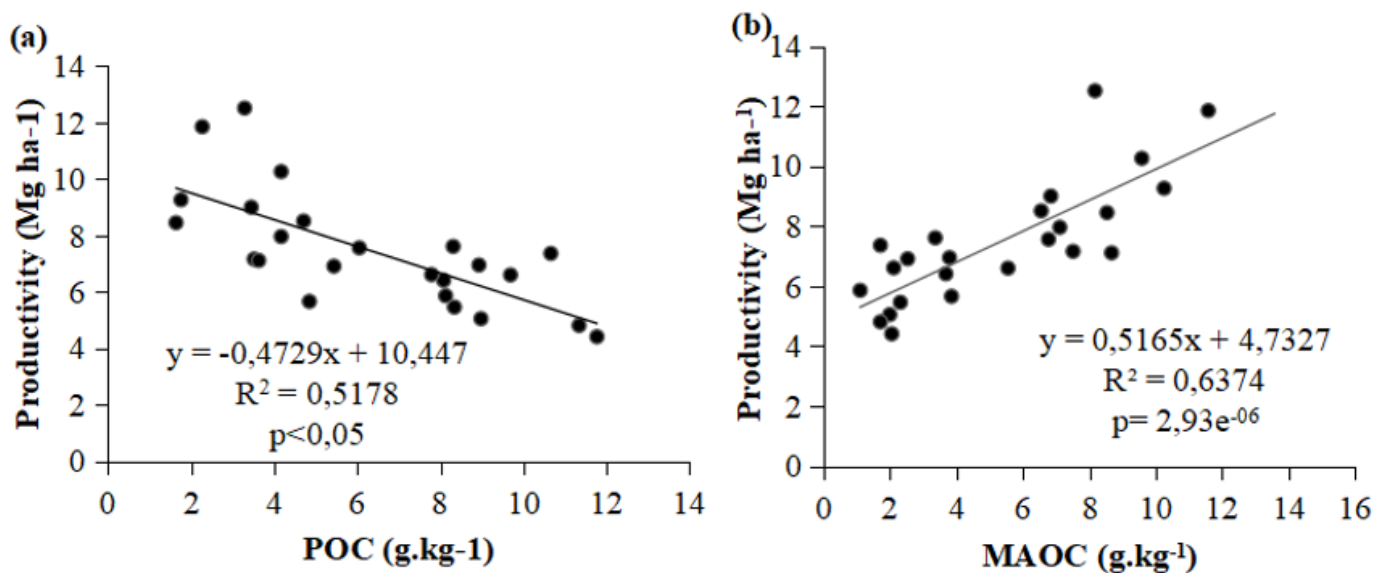


Figure 2

Linear regression analysis of particulate organic carbon (a) and organic carbon associated with minerals (b) versus maize grain yield

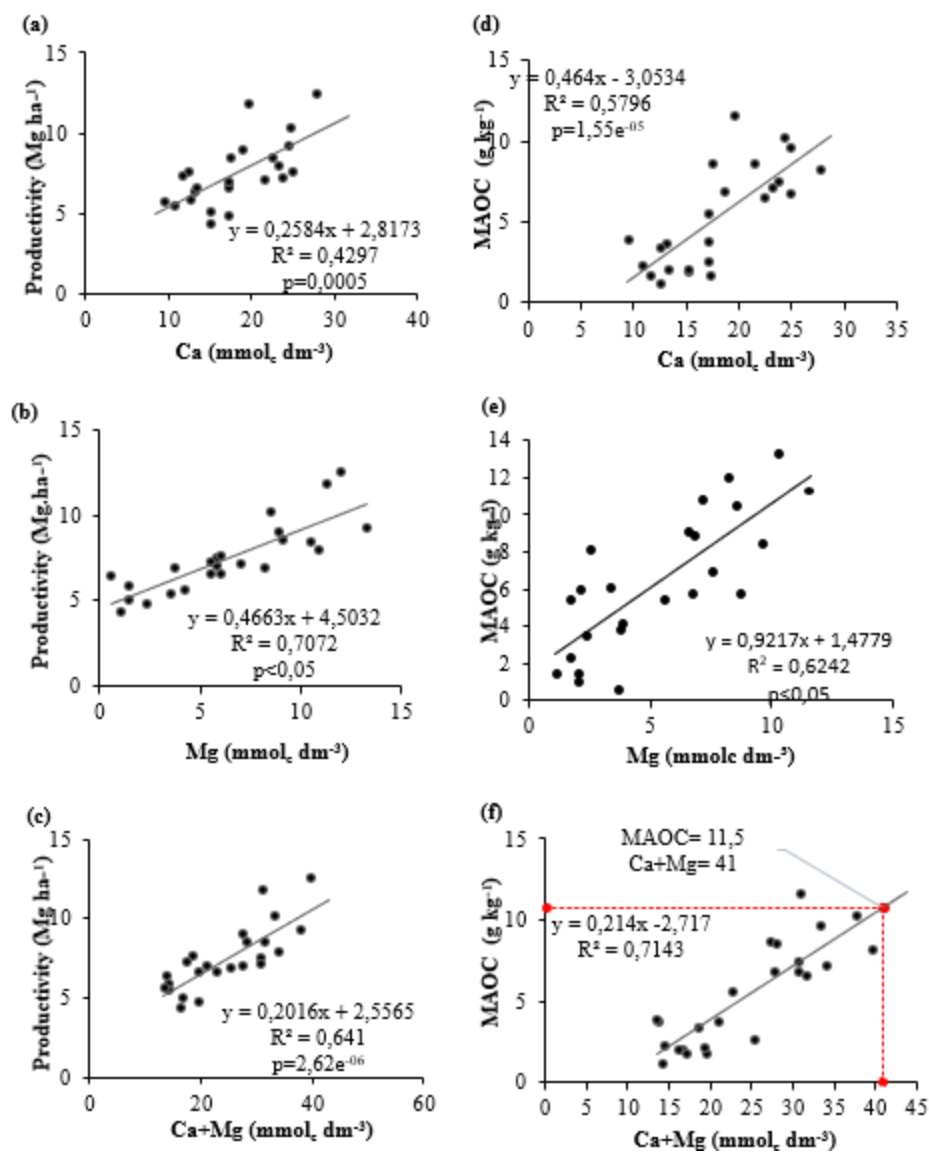


Figure 3

Linear regression analysis of calcium (a), magnesium (b), calcium plus magnesium (c) versus maize grain yield and calcium (d), magnesium (e), calcium plus magnesium (f) versus mineral associated organic carbon

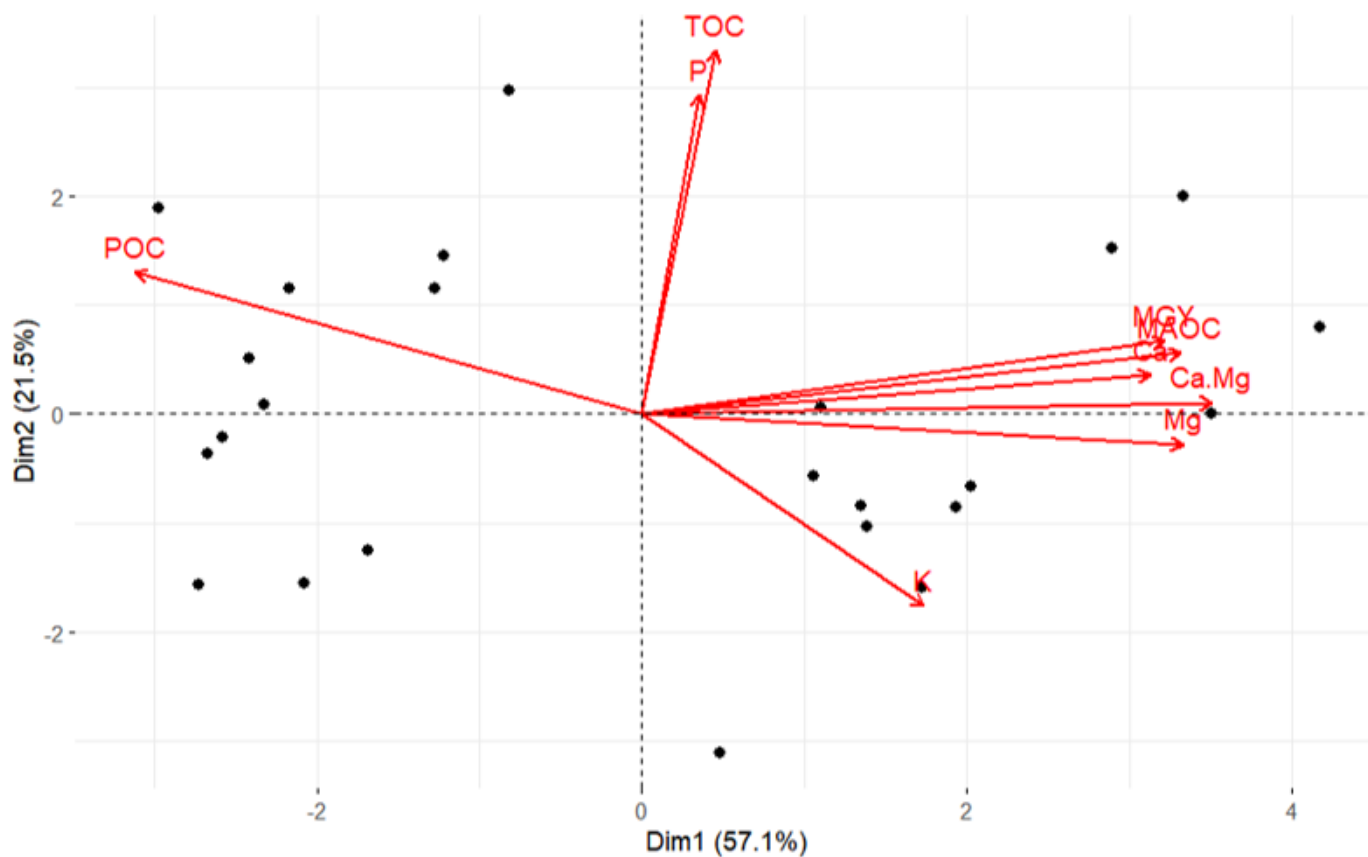


Figure 4

Principal component analysis (PCA) ordination plot of the importance of associations between chemical attributes of the soil and maize productivity. TOC (total organic carbon), POC (particulate organic carbon), MAOC (mineral associated organic carbon), Ca (calcium), Mg (magnesium), Ca.Mg (calcium plus magnesium), P (phosphorus), K (potassium) and MGY (maize grain yield)