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Sampling-based on plant vigor zones as a strategy for creating soil attribute maps

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Abstract.

Mapping agronomically relevant soil properties for fertilizer recommendation remains challenging in precision agriculture. Traditionally, this mapping is conducted through soil sampling on a regular grid basis, where points are equally spaced primarily to ensure spatial coverage. However, directing soil sampling points based on plant vigor may be more efficient in capturing soil variability that directly affects plant development. Several commercial platforms offer solutions for defining management zones for soil sampling or directing sampling points. These zoning strategies rely on auxiliary variables that are typically abundant, easy to obtain, and have some relationship with soil attributes. Each platform has its own characteristics and peculiarities. For this study, we tested a commercial platform that defines homogeneous zones based on vegetation vigor obtained from historical satellite imagery. We tested two sampling densities (1 sample/ha and 0.4 sample/ha) and evaluated their effect on mapping available phosphorus and potassium, as well as clay and sand content, in a sugarcane-cultivated area in São Paulo state, Brazil. Each sample point was positioned at the centroid of the vigor zones. Subsequently, after simulating the sampling grids, we performed interpolation using ordinary kriging. Validation against external data points allowed us to compare the predictive accuracy of the mappings. Directing soil sampling points based on vegetation vigor zones suggested by the commercial platform resulted in more precise soil maps compared to those generated by regular grid sampling. Therefore, directing soil sampling based on plant vigor emerges as an alternative to optimize sampling grids and reduce costs.

Keywords.
Digital Soil Mapping, Soil Fertility, Sample Optimization

Introduction

Soil property mapping to guide variable-rate fertilization is commonly carried out using regular sampling grids (Brus 2019). The regular grid ensures homogeneous spatial coverage, guaranteeing a good representation of the entire field, with regular spacing predetermined by the samplers. In sample planning, the variation in the number of sample points is usually predetermined by those conducting the work, primarily due to financial and/or operational constraints. In Brazil, the sampling grid size varies greatly depending on the region and the producer's profile (Molin 2017). However, this "usual" management contradicts the ideal grid size recommendations, which should be based on the variability of the attributes of interest, compromising decision-making regarding fertilizer doses to be applied in the fields (AmaraL and Justina, 2019; Cherubin et al. 2014; Nani et al. 2011).

Several studies have sought to optimize sampling grids to obtain more accurate digital soil maps (Baio et al., 2023). Some promising approaches are based on directing sampling points using auxiliary terrain information that shows a spatial relationship with the soil variables to be mapped (Pusch et al. 2023; Wang et al. 2023). One of the challenges in the sample planning stage is determining, in a coherent way, where these samples should be allocated. One method that can be used is the application of environmental variables that correlate with the target attributes, allowing the variability of one to be inferred from the other, given that the former commonly incur lower costs for abundant data collection. Thus, using vegetative vigor as a guide for sampling points can be interesting, as the variability of soil attributes influences it.

Several commercial platforms offer services related to the management practices of the target attributes of the study, assisting in the collection of soil samples. Some, for example, allow the creation of vegetative vigor zones based on the historical data of the area measured by automatic satellite image selection. Based on this, the platform's algorithm allows for the creation of sampling zones according to user demand in terms of size and complexity, thus establishing soil sampling points. However, this sampling point allocation method generates an irregular grid, hindering spatial interpolation (Soares 2014). Moreover, it depends on the historical vegetative vigor related to the soil properties intended to be mapped (Pusch et al. 2023).

The general objective of this research was to test whether directing sampling points based on these homogeneous zones of plant vegetative vigor can produce more accurate digital soil maps compared to traditional ones from regular grids, as well as to evaluate whether sample density impacts the results of sampling point direction.

Material and Methods

The experiment was conducted in a commercial sugarcane field (20°51'42" S and 47°57'15" W) in the municipality of Sales Oliveira, São Paulo, Brazil. The study area covers 78 hectares and has been cultivated for ten years without soil tillage. The predominant soil in the area is Ferralson, and the climate is classified under the Köppen system as Aw - tropical mesothermal, with an average annual temperature of 22°C and an average annual precipitation of about 1300 mm.

A digital commercial platform was used to define the zones of vegetative vigor, which groups areas with similar vigor (OneSoil®). Since this study involved two different sampling densities, zones of 1 ha and 2.5 ha were created, ensuring each zone received a sample collection point directed to its centroid. Both the directed grids were compared with regular grids of the same density to test which one performed better in characterizing the soil attributes of agronomic interest. The total number of sample points was 61 for the density of 1 point per hectare and 29 for 1 point per 2.5 hectares. The sampling grids were interpolated using the ordinary kriging method. External validation sampling points with known values were compared with the values estimated by the interpolation using RMSE and Spearman's correlation to observe which had the lowest sampling error. The research flowchart is represented in Figure 1.

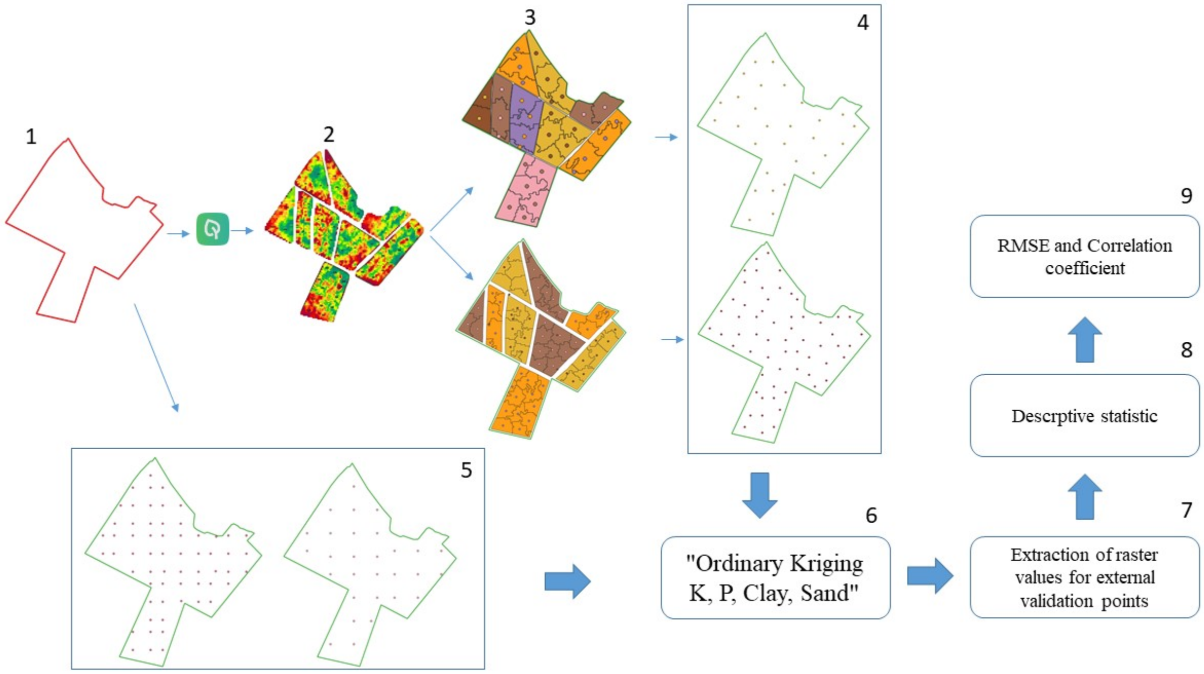

Figure 1. Experimental design: 1) Delimitation of the area and importation of the field boundary into the digital platform; 2) Creation of the vegetative vigor map; 3) Generation of vegetative vigor zones of 1 ha and 2.5 ha; 4) Each zone received 1 sample point, thus creating two directed grids of 29 and 61 ha; 5) Two regular sample grids were created with the same number of points as the directed ones; 6) The regular and directed grids were interpolated using ordinary kriging; 7) The rasters of the interpolations had their values extracted according to the coordinates of the external validation points; 8) The estimated values of the sample points underwent descriptive statistics; 9) The estimated values of the points were compared with their actual values using RMSE and correlation coefficient.

In the entire study area, dense soil sampling was carried out using a regular sampling grid of 40 by 40 meters, corresponding to 6 sampling points per hectare, totaling 450 points (Figure 2). Each sampling point consisted of a composite sample made up of six subsamples collected at a depth of 0 to 25 cm within a five-meter radius of the central point. The composite samples were sent to a commercial soil analysis laboratory for the determination of Phosphorus (P) and Potassium (K) levels, as well as soil texture (clay and sand). The descriptive statistics of the analyses are presented in Table 1.

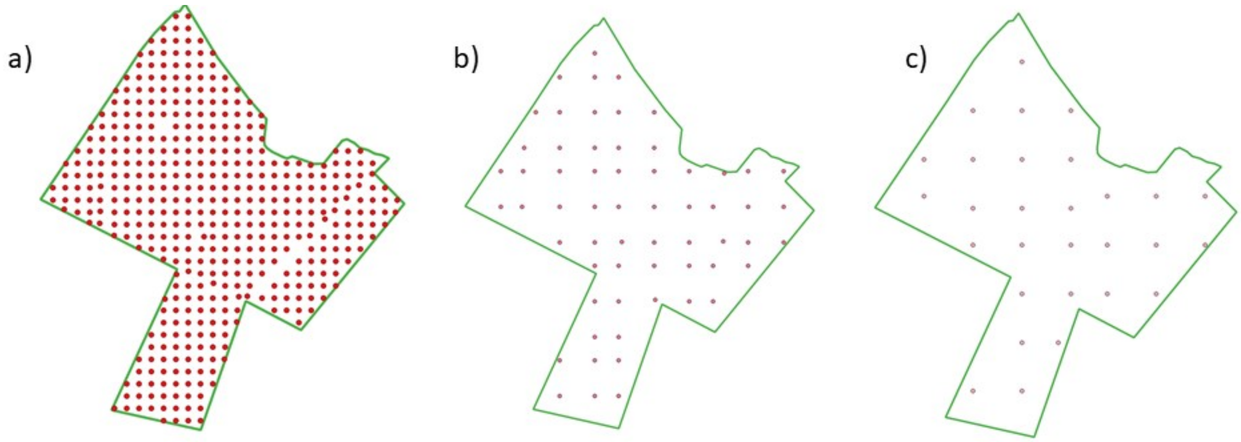

Figure 2. Study Area and the sampling scenarios: total sampled points (a), on sample per ha regular grid (b), and 0.4 samples per ha regular grid (c).

Table 1. Descriptive statistics of the complete sampling for phosphorus, potassium, sand and clay content in the study area.

	Mean	Median	St.Deviation	C.V	Minimum	Maximum
Clay	530.16	531.50	36.14	6.82	426.00	626.00
K	1.42	1.30	0.37	26.07	0.80	3.30
P	15.06	14.00	6.76	44.90	6.00	45.00
Sand	125.50	121.00	27.86	22.20	79.00	256.00

In this study, we tested two sampling densities: a denser one (1 sample per hectare), typically recommended in the literature (Cherubin et al. 2014), and a sparser one, reflecting some observed situations in Brazil (1 sample every 2.5 hectares). Thus, we simulated two regular grids according to these pre-established densities (Figure 2b - Figure 2c). We used the same sampling densities to compare the mapping results, but the sampling points were directed by the plant vigor map provided by a commercial platform. We imported the shape of the area's fields into the platform, and it's important to note that for each field's perimeter creation, we applied a buffer of -10 meters from the original perimeter to avoid edge contamination due to reflectance from the access roads. After deducting the area of the access roads and the buffer, we obtained 61 hectares divided into nine fields. We then set up two sampling plans in the platform: one by creating 61 zones of approximately 1 hectare each and another by creating 29 zones of around 2.5 hectares each, with each zone containing a sampling point at its centroid, representing both sampling densities (Figure 3a - 3b). These points were selected based on the manual selection of points from the original grid of 450 samples.

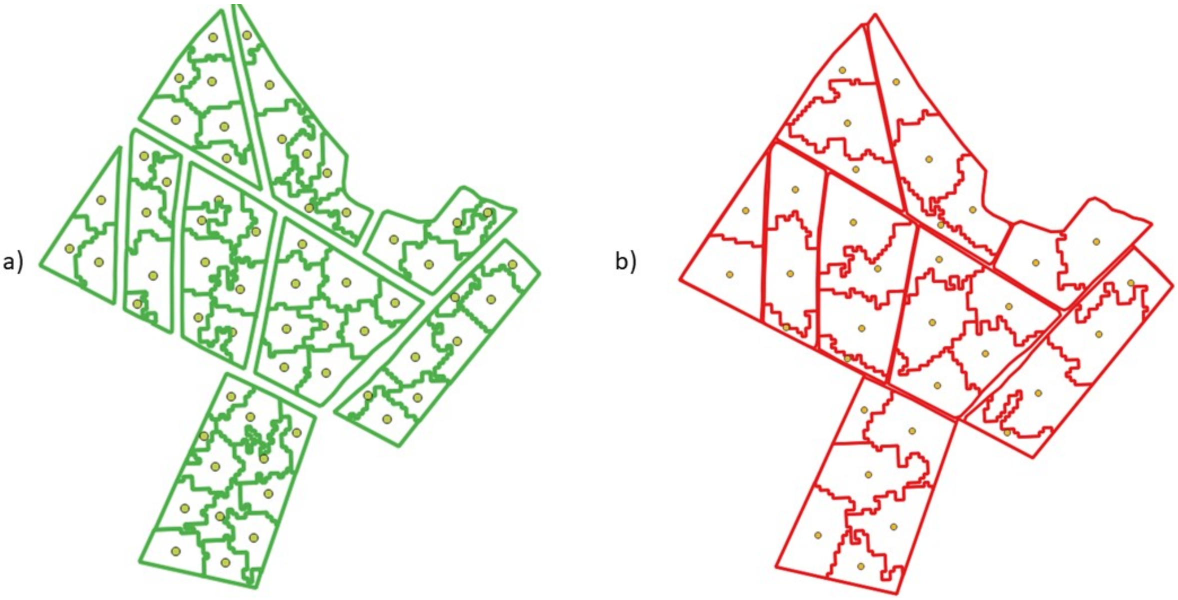

Figure 3. Vegetative vigor zones and sampling point allocation obtained through the commercial platform. Density of 1 sample per ha a) and 0.4 samples per ha b).

All grids were interpolated using Ordinary Kriging method with the geostat package in R. The attributes estimated by interpolation were K, P, Clay, and Sand, as they are important variables for agricultural management and fertilizer recommendation. The sample points from the total grid that were not used in the tested grids were used as external validation samples (n = 336).

Results and Discussion

The targeted grid with a density of one sample per hectare yielded the best prediction results compared to the regular grid of the same density (Figure 4), due to the irregular spacing of points allowing for a more precise characterization of soil variations at short distances in the initial lags of the variogram (Teixeira et al. 2017). Similarly, the sparser grid also showed better results for targeting, except for mapping available soil potassium. For Ordinary Kriging interpolation, it is recommended that the dataset include at least 50 samples (Oliver and Webster 2014), which is the case for the 1 ha grid (n = 61). However, since this study aimed to simulate the reality commonly practiced in digital soil mapping in Brazil (Molin 2017), where the sample density was lower (0.4 samples per ha), the grid comprised only 29 samples. Despite this, evaluating the prediction results at the validation points (Figure 4 and Figure 5), it is observed that the predictive performance of the interpolations at different sample densities was similar. However, it is erroneous to generalize that the difference in results between different grid densities will repeat in other areas, as this may be due to the low variation in data, as observed for sand, clay, and potassium (CV = 22.2%, 6.81%, and 26.07%), which does not make the soil as heterogeneous (Table 1).

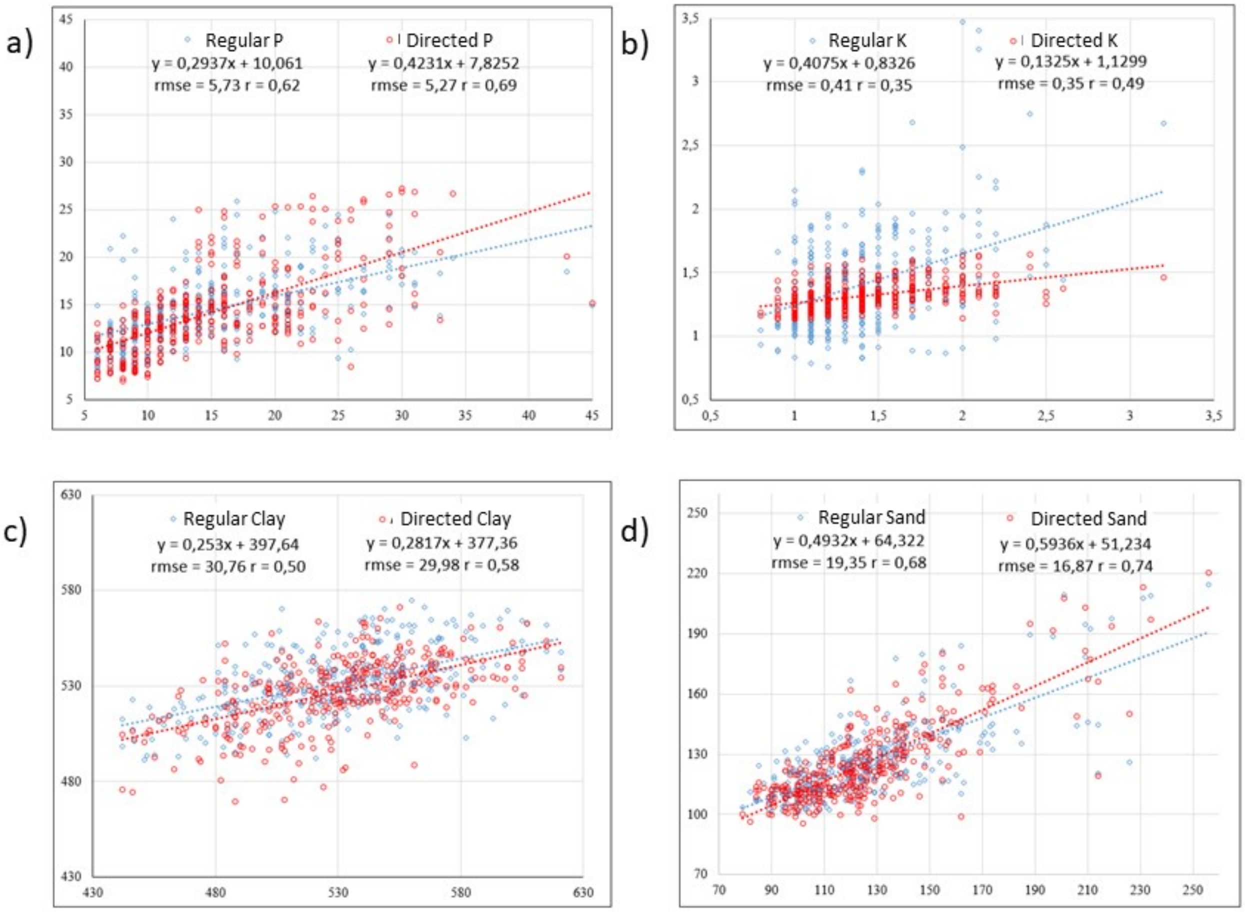

Figure 4. Scatter plots between predicted and observed values in the external validation samples for the regular and directed 1 ha sampling grids, for the attributes of phosphorus (a), Potassium (b), Clay (c), and Sand (d), also showing the performance of the interpolations (RMSE and correlation coefficient).

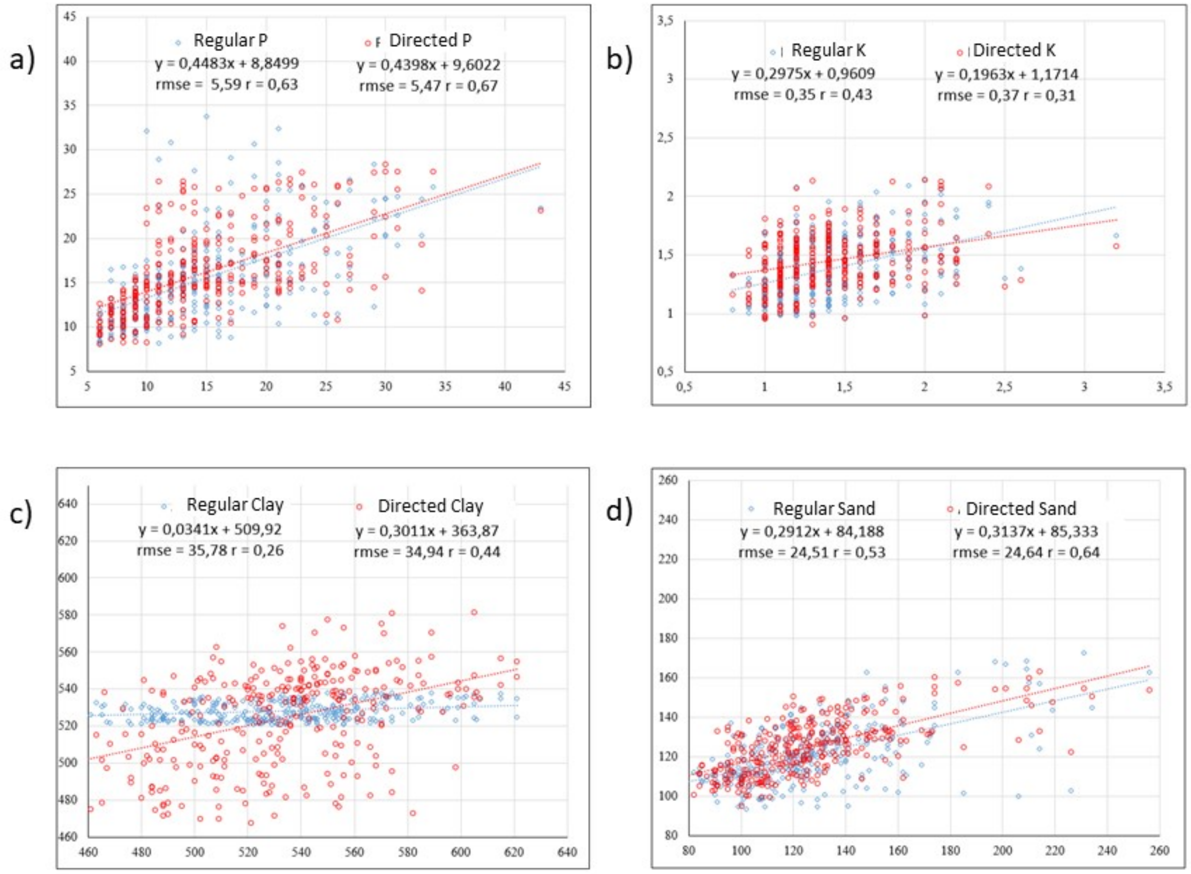

Figure 5. Scatter plots between predicted and observed values in the external validation samples for the 0.4 ha regular and directed sampling grids for the attributes of phosphorus (a), Potassium (b), Clay (c), and Sand (d), also presenting the performance of interpolations (RMSE and correlation coefficient).

There were no predictive gains when targeting points in the lower-density sampling grid for mapping K (Figure 5). The spatial dependence of potassium content was low for this grid, even in the denser grid (1 ha), indicating a high nugget effect and low contribution, as observed from the variograms (Figure 6b). The poorer results for K seem to be associated with the poorer fit of the variograms (Figure 7b), since the directed grid does not prioritize equidistance between samples. Sugarcane cultivation requires large quantities of this nutrient (Cantarella et al. 2022), generally applied at fixed rates across areas. Therefore, due to over-fertilization cycles, the spatial distribution of this attribute becomes more random due to management and crop uptake. Thus, in this case, using a regular grid would be more suitable as it covers the entire area uniformly.

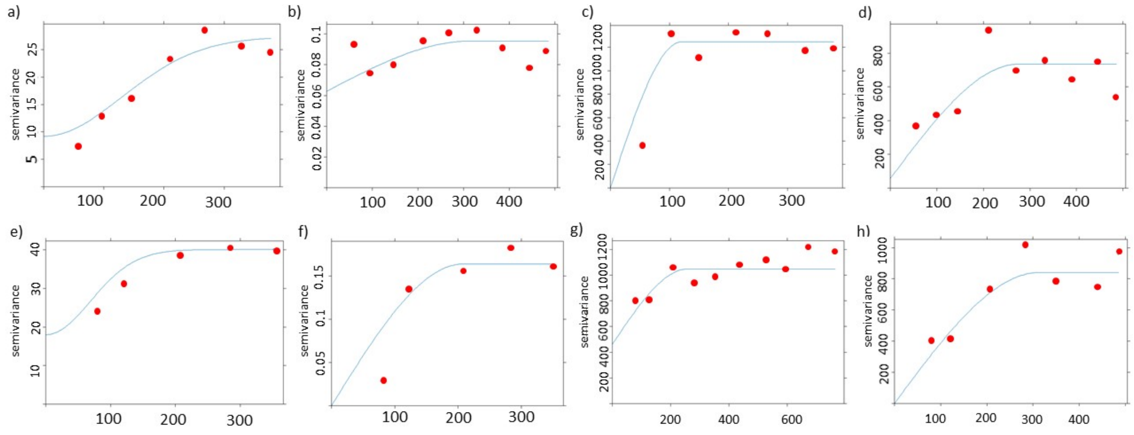

Figure 6. Variogram models fitted to the data from the directed 1 ha sampling grid of available phosphorus (a), potassium (b), clay (c), sand (d), and from the regular grid of available phosphorus (e), potassium (f), clay (g), and sand (h).

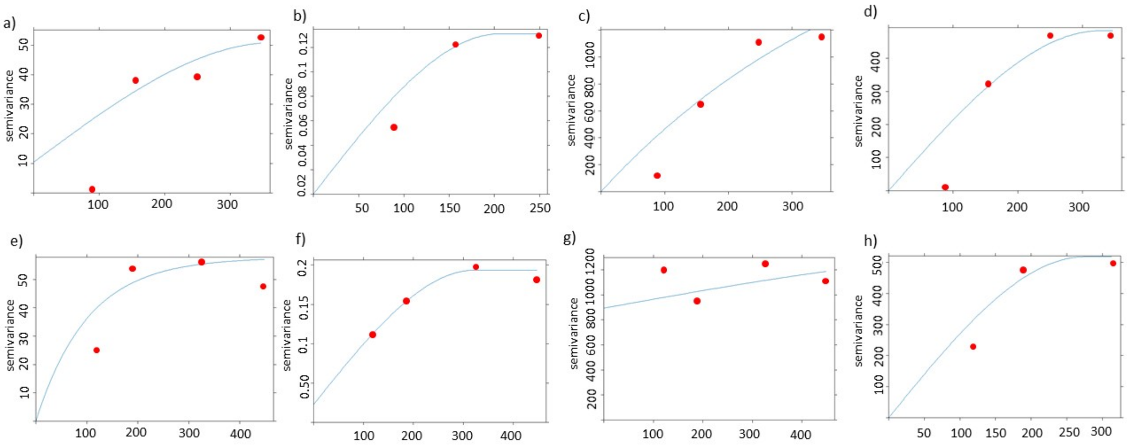

Figure 7. Variogram models fitted to the data from the directed 0.4 points per ha sampling grid of available phosphorus (a), potassium (b), clay (c), sand (d), and from the regular grid of available phosphorus (e), potassium (f), clay (g), and sand (h).

For the texture maps, directed sampling also resulted in lower prediction errors and higher similarities with actual values of the regular grid (Figures 4c and 4d - 5c and 5d). Texture exhibits higher spatial stability, with less likelihood of abrupt value changes over short distances, and it undergoes minimal alteration over time. In this case, these maps may warrant higher sampling investment since there's no need for future sampling repetitions for this purpose. However, if financial costs are a constraint, directed sampling showed a closer resemblance to actual values than regular sampling in the smaller grid size, making it a viable alternative for soil texture sampling.

The importance of vegetative vigor in aiding texture characterization can be attributed to its ability to govern nearly all soil attributes (Katerji and Mastrorilli 2009; Kong et al. 2009; Kettler et al. 2001). These authors emphasize that water-holding capacity, soil fertility, and organic matter dynamics are influenced by textural variation. Consequently, these factors are correlated with plant vigor, allowing for directed sampling to utilize historical vegetative vigor measured by platform methodology.

The characterization of phosphorus through directed sampling was more effective than regular sampling at both densities (Figure 4a and 5a). This targeting allows for better identification of areas with pronounced variations, unlike the regular grid, which tends to smooth estimates due to the absence of smaller lag distances (Figures 4e and 5e). Other authors have also found improvements in estimating certain chemical attributes by directing sampling based on auxiliary variables (Pusch et al., 2023; Pusch et al., 2022; Wang et al., 2023). However, these authors emphasize the need to consider specific parameters, such as the correlation between auxiliary variables and the target attribute, to enhance mapping accuracy truly. In this study, the improvement in predictions aligns with these authors, particularly in the sparser grid, as using auxiliary information mitigates the effect of reduced soil property sampling density (Teixeira et al. 2017). Thus, the zones of vegetative vigor grouped by the platform differentiate regions with significant differences in vigor across crop cycles. It is well known that phosphorus is crucial in vegetative growth and starch accumulation in leaves (Taiz et al., 2017). Therefore, areas of the field with high phosphorus availability correlate with plant vigor, a characteristic detectable through orbital imaging, which groups zones based on this effect, thereby enhancing accuracy in mapping this chemical attribute. Consequently, the directed map more precisely captured the spatial variability of phosphorus, resulting in better agreement with observed values in independent validation data at both densities (Figure 4a – Figure 5a).

Conclusion

Considering vegetative vigor zones to deduce homogeneous soil zones and subsequently directing soil sampling points based on them proves to be an option to improve soil attribute mapping compared to traditional regular grids. Thus, the sampling methodology using vigor zones from commercial platforms is an interesting option. However, in some situations, the expected improvement in mapping may not occur, demanding further studies to understand the data characteristics that prevent this improvement.

Acknowledgments

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