Management zones from proximal soil sensors capture within-field soil property and terrain variations

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Abstract
The objectives are to delineate soil management zones from soil proximal sensor data, and compare soil property values among zones in a 72-ha crop field in southeastern Brazil. Apparent electrical conductivity (aEC) and magnetic susceptibility (aMS), and equivalent Th (eTh) and U (eU) were measured across the field by a Geonics EM38-MK2 and a Medusa MS1200 sensors, respectively. These properties were kriged and used as input for delineating three management zones by fuzzy k-means clustering. Soil properties were measured at 0-10 cm at 72 sites, and their means were compared among the zones. Soil clay, organic C and exchangeable Ca and Mg vary significantly among the zones, according to Brown-Forsythe and Games-Howell tests (p=0.05), while pH, available P and exchangeable K do not. Zone delineation from proximal sensor data constitutes an efficient data-driven approach to separate the field into meaningful parts for soil, irrigation and crop management based on soil variation.
Keywords: Geophysics; Electrical conductivity; Gamma radiometrics; Geostatistics; Precision agriculture

Introduction

Site-specific crop management has been proposed as an alternative to conventional cropping that accounts for the within-field variation of soils, relief, crops and other factors aiming to increase profitability by increasing productivity, optimizing inputs and minimizing negative environmental impacts. This can be accomplished by splitting the field into homogeneous zones, so-called management zones, based on the variation of soils and/or other factors across the field. Then, each zone is managed differently by varying the rates of sowing, fertilizers, amendments, pesticides, irrigation, and other inputs, according to the characteristics of the zone.

However, assessing the soil variation can be costly if soil samples are taken on a grid with, say, one sample per hectare. Proximal and remote sensors can efficiently provide input soil data for management zone delineation, expediting sampling and reducing costs by measuring (usually electromagnetic) soil properties at many (hundreds to thousands) sites covering the field in a single survey. These sensors have been used in different regions and soil types to delineate management zones (BENEDETTO et al., 2013; HAGHVERDI et al., 2015; SCUDIERO et al., 2018; ORTUANI et al., 2019; VALLENTIN et al., 2020).

Thus, the objectives are to: (a) delineate soil management zones from soil proximal sensor data; and (b) compare soil property values among zones.

Methodology

The study was conducted in a 72-ha crop field under no-till crop rotation system and central pivot irrigation located in Itaí, São Paulo, southeastern Brazil, with central coordinates 23.5854° S and 48.9395° W. Soils in the area are *Latossolos* (Oxisols, Ferralsos).

To delineate soil management zones, a EM38-MK2 sensor (Geonics, Mississauga, Canada) (1-m coil spacing, vertical orientation) dragged on a rubber mat behind a pickup truck, and a MS1200 gamma radiometer (Medusa, Groningen, Netherlands) mounted on the bull bar of the truck, were used to take 4306 apparent electrical conductivity (aEC) and magnetic susceptibility (aMS), and 4896 equivalent thorium (eTh) and uranium (eU) measurements, respectively, along 25 parallel lines about 40 m apart across the field (Figure 1a). The four proximal sensor variables (aEC, aMS, eTh and eU) were kriged across the area with 5-m spatial resolution, and the kriged maps were used as input to delineate three soil management zones by fuzzy k-means clustering.

To compare soil property values among the delineated zones, a regular grid comprising one site per hectare (Figure 1a) was derived across the study area, and soil samples were taken at 0-10 cm at the 72 sites and analyzed for clay, organic C (OC), pH, available P, and exchangeable bases, according to Teixeira et al. (2017). Soil property means were compared among soil management zones by Brown-Forsythe tests (p=0.05), followed by Games-Howell post hoc tests (p=0.05).

Results and discussion

The spatial variations of aMS and eTh are very similar, and differ from those of aEC and especially eU (Figure 1b-e). The aEC, aMS and eTh variograms were best fitted by spherical models, while a Gaussian model was used for eU, explaining the smoother eU spatial patterns. Variogram ranges were 500, 495, 668 and 443 m for aEC, aMS, eTh and eU, respectively.

The distinct spatial features in the southwest portion of the area, observed in the aEC and aMS maps (Figure 1b, c), are due to the presence of a catchment area of a spring at the extreme southwest. This constitutes one of the delineated management zones (Figure 1f, "Southwest" zone). In comparison, the "North" zone has distinct eTh and eU values from the other zones, and the "Southeast" zone differs in aEC, aMS, eTh and eU from the other two zones (Figure 1b-e).

Soil clay, OC and exchangeable Ca and Mg vary significantly among the zones, according to Brown-Forsythe tests, with significant differences found between the "North" and "Southeast" zones for all of them, and between the "North" and "Southwest" zones for clay, according to Games-Howell tests (Table 1). Mean soil pH, available P and exchangeable K are not statistically different among zones, but P and K have noticeably larger means in the "Southeast" zone, especially against the "Southwest" zone, though they vary too much for the differences to be statistically significant (Table 1).

The "North" and "Southwest" zones could be merged based on the similarity of aMS and eTh (Figure 1c, d), and of soil properties at 0-10 cm (Table 1). However, the

“Southwest” zone has steeper slopes and higher clay content as it encompasses a catchment, while the “North” zone has plain terrain and smaller clay content. Also, the “Southwest” zone has wetter soils, due to its relief position, which is evident from the aEC map (Figure 1b). Thus, keeping the “Southwest” zone apart from the other zones for soil and irrigation management is recommended.

On the other hand, the northernmost portion of the area has similar aEC, aMS and eTh values to the “Southeast” zone (Figure 1b, c, d, f) in contrast to the “North” zone where it belongs. It also has higher clay, OC, Ca, Mg and K compared to the rest of the “North” zone (not shown). Thus, it could be split from the “North” zone, and whether managing it separately is worth the extra effort could be evaluated.

Conclusions

Proximal soil sensors capture soil variation patterns across the field, providing a large amount of data that can be used to delineate soil management zones efficiently. The properties the sensors measure (aEC, aMS, eTH and eU) are affected by the soil constituents and by relief and water dynamics, and thus, they indirectly carry information on soil formation factors and processes, which is encapsulated in the delineated zones, reducing the need for extra data.

In turn, the proposed delineated zones need to be judged from: a soil perspective with the aid of field soil samples besides proximal sensor data; a terrain perspective, if the area has variable, irregular terrain, which is the case in the “Southwest” zone; and from an agronomic and logistic perspective, pondering soil, irrigation, and crop management. As such, the results presented in the study are open for discussion, field testing and decision making, for which the farmer needs to be involved.

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Table 1. Variation of soil properties among management zones. Equal letters indicate equal means among zones, according to Games-Howell tests at p=0.05.

Property	N	Mean	Stdev	N	Mean	Stdev	N	Mean	Stdev
	North			Southeast			Southwest		
Clay (g kg^{-1})	33	392^b	49	27	430^a	38	12	433^a	21
OC (g kg^{-1})	33	14^b	1	27	16^a	1	12	15^{ab}	2
pH	33	6.6^a	0.3	27	6.6^a	0.3	12	6.4^a	0.4
P (mg dm^{-3})	33	141^a	83	27	151^a	63	12	127^a	55
Ca (cmol$_c$ dm^{-3})	33	6.0^b	0.8	27	6.7^a	0.8	12	6.4^{ab}	1.0
Mg (cmol$_c$ dm^{-3})	33	1.8^b	0.2	27	2.1^a	0.3	12	1.9^{ab}	0.3
K (cmol$_c$ dm^{-3})	33	451^a	880	27	583^a	1094	12	197^a	52

N, number of observations; Stdev, standard deviation.

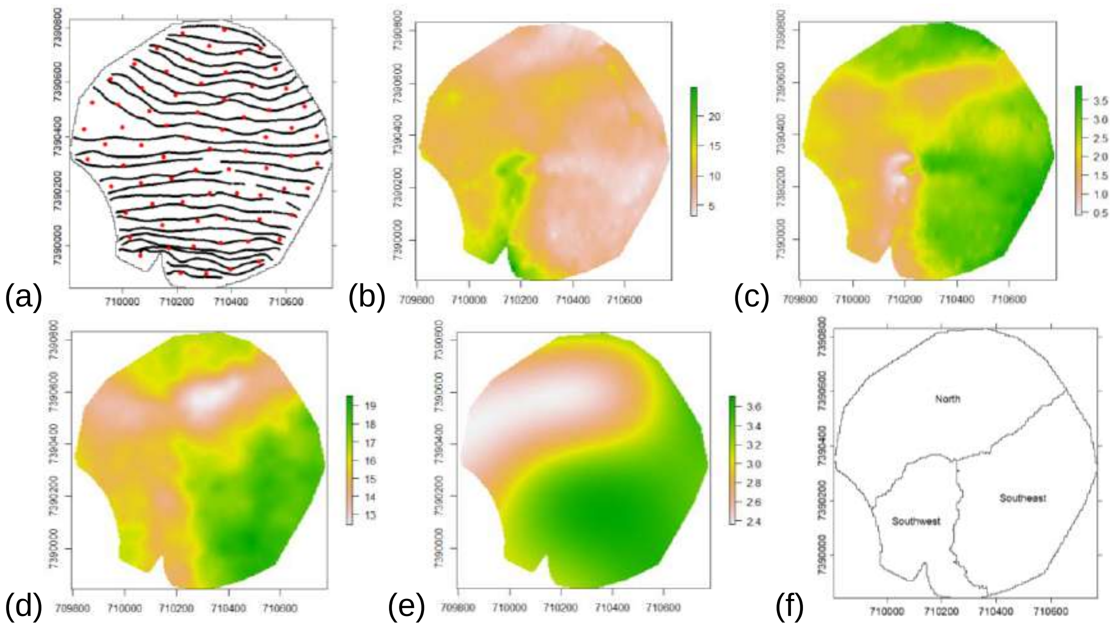

Figure 1. (a) Proximal sensor survey lines (black lines) and soil sampling sites (red dots); (b-e) Kriged maps of aEC (mS m^{-1}), aMS (ppt), eTh (ppm) and eU (ppm), respectively; and (f) Delineated soil management zones. Coordinates are in UTM zone 22S.