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Spatial variability of soil and vegetation properties in integrated production systems[1]

Variabilidade espacial de atributos do solo e da vegetação em sistemas integrados de produção

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HIGHLIGHTS:

Several potential sources of information support the accurate management of agricultural inputs.
Information on the spatial variability of soil and crop properties is essential for site-specific management.
The spatialization of wood yield and soil parameters in an integrated system helps understand spatial heterogeneity.

ABSTRACT: Integrated production systems have emerged as a sustainable production strategy in intensifying land use with minimal impact on ecosystem functions. This study used precision agriculture tools to investigate the spatial variability of soil and vegetation properties in an integrated crop-livestock-forestry (ICLF) and in an integrated livestock-forestry (ILF) area of São Carlos city, SP, Brazil. Consequently, the following were assessed: (1) the soil physicochemical properties, (2) the electrical resistivity, and (3) the attributes of the *Eucalyptus urograndis* crop comprising the study area. Samplings were performed in (1) August 2021 at depths of 0-0.2 and 0.2-0.4 m; (2) October 2021 at depths of 0-0.5, 0-1.0, and 0-2.0 m; and (3) April 2021 and April 2022. Results indicated that the values for soil fertility parameters were suitable for crop development and presented low spatial variability. Soil analyses indicated low acidity, high levels of organic matter, average cation exchange capacity, phosphorus and potassium contents, high base saturation, and calcium and magnesium levels. However, locations with greater spatial variability for calcium were observed, reflecting cation exchange capacity and base saturation variability. Soil granulometry and electrical resistivity had a low spatial variability at the surface layer. Even without differences in the soil properties, there was a difference of 15% in the larger wood volume in the ILF then ICLF system.

Key words: agricultural management, precision agriculture, spatial interpolation, sustainability

RESUMO: Os sistemas de produção integrados surgiram como uma estratégia de produção sustentável na intensificação do uso da terra com impacto mínimo nas funções do ecossistema. Este estudo utilizou ferramentas de agricultura de precisão para investigar a variabilidade espacial de propriedades do solo e da vegetação em área de Integração Lavoura-Pecuária-Floresta (ILPF) e área de Integração Pecuária-Floresta (IPF) em São Carlos, SP, Brasil. Consequentemente, foram avaliados: (1) as propriedades físico-químicas do solo, (2) a resistividade elétrica, e (3) os atributos da cultura do *Eucalyptus urograndis* que compõem a área de estudo. As amostragens foram realizadas em (1) agosto de 2021 nas profundidades de 0-0,2 e 0,2-0,4 m; (2) outubro de 2021 nas profundidades de 0-0,5, 0-1,0 e 0-2,0 m; e (3) abril de 2021 e abril de 2022. Os resultados indicaram que os valores dos parâmetros de fertilidade do solo foram adequados ao desenvolvimento da cultura e apresentaram baixa variabilidade espacial. As análises de solo indicaram baixa acidez, altos teores de matéria orgânica, teores médios de fósforo, potássio e capacidade de troca catiônica e altos teores de cálcio, magnésio e saturação por base. Entretanto, foram observados locais com maior variabilidade espacial para cálcio, refletindo variabilidade na capacidade de troca catiônica e saturação por base. A granulometria e a resistividade elétrica do solo apresentaram baixa variabilidade espacial na camada superficial. Mesmo sem diferenças nas propriedades do solo, houve diferença de 15% no maior volume de madeira no sistema IPF em comparação ao ILPF.

Palavras-chave: gestão agrícola, agricultura de precisão, interpolação espacial, sustentabilidade

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INTRODUCTION

Currently, humanity is facing increasing challenges in the production of food, fiber, energy, timber, and non-timber products that are compatible with the availability of natural resources. Consequently, there is considerable demand for sustainable agriculture. According to sustainability concepts, agrosystems must maximize the quantity of high-quality agricultural products while preserving their natural resources (Lemaire et al., 2014). In this context, integrated crop-livestock-forestry (ICLF) systems have emerged as a sustainable production strategy (Polidoro et al., 2021) that provides an opportunity to intensify land use with minimal impact on ecosystem functions (Valani et al., 2020).

Regarding agricultural systems, soil and vegetation properties might vary spatially (Cambardella & Karlen, 1999), and understanding their spatial and temporal variability potentially enhances knowledge regarding different production systems to increase productivity and quality, conserve resources, and reduce environmental impacts (Bernardi et al., 2017; Feitosa et al., 2019; Souza et al., 2021; Babos et al., 2024). Spatial variability substantiates an agricultural management system called precision agriculture (PA), which is a management strategy that considers time and spatial variability to support management decisions to improve resource use, rational input, yield, quality, profitability, and sustainability of agricultural systems (Bernardi et al., 2015). Therefore, this study aimed to use PA tools to investigate the spatial variability of soil and vegetation properties in an integrated crop-livestock-forestry (ICLF) and in an integrated livestock-forestry (ILF) area of São Carlos city, SP, Brazil.

MATERIAL AND METHODS

The present study considered an experimental area of the Embrapa Pecuária Sudeste at São Carlos city, SP, Brazil (21° 57” S, 47° 51” W, altitude of 860 m). Local soil is a dystrophic Red Yellow Latosol (medium-textured), i.e., Hapludox (Soil Taxonomy) or Orthic Ferralsol (FAO), with a smooth undulating relief, class B (slope between 3 and 8%), according to Calderano Filho et al. (1998). The climate is humid subtropical with dry winter and hot summer (Cwa), according to Köppen's classification (Alvares et al., 2013), with two well-defined seasons: (a) A dry season from April to September with an average annual temperature of 19.9 °C, including a mean annual rainfall of 250 mm; (b) A wet season from October to March with an average annual temperature of 23 °C and mean annual rainfall of 1,100 mm (Pezzopane et al., 2021).

According to the planting history, the study area encompasses two systems (Pezzopane et al., 2021): (i) ICLF - Piatã grass pasture (*Urochloa brizantha*) planted with *Eucalyptus urograndis* (GG100) in single rows with 15-m spacing and a 2-m distance (333 plants ha^{-1}); and one-third of the pastures were renewed yearly with corn (*Zea mays* L.) intercropped with Piatã grass between trees; and (ii) ILF - pasture of Piatã grass planted with *Eucalyptus urograndis* (GG100) in single rows with 30-m spacing and a 4-m distance between trees (333 plants ha^{-1}). In both systems, the grass pastures were managed through a rotational system of 6-day grazing followed by a 35-day interval. Each integrated system reached 6 ha, half related to each experimental area, and was divided into six 0.5-ha plots (Figure 1). In 2016 and 2019, the systems were thinned to 50% of the remaining trees, resulting in 165 plants ha^{-1} (2016) and 83 plants ha^{-1} (2019) with 30 × 4 m spacing.

Between 2013 and 2021, lime and fertilizer recommendations were calculated based on soil analysis (Bernardi et al., 2017; 2019a). Liming was applied to increase the base saturation to 70% for the corn crops and 60% for the pasture; phosphate fertilizer (single superphosphate, 18% P_2O_5) to increase the soil P to 12 mg dm^{-3}, and potassium fertilizer (KCl, 60% K_2O) to increase the soil K to 3% of the cation exchange capacity. Nitrogen fertilization improved the production systems at an average of 110.9 kg N ha^{-1} per crop.

For the physicochemical analyses, six subsamples from each plot in the study area were collected during the dry season (August 2021). The subsamples comprise a composite sample georeferenced by the plot's centroid (Figure 1). The samples were collected at 0-0.2 and 0.2-0.4-m depths. The following properties were analyzed for each soil sample: granulometry (sand, clay, silt), soil pH in H_2O, soil pH in $CaCl_2$, organic matter (OM), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), cation exchange capacity (CEC), base saturation (V), and sulfate.

Electrical resistivity (ER) measurements of the soil used an Automatic Resistivity Profiling (ARP$^{®}$) system (Geocarta, Paris, France). Samplings were performed in October 2021 at depths of 0-0.5, 0-1.0, and 0-2.0 m, assayed by the previous methodology (Bernardi et al., 2019b), reaching approximately 480,000 values at each depth.

Height and diameter measurements at 1.3 m from the soil (Diameter at Breast Height - DBH) allowed for evaluating the *Eucalyptus* tree development from the study area. Measurements from 15 trees per plot were obtained from the experimental area in April 2021 and April 2022. These results estimated the *Eucalyptus* volume data using the Schumacher-Hall model (Pezzopane et al., 2021).

After removing the outliers from the set, an IDW interpolation was performed for each assessed attribute.

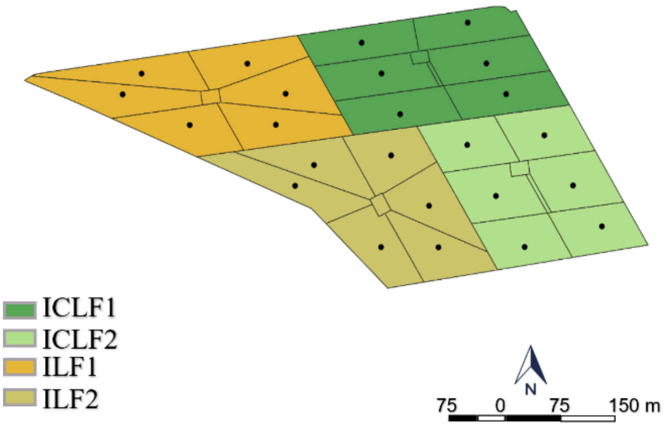

Figure 1. Study area: integrated crop-livestock-forestry (ICLF) and integrated livestock-forestry (ILF) systems in São Carlos city, SP, Brazil

After interpolation, the ranges of the dataset results for soil chemical properties and soil texture analysis were organized according to Raij et al. (1996) and Venegas et al. (1999). The values were equal-sized in sub-intervals using the equal interval classification method for the interpolated data of soil ER and vegetation properties. All statistical analyses were performed using the R software (R Core Team, 2021).

RESULTS AND DISCUSSION

The maps generated for pH in H_2O (Figures 2A and B) indicated that the interpolated values on the surface remained within the 6-7 range, except for two small areas in the ILF system, where the values were within the 5-6 range. For the subsurface, the values remained within the 5-6 range, apart

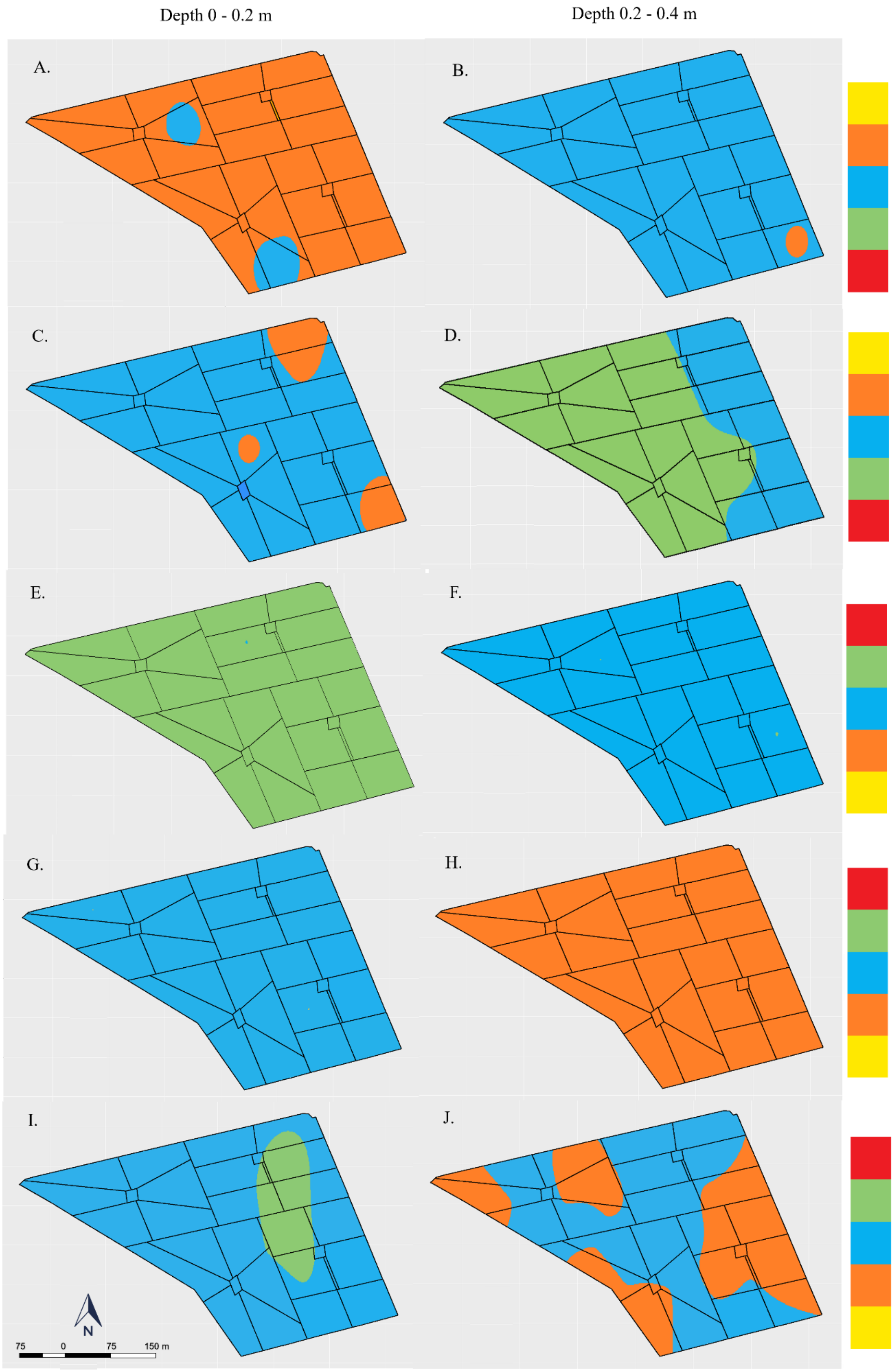

Figure 2. Spatial distribution of pH in H_2O (A and B), pH in $CaCl_2$ solution (C and D), organic matter (g dm^{-3} - E and F), phosphorous (mg dm^{-3} - G and H), and potassium (mmol$_c$ dm^{-3} - I and J) in ICLF and ILF systems in São Carlos city, SP, Brazil

from a tiny area from the ICLF system, where the values were within the 6-7 range. Therefore, the soil pH values in the area satisfy ideal conditions for nutrient availability (Venegas et al., 1999).

The pH values in the $CaCl_2$ solution (Figures 2C and D) were mainly within the 5-5.5 range on the surface and 5.5-6 in 2 small areas of the ICLF system, which was also observed in a small area of the ILF system. In the subsurface, however, for the ILF system, the pH was within the 4.3-5 range, which occurred in virtually half of the area corresponding to the ICLF system. However, the values remained at 5-5.5 for the other half.

The higher pH values on the surface could be explained by the positive effects of liming conducted annually in the area. Although lime was applied by plowing, a correction effect was observed in the total area without lime incorporation, particularly on the surface layer. Tiritan et al. (2016) and Rheinheimer et al. (2018) found that liming reduced soil acidity. In addition, the surface undergoes a more significant decomposition of organic matter (OM), which interferes with the soil pH (Mello & Vitti, 2002). The higher pH values in the ICLF system were probably derived from the greater storage of plant residues because corn was cultivated in addition to trees and pastures.

All the OM values (Figures 2E and F) on the surface were within the high range (green), whereas the values on the subsurface were within the medium range (blue). The OM of the soil contained an average of 58% organic carbon. According to Bernardi et al. (2023), the amount of organic carbon is directly associated with the amount of plant material in the soil, and long-term conservation management practices, such as this integrated system, can increase soil organic matter. According to Freitas et al. (2020), animal residues in the soil can also influence OM content. Therefore, the amount of OM in the area supported considerable diversification and plant residue production. The OM content would be higher at the surface because of the considerable deposition of residues on the soil surface layer (Salton et al., 2014). Furthermore, the OM is associated with generating adsorption sites on soil particle surfaces that increase the adsorption capacity of cations (K^+, Ca^{2+}, Mg^{2+}).

The P values (Figures 2G and H) on the surface were within the middle range (blue), whereas the values in the subsurface were within the low range (orange). The P availability is directly linked to the degree of weathering, mineralogy, texture, OM content, physicochemical characteristics, biological activity, predominant vegetation, and fertilization. Consequently, the higher P content on the surface layer is associated with, among other factors, the effect of annual surface application of phosphate fertilizer and greater OM levels in this soil layer (Bernardi et al., 2017; 2019a). The soil OM coats iron and aluminum oxides and hydroxides, thus blocking the adsorption sites on its surface and reducing its capacity to adsorb anions such as phosphate.

In contrast, the K values (Figures 2I and J) for most of the surface areas were within the middle range (blue color), with a few values within the considered high range (green color) in part of the ICLF system. The values were also within the middle range in most subsurface areas. However, in particular system regions, they are classified as low values (orange). Such differences among the depths occurred because potassium dynamics depend, among other factors, on pH, cation exchange capacity (CEC), and the relationship $Ca^{+2} + Mg^{+2}/K$, all of which regulate its availability (Tiritan et al., 2016; Rheinheimer et al., 2018). All these factors were present on a larger scale on the surface in the study area, implying a higher amount of K in the soil surface layer. This also explains the higher K values observed in some areas of the ICLF system.

The Ca results (Figures 3A and B) showed a significant difference at each depth, reinforcing the effect of surface liming and indicating that the effect of lime on depth was slower than that on the subsurface (Tiritan et al., 2016). In the ILF system, the surface showed patches of land within a very high range (red), one slightly larger patch within the high range (green), and two smaller patches within the middle range (blue). However, in the ICLF system, the entire region was within the very high ranges at the same depth. Conversely, the entire region was within the middle range of the subsurface. Although not very mobile, Ca is a highly recycled element in plant remains that linger in the soil. Furthermore, the soil moisture must be high for relatively rapid element decomposition. These factors explain the higher amount of Ca on the surface layer of the soil and the ICLF system because it produces more plant residues owing to its tillage component.

The superficial Mg content was very high range (red color) (Figures 3C and D) on almost the entire extension of the ICLF, whereas, in the area corresponding to the ILF system, the values were mainly in the medium range. However, the values were within the high range (green color) on a significant area extension. In contrast, the Mg values were lower in the subsurface, and virtually the entire extension of the ILF system showed contents within the middle range (blue color), whereas in the ICLF system, the values were intercalated between the middle and high ranges. The difference in Mg content between depths can be explained by the considerable amount of OM in the soil surface layer, in addition to the greater presence of dry biomass in the subsurface.

In the case of CEC (Figures 3E and F), the cation retention capacity of the area was medium (blue) to high (green) on the surface and medium on the subsurface. Owing to the higher OM content and pH, the surface showed a greater retention of cations than the subsurface. According to Baldotto & Baldotto (2018) and Bernardi et al. (2023), high levels of OM improve soil fertility by promoting changes in soil properties, including CEC. Regarding the spatial variability obtained for this attribute on the surface, higher CEC contents occurred mainly in the areas corresponding to the ICLF system because it involved more diverse plant residues by integrating all types of systems.

The base saturation (V) values (Figures 3G and H) on the surface intercalated between the middle (blue) and high (red) ranges, and the ICLF system showed a higher prevalence of high values than the ILF system. Nevertheless, the saturation values were lower on the subsurface, intercalating between the low (orange) and middle (blue) ranges, with values corresponding to the middle range appearing only in the ICLF system. The lower V on the subsurface is derived from the reduced presence of OM, Ca, Mg, and K as a function of depth

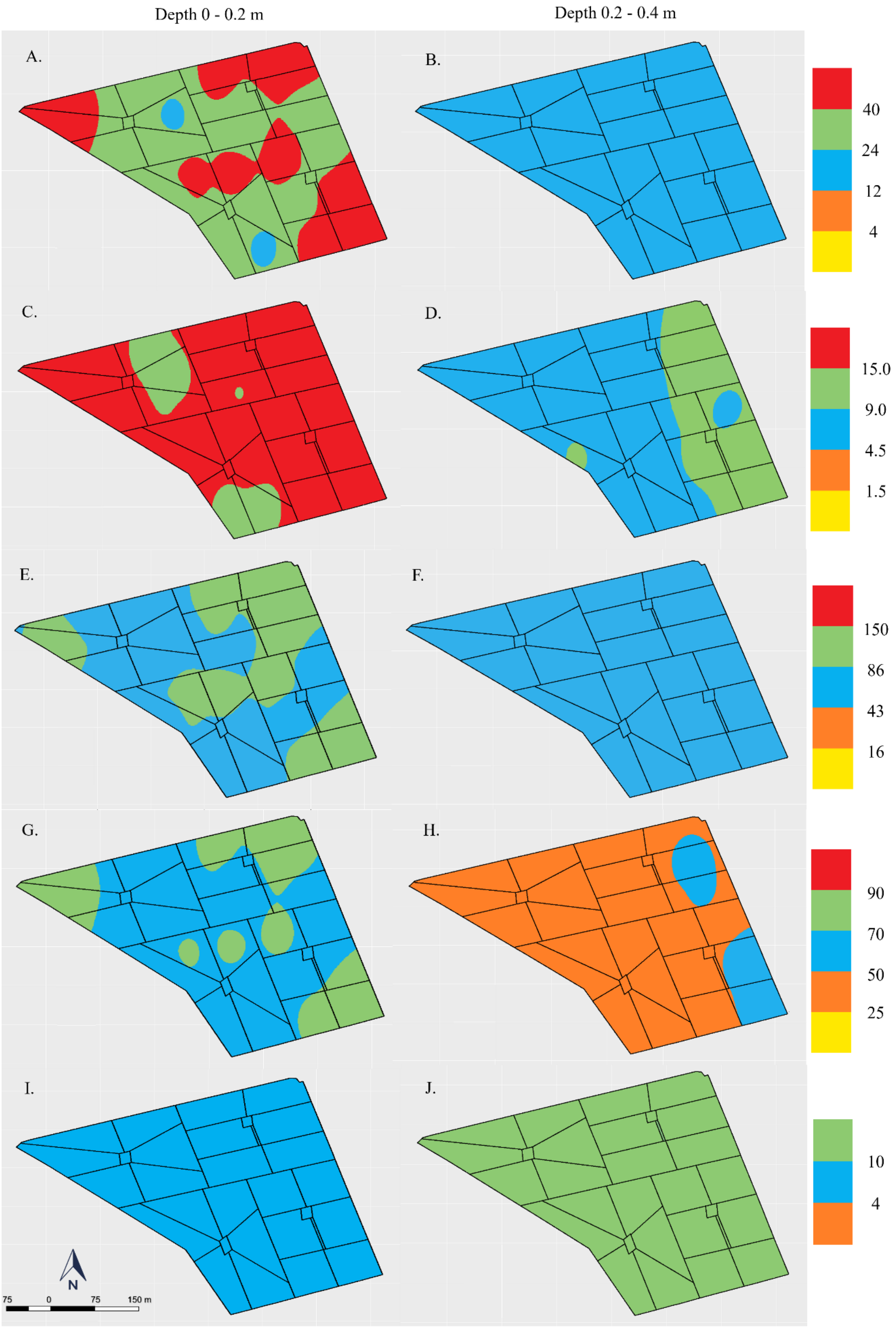

Figure 3. Spatial distribution of calcium (mmol$_c$ dm^{-3} - A and B), magnesium (mmol$_c$ dm^{-3} - C and D), cation exchange capacity (mmol$_c$ dm^{-3} - E and F), base saturation (% - G and H), and sulfate (mg dm^{-3} - I and J) in ICLF and ILF systems in São Carlos city, SP, Brazil

because saturation is directly associated with such elements (Tiritan et al., 2016; Rheinheimer et al., 2018). The higher saturation in the ICLF, when compared to the ILF, results from its greater Ca^{2+} and Mg^{2+} cations content because the V value is directly associated with these components.

In contrast, the amount of sulfate (Figures 3I and J) on the subsurface was relatively high, in contrast with the other chemical attributes assessed. Anion adsorption, such as sulfate, tends to be higher in soil subsurface layers of highly weathered soils owing to the low organic matter content

(Figures 2E and F), relatively low pH (Figures 2A, B, C, and D), and prevalence of Fe and Al oxides in the main surface of ionic exchange. Moreover, the cation exchange capacity (CEC - Figures 3E and F) is relatively low and may be surpassed by the anion exchange capacity (Havlin et al., 2016). However, the greater sulfate retention in subsurface layers of weathered soils, such as the one in the study, is important for fertility management because it can reduce anion losses through leaching. None of the depths showed any differences between the two production systems.

The results indicate that managing fertilization at varying rates adopted in the area (Bernardi et al., 2019a) has positively reduced variability. Babos et al. (2024) also pointed out that both systems (Integrated crop-livestock-forest and livestock-forest) had similar adequate fertility levels. Nevertheless, liming the site-specific application is justified.

Soil granulometry affects soil chemistry and hydric behavior. Regarding granulometric components, there were no differences between the sampled depths, as the amount of sand remained at 492 to 592 g kg^{-1} (Figures 4A and B), and the amount of clay and silt within the ranges of 297 to 398 and 23 to 166 g kg^{-1}, respectively (Figures 4C, D, E and F). The soil granulometry also presented very low spatial variability at both depths. Babos et al. (2024) related similar values to this study area. The results indicated that the soil under these integrated systems predominantly has a sandy clay texture. The proportion of the granulometric components (sand, silt, and clay) indicates that the soil of this study predominantly has a sandy clay texture. This homogeneity was already expected because the soil class below the integrated system under study (Red-Yellow Oxisol) presents a slight variation in the profile (Calderano et al., 1998). According to Valani et al. (2020) and Silva et al. (2021), the soil OM favors a more optimized structural quality of the soil and influences clay flocculation.

Electrical resistivity (ER) presents significant correlations with the amount of water and soil properties such as clay content, organic matter, and concentration of salts or humidity (Bernardi et al., 2019b; Santos et al., 2020b), and these parameters showed low spatial variability. Therefore, the observed values' low variability would be expected, particularly in the surface layer (0.5 m) evaluated by the equipment. Furthermore, the observed values for this area are close to those of Bernardi et al. (2019b).

Electrical resistivity (ER) values increased with depth (Figure 5). Bernardi et al. (2019b) studied soil ER in this integrated agricultural-livestock production system over two seasons (dry and wet) when soil resistivity decreased as water content increased. Therefore, the surface layers of the soil in the study area may have retained a considerable amount of water, as Bernardi et al. (2019b) reported.

The specific features of the integrated production systems could explain the lower ER values observed on the surfaces of both systems, indicating a high soil humidity. According to Fonseca et al. (2018), higher soil moisture is directly associated with the presence of vegetation because it helps maintain the environmental temperature, decreases the occurrence of sun radiation, and reduces the evaporation of water present in the soil surface layers (Santos et al., 2020b). In addition, the high OM on the surface of this integrated system is responsible for providing more optimized water retention by the soil, thereby increasing the moisture content (Bernardi et al., 2023). Additionally, for the 30 days preceding the ER data collection, the accumulated rainfall was 97.2 mm, indicating a relatively high amount of water in the soil. Finally, ER did not differ between the ICLF and ILF systems, considering that the value distribution of both systems was homogeneous in the study area.

Eucalyptus urograndis, used in the study area, is a hybrid derived from crossing *E. grandis* with *E. urophylla*. *E. grandis* is characterized by height growth, and *E. urophylla*, by diameter growth, promotes yield improvement and good-quality timber

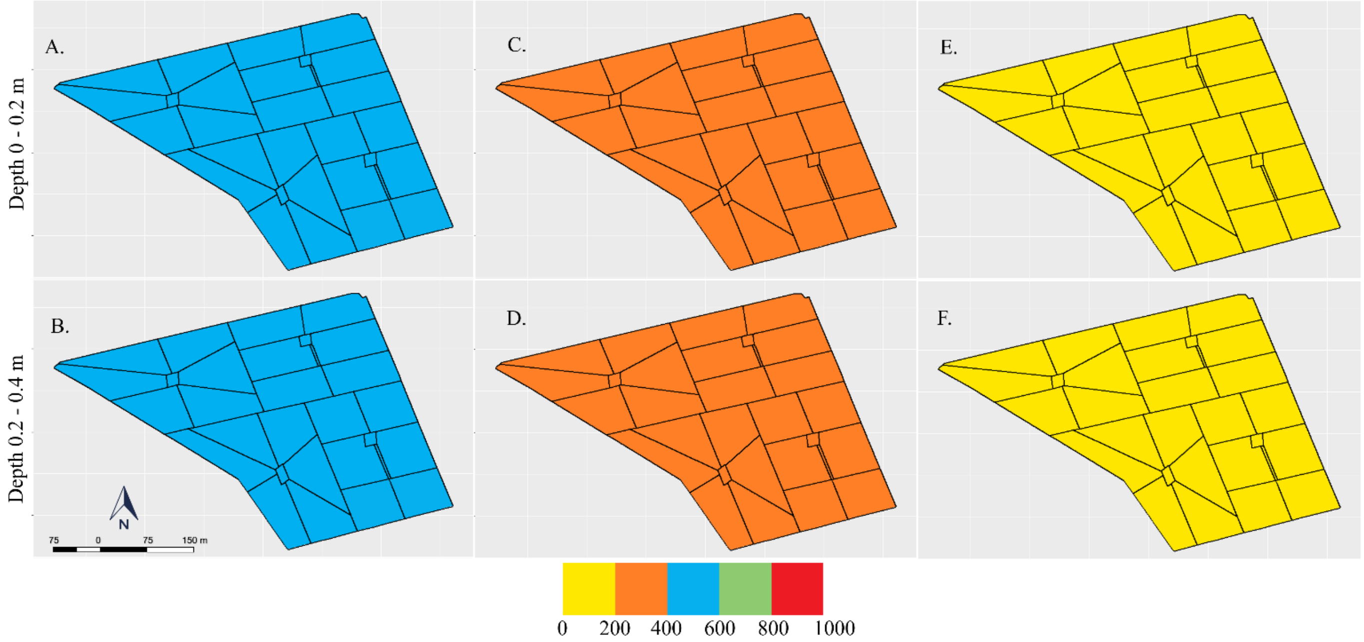

Figure 4. Spatial distribution of sand (g kg^{-1} - A and B), clay (g kg^{-1} - C and D), and silt (g kg^{-1} - E and F) in ICLF and ILF systems in São Carlos city, SP, Brazil

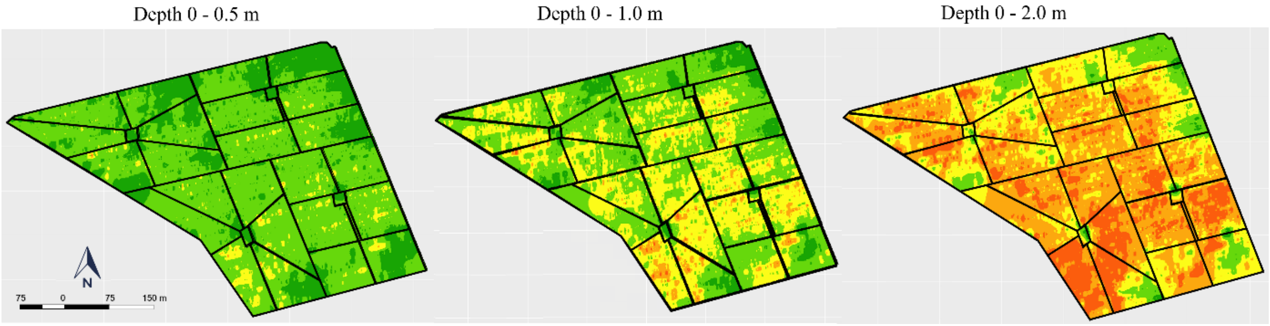

Figure 5. Spatial distribution of soil electrical resistivity (Ωm) in ICLF and ILF systems in São Carlos city, SP, Brazil

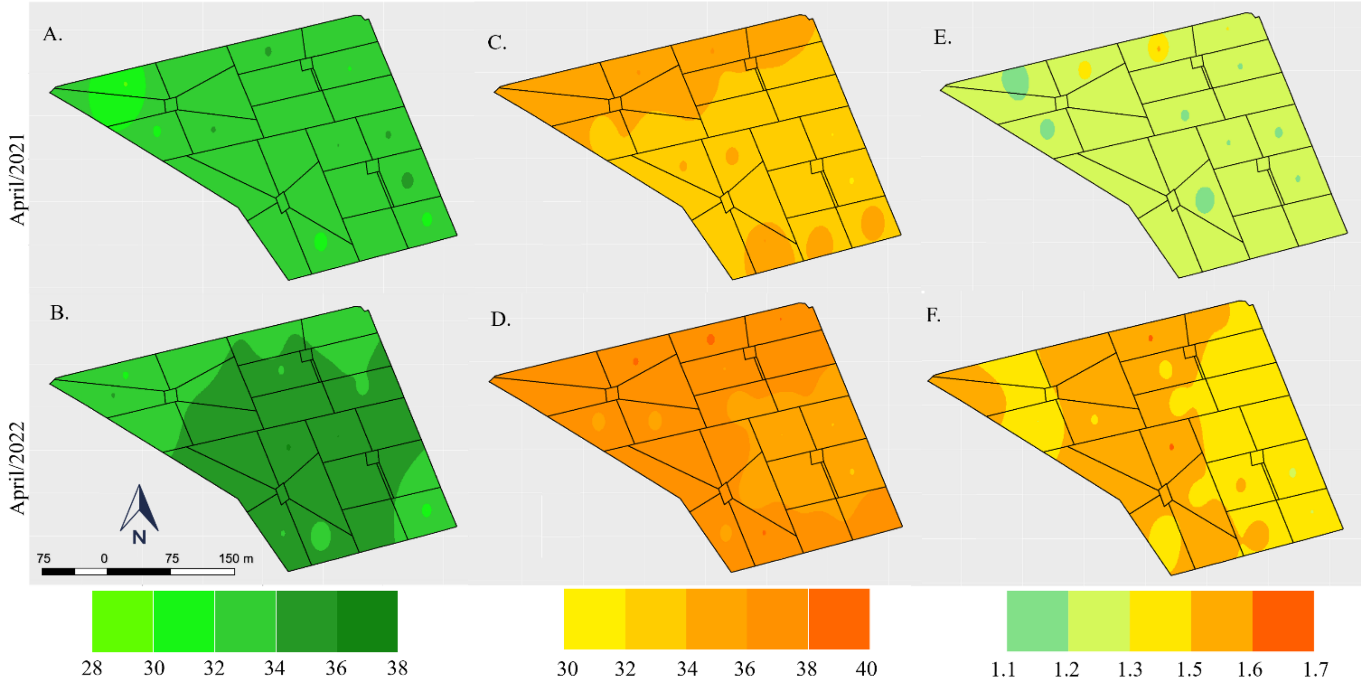

Figure 6. Spatial distribution of height (m - A and B), diameter at breast height (cm - C and D), and volume (m^3 - E and F) of *Eucalyptus* trees in ICLF and ILF systems in São Carlos city, SP, Brazil

(Faria et al., 2015). Trees originating from species crossing grew more homogeneously for both parameters (Santos et al., 2020a). *E. urograndis* is easily adaptable, and problems associated with fertility, compaction, and acidity can be corrected through management practices.

The height, diameter at breast height (DBH), and volume of the *Eucalyptus* trees increased from 2021 to 2022. A comparison between the ILF and ICLF systems revealed no significant differences in tree height in any season (Figures 6A and B). The same trend was observed for DBH and volume in 2021 (Figures 6C and E). In 2022, however, the DBH and tree volume of the ILF system were slightly higher, with a variation of around 15% (Figures 6D and F), with a predominant volume class in the ICLF system of 1.3 to 1.5 m^3, while in the ILF the class was 1.5 to 1.6 m^3. Pezzopane et al. (2021), in a previous study conducted in the same area, had pointed out differences in the tree trunk volume, however with values around 5% higher in the ICLF than in the ILF but with a tendency towards higher growth rates in the ILF system. The survey carried out in the current study confirmed the trend of greater elevations in the ILF system. Santos et al. (2020a) confirmed this trend and observed differences between *Eucalyptus* planting systems from six years onwards.

Conclusions

1. Results indicated that values for soil fertility parameters were suitable for crop development and presented low spatial variability.

2. Soil analyses indicated low acidity, high levels of organic matter, average cation exchange capacity, phosphorus and potassium contents, high base saturation, and calcium and magnesium levels. However, locations with greater spatial variability for calcium were observed, reflecting cation exchange capacity and base saturation variability.

3. Soil granulometry and electrical resistivity had low spatial variability at the surface layer.

4. Even without differences in the soil properties, there was a 15% difference in the larger wood volume in the integrated livestock-forestry system.

Contribution of authors: Nicolle Laurenti, José R. M. Pezzopane, and Alberto C. de C. Bernardi performed the field experiments and data collecting; Nicolle Laurenti, Edilson da Silva Guimarães, and Josiane Rodrigues worked in implementation of the computational methods and performed the data analysis; Nicolle Laurenti, José R. M. Pezzopane, Alberto C. de C. Bernardi, and Josiane Rodrigues wrote de manuscript.

Supplementary documents: There are no supplementary sources.

Conflict of interest: The authors declare no conflict of interest.

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