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# Measurement of apparent electrical conductivity of soil and the spatial variability of soil chemical properties by electromagnetic induction

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**The aim of this research is to evaluate the relationship between the measurement of apparent electrical conductivity of soil and its chemical attributes by electromagnetic induction. Geophysics methods used for soil measurement, with electromagnetic induction technique for measuring apparent electrical conductivity of the soil ($EC_a$) is important for soil digital mapping, as it determines soil properties, with which $EC_a$ is directly related. The apparent soil electrical conductivity ($EC_a$) was measured by electromagnetic induction with EM38-DD device (Geonics Ltd) at two depths: Vertical dipole (effective depth of 1.5 m- $EC_a$-V) and horizontal dipole (effective depth of 0.4 m - $EC_a$-H) in 6 ha of land located in the Northwest of Spain (Castro de Ribeiras de Lea, Lugo) on several dates. The experimental semivariogram showed that there was a drift for $EC_a$-V and $EC_a$-H data. Soil chemical properties were shown in 23/06/2008 following the sample scheme building by ESAP program (40 spots). At the 40 optimized sampling points, the following soil properties were measured at 0.0 to 0.3 m depth: Organic matter (OM), pH in $CaCl_2$, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), potential acidity (H+Al), sum of the basis (SB), cation exchange capacity (CEC) and percent of base saturation (V%). The moderate negative correlation coefficient was found between Log $EC_a$-V and organic matter. Both $EC_a$-H and $EC_a$-V exhibited comparatively low correlations with the chemical properties of soil.**

**Key words:** EM38-DD, geostatistics, soil management, precision agriculture.

## INTRODUCTION

Precision agriculture follows the management of agricultural production areas, taking into account soil heterogeneity. For this reason, it uses advanced techniques for the spatial application of inputs variable,

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allowing low production costs and the environmental impacts of agricultural activity (Siqueira et al., 2015). According to Schueller (2000), the precision agriculture is divided into three subsystems: monitoring (data collection and storage); management (decision-making); and control (management and manipulation of information).

Spatial technologies give room for the elaboration of maps and interpretation of soil properties of plants. This step that tries to get the sampling process of soil is the most efficient and economical in precision agriculture. The costs of the soil samples are higher, making propagation difficult for most of the farmers (Juan et al., 2011; Rodrigues et al., 2012).

The sampling techniques in most cases cause system series. Some of the experimental character and others already in commercial use aim to develop indirect techniques for measuring soil proprieties (Juan et al., 2011). In this way, the use of geophysics methods for measuring soil properties, and electromagnetic induction technique for measuring the apparent electrical conductivity of soil ($EC_a$) are really important for digital mapping soil, as it determines soil properties, with which $EC_a$ is directly related (Heil and Schmidhalter, 2012; Doolittle and Brevik, 2014). Apparent electrical conductivity is the ability of a material to transmit or conduct electrical current (Doerge, 2004). It is influenced by various factors of soil such as porosity, dissolved electrolyte concentration, texture, quantity and composition of colloids, organic matter, inorganic C and water content (Machado et al., 2015; Neely et al., 2016). Some research reports that $EC_a$ readings are related to soil characteristics and properties such as pH, humidity, texture and CEC (Molin and Rabello, 2011). It is possible to obtain good correlations between them since the $EC_a$ readings are obtained in the field (Sudduth et al., 2005). Several studies (Amezketa, 2007; Morari et al., 2009; Saey et al., 2009) have demonstrated the efficiency of the use of $EC_a$ data as secondary information for the sample of other soil properties. Bronson et al. (2005) reported that soil properties that correlated with $EC_a$ included soil extractable $Ca^{2+}$, $Mg^{2+}$, $Na^+$, CEC, silt and soluble salts.

This study aimed to determine the relation between the apparent soil electrical conductivity measured by electromagnetic induction and soil chemical attributes (organic matter, pH, phosphorus, potassium, calcium, magnesium and H+Al, the sum of bases, cation exchange capacity, and percent base saturation).

## MATERIALS AND METHODS

### Study area description

The study area is located in Terra Chá Region in the inner area of Northeast of Lugo (Galicia, Spain); the largest Galicia District, occupying an extensive area of 1.624 km$^2$ (Tragsa, 2009); it is delimited at the edges by mountain reliefs and runs inside a dense network of watercourses (Figure 1). Geographic coordinates are 43°09′49″N and 7°29′47″W, the average elevation is 410 m, and the mean slope is 2% (Figure 2). The annual average temperature is 11,2°C, with a total average precipitation of 930 mm.

The climate classification according to Koppen is Cfb type; with humid climate and warm summer; there is no dry season.

Table 1 shows the analytics data of soil in the study area. The texture of the fine earth is sandy-loam in Ap horizon, sandy-clay-loam in Bw horizon, and clayey in the Btg horizon, and there is a general clay increase with soil depth.

The organic matter content is rather high on $A_p$ horizon (5.05%), contrasting with the lower contents at the underlying horizons of the soil profile.

### Determination of the apparent electrical conductivity of soil

The apparent soil electrical conductivity was determined by an electromagnetic induction tool- EM38-DD. The tool is composed of two interpretation units, one in the horizontal position ($EC_a$-H) and the other in the vertical position ($EC_a$-V); the relative response curve demonstrates a high sensitive to the equipment at 0.4 m in the horizontal dipole and at 1.5 m in the vertical dipole (Siqueira et al., 2015).

According to Wait (1962) and McNeill (1980), the relative response of the electromagnetic induction of the equipment in the soil profile can be described by the following equations.

$$\varphi_{V\ V}(Z) = 2 \quad \frac{4Z}{\left(4Z^2+1\right)^{\frac{1}{2}}} \tag{1}$$

$$\varphi_{H\ H}(Z) = 2 \quad \frac{4Z}{\left(4Z^2+1\right)^{\frac{1}{2}}} \tag{2}$$

Where the relative sensibility of the electromagnetic induction sensor decreased with the increase of the depth in the horizontal dipole ($\Phi_{H-H}$) and vertical dipole ($\Phi_{V-V}$).

Electrical conductivity of the soil sample was done in 3/14/2008 (1887 samples), 4/3/2008 (1871 samples), and 6/23/2008 (1859 samples). To do the georeferencing interpretation of the equipment, EM38-DD, GPS RTK (StarFire de John Deere) was used. It was mounted in a metallic car developed in the hydraulic laboratory of the Superior Polytechnic School, University of Santiago de Compostela.

### Soil chemical properties

The soil chemical properties were sampled on 6/23/2008 following the optimized sample scheme building by ESAP program (40 spots). In the laboratory, the samples removed at 0.0-0.3 m depth were dried in stove at 105° C and divided into sub-samples to determine the chemical properties of the soil. The chemical properties (OM, pH, H+Al, CEC, K, Ca, Mg, SB, P, and V%) were determined according to the method proposed by Raij et al. (2001).

The organic matter was determined by humid oxidation and colorimetric interpretation. The pH was determined in a solution of 0.01 mol $L^{-1}$ of $CaCl_2$. The potential acidity (H+Al) was estimated by the pH values of one soil suspension in buffer solution (Raij et al., 2001). To determine the percentage saturation by basis (V, %), Ca contents ($mmol_c\ dm^{-3}$), Mg ($mmol_c\ dm^{-3}$), K ($mmol_c\ dm^{-3}$) and Na ($mmol_c\ dm^{-3}$) (Raij et al., 2001) were determined first. The cation exchange capacity (CEC, $mmol_c\ dm^{-3}$) was determined considering the summation of the sum of the bases (K, Ca, Mg and Na) and potential acid (H+Al, $mmol_c\ dm^{-3}$).


**Figure 1.** Geographical location of the study area.

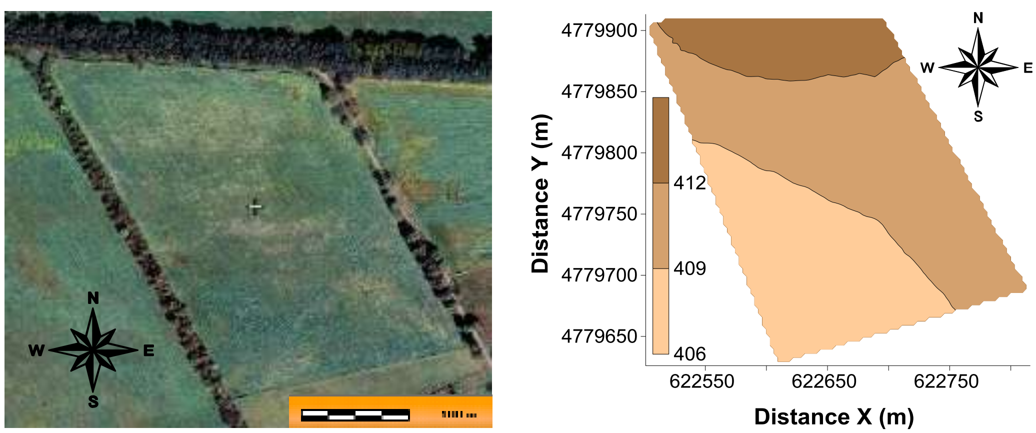


**Figure 2.** Study area and digital elevation map.

**Table 1.** Soil texture data for a representative profile of the study area.

| Horizon | Depth (m) | Organic Matter ($g\ dm^{-3}$) | Clay | Silt | Sand | Gravel |
|---|---|---|---|---|---|---|
| | | | $g\ kg^{-1}$ | | | |
| $A_p$ | 0,0-0,35 | 50,50 | 175,00 | 191,00 | 634,00 | 370,00 |
| $B_w$ | 0,35-0,70 | 7,20 | 192,00 | 207,00 | 591,00 | 448,00 |
| $B_{tg}$ | +0,70 | 2,60 | 479,00 | 280,00 | 241,00 | - |

**Statistical and geostatistical analysis**

The statistical analyses were made by R software (Ayres et al., 2007), providing the main statistics moments: average, variance, average deviation, the coefficient of variation, asymmetry, kurtosis and maximum deviation related to the normal frequency distribution by the Kolmogorov-Smirnov test, with a probability of 1% error. In this research, the geostatistics analyses were made by building and modeling the experimental semivariogram and the values of the sampled spots were determined by kriging interpolation technique. The initial analysis shows that some variables had some tendencies; in this case, the ordinary residual kriging and universal kriging were used.

In the case of ordinary residual kriging, first, the tendency was removed using the following equations (3, 4 and 5) to determinate the residues.

1. Linear

$$m(x) = A_0 + A_1 x + A_2 y + A_3 xy \quad (3)$$

2. Quadratic or parabolic

$$m(x) = A_0 + A_1 x + A_2 y + A_3 x^2 + A_4 y^2 + A_5 xy \quad (4)$$

3. Cubical

$$m(x) = A_0 + A_1 x + A_2 y + A_3 x^2 + A_4 y^2 + A_5 xy + A_6 x^3 + A_7 y^3 + A_8 x^2 y + A_9 xy^2 \quad (5)$$

For those with tendency removal, it was possible to determine the experimental semivariogram of residuals, adjusting the semivariogram model by cross-validation using PROGEOESTAT software (Vieira et al., 2002). For the maps of isolines building, tSURFER 11 software (GOLDEN SOFTWARE, 1999) was used, considering the determined values by residual kriging, where the drift *m(x) is* supposed to to be known. The spatial drift was estimated by the quadratic minimum method, and the sediments were calculated by equation 6.

$$R(x) = Z(x) \quad m(x) \quad (6)$$

The residue would be the difference between regionalized variable and the drift

## RESULTS AND DISCUSSION

### Apparent electrical conductivity variability of soil

The mean values (Table 2) show that in the first two sample dates (3/14/2008 and 4/3/2008) were found the highest mean values of apparent soil electrical conductivity measured in the vertical ($EC_a$-V) and horizontal dipoles ($EC_a$-H). The variance values are similar in the first two sample dates (3/14/2008 and 4/3/2008), showing an increase of two variance units in the third sample date (6/23/2008).

The statistical analysis (Table 2) shows that the data presented lognormal frequency distribution using the Kolmogorov-Smirnov test with a probability error of 1%. In all dates sampled, $EC_a$ presented the highest values of skewness coefficient, mainly because the dates are concentrated at the beginning of the frequency distribution graph, presenting a large dispersion of dates with a difference of the main value.

According to Stadler et al. (2015) and Costa et al. (2014), the $EC_a$ is influenced by soil humidity content. Table 3 presents the accumulated precipitation and evapotranspiration between the sample dates. In the period before the first sample date (3/14/2008) there was a period with low precipitation, but with low values of evapotranspiration, which provides a high water content in the soil. Moreover, in the Southwest zone of the parcel level groundwater is closest to the surface. In the period before the second sample date (4/3/2008), there was an increase in precipitation allowing the storage of water on the soil surface. This led to a higher main value of $EC_a$-H with 14.59 mS $m^{-1}$. During this period, there were practically no changes in evapotranspiration values. From June 2008, the amount of precipitation over the study area was significantly decreased, with an increase in evapotranspiration values.

The highest $EC_a$-V average value is 14.04 $mSm^{-1}$ on 4/3/2008 due to winter precipitation combined with a B horizon of reduced permeability and flat topography of the area. This caused high phreatic level during most of the year. In the present study, the $EC_a$-H measured in 3/14/2008 (5.53 %) and the $EC_a$-H in 03/04/2008 (5.32%) showed low values of variation coefficient (CV, %); all other measured variables at different sample dates presented average coefficients variations. Vitharana et al. (2008), studying the use of $CE_a$ dates in Belgium, observed CV values of 25,30 % and 19,80 % respectively in $EC_a$-V and $EC_a$-H. These values were higher than those described in the present study for $EC_a$.

The $EC_a$-H on 4/3/2008 presented the lowest value of the range (a, 40 m). $EC_a$-H presented the lowest values of range in all sampled dates. In general, $EC_a$-V presented an average value range of 126.66 m and $EC_a$-H has an average value range of 58.00 m. Molin et al. (2005) described the range values for $EC_a$-V of 255.60 m and 281.50 m for the $EC_a$-H in a clay Ferralsol in the Southern region of Brazil. On all sampled dates, $EC_a$-V and $EC_a$-H values were different. The relative sensibility of the electromagnetic induction sensor decreases with incease in depth. Note that the horizontal dipole has a higher sensibility than the vertical dipole, which influences the values found in this way.

The semivariograms of $EC_a$-H and $EC_a$-V were fitted to the spherical model, coinciding with other authors who stated that this model prevails in soil science studies (Siqueira et al, 2008; Molin and Faulin, 2013) (Table 4).

### Spatial variability of the soil chemical properties ($EC_e$, MO, pH, P, K, Ca, Mg, H+Al, SB, CEC and V%)

The statistical parameters of the chemical properties of the soil ($EC_e$, MO, pH, P, K, Ca, Mg, H+Al, SB, CEC and V%) are presented in Table 5. The value of coefficient variation (CV %) shows the dates of organic matter (O.M) and the pH present the lower values of CV (7.88 and 6.07%). The other properties show the CV average value according to the classification of Warrick and Nielsen (1980).

The content of K and Mg presents the log normal frequency distribution (Ln) by the average of the Kolmogorov-Smirnov with an error probability of 1% (D, Table 5); other studied properties ($EC_e$, MO, pH, P, K, Ca, H+Al, SB, CEC, and V%) present normal frequency distribution (n). The electrical conductivity of the saturation extract ($EC_e$) presents an average value of 13.82 mS $m^{-1}$,

**Table 2.** Statistical parameters of the continuously recorded $EC_a$ data sets.

| Date | Variable | Unit | N | Mín. | Máx. | Mean | Variance | CV | Skew | Kurt | D |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3/14/2008 | $EC_a$-V | | 1887 | 5.75 | 18.38 | 10.48 | 4.42 | 20.07 | 0,527 | 0.124 | 0.045Ln |
| | $EC_a$-H | | | 9.25 | 19.00 | 14.10 | 0.60 | 5.53 | 0.065 | 1.810 | 0.040Ln |
| 4/3/2008 | $EC_a$-V | mS $m^{-1}$ | 1871 | 9.63 | 20.50 | 14.04 | 4.64 | 15.34 | 0.662 | 0.083 | 0.073Ln |
| | $EC_a$-H | | | 6.63 | 19.50 | 14.59 | 0.60 | 5.32 | 0.160 | 10.514 | 0.095Ln |
| 6/23/2008 | $EC_a$-V | | 1859 | 4.13 | 20.13 | 11.21 | 6.12 | 22.07 | 0.485 | -0.243 | 0.071Ln |
| | $EC_a$-H | | | 6.63 | 20.00 | 12.12 | 3.22 | 14.81 | 0.839 | 1.285 | 0.092Ln |

*N*, Number of measures; Min., minimum value; Max., maximum value; Mean ± SD: mean ± standard deviation; CV: coefficient of variation (%); Skew, skewness; Kurt, kurtosis; *D*: normality of the data for test of Kolmogorov-Smirnov ($P < 0.01$, n, normality, and Ln: log-normality).

**Table 3.** Precipitation and evapotranspiration of cumulative reference between successive dates, in which apparent electrical conductivity of the soil ($EC_a$-V and $EC_a$-H) was recorded.

| Period | Precipitation (mm) | Evapotranspiration reference (mm) |
|---|---|---|
| 2/15/2008-3/14/2008 | 52.60 | 38.00 |
| 3/15/2008-4/3/2008 | 80.40 | 37.07 |
| 4/4/2008-6/23/2008 | 397.80 | 214.55 |

**Table 4.** Fitted semivariogram parameters ($EC_a$-V and $EC_a$-H) measured on sample dates.

| Date | Variable | Unit | Model | $C_0$ | $C_1$ | a (m) | GD (%) |
|---|---|---|---|---|---|---|---|
| 3/14/2008 | Log $EC_a$-V Residual | | Spherical | 0.0001 | 3.14 | 105.00 | 0.00 |
| | Log $EC_a$-H Residual | | Spherical | 0.14 | 0.302 | 44.00 | 31.67 |
| 4/3/2008 | Log $EC_a$-V Residual | mS $m^{-1}$ | Spherical | 0.00 | 5.10 | 145.00 | 0.00 |
| | Log $EC_a$-H Residual | | Spherical | 0.10 | 0.32 | 40.00 | 23.80 |
| 6/23/2008 | Log $EC_a$-V Residual | | Spherical | 0.001 | 0.01 | 130.00 | 9.09 |
| | Log $EC_a$-H Residual | | Spherical | 0.001 | 0.05 | 130.00 | 1.96 |

$C_0$: nugget effect; $C_1$: structural variance; a: range; SD: spatial dependence (%).

**Table 5.** Statistical parameters of the soil chemical properties.

| Variable | Unit | N | Min. | Max. | Mean | Variance | CV | skew | Kurt. | D |
|---|---|---|---|---|---|---|---|---|---|---|
| $EC_e$ | | 40 | 7.00 | 28.00 | 13.82 | 25.94 | 36.84 | 1.200 | 1.008 | 0.159n |
| MO | g $dm^{-3}$ | 40 | 64.00 | 98.00 | 81.50 | 41.28 | 7.88 | -0.076 | 0.773 | 0.132n |
| pH | - | 40 | 4.40 | 6.00 | 4.87 | 0.08 | 6.07 | 1.813 | 5.423 | 0.186n |
| P | mg $dm^{-3}$ | 40 | 81.00 | 425.00 | 160.00 | 7479.74 | 54.05 | 1.959 | 3.295 | 0.248n |
| K | | 40 | 1.50 | 14.80 | 3.52 | 6.95 | 74.90 | 2.925 | 9.651 | 0.253Ln |
| Ca | | 40 | 24.00 | 110.00 | 46.75 | 280.50 | 35.82 | 2.121 | 5.729 | 0.200n |
| Mg | $mmol_c$ $dm^{-3}$ | 40 | 3.00 | 26.00 | 5.90 | 17.32 | 70.54 | 3.668 | 15.248 | 0.291Ln |
| H+Al | | 40 | 31.00 | 121.00 | 69.30 | 280.57 | 24.17 | 0.684 | 1.668 | 0.199n |
| SB | | 40 | 31.50 | 134.50 | 56.17 | 446.70 | 37.63 | 2.449 | 7.163 | 0.238n |
| CEC | | 40 | 98.90 | 174.00 | 125.50 | 360.46 | 15.13 | 1.000 | 0.429 | 0.198n |
| V% | % | 40 | 29.00 | 81.00 | 44.20 | 127.08 | 25.51 | 1.473 | 3.180 | 0.147n |

*N,* number of measurements; Min., minimum value; Max., maximum value; Mean ± SD, mean ± standard deviation; CV,: coefficient of variation (%); Skew, skewness; Kurt, kurtosis; *D*, normality of the data for test of Kolmogorov-Smirnov ($P < 0.01$, n: normality, and Ln: log-normality).

according to USDA classification (1999). The studied area soil is classified as non- saline ($CE_e$ < 98.00 mS $m^{-1}$), presenting no problems to the development of the plants and microorganism of the soil.

**Table 6.** Linear correlation matrix between the apparent electrical conductivity ($EC_a$-V and $EC_a$-H) and the chemical properties ($EC_e$, MO, pH, P, K, Ca, Mg, H+Al, SB, CEC and V%) of soil, measured on 23/06/2008.

| Log $EC_a$-V | Log $EC_a$-H | $EC_e$ | OM | pH | P | Log K | Ca | Log Mg | H+Al | SB | CEC | V% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.000 | | | | | | | | | | | | |
| 0.751 | 1.000 | | | | | | | | | | | |
| 0.156 | 0.224 | 1.000 | | | | | | | | | | |
| -0.627 | -0.446 | 0.164 | 1.000 | | | | | | | | | |
| 0.050 | 0.246 | 0.475 | -0.008 | 1.000 | | | | | | | | |
| -0.084 | 0.000 | 0.515 | 0.372 | 0.033 | 1.000 | | | | | | | |
| -0.018 | 0.214 | 0.470 | 0.210 | 0.037 | 0.697 | 1.000 | | | | | | |
| -0.118 | 0.043 | 0.525 | 0.271 | 0.879 | 0.378 | 0.171 | 1.000 | | | | | |
| 0.066 | 0.121 | 0.565 | 0.024 | 0.850 | 0.265 | 0.168 | 0.862 | 1.000 | | | | |
| -0.248 | -0.331 | -0.332 | 0.292 | -0.816 | 0.331 | 0.228 | -0.554 | -0.670 | 1.000 | | | |
| -0.073 | 0.098 | 0.585 | 0.258 | 0.861 | 0.465 | 0.307 | 0.983 | 0.888 | -0.519 | 1.000 | | |
| -0.318 | -0.183 | 0.359 | 0.547 | 0.239 | 0.813 | 0.546 | 0.607 | 0.399 | 0.302 | 0.657 | 1.000 | |
| 0.052 | 0.214 | 0.544 | 0.074 | 0.950 | 0.189 | 0.130 | 0.927 | 0.904 | -0.794 | 0.917 | 0.323 | 1.000 |

$EC_a$-V, $CE_a$ in vertical dipole; $EC_a$-H, $CE_a$ in horizontal dipole; $EC_e$, Electrical conductivity of soil saturation extract; OM: Organic Matter; P, phosphorous; Log K, Potassium logarithmic; Ca, Calcium; Log Mg, Magnesium logarithmic; H+ Al, hydrogen + aluminum; SB, sum of bases; CEC, Cation exchange capacity; V%, percent base saturation.

Table 6 shows a matrix with a linear relation between the apparent electrical conductivity ($EC_a$-V and $EC_a$-H) and the chemical properties ($EC_e$, MO, pH, P, K, Ca, Mg, H+Al, SB, CEC and V%) of soil. $EC_a$ values on 3/23/2008 were used because it was the date used for the determination of 40 optimized sampling for the chemical attributes.

Electrical conductivity of the saturation extract ($EC_e$, mS $m^{-1}$) presented one low positive relation (Table 6) with the apparent electrical conductivity of the soil measured by electromagnetic induction in the vertical ($EC_a$-V, mS $m^{-1}$) and horizontal dipoles ($EC_a$-H, mS $m^{-1}$); $r$ = 0.156 to $EC_e$ x Log $EC_a$-V and $r$ = 0.224 to $EC_e$ x Log $EC_a$-H. Corwin and Lesch (2005) found the highest coefficient correlation value of $EC_e$ x $EC_a$-V ($r$ = 0.840) and $EC_e$ x $EC_a$-H ($r$ = 0.890) at 0.00-1.20 m depth. Slavich and Petterson (1990) and Sharma and Gupta (2000) found correlation values between $EC_e$ x $EC_a$-V and $EC_e$ x $EC_a$-H, similar to that described by Corwin and Lesch (2005).
Usually, the $EC_a$ values are different from those measured from the saturation extract because they are determined in the field and are influenced by factors such as slope soil, humidity and soil volume.

The saturation extract of the electrical conductivity ($EC_e$, mS $m^{-1}$) presents one positive moderate relation with the content of P ($r$ = 0.515), Ca ($r$ = 0.525), Log Mg ($r$ = 0.565), SB ($r$ = 0.585) and V% ($r$ = 0.544). Valente et al (2012) obtained low correlations between EC and soil properties. In this study, the highest correlation coefficients for EC was found in the remaining phosphorus, which had values of 0.447.

The relation between $EC_e$ x MO ($r$ = 0,164), $EC_e$ x pH ($r$ = 0.475) and $EC_e$ x K ($r$ = 0.438) was low. The moderate value of the relation coefficient between the exchange complex elements (P, K, Ca e Mg) was expected, dates that the $EC_e$ was an indicator of the salinity of soil, represented in this way the quantity of salt in the solution of the soil. In the present study, there was a positive relation between P x $EC_e$ ($r$ = 0.515). Heiniger et al. (2003) also described the content of P as a part of the salinity of the soil, and the agricultural excrement in the soil is due to the degradation of organic matter.

The linear relation between MO x Log $EC_a$-V ($r$ = -0.627) is almost a moderate negative and the correlation between the MO x $EC_a$-H ($r$ = -0.446) is classified as low negative. These values are smaller than the others indicated by Kitchen et al. (2003); it was ≥ 0.80 between the organic matter content and the apparent electrical conductivity of the soil ($CE_a$).

Linear relation between pH x Log $EC_a$-V ($r$ = 0.050) is null and the relation between pH x Log $EC_a$-H ($r$ = 0.246) is low. Aini et al. (2014), studying the determination of the soil pH value in oil palm plantation based on ECa parameter measured by the soil sensor, found that ECa parameter had a significant negative correlation with soil pH and was highly related to deep ECa at the depth of 15 - 30 cm with R 2 = 0.484.

In the present study, the values of relation between K, Ca, Mg with the $EC_a$-V and $EC_a$-H are classified as low: Log K x Log $EC_a$-V ($r$ = -0.018), Log K x Log $EC_a$-H ($r$ = 0.214), Ca x Log $EC_a$-V ($r$ = -0.118), Ca x Log $EC_a$-H ($r$ = 0.043), Log Mg x Log $EC_a$-V ($r$ = 0.066) and Log Mg x Log $EC_a$-H ($r$ = 0.121). Heiniger et al. (2003) described that the presence of low values of relation ($r$ < 0.7) between K, Ca and Mg are indicative of the interaction of other soil parameters above the $EC_a$, such as water content, composition of texture and quantity of the free salt in the soil solution.

**Table 7.** Fitted semivariogram parameters (Log $EC_a$-V Residual, Log $EC_a$-H Residual, $EC_e$, OM, pH, P, K, Ca, Mg, H+Al, SB, CEC and V%) measured on 6/23/2008.

| Variable | Unit | Model | $C_0$ | $C_1$ | a (m) | SD (%) |
|---|---|---|---|---|---|---|
| Log $EC_a$-V Residual | $mS\ m^{-1}$ | Spherical | 0.001 | 0.01 | 130.00 | 9.09 |
| Log $EC_a$-H Residual | | Spherical | 0.001 | 0.05 | 130.00 | 1.96 |
| $CE_e$ Residual | | Spherical | 0.001 | 0.01 | 130.00 | 9.09 |
| MO Residual | $g\ dm^{-3}$ | Spherical | 0.001 | 35.00 | 130.00 | 0.00 |
| pH Residual | - | Spherical | 0.00 | 0.07 | 110.00 | 0.00 |
| P Residual | $mg\ dm^{-3}$ | Spherical | 0.00 | 6500.00 | 80.00 | 0.00 |
| Log K | | | | **Pure nugget effect** | | |
| Ca Residual | $mmol_c\ dm^{-3}$ | Spherical | 0.00 | 325.00 | 100.00 | 0.00 |
| Log Mg | | Spherical | 0.00 | 0.050 | 100.00 | 0.00 |
| H+Al Residual | | Spherical | 0.00 | 320.00 | 80.00 | 0.00 |
| SB Residual | | Spherical | 0.00 | 470.00 | 100.00 | 0.00 |
| CEC Residual | | Spherical | 0.00 | 360.00 | 70.00 | 0.00 |
| V% Residual | % | Spherical | 0.00 | 135.00 | 70.00 | 0.00 |

$C_{0,}$: Nugget effect; $C_1$, structural variance; a: range; SD, spatial dependence (%).

The correlation between CEC x Log $EC_a$ -V (r = -0.318) and CEC x Log $EC_a$-H (r = -0.183) has low negative. Korsaeth et al. (2005), studying the correlation between CEC x $EC_a$ in two areas of study, found low correlations in the Apelsvoll area (NC, USA) (CEC x $EC_a$-V = 0.210 and CEC x $EC_a$-H = 0.290 ) and high correlations in the area of Kise (NC, USA) (CEC x $EC_a$-V = 0.930 and $EC_a$-H x CEC = 0.930). Sudduth et al. (2001) reported for saline soils, that their texture is related more to the $EC_a$ than the CEC, justifying the differences in the values of correlation between CEC x $EC_a$ found by Korsaeth et al. (2005), and low correlation values found in this study.

The potential acidity (H+Al, $mmol_c\ dm^{-3}$), the sum of bases (SB, $mmol_c\ dm^{-3}$) and the percentage of saturation bases (V%) present low values of relation with the apparent electrical conductivity of the soil ($EC_a$-V and $EC_a$-H): H+Al x Log $EC_a$-V = -0.248; H+Al x Log $EC_a$-H = -0.331; SB x Log $EC_a$-V = -0.073; SB x Log $EC_a$-H = 0.098; V% x Log $EC_a$-V = 0.052 and V% x Log $EC_a$-H = 0.214.

Table 7 presents the semivariogram parameters adjusted to the soil properties in this study ($EC_e$, MO, pH, P, K, Ca, Mg, H+Al, SB, CEC y V%). All the properties in the study were adjusted in spherical math;n the content of K in the soil presented pure nugget effects.

The higher value range (a, m) data were found of MO Waste and $EC_e$ waste, which had a value range of 130.00 m. Paz González et al. (2000) studied the spatial variability of cultivated land and other natural vegetation in Gayoso-Castro (Galicia, Spain) in a soil similar to the one found in this study values range (a) for OM around 6.5 m. The remaining properties values range presented in the following order of highest to lowest: pH Waste (110.00 m), Ca Waste (100.00 m), Log Mg (100.00 m), SB Waste (100.00 m), BS Residues (80.00 m), H + Al Waste (80.00 m), CEC Waste (70.00 m) and V% waste (70.00)

The degree of spatial dependence (GD%) is high for all properties under the study according to the classification of Cambardella et al. (1994). The presence of low nugget effect values ($C_0$) for soil chemical properties match the values found by Paz González et al. (2000) and Al-Omran et al. (2013). The spatial variability maps in the properties of the study are presented in Figure 3 ($CE_e$, pH, P and Ca) and 4 (Mg, H+Al, SB, CEC and V%).

The spatial variability maps of the matter content (MO, $g\ dm^{-3}$) show that the higher value of OM is located in the Northeastern area (≥ 84 $g\ dm^{-3}$). The pH map in the study area demonstrated in the west part of the area presented the lower value (≤ 4.9), and therefore, the soil is more acidic in this zone. The spatial variability maps (Figures 3 and 4) for other soil chemical element (P, Ca, Mg, SB, CEC, and V%) showed a similar behavior in the distribution of contour lines, there being a rise in values mainly in the northeastern part of the study area. The comparative analysis of P, Ca, Mg, SB, CEC, and V% maps with the electrical conductivity of extract saturation map ($EC_e$, $mS\ m^{-1}$) demonstrate a similar pattern between soil chemical properties.

Several authors (Corwin and Lesch, 2005; Amezketa, 2007; Triantafilis et al., 2009; Neely et al., 2016) have shown strong correlations between the soil electrical conductivity and the electrical conductivity of extract saturation (CEe, $mS\ m^{-1}$), the content of organic matter (OM, $g\ dm^{-3}$) and cation exchange capacity (CEC, mmolc $dm^{-3}$); but in this study the greatest correlation coefficient values were found for OM.

According to Figure 5, it was not observed spatial similarity among the maps of the apparent electrical conductivity of the soil ($EC_a$-V and $EC_a$-H) and the soil

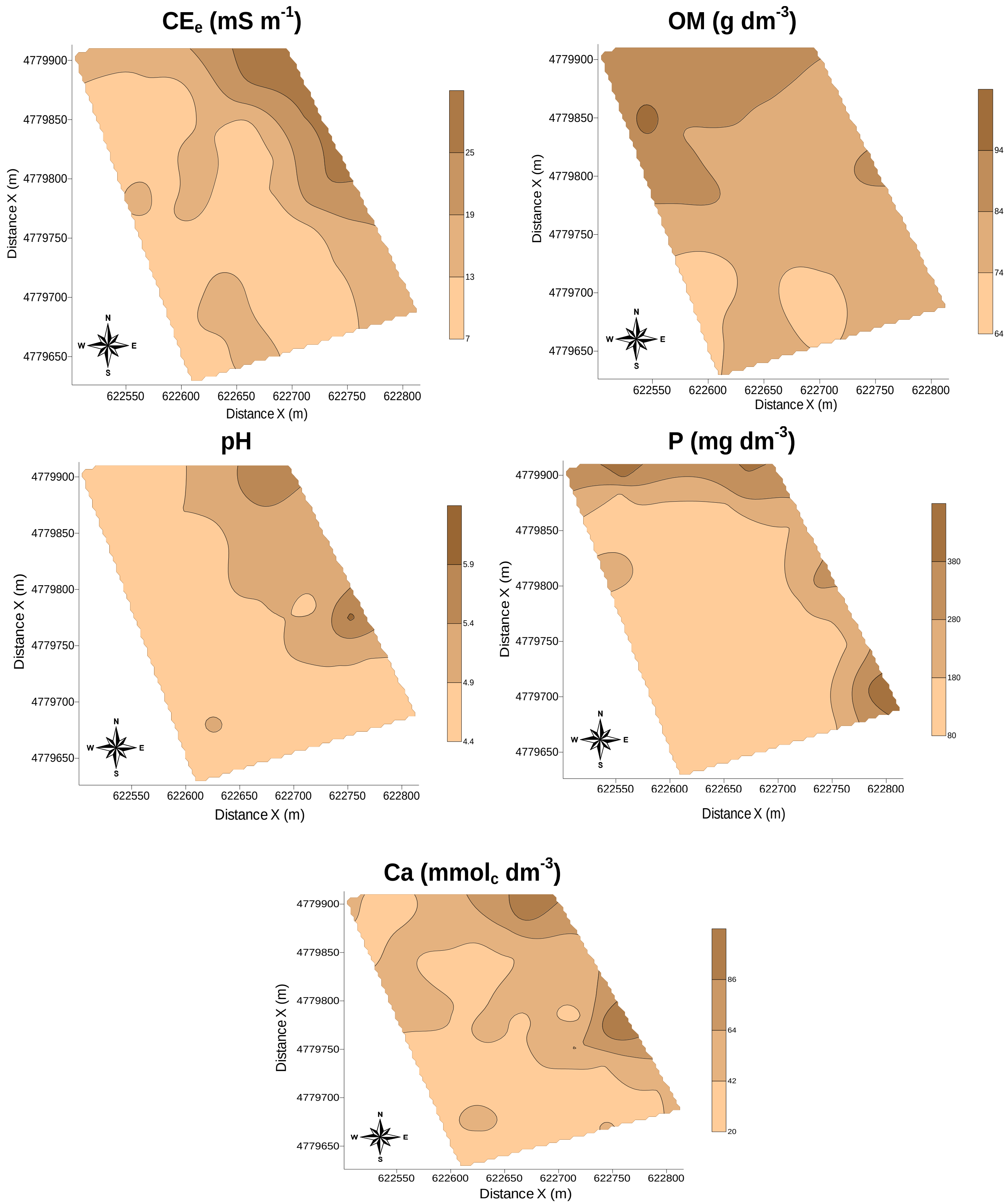


**Figure 3.** Spatial variability maps of the electrical conductivity of soil extract saturation ($EC_e$). Organic Matter (OM), pH, phosphorus (P) and calcium (Ca).

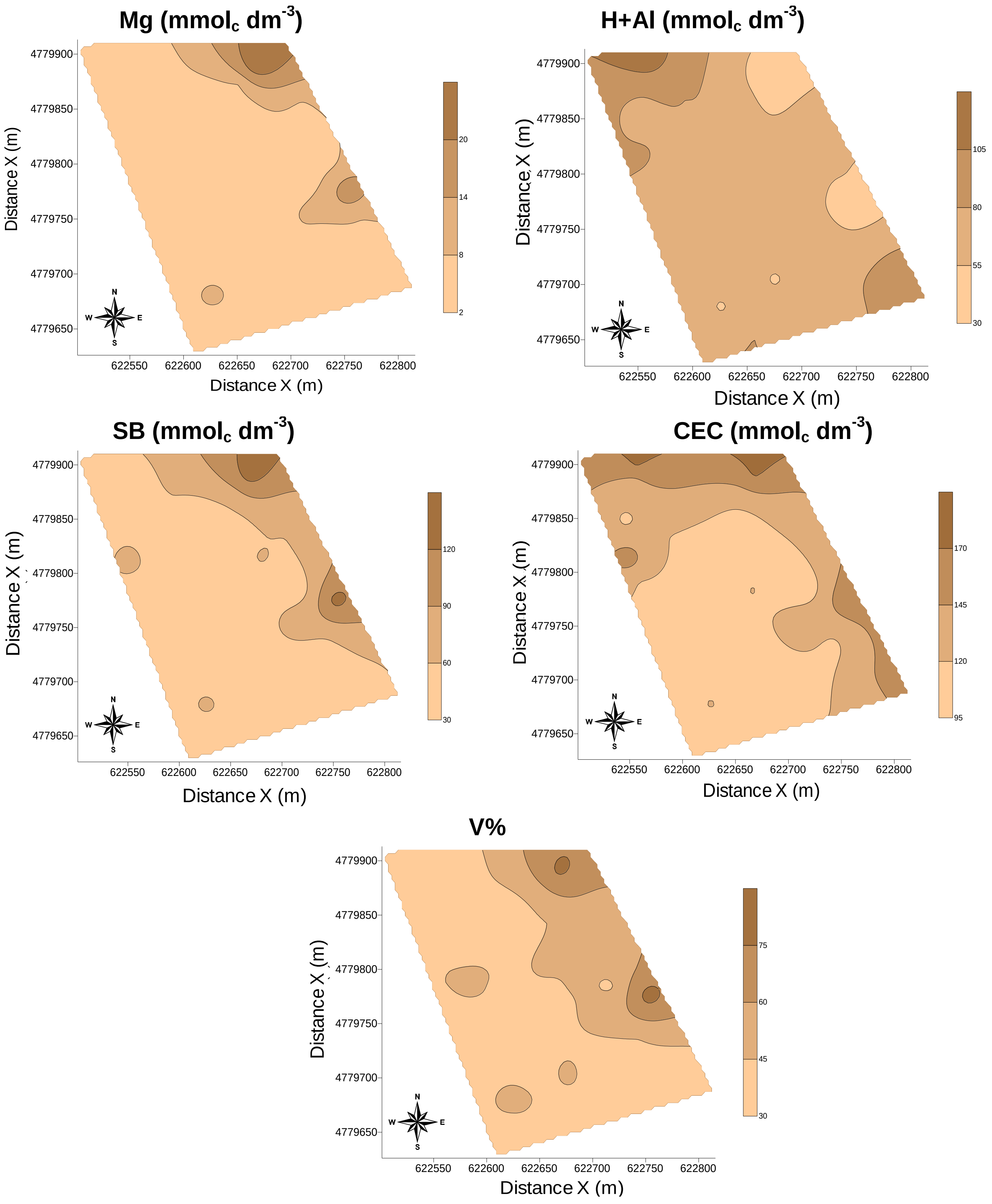


**Figure 4.** Spatial variability maps of the magnesium (Mg), potential acidity (H+Al), sum of bases (SB), Cation exchange capacity (CEC) and percent base saturation (V%)

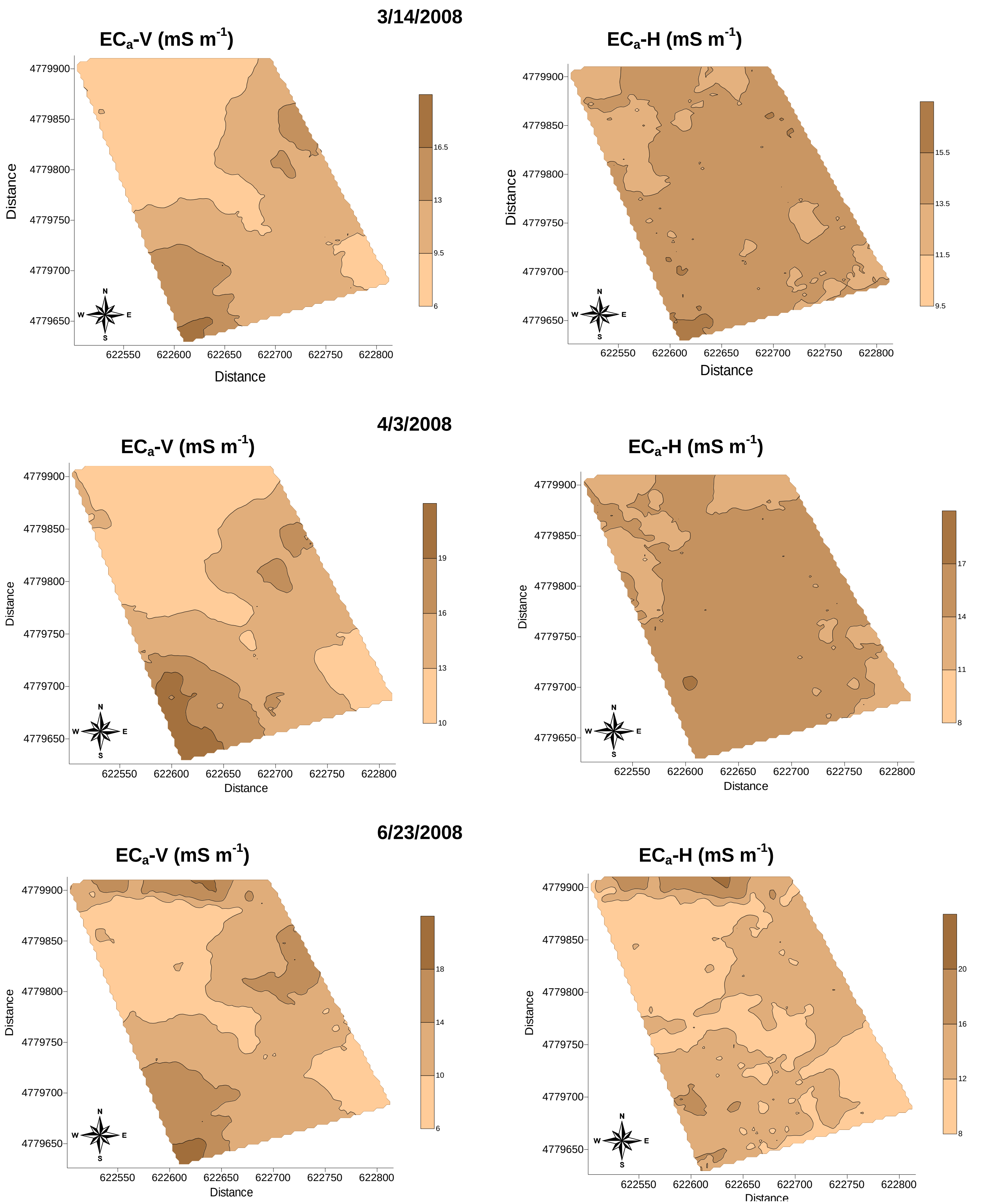


**Figure 5.** Spatial variability maps of the $EC_a$-V and $EC_a$-H in different sample dates.

chemical properties maps (Figures 3 and 4).

## Conclusion

The electrical conductivity of the extract saturation ($EC_e$, mS $m^{-1}$) presented a positive moderate relation with the content of P (*r* = 0.515), Ca (*r* = 0.525), Log Mg (*r* = 0.565), SB (*r* = 0.585) and V% (*r* = 0.544). The moderate negative correlation coefficient was found between the Log $EC_a$-V and the organic matter. Both $EC_a$-H and $EC_a$-V exhibited comparatively low correlations with the soil chemical properties. The moderate negative correlation coefficient was found between the Log $EC_a$-V and the organic matter.

## Conflict of Interests

The authors have not declared any conflict of interests.

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