J. J. Cancela, J. Dafonte, E. Corral, M. Rodríguez-Febereiro and M. Fandiño

Physical and chemical soil variability in a characteristic Hop field of Galicia (Spain)

The variability of the physical properties of the soil, as well as the nutritional levels, is a crucial aspect toward improving the management of hop cultivation, increasing its productivity. The European regulations that pursue a reduction in inputs, such as efficient control of nitrogenous fertilizers, require detailed studies to allow differential nutrition to be carried out. Specific fertilizer recommendations for the cultivation of hops depend on the type of soil and cultivar, and so they must be obtained based on soil analysis. Laboratory analyses are highly demanding in terms of time and cost, and so the existence of other analysis techniques should be explored. The determination of the soil apparent electrical conductivity (EC_a) has shown a close relationship with various physical-chemical properties of the soil, for which the following objectives were established in this work: i) analyzing the relationships between EC_a and the main physical-chemical parameters of the soil, and ii) evaluating the spatial variability of soil properties in a characteristic plot of hops. A soil sampling design was carried out, where the results of the soil samples show a great degree of spatial variability, with variables such as P and N, and with variation coefficients (CV) of > 50 %. Positive relationships (Spearman correlations) were obtained between C, N, and OM and EC_a-H (EC_a, 0.75 m), and a negative relationship was obtained with EC_a-V (EC_a, 1.5 m); moreover, a positive relation was obtained with the effective cation exchange capacity ($_e$CEC) and EC_a-H. The spatial distribution shows different patterns depending on the property represented, where areas with low levels of P and low pH are observed. Based on the relationships established between EC_a and OM, and C and N, it is possible to monitor these parameters over the years. In the case of elements such as P, it is necessary to continue with a classical soil analysis, combined with foliar analysis. Areas with extreme values obtained in the study should be used as sampling areas to assess the nutrients and to proceed with their correction, when necessary.

Descriptors: soil apparent electrical conductivity, spatial variability, soil nutrition, Nugget.

1 Introduction

Hop (*Humulus lupulus* L.) is an herbaceous perennial plant that is appreciated in several industries for its female flowers, named hop cones, which contain bitter acids, including alpha and beta acids [1]. Hop cone yield and the concentrations of alpha and beta acids within the cones in a given cultivar depend on the weather conditions, soil nutrients, pests and diseases, management practices (pruning and harvesting), and water availability over the growing season [2]; in this sense, hops is particularly vulnerable to climate change [3]. Due to their large leaf surface, hops require large amounts of water and specific nutrients in the soil during the growing season. Soil quality is an essential factor in the cultivation of hops [4]. General studies have some relevance of focus for the fertilization of nitrogen, phosphorus, potassium, and magnesium as key macronutrients [5]. Hop nutrient requirements vary depending on soil testing, cultivars, yield potential, and growing region. A recent review [6] showed a variation of recommended N amounts of between 100 and 168 kg ha^{-1}, of P between 50 and 110 kg ha^{-1}, and of K, depending on soil practices (cover crop, compost, slurry, etc.), with values of between 90 and 170 kg ha^{-1}.

https://doi.org/10.23763/BrSc22-17cancela

Authors

Javier José Cancela, Jorge Dafonte, Marta Rodríguez-Febereiro, María Fandiño, GI-1716, Projects and Planification, Dpto. Ingeniería Agroforestal, Universidad de Santiago de Compostela, Escola Politécnica Superior de Enxeñaría, Lugo, Spain; Emilio Corral, Lúpulo Tecnología de Galicia, Sociedad Cooperativa Gallega (LU.TE.GA.), Betanzos, Spain; corresponding author: javierjose.cancela@usc.es

Organic matter is a key component of soil fertility, and an important factor in soil structure formation [7]. Soil pH is another major factor affecting nutrient availability and plant growth [8]. Depending on the soil pH, several essential nutrients (N, P, K) become more or less available for root uptake, so that in acidic soils, the risk of Al and Mn toxicity increases [9]. The pH range considered to be the most adequate for hop is between 6.0 and 6.7 [10]; however, in acid soils, when the Al saturation is lower than 20 %, there are no Al toxicity problems, with a good degree of nutrient availability for the crop. Recent studies in the north of Portugal, have shown a higher soil variability for the Nugget variety, mainly due to the use of surface irrigation systems, which show poor soil aeration and toxic levels of soil Mn and Fe [11].

In this context, electromagnetic induction sensors can provide useful information for the spatial variability of certain soil properties within a given field [12]. The soil apparent electrical conductivity (EC_a) measured using geophysical methods, such as electromagnetic induction, can be an indirect indicator of important physical and chemical soil properties, such as salinity, clay content, cation exchange capacity, organic matter, and soil water content [13]. Indeed, EC_a has been used as a surrogate measure of soil texture [14] and clay content [15]. A recent study in a vineyard in northwestern Spain [16], showed that EC_a measurements improved the predictions of soil water content, which suggests the usefulness of these measurements to delimit areas within the vineyard that are susceptible to site-specific management. In a similar way to vineyards, other authors show the relevance of the study of soil variability to establish zoning in a new vineyard, using EC_a and other soil properties [17].

In this context, the aims of this research are i) to determine the soil property variability in a characteristic hop plot (cv. Nugget) in Galicia of 2.0 ha, and ii) to analyze the relationships between EC_a and the main physical-chemical parameters of the soil, to establish general fertilizer recommendations, based on spatial zoning, to facilitate their adaptation in commercial hop yards.

Fig. 1 **a) Irrigation sectors in the study plot (dashed lines), and b) Sampling points (yellow points) analyzed after ESAP software application**

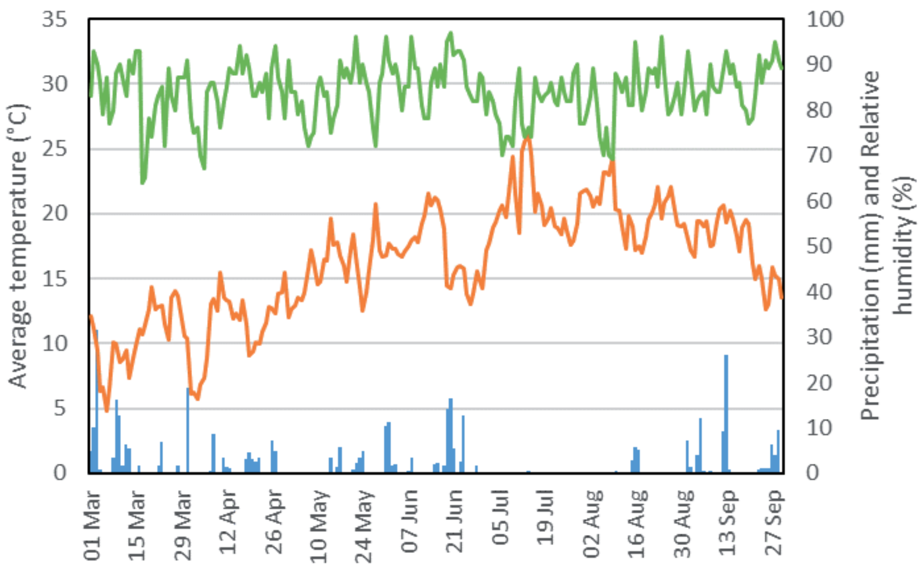

Fig. 2 **Evolution of average temperature (°C, orange line), relative humidity (%, green line), and precipitation (mm, blue columns)**

2 Materials and methods

2.1 Site description

The study was conducted in a commercial hop yard (*Humulus lupulus* L. cv. 'Nugget') located at 'Presedo' (LU.TE.GA.) in Abegondo, A Coruña, Galicia, NW Spain, (43° 12' 7.0'' N, 8° 16' 2.5" W, elevation 165 m). The field has an average slope of 5 %, and is 2.0 ha in surface. The crop was established in 2008, with 3 × 1.5 m spacings (2,222 plants ha^{-1}), and was trellised to a height of 6 m. The orientation of the rows was north-south. The hop yard was divided into four drip irrigation sectors, with 0.5 ha per sector (Fig. 1a). Irrigation started in early July and ended a few days before harvest. A drip irrigation system was installed, with lateral pipes equipped with compensating emitters (2 L h^{-1}) spaced at 75 cm along the crop row. It was considered in the study plot, divided into four irrigation sectors (A, B, C, and D), as mentioned previously (Fig. 1a).

The soil is developed over a basic underlying schist layer, referred to as 'Ordenes Complejo' [18]. The soil is classified as Cambisol [19], without relevant changes in the first meter of soil depth. Soil at the site was loam textured, with 37 %, 43 %, and 20 % sand, silt, and clay, respectively. The soil organic matter content was 6.2 % on average. Oxides and carbonates have not shown management problems over the 14 years of plantation management.

The average effective cationic exchange capacity (eCEC) was 8.38 (cmol (+) kg^{-1}). The annual plot fertilization program is based on annual extractions, and includes the application of 400 kg ha^{-1} of nitrogen-phosphorus-potassium (NPK) (8:15:15) in March and 250 kg ha^{-1} of calcium ammonium nitrate (27 %) split into two applications (June and July). The crop annual extractions were determined based on the work carried out at the CIAM-Galicia over the last 20 years [20].

The climate of the site is Atlantic, of the typical warm summer Mediterranean type (Csb), according to the Köppen-Geiger classification, with a dry and warm summer [21]. Weather data, including maximum and minimum temperatures, wind speed, and rainfall, were collected from an automatic station (Mabegondo, managed by MeteoGalicia) located near the hop yard. Reference evapotranspiration (ET_o) was computed according to the standard methodology [22]. The weather conditions in 2022 during the hop growing cycle, from March to September, showed a mean temperature of 16.1 °C, a relative humidity of 84 %, and an ETo of 3.54 mm day^{-1}. In contrast, the rainfall was 382 mm (Fig. 2).

2.2 Soil sampling scheme design

For the determination of the soil variability in the study plot, the previous results of EC_a (data not shown), carried out in previous years, were used. From the EC_a values, the Electrical Conductivity Sampling Assessment and Prediction (ESAP) software [23] of the US Salinity Laboratory was used to choose the appropriate locations for soil sampling using design module response surface sampling (RSSD).

The ESAP program [23-24] was used to process the EM38 survey data and to generate sampling plans for calibration using soil core saturation extracts. The algorithm in this program selects a limited set of calibration sites with desirable spatial and statistical characteristics, based on an analysis of EC_a values and study site location information using response surface design techniques. The ESAP software package identifies optimal locations for the soil sampling of site data from an EC_a measurement survey. These sites are selected based on spatial statistics to reflect the observed spatial variability in the EC_a measurements. The optimal locations of a minimal subset of EC_a study sites for obtaining soil samples are identified [25]. After application to the ESAP software, 25 sampling points were selected, and their distribution is shown in figure 1b.

2.3 Field and laboratory determinations

Soil apparent electrical conductivity (EC_a) data were measured on May 30, 2022, at 28 % of soil water content near field capacity level, using an electromagnetic induction sensor (EM-38DD, Geonics Ltd., Mississauga, ON, Canada). This device consists of a transmitting and a receiving coil installed 1.0 m apart at opposite ends of a non-conducting bar. The system is powered by a 9 V battery and operates at a frequency of 14.6 kHz. The measurement obtained is not only a function of the different conductivities in the subsoil, but also of other factors, such as the orientation (vertical or horizontal) of the coils, the operating frequency, and the magnetic susceptibility. A complete description of the EM-38 equipment can be found in [26].

The distribution of particles and pores determines the amount of soil conductivity. However, the conductivity is also affected by the

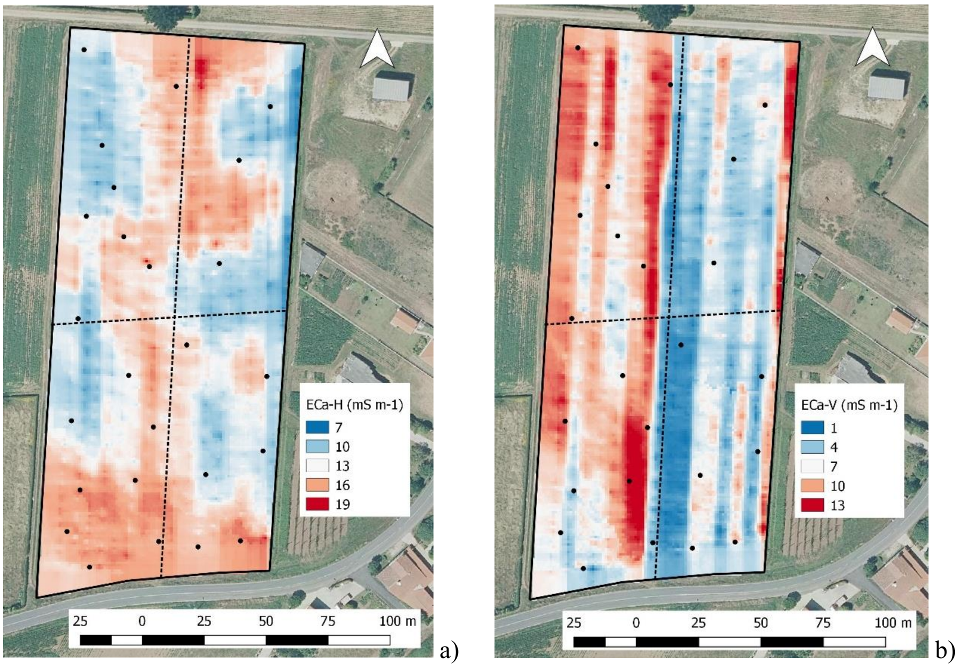

Fig. 3 **Soil apparent electrical conductivity ($_E$Ca) maps obtained with the horizontal (a) and vertical (b) dipoles of the EM-38 equipment, and interpolated through the Random Forest Regression Kriging technique (RK-RF) on 30 May 2022; irrigation sectors in the study plot (dashed lines), and sampling points (points)**

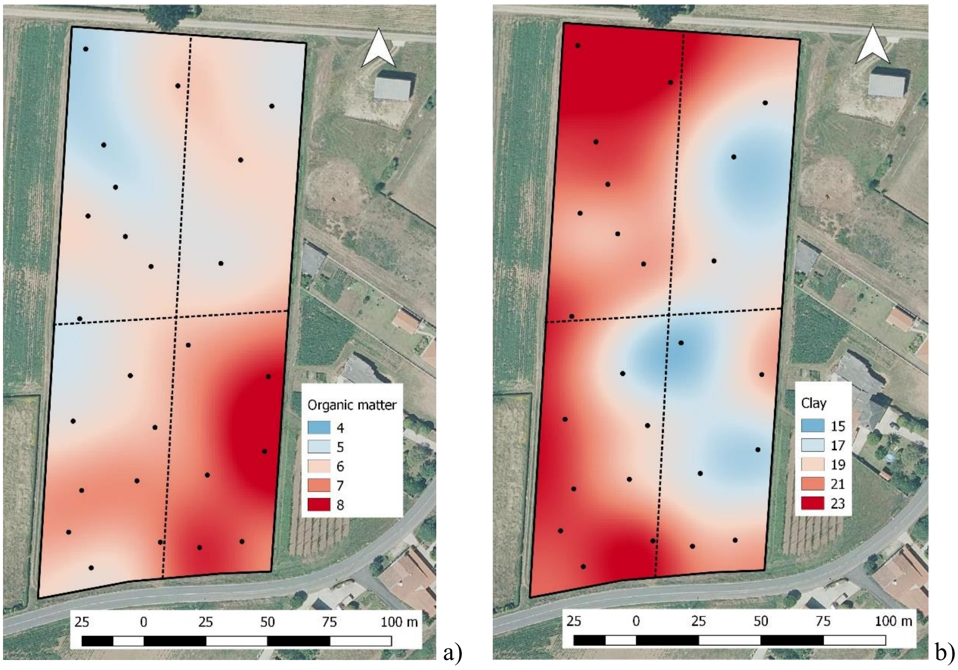

Fig. 4 **Organic matter (%, a) and clay (%, b); maps obtained with QGis-'v.surf.rst'; irrigation sectors in the study plot (dashed lines), and sampling points (points)**

Table 1 List of abbreviations used within the text

Abbreviation	Description
CV	variation coefficients
eCEC	effective cationic exchange capacity
EC_a	soil apparent electrical conductivity
EC_{ss}	electrical conductivity in the soil solution
ESAP	electrical conductivity sampling assessment and prediction
ET_o	reference evapotranspiration
OM	organic matter
SD	standard deviation

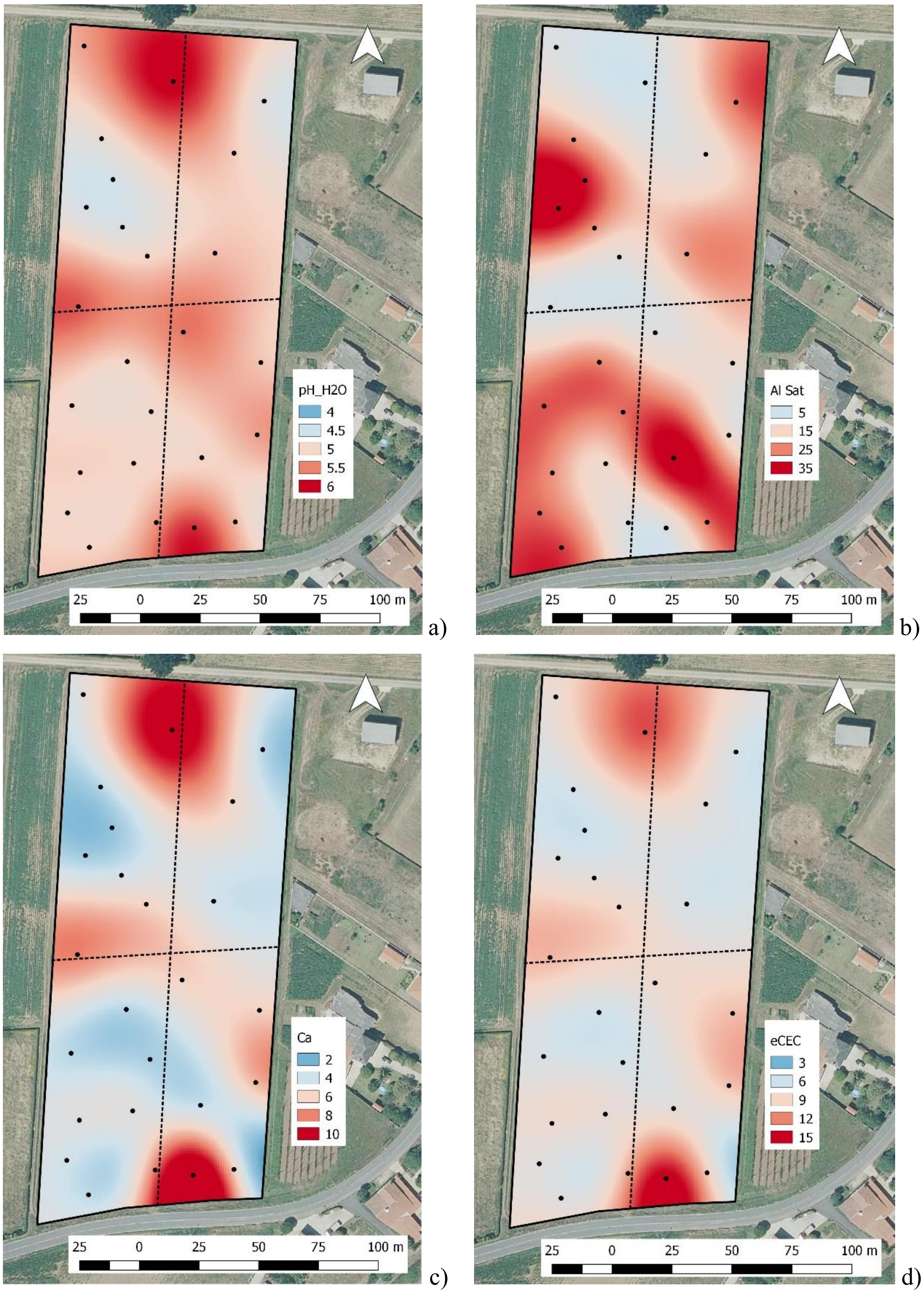

Fig. 5 **pH (-, a), Al Sat (%, b), Ca (c), and eCEC (d) (cmol(+) kg⁻¹); maps obtained with QGis-'v.surf.rst'; irrigation sectors in the study plot (dashed lines), and sampling points (points)**

concentration of electrolytes in the pore water [27]. Soil conductivity depends on the presence of dissolved inorganic solutes in the aqueous phase, consisting of soluble and readily soluble salts in the soil, including charged species (e.g., Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^-, NO_3^-, SO_4^{2-} and CO_3^{2-}), non-ionic solutes, and ions, which combine to form ion pairs [28]. This also includes the soil texture, soil temperature, bulk density, water content, and soil organic matter. Therefore, the clay minerals contribute significantly to the soil conductivity. Some soil particles do not conduct electricity and they act as insulators, reducing current flow; for example, quartz, mica, calcium carbonate, and gypsum have this property [29].

The depth range of the measurements depends on the orientation of the coils. According to [29], the sensitivity in vertical dipole is highest at 40 cm below the instrument, while the sensitivity in horizontal dipole is highest directly below the instrument. Normally, the depth range is considered to be 1.5 m or 0.75 m, respectively, when the vertical or horizontal dipole is used. In our study, simultaneous measures of the apparent electrical conductivity (EC_a) in the horizontal (EC_a-H) and vertical (EC_a-V) dipoles were determined, and for a homogeneous terrain, this reaches 70 % of the response at the upper 1.5 m in the vertical dipole, and at the upper 0.75 m in the horizontal dipole. Rhoades et al. (1999) [13] investigated soils with a strong relationship between ECs (electrical conductivity of the solid part of the soil) and soil texture. The soil volumetric water content at saturation is closely related to bulk density, and EC_a is a function of bulk density, soil volumetric water content, and the electrical conductivity of the soil solution (EC_{ss}). These authors recommended performing EC_a measurements at higher water contents (i.e., field capacity) to assess the value of the electrical conductivity of the soil solution.

One of the main problems of the EM38 equipment is the drift of the EC_a values produced by changes in the measurement conditions (climate and soil) throughout the day [30]. According to the experience of [29], a suitable way to reduce such influences includes the following steps: (i) allow the system to be in equilibrium with the environment at the beginning of the measurement, and (ii) avoid direct sunlight during the study, particularly at higher temperatures. Changes in direct sunlight and shadows can produce enormous drift. Therefore, measurements were made on a calibration transect with a frequency of one measurement every hour.

The ground temperature influences the electrical conductivity values. Electrolytic conductivity increases at a rate of approximately 1.9 % for every 1 °C increase in temperature. Because of this, all of the EC_a values are recalculated at a temperature of 25 °C (EC_a^{25}). The function described in Equation 1 by [31] was used.

$$EC_a^{25} = EC_a * (0.447 + 1.4034 * \exp(-26.815 * T)$$

T: soil temperature [°C]

EC_a^{25}: EC_a recalculated at a soil temperature of 25 °C

(Eq. 1)

A GNSS-RTK receiver (Hi-Target V200, Guangzhou, China) was used to find the 25 measurement points, established previously using ESAP software (Fig. 1b). Soil samples were taken from the surface horizon (0 – 40 cm depth) in the row for physico-chemical analysis. Samples were oven dried (40 °C) and sieved to 2.00 mm, to separate the fine soil fraction. Soil physical and chemical properties were determined according to standard methods [32].

Textural analysis (contents in sand, silt, and clay) was conducted after organic matter destruction with H_2O_2, the elimination of Fe and Al oxihydroxides with HCl, and dispersion with hexametaphosphate and sodium carbonate. Soil pH was determined in water and 1 M KCl (soil: solution 1:2.5) using a pH meter (Multimeter MM41, Crison, L'Hospitalet de Llobregat, Barcelona, Spain), and the electrical conductivity in the soil solution (EC_{ss}) was determined according to standards [32]. Total organic carbon and nitrogen contents were measured using an elemental analyzer (TruSpec-CHNS, LECO Corporation, St. Joseph, MI, USA). Organic matter (OM) was computed from the carbon content [33] using Equation 2.

$$OM (\%) = C (\%) \times 1.724 \quad \text{(Eq. 2)}$$

Exchangeable Ca, Mg, Na, K, and Al, and effective cation exchange capacity (eCEC) were determined following extraction with 1 M ammonium chloride, using atomic absorption and emission spectroscopy (Optima 4300 DV, Perkin Elmer, Boston, MA, USA) [34]. Al saturation was calculated as the ratio between Al in the

Table 2 Statistical summary of the soil properties studied

Variable	Units	Mean	Median	SD	CV	Min.	Max.	Skewness	Kurtosis
pH (H_2O)	–	5.11	5.02	0.41	21.2	4.57	6.14	1.189	1.195
pH (KCl)		4.36	4.30	0.39	9.6	3.70	5.48	1.164	1.904
Ca	cmol(+) kg^{-1}	5.38	4.63	2.83	7.9	2.68	15.37	2.172	5.520
Mg		0.85	0.78	0.39	9.0	0.39	2.05	1.514	2.502
Na		0.21	0.20	0.08	41.0	0.09	0.38	0.862	0.414
K		0.58	0.53	0.24	52.6	0.26	1.20	0.822	0.012
Al		1.36	1.53	0.86	46.2	0.04	3.10	0.152	– 0.763
$_e$CEC		8.38	7.57	2.66	35.7	5.72	18.46	2.505	7.664
Al Sat.	%	18.90	22.77	12.77	42.2	0.20	42.93	-0.107	– 1.121
P	mg kg^{-1}	53.27	48.16	20.41	63.0	21.73	128.40	1.894	6.275
C	%	3.62	3.53	0.61	31.7	2.67	5.15	0.658	0.229
N		0.33	0.32	0.05	67.6	0.24	0.46	0.586	0.062
Organic matter		6.25	6.09	1.05	38.3	4.60	8.88	0.653	0.228
Coarse fraction		31.07	31.21	6.59	16.7	18.87	43.37	0.083	– 0.762
Fine fraction		68.93	68.79	6.59	16.0	56.63	81.13	– 0.083	– 0.762
Sand		36.67	37.28	3.02	16.7	31.77	43.28	0.261	– 0.690
Silt		43.25	43.93	3.07	4.5	36.07	50.14	– 0.130	0.447
Clay		20.08	20.29	2.68	32.8	14.65	26.23	– 0.009	– 0.182
C / N	–	10.85	10.84	0.49	39.0	10.00	11.77	0.060	– 0.904
K / Mg		0.73	0.71	0.24	8.2	0.26	1.33	0.204	0.629
Ca / Mg		6.71	6.04	2.62	7.1	2.39	13.38	0.942	0.595
EC_{ss}	mS m^{-1}	18.30	20.00	7.51	13.3	5.79	39.60	0.564	1.310
EC_a-H median		13.35	12.93	1.82	14.9	10.51	16.25	– 0.092	– 1.590
EC_a-H min		12.78	12.55	1.91	13.3	9.52	15.90	0.008	– 1.276
EC_a-H max		13.97	14.69	1.86	13.6	10.82	16.92	– 0.067	– 1.526
EC_a-V median		7.38	7.08	2.61	36.4	2.06	13.16	0.154	– 0.524
EC_a-V min		6.24	6.66	2.27	31.1	1.79	11.82	0.057	0.238
EC_a-V max		8.43	8.16	2.62	35.3	2.18	13.43	– 0.224	– 0.575

SD: standard deviation; CV: coefficient of variation (%); Min.: minimum; Max.: maximum; eCEC: effective cation exchange capacity; Al Sat.: aluminum at saturation; EC_{ss}: electrical conductivity in the soil solution; EC_a-H: soil apparent electrical conductivity in the horizontal dipole; EC_a-V: soil apparent electrical conductivity in the vertical dipole exchange complex and the effective cationic exchange capacity, and expressed as a percentage [35]. The available P was extracted in 0.5 M $NaHCO_3$ and determined colorimetrically using UV-visible spectroscopy (Jenway6300, Cole-Parmer Ltd., Staffordshire, UK) [36].

2.4 Statistical analysis

A descriptive analysis of the different variables determined in the soil analysis was carried out (mean, median, standard deviation, coefficient of variation (CV), minimum, maximum, skewness, and kurtosis), including a data normality analysis (Shapiro–Wilk test), for assessing a central trend and data spread. EC_a-H and EC_a-V, and the relationships between EC_a (both EC_a-H and EC_a-V) and soil physico-chemical properties were assessed through the Spearman correlation coefficient, *rho*, due to the absence of normality in the dataset [17].

The spatial distribution of EC_a over the study plot was evaluated via deterministic and geostatistical methods using the GSTAT software for R [37], and the estimated values of EC_a were obtained via the Random Forest regression kriging technique (RK-RF), using the GSIF package for R [38], and mapping with QGIS v3.8 (https://qgis.org). The extraction of the median, maximum, and minimum values of EC_a (EC_a median, EC_a max, and EC_a min) was carried out considering a buffer of 2 m, using the final EC_a maps for both dipoles, and using the 'zonal statistics' command (QGIS v3.8, https://qgis.org). Mapping was carried out using regularized spline with tension, which performs surface interpolation from a vector points map using splines [39–40]. These maps were implemented in the geographical information system (QGIS v3.8, https://qgis.org) using the command: 'v.surf.rst'.

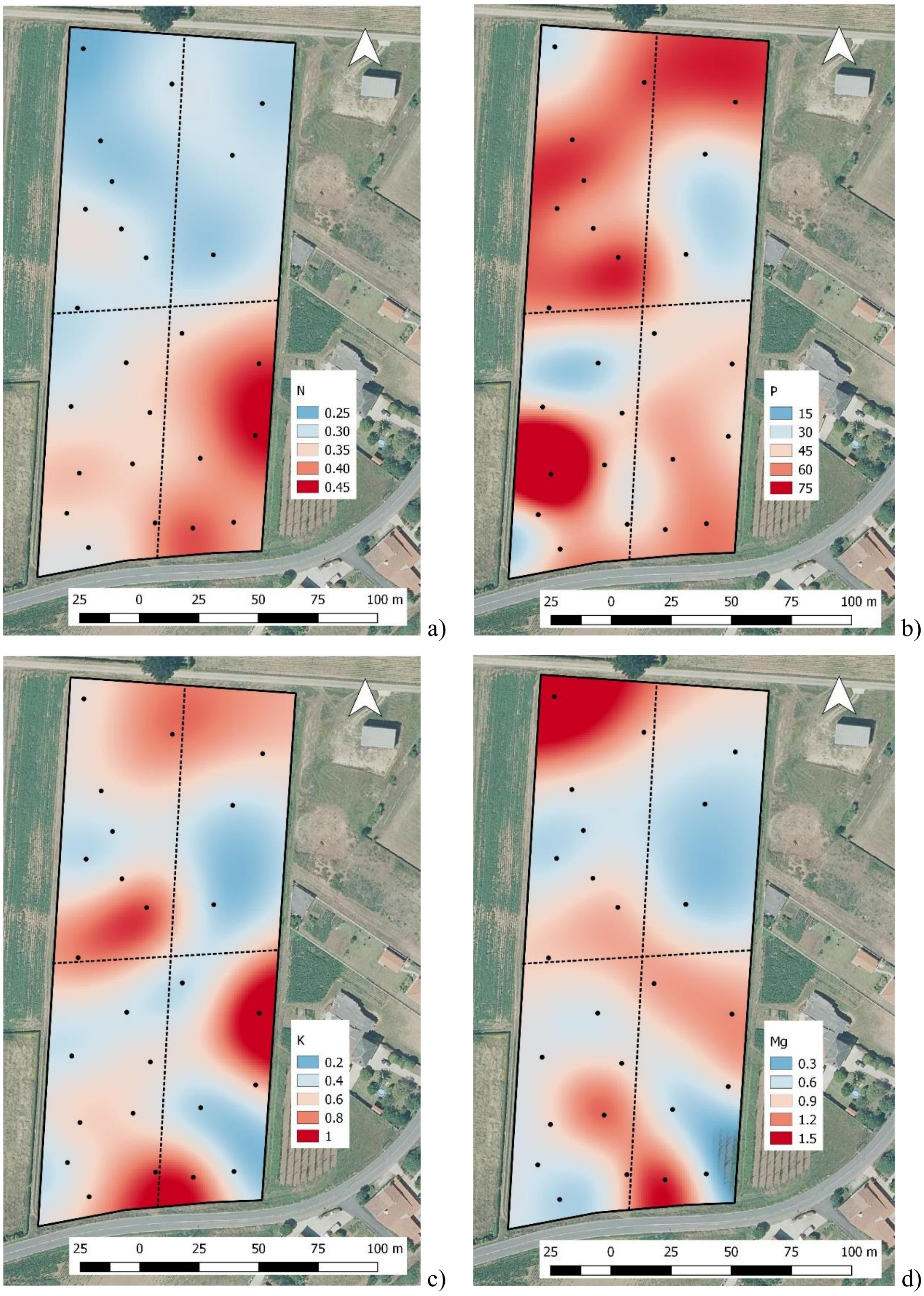

Fig. 6 Nitrogen (%, a), phosphorus (mg kg^{-1}, b), potassium (c), and magnesium (d) (cmol(+) kg^{-1}); maps obtained with QGis-'v.surf.rst'; irrigation sectors in the study plot (dashed lines), and sampling points (points)

3 Results and Discussion

3.1 Soil apparent electrical conductivity (EC_a) results

The EC_a variation, both vertical and horizontal dipole, is greater vertically (CV > 30 %) compared to CV < 15 % horizontally (Table 2 and Fig. 3). The spatial distribution of EC_a variability shows different spatial patterns, depending on whether the data are analyzed at the surface (EC_a-H, Fig. 3a) or at depth (EC_a-V, Fig. 3b). The maximum measured values of EC_a are related to the characteristics of the acid soils of Galicia, where values of below 20 mS m^{-1} are common [16]. In sectors B and D, the lowest values of EC_a-V are observed, which is indicative of a lower soil depth [17]. A clear soil heterogeneity in terms of its vertical profile, as shown in the differences between figure 3a and 3b.

3.2 Statistical Characterization of Soil Properties

The means and medians of the studied properties were rather similar; however, the skewness and kurtosis coefficients were highly variable (Table 2). Shapiro–Wilk's test confirmed the absence of normality in the data distributions for several properties: pH (H_2O), pH (KCl), Ca, Mg, $_e$CEC, P, and EC_a-H max and EC_a-H median. Correlation coefficients between EC_a and the measured soil properties were low (Table S1, see page 141), although they were significant in some cases, such as the pairs C, N, and OM with EC_a-H min, EC_a-H max, and EC_a-H median (*rho*: 0.462 – 0.545), in a negative way to EC_a-V min and EC_a-V median (*rho*: –0.445 and –0.547). Other correlations were obtained for eCEC/EC_a-H max (positive, *rho*: 0.462; p-value: 0.020) and Silt / EC_a-V min (negative, *rho*: –0.460; p-value: 0.021). The correlations between soil properties and EC_a-V measurements are negative or non-existent, because the soil samples refer to the first 40 cm of the soil, and in the case of EC_a-V the effective measurement depth is 1.5 m.

3.3 The zoning of hopyard soil properties

Figures 4, 5, and 6 show the spatial variability of the main soil properties related to fertilization. The organic matter shows an arrangement contrary to the clay, where higher values of OM are related to a lower clay content (Fig. 4a, 4b). Organic matter is related to the adsorption process of nutrients [41]. In general, the areas of the plot with lower clay values are related to those that have shown lower EC_a-V values (Fig. 3b). The variability of the pH of between 4 and 6 is of great relevance to understanding productive behavior in the study plot, as well as for evaluating the availability of nutrients [5]; in global terms, all micronutrients are available in these pH values, with the exception of P.

The lowest pH values are associated with high values of % of saturated aluminum, with low values of Ca, and in summary of eCEC (Fig. 5). The nitrogen content in the soil (Fig. 6a) is directly related to OM, so its spatial variability is similar to this. The distribution of the P content, where there are zones with values lower than 30 ppm (blue colors, Fig. 6. b), shows a different spatial pattern compared to those shown for the pH and the remaining cations of the exchange complex. The phosphorus availability reaches its maximum at a pH of close to 6.5; below this value, phosphorus precipitates in the form of iron and aluminum phosphates. In addition, at an acidic pH, phosphorus adsorption by soil colloids increases. A significant proportion of the phosphorus is found as fixed inorganic phosphorus [42].The variability of P is related to a CV > 60 %, being together with N, the element that presents the greatest variability. However, P presents a positive correlation with the K/Mg ratio (Table S1). For Mg in the exchange complex (Fig. 6d), a spatial variability related to CV (Table 2) of greater than 50 % was observed, with similar patterns to that of K (Fig. 6c).

In global terms, it is recommended to carry out a differential fertilization treatment to correct low pH values, as well as to increase the areas with low P values. The rest of the nutrients are within normal values, as established in the bibliography [11, 20], for acid soils, although the interactions between nutrients must be analyzed in depth, to evaluate possible negative effects on the availability of nutrients. As a summary of the results, low values of clay and phosphorus are observed in sectors B and C. In the case of pH, it is recommended to increase it in all sectors, with a special emphasis on sectors A and B, with the objective of minimizing the problems derived from a high Al content through liming. The repeatability of the study requires a correlation between the soil parameters and EC_a values (H and V) for each specific plot. If the soils that are studied are neutral or alkaline, there will be great differences in comparison with the acid soils present in Galicia. Based on the relationships established between EC_a and OM, C, and N, it is possible to monitor these parameters over the years. In the case of elements such as P, it is necessary to continue with the classical soil analysis, combined with foliar analysis. Areas with extreme values obtained in the study should be used as sampling areas, to assess the nutrients, and proceed to their correction, when necessary.

4 Conclusions/Summary

Since a hop yard has an estimated lifespan of 20 – 50 years, soil characterization is essential for delineating the site-specific management zones. EC_a as a non-invasive technique might provide useful information for hop yard zoning. Positive significant were found with the EC_a (horizontal dipole) for C, N, OM, and $_e$CEC, which suggests that the determination of the EC_a can help to evaluate the nutritional status (N, OM, and eCEC) of the soil at a lower cost. However, the lack of correlation of the EC_a with parameters such as the percentage of aluminum saturation and P should be based on classical soil and leaf samples. Hopgrowers must make adaptations in order to carry out efficient fertigation, accounting for the variability detected. The spatial variability of several nutrients, such as P, does not coincide with the existing irrigation sectors. The use of fertigation as a fertilizer technique would require modifications that divide the current irrigation/fertigation sectors to adapt to the existing variability.

Acknowledgement

The authors thank the administrative staff of 'Lúpulo Tecnología de Galicia, Sociedad Cooperativa Gallega (LU.TE.GA.)', and the soil laboratory of 'Departamento de Edafoloxía – Campus de Lugo' of University of Santiago de Compostela.

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Received 17 October 2022, accepted 30 November 2022

Table S1 Significate Spearman correlation between all study variables measured

		CF	FF	pHH2O	pHKCl	ECss	Ca	Mg	Na	K	Al	CECe	P	C	N	OM	Ca/Mg	Sand	Silt	ECa-Hmin	ECa-Hmax	ECa-Vmin	ECa-Vmax
CF	rho	-1,000**	--																				
	p-value	0	.																				
pHKCl	rho			,914**	--																		
	p-value			<,001	.																		
ECss	rho	,423*	-,423*																				
	p-value	0,035	0,035																				
Ca	rho			,854**	,870**																		
	p-value			<,001	<,001																		
Mg	rho			,498*	,732**		,645**																
	p-value			0,011	<,001		<,001	.															
Na	rho			,531**	,571**		,525**	,602**															
	p-value			0,006	0,003		0,007	0,001															
K	rho				,559**	,726**	,564**	,636**															
	p-value				0,004	<,001	0,003	<,001															
Al	rho			-,743**	-,862**		-,801**	-,748**	-,563**	-,484*													
	p-value			<,001	<,001		<,001	<,001	0,003	0,014													
CECe	rho			,796**	,808**		,938**	,626**	,489*	,602**	-,635**	--											
	p-value			<,001	<,001		<,001	<,001	0,013	0,001	<,001	.											
AlSat	rho			-,788**	-,888**		-,888**	-,772**	-,532**	-,527**	,967**	-,753**											
	p-value			<,001	<,001		<,001	<,001	0,006	0,007	<,001	<,001											
C	rho	-,430*	,430*									,512**		--									
	p-value	0,032	0,032									0,009		.									
N	rho											,435*		,941**	--								
	p-value											0,03		<,001	.								
OM	rho	-,430*	,430*									,512**		1,000**	,941**								
	p-value	0,032	0,032									0,009		0	<,001								
C/N	rho	-,595**	,595**																				
	p-value	0,002	0,002																				
K/Mg	rho					,510**				,568**			,451*										
	p-value					0,009				0,003			0,024										
Ca/Mg	rho			,534**			,518**					,533**											
	p-value			0,006			0,008					0,006											
Silt	rho	-,447*	,447*											,464*	,414*	,464*		-,602**					
	p-value	0,025	0,025											0,019	0,04	0,019		0,001					
Clay	rho	,530**	-,530**			,489*				,398*									-,433*				
	p-value	0,006	0,006			0,013				0,049									0,031				
ECa-Hmin	rho													,462*	,463*	,462*							
	p-value													0,02	0,02	0,02							
ECa-Hmax	rho											,475*		,545**	,527**	,545**				,862**	--		
	p-value											0,016		0,005	0,007	0,005				<,001	.		
ECa-Hmedian	rho											,408*		,508**	,533**	,508**				,935**	,940**		
	p-value											0,043		0,01	0,006	0,01				<,001	<,001		
ECa-Vmin	rho													-,547**	-,513**	-,547**	-,514**		-,460*				
	p-value													0,005	0,009	0,005	0,009		0,021				
ECa-Vmax	rho	,409*	-,409*														-,398*					,808**	
	p-value	0,043	0,043														0,049					<,001	
ECa-Vmedian	rho													-,445*	-,461*	-,445*	-,415*					,892**	,948**
	p-value													0,026	0,02	0,026	0,039					<,001	<,001