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Mobile and georeferenced electromagnetic sensors and applications for salinity assessment

V. Urdanoz[1], E. Amezketa[2,3], I. Clavería[1], V. Ochoa[2] and R. Aragüés[1]*

[1] *Unidad de Suelos y Riegos. Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA). Unidad Asociada al CSIC. Gobierno de Aragón. Avda. Montañana, 930. 50059 Zaragoza. Spain*
[2] *Sección de Evaluación de Recursos Agrarios. Departamento de Agricultura. Gobierno de Navarra. Ctra. Sadar, s/n. Edificio «El Sario», 3º dcha. 31006 Pamplona (Navarra). Spain*
[3] *Trabajos Catastrales, S. A. Ctra. Sadar, s/n. Edificio «El Sario», 4º. 31006 Pamplona (Navarra). Spain*

Abstract

Soil salinity is a major threat in irrigated agriculture because of its negative on-site (decreased productivity) and off-site (salinization of irrigation return flows) effects. The delineation of the spatial variability of soil salinity is best suited using non-invasive geophysical measurements of the apparent soil electrical conductivity (ECa) using mobile GPS-based systems. Two simple and cost-effective Mobile Georeferenced Electromagnetic Sensors (MGES) developed in Aragón and Navarra (Spain) are described. These devices involve electromagnetic instruments towed by all terrain vehicles and combined with GPS units and data acquisition systems that collect both ECa readings and GPS coordinates. Two applications of the MGES aimed at delineating ECa maps for (i) selecting the most suitable crops in a 43-ha saline site (Hondo de Espartosa) and (ii) correlating ECa with drainage water salinity to ascertain the salinity-source areas in a new 715 ha irrigated basin (Barranco de Lerma) were examined. These examples demonstrate the MGES surveying capacities for management of salt-affected agricultural areas.

Additional key words: drainage water salinity, geophysical measurements, salinity tolerance of crops.

Resumen

Sensores electromagnéticos móviles georreferenciados y aplicaciones para la determinación de la salinidad

La salinidad del suelo es una importante amenaza para la agricultura de regadío debido a sus efectos negativos internos (descenso de la productividad) y externos (salinización de los flujos de retorno del riego). El procedimiento más adecuado para delinear la variabilidad espacial de la salinidad edáfica es mediante la medida geofísica de la conductividad eléctrica aparente del suelo (ECa) efectuada con sistemas móviles georreferenciados. En este trabajo se describen dos Sensores Electromagnéticos Móviles Georreferenciados (MGES) sencillos y económicos desarrollados en Aragón y Navarra (España). Estos equipos incluyen instrumentos electromagnéticos arrastrados por un vehículo todo terreno, combinados con una unidad de GPS y un sistema de adquisición de datos que recopila las lecturas de ECa y las coordenadas geográficas. Se presentan dos aplicaciones del MGES en las que se levantan mapas de ECa para (i) seleccionar los cultivos más apropiados en un regadío salino de 43 ha (Hondo de Espartosa) y (ii) correlacionar la ECa con la salinidad de las aguas de drenaje para identificar las áreas-fuente mas importantes de salinidad en una nueva cuenca de regadío de 715 ha (Barranco de Lerma). Estos ejemplos demuestran las capacidades de análisis del MGES para el manejo de áreas agrícolas afectadas por salinidad.

Palabras clave adicionales: medidas geofísicas, salinidad del agua de drenaje, tolerancia de los cultivos a la salinidad.

* Corresponding author: raragues@aragon.es
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Abbreviations used: Ai (surface area in each ECah interval of each watershed in Barranco de Lerma), At (sum of surface areas of all the intervals for each watershed in Barranco de Lerma), ECa (apparent soil electrical conductivity), ECah (horizontal-dipole ECa), ECav (vertical-dipole ECa), ECdw (electrical conductivity of drainage water), ECe (electrical conductivity of the soil saturation extract), EGNOS (European Geostationary Navigation Overlay Service), EM (electromagnetic), ER (electrical resistivity), ESAP (Electrical conductivity Sampling Assessment and Prediction), GIS (Geographic Information System), GPS (Global Positioning System), MGES (Mobile Georeferenced Electromagnetic Sensor), MSE (mean square error), P (probability value).

Introduction

Soil salinity reduces soil and water quality, constrains crop yield and agricultural productivity, and, in severe cases, leads to the abandonment of agricultural soils. According to FAO, the total global area of salt-affected soils is 831 million hectares (Martínez-Beltran and Manzur, 2005). From this total, 32 and 45 million are soils cultivated under dry land and irrigated agriculture, respectively. Secondary salinization is a relevant threat in irrigated agriculture. Thus, FAO (2002) estimates that 0.25 to 0.5 million hectares of irrigated land are salinized yearly. Soil salinization has been identified by the European Commission as one of the eight major threats to European soils, mainly in the Mediterranean area (EC, 2003), and Herrero and Aragüés (1988) indicated that about 25% of the irrigated land in the Middle Ebro basin of Spain is salt-affected.

Traditional methods for determining soil salinity based on soil sampling and analyses are time consuming, labor intensive and costly. As a consequence, the developed soil maps are generally inappropriate to characterize the typical spatio-temporal variability of salinity and can lead to errors of interpretation. In contrast, high resolution soil salinity maps may be obtained using electromagnetic (EM) induction sensors which measure the apparent electrical conductivity (ECa) of the bulk soil. To improve the efficiency of ECa data collection, EM instruments, GPS and data loggers have been combined onto mobile electromagnetic sensing systems (Rhoades *et al.*, 1999). Mobile Georeferenced Electromagnetic Sensors (MGES) have been successfully used for over a decade, particularly in the United States and Australia. The earliest research mobile EM equipments (Carter *et al.*, 1993; Rhoades, 1993) used analogue Geonics-EM38 sensors operating in a stop-and-go mode, taking at each point the horizontal and vertical dipole measurements. Custom-made data logger and software were used (Triantafilis *et al.*, 2002) because the original Geonics data logger was not designed to accept GPS data. Later, the systems were improved by upgrading the instruments to digital output data and replacing the analogue sensor by digital dual-dipole units which record simultaneously in the horizontal and vertical dipole orientations, and by operating in a fully automated on-the-go mode. Commercial MGES (Rhoades *et al.*, 1999) are complex and costly, and other mobile devices based on four electrode electrical resistivity (ER) sensors (Carter *et al.*, 1993; Rhoades, 1993; Sudduth *et al.*, 1999) need a proper contact between the soil and the inserted electrodes and cannot be used in dry or stony soils and in fields with beds and furrows. In consequence, simpler, less expensive and updated prototypes have been developed at a local level.

Two simple and cost-effective MGES prototypes were developed in Spain (Aragon and Navarra) that incorporate the latest technological advances with respect to EM sensors, GPS systems, software and field computers. In this paper, the main components, characteristics and costs in Spain of these devices are described and their advantages, limitations and potential applications are discussed.

To demonstrate some MGES applications, two case studies carried out in semi-arid Ebro river basin agriculture (Spain) are presented. The aim of the first case study (Hondo de Espartosa) is to select the most suitable crops on the basis of their salinity tolerances and the detailed ECa map of the 43-ha field obtained with the MGES. Since the salinity tolerance of crops is based on ECe (electrical conductivity of the soil saturation extract) (Maas, 1990), ECa must be converted into ECe using appropriate calibration equations. Thus, details of the calibration procedure are given for this case study.

The second MGES application is given for the 715 ha Barranco de Lerma basin, an area that is being transformed into irrigation. Since the drainage waters of this presently dry-land basin are moderately saline (ECdw values up to about 5 dS m^{-1}) it was anticipated that already present salt-affected soils could be the source for these saline drainage waters. Thus, a detailed ECa map was obtained with the MGES and the spatial variability of ECa was related to the spatial variability of ECdw in order to ascertain the salinity-source areas in this basin. This information is essential in assessing the severity of the problem and in developing alternatives for mitigation under future irrigated conditions.

The objectives of this work are therefore (i) to describe two simple and cost-effective MGES prototypes developed in Spain and (ii) to present two potential applications of this surveying technique that will aid in the efficient management of saline agricultural areas.

Material and Methods

The Mobile Georeferenced Electromagnetic Sensor (MGES)

Table 1 summarizes the components, main characteristics and costs of the two MGES prototypes developed

Table 1. Synoptic description of components, characteristics and costs (in €, year 2006) of the two Mobile Geo-referenced Electromagnetic Sensors (MGES) developed in Aragón and Navarra (Spain)

Components	**MGES-Aragón**	**MGES-Navarra**
1. *Electromagnetic sensor*		
Model	1S (Dualem)	EM38RT (Geonics)
Readings	Simultaneous ECah/ECav	ECah or ECav
Cost	11,000 €	11,000 €
2. *GPS unit*		
Receiver model	Garmin etrex	Trimble Pathfinder Pro-XT
Differential correction	No	Yes (post-processing)
Absolute position accuracy	5 m (2 m with EGNOS)	<1 m with post-processing
External GPS antenna	No	Yes
Receiver-computer connect.	Serial RS232	Bluetooth® or Serial RS232
Cost	300 €	2,500 €
3. *Data acquisition system (computer and software)*		
Field computer model	Allegro CX-Juniper System	Tablet PC-Hammer. XRT
Operation system	Windows CE	Windows XP
Serial ports	2	2
Bluetooth technology	Yes	Yes
Field-access to internet	Yes	Yes
Field computer price	3,000 €	4,000 €
Surveying field software	HGIS Prof., StarPal, Inc.	TerraSync™®
Office software	DAT38W	PathFinder Office®
Software cost	600 €	2,500 €
4. *Sled*		
Material	Polyester resin reinforced with fiberglass	Polycarbonate sled with polypropylene skids
Size (l × w × h, cm)	130 × 50 × 20	134 × 50 × 22
Sensor height above ground	1 cm	7 cm
Connection to vehicle	Strap	PVC-hollow tube
Cost	200 €	4,000 €*
5. *Vehicle: any all-terrain vehicle susceptible of traveling at low speed*		
Total cost (€)	12,100 €+ vehicle	20,000 €+ vehicle

* Cost includes the design of several prototypes and the manufacture of current model.

in Aragón and Navarra (Spain). Excluding the vehicle, the total costs are 12,100 € (Aragón) and 20,000 € (Navarra), substantially lower than similar commercial systems. This cost is quite affordable taking into account the saving in time, labor and personal resources as compared to pedestrian EM measurements or classical soil surveys. Thus, with the MGES traveling at a speed of about 7 km h^{-1}, 3600 ECa readings are collected per hour, and with a 14 m spacing between transects it is possible to map 10 ha h^{-1}. For comparison purposes, mapping of this 10 ha-field using the pedestrian EM sensor will require more than 30 hours, whereas the classical soil survey will be absolutely unfeasible at this level of resolution.

Both MGES prototypes consist of five basic components (Fig. 1): (1) an electromagnetic (EM) sensor, (2) a Global Positioning System (GPS) unit, (3) a data acquisition system (field computer and specific software), (4) a non-metallic sled, and (5) an all-terrain vehicle that pulls behind the sled while trafficking through the study area.

Two EM sensors were selected that measure the ECa to soil depths of about 1 and 2 m depending on coils' orientation (horizontal and vertical to the soil, respectively). The Dualem-1S measures ECa at the two depths simultaneously while the Geonics-EM38RT must be positioned in one or another orientation (i.e., if both readings are desired, trafficking must be repeated in

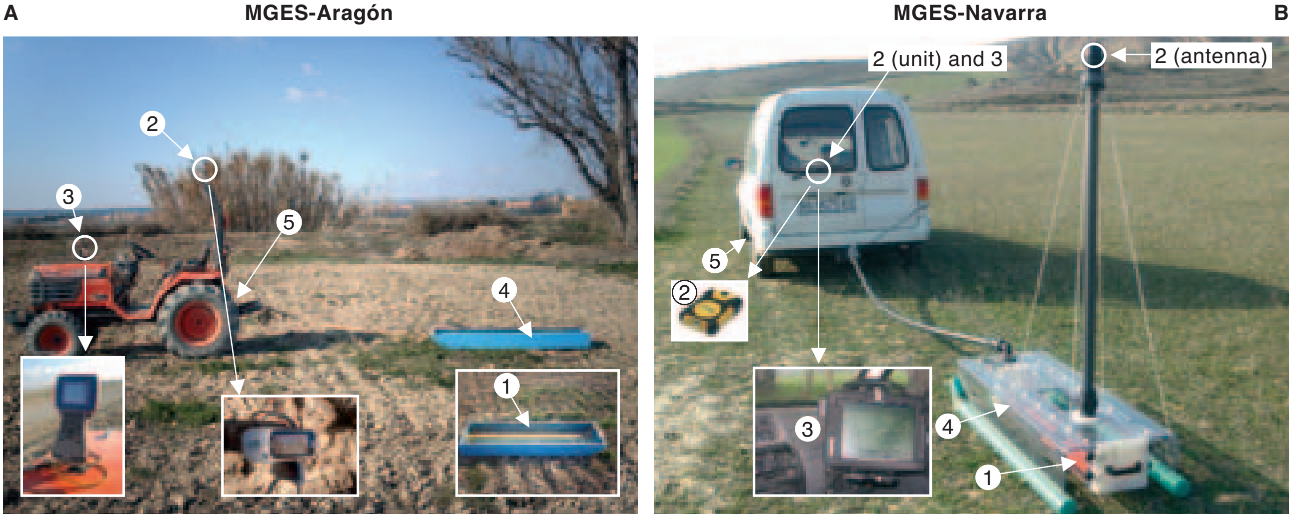

Figure 1. The mobile, georeferenced electromagnetic sensor (MGES) developed in (A) Aragón and (B) Navarra, integrated by the five basic components: 1, electromagnetic sensor; 2, GPS unit; 3, data acquisition system; 4, sled, and 5, all-terrain vehicle.

the horizontal and vertical coil orientations). Both sensors are lightweight, compact, noninvasive, can be used in stony soils, and characterize a large volume of soil. Disadvantages of both models include that ECa (i) must be corrected to the reference temperature of 25°, so that soil temperature must be measured at the time of surveying, (ii) is affected by metallic objects closer than 1 m, (iii) should be taken when soil moisture is at least greater than one-half of field-capacity (Rhoades *et al.*, 1999), and (iv) requires calibration for conversion to ECe values. The EM sensor is connected to a field computer through an RS-232 serial connection for automatically storing ECa. Since ECa is affected by metallic objects within approximately 1 m, the EM sensor is installed in a non-metallic sled that is pulled by the all-terrain vehicle at a distance of about 3 m.

Two sleds were developed to tow the EM sensor parallel to the travel direction, one on polyester resin reinforced with fiberglass (Aragón) and the other on polycarbonate with polypropylene skids (Navarra). Both sleds are stable to avoid overturning, are heavy enough to work over stubble, fix the EM sensor to avoid vibrations and movements during the survey, and are configured to move between 70 cm seedbeds or multiples of that distance.

The GPS unit records the coordinates of the ECa readings with accuracies within 1 m in the Navarra configuration after a post-processing differential correction, and within 5 m in the Aragón configuration (2 m using automatic corrections with the EGNOS satellite). The GPS receiver is mounted over the all terrain vehicle and is connected to the field computer via Bluetooth® (Navarra) or RS232 serial connection (Aragón). The Navarra GPS unit has an antenna located 1.5 m above the EM sensor, whereas in the Aragon unit the antenna is installed in the vehicle and the distance between it and the EM sensor is corrected using an application installed in the field computer.

The data acquisition system is located in the all-terrain vehicle in front of the operator and consists of a robust, rugged and sealed field computer with specific software for logging and integrating the ECa and the coordinate's readings into a single file.

The all-terrain vehicle must allow driving at a slow speed (generally, less than 10 km h^{-1}) without heating the engine. The most appropriate vehicles are small tractors or quads because of their small size and ease of maneuverability.

Functioning of the MGES

The MGES traffics through the field while ECa readings and GPS coordinates are taken in a fully automated on-the-go mode. The equipment is designed to work in irregular topography, even though the ideal conditions are those of extensive fields with gentle slopes and smooth surfaces.

The field computer with the specific software logs the acquired data at given times or distances, depending on the objectives and scale of work. The data acquisition software integrates the coordinates and ECa data into a single file, which is then downloaded to the office computer, exported to GIS, CAD or ASCII format, and incorporated into geographic information systems for storing, analyzing and mapping the spatial information.

The use of GIS packages (such as *ArcView*) or other specific applications such as *Surfer* or *ESAP* (Lesch *et al.,* 2000, 2002a,b), specifically developed for analyzing, processing and mapping the information collected by the MGES, are useful for assessing, interpreting and mapping soil salinity data.

Applications of the MGES

A general overview of applications of the new equipment and two case studies for efficiently managing salt-affected agricultural areas are presented. The most common application of MGES is mapping and monitoring of soil salinity in either naturally-salt-affected environments or in anthropogenic-salinized areas. However, MGES is more frequently applied in irrigated agriculture because of its higher economical value and higher potential negative environmental impacts. Measurement intensities can vary from 2-5 m for intensive surveys and detailed field-scale studies, to 75-100 m for basin-scale studies. For very extensive areas (thousands of hectares or higher), airborne EM techniques may be best suited than terrain MGES (Spies and Woodgate, 2005). Detailed field-scale MGES surveys are useful for establishing proper management (including selection of suitable crops) and rehabilitation strategies. Irrigation district-scale MGES surveys are useful for crops and irrigation-water planning, for prioritizing salt-affected land abandonment, and for identifying recharge and discharge saline areas. Regional-scale MGES studies can be used for delineating soil salinity phases and for soil quality monitoring, as will be required by the EU Soil Framework Directive in preparation [COM (2006) 232 final].

Finally, because of the ability of ECa to detect other soil variables besides salinity, MGES surveys have been undertaken in precision agriculture for mapping of nutrients, texture-related properties (e.g., sand, clay, depth to claypans or sand layers), water content-related properties (e.g., depth to shallow water tables), bulk density-related properties (e.g., compaction), organic matter-related properties, and for identifying soil properties influencing crop productivity (Corwin and Lesch, 2003).

Two case studies (Hondo de Espartosa and Barranco de Lerma) are presented to demonstrate MGES applications. The MGES-Navarra was used in Hondo de Espartosa and the MGES-Aragón in Barranco de Lerma. In both cases, the surveying was performed when the soil water content was close to field capacity, as recommended for optimum sensor performance (Rhoades *et al.,* 1989). Trafficking was performed at a mean speed of 6-7 km h^{-1}, following orthogonal grids of variable size depending on fields' surface areas (Table 2). The ECa readings (dS m^{-1}) were transformed to a reference temperature of 25°C (USSL Staff, 1954) from the soil temperatures measured at depths of 20 and 60 cm.

The GPS readings of the coordinates were recorded in the UTM system (ED50 Spain Peninsula). In Hondo de Espartosa, the readings were post-processed with a Trimble's Pathfinder Office program (vs. 2.57®) using the Base Station (BS) of the Department of Public Works of the Government of Navarra located 68 km from the study area. This post-processing provides for a mean position accuracy of about 0.4 m. In Barranco de Lerma, the coordinate's readings were corrected with an application specifically developed to adjust the 4 m-gap between the GPS located in the tractor and the EM sensor located in the sled. Since the EGNOS satellite was operative during the survey, the mean coordinate's accuracy was about 2 m.

Table 2. General characteristics of the two study areas (Hondo de Espartosa in Navarra and Barranco de Lerma in Zaragoza)

	Hondo de Espartosa	Barranco de Lerma
Surface (ha)	43	750
MGES survey		
Survey date	Feb. 2006	Oct-Dec 2005
Grid size (m)	14 × 2	30 × 7
Number of ECa readings	11,721	42,275
ECa readings ha^{-1}	273	56
Surveying time (h)	4.1	75
Surveying time ha^{-1} (min ha^{-1})	6	6
Soil sampling for MGES calibration		
Nº of calibration sites	27	—
Nº of calibration sites ha^{-1}	0.63	—
Maximum depth sampled	0.9 m	—
Nº of soil samples	81	—

Case study 1 (Hondo de Espartosa): soil salinity mapping for determining the suitability of cropping patterns in a salt-affected field

The study was conducted in a 43 ha sprinkler irrigated field in Hondo de Espartosa (Navarra, Spain; latitude: 4680791, longitude: 4680791). Geographic elevation ranges from 290.5 to 294.5 m above see level. The area is characterized by mean annual temperature of 13.9°C, precipitation of 376 mm, and ETo of 1171 mm (following Penman-Monteith Method) based on data from the Cadreita weather station (Gobierno de Navarra, 2001), 7 km from the plot. The soil moisture and temperature regimes are ustic and mesic respectively, as defined by Soil Survey Staff (1999).

Horizontal-dipole readings (ECah) were taken with the MGES as described above. Since the aim of this case study is to ascertain the expected yield losses due to soil salinity, the ECah readings were converted into ECe. Twenty seven sampling sites covering the full range of the ECah readings over the whole study area were selected for ECe-ECah calibration purposes (Table 2). After reading of the ECah at each site, soil core samples were taken beneath the EM sensor at 0.3 m increments to a depth of 0.9 m. The ECe was measured by standard methods (USSL Staff, 1954) after the soil samples were air-dried, ground and sieved (< 2 mm).

ECah readings were calibrated against 0-0.9 m average profile ECe through simple linear regression using raw or log-transformed variables (ln ECah, ln ECe). Decorrelated ECah data (z1) were used in place of the signal readings as the predictor variable in the regression equation to reduce possible autocorrelation within the data:

$$\ln \mathrm{ECe} = b0 + b1\ (z1)$$

where $z1 = \dfrac{\ln \mathrm{ECah} - \mathrm{mean}\ (\ln \mathrm{ECah})}{\mathrm{std.\ dev.}\ (\ln \mathrm{ECah})}$

In order to select the best calibrating equation, the model with the smallest «sum of squares of prediction errors» (*PRESS* score, i.e., *P*redicted *R*esidual *S*um of *S*quares), was chosen. The residual spatial independence was examined by the Moran residual autocorrelation test (Brandsma and Ketellaper, 1979; Lesch *et al.*, 1995a,b). The statistical analyses were carried out using the *ESAP* software package (Lesch *et al.,* 2000, 2002a,b), and the *Statgraph Plus 5.1* (Statgraphics Plus for Windows 5.1, 2000).

The optimal calibration equation was used to predict average profile ECe in the remaining non-sampled sites from the ECah readings. Then, the ECe raster map (Fig. 2) was obtained with *ArcView 9.1* using the krigging interpolation routine. Seven 2 dS m^{-1} ECe intervals in the 2 to 16 dS m^{-1} range plus the ECe values above 16 dS m^{-1} were selected using *ESAP-Calibration* and the surface area falling in each interval was calculated.

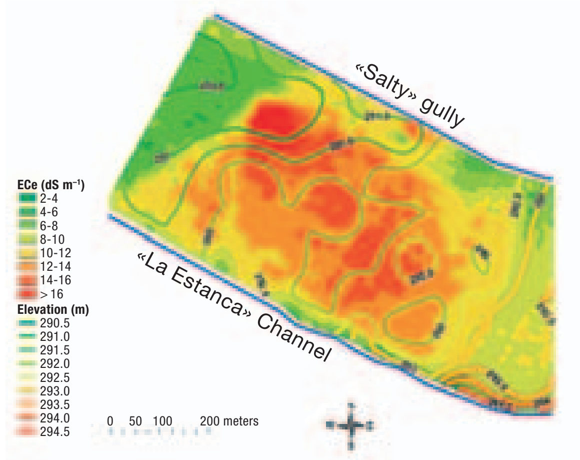

Figure 2. Raster map of average soil profile electrical conductivity of the soil saturation extract (ECe) for the Hondo de Espartosa study area. The digital elevation model contour lines are also shown.

Yield-loss estimates for thirteen local crops were obtained based on these areas, the mean ECe of each interval, and the salinity tolerance of each crop as given by the Maas and Hoffman «threshold-slope» model (Maas, 1990). Linear weighting across soil depths was used to calculate the depth-specific salinity effect on crop yield.

Case study 2 (Barranco de Lerma): ECa mapping and its relationship with drainage water salinity

The 715 ha Barranco de Lerma basin was selected in the XII irrigation sector of the Bardenas II irrigation scheme (Zaragoza) (latitude: 42° 3' 34.84" N; longitude: 1° 8' 2.86" W). Geographic elevation ranges from 329 to 489 m above see level. The area is characterized by mean annual temperature of 13.3°C, precipitation of 454 mm, and ETo of 1069 (following Penman-Monteith Method) based on data from the Ejea de los Caballeros Weather Station, 6 km from the area.

This basin is presently under transformation into solid-set sprinkler irrigation, but it was a dry-land area when the measurements were taken. The MGES-Aragón was used to delineate the ECa map. This preliminary map will serve as the baseline reference for analyzing future salinity trends under irrigation and assess the impact of irrigation on soil salinity. To this aim, soil samples are being taken to obtain the ECe-ECa calibration equation (data not given).

Details of this survey are given in Table 2. The survey was done from 25 October to 8 November with the MGES, and on 23-24 November and 13-21 December by walking with the Dualem 1S in sloppy areas close to the gullies where the vehicle could not be used. These dates were selected because of the precipitation occurring before them (i.e., soil close to field capacity). Simultaneous georeferenced horizontal (ECah) and vertical (ECav) readings were obtained with the Dualem-1S sensor, but only the ECah data are given in this work. Since ECa is closely related to soil salinity (ECe) when other soil variables (as water content or texture) are relatively uniform (Corwin and Lesch, 2005), the ECah map was the basis for relating soil salinity to drainage water salinity (ECdw).

The Barranco de Lerma basin was disaggregated into 25 watersheds (Fig. 3) using a terrain digital model (pixel resolution = 20 m). Water samples were taken at the drainage exit of each watershed on April 26, 2006, after a precipitation event. The EC of these samples are given in Figure 3. Two additional drainage water surveys were performed in April 3 and 11, 2007. The EC values on these dates (data not given) were significantly correlated ($P < 0.001$) with the EC measured in 2006, indicating the consistency of the measurements performed in both years.

The ECah map of the study area was disaggregated into 25 ECah maps for each of the above mentioned watersheds. Eleven ECah intervals in the 0.03 to 0.92 dS m^{-1} range plus an additional interval for those values above 0.92 dS m^{-1} were selected and the surface area falling in each interval was calculated. The surface-weighted ECah* for each watershed was calculated as:

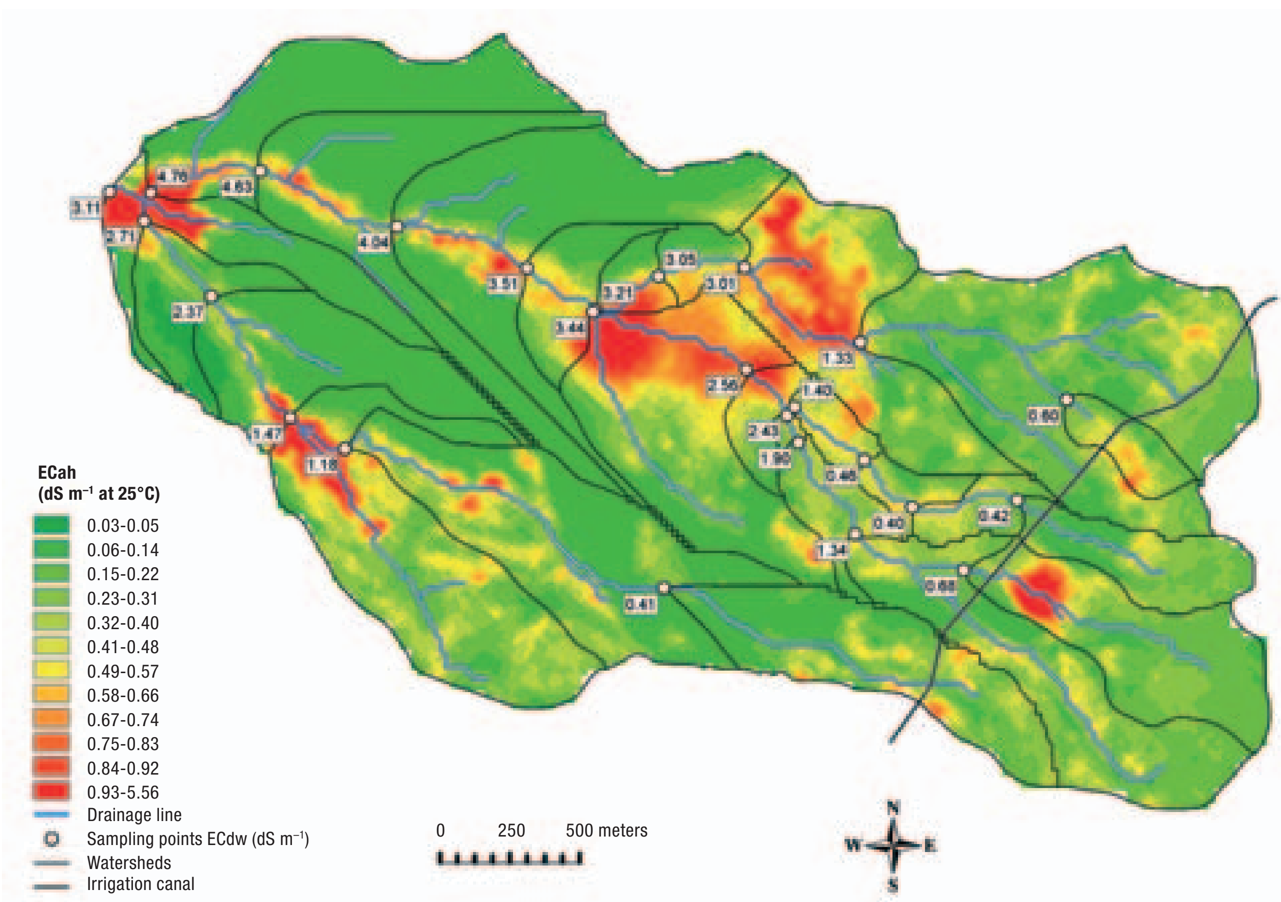

Figure 3. Raster map of apparent soil electrical conductivity (ECah) for the Barranco de Lerma study area. The delineation of the 25 watersheds within this area and the EC of the drainage waters (ECdw) at the exit of each watershed are also shown.

$$ECah^* = \frac{\sum_{i=1}^{n} ECah_i \cdot A_i}{A_t}$$

where n = 8 (i.e., the ECa intervals); $ECah_i$ = the mean of each interval, except for the interval ECah > 0.92 dS m^{-1} where the value of 2.6 dS m^{-1} was taken because it was the mean of all the values within this interval; Ai = surface area (m^2) in each ECah interval; At = sum of surface areas of all the intervals (m^2). The areas with ECah < 0.2 dS m^{-1} were not included in this analysis because they correspond to non-saline soils (i.e., ECe < 1 dS m^{-1} approximately) and, therefore, its salt contribution to the drainage waters is negligible.

A linear regression analysis of ECah* on ECdw was performed in order to ascertain its significance and to identify the main salinity-source areas contributing to the salt concentrations in the drainage waters of the Barranco de Lerma study area.

Results and Discussion

Efficiency of the MGES for ECa mapping

The MGES system allows on-the-go ECa measurements without a pre-established and fixed grid survey. However, depending on the objectives of the survey and the area of the study site, it is recommended to establish an approximated distance between transects as well as the distances between readings within transects. Thus, in the 43 ha Hondo de Espartosa field the distance between transects was about 14 m and the distance between readings was 2 m, whereas in the 715 ha Barranco de Lerma study area these values were, respectively, 30 and 7 m (Table 2). Traversing the entire 43 and 715 ha areas required about 4.1 and 75 h for a total of about 12,000 and 42,000 readings. Thus, the surveying time per unit area was similar in both study areas (6 min ha^{-1}) (Table 2), although the resolution was higher in Hondo de Espartosa than in Barranco de Lerma (273 and 56 readings ha^{-1}, respectively).

The manual collection of georeferenced EM data (i.e., the conventional pedestrian EM survey) will require surveying times orders of magnitude higher than those with the MGES. Obviously, the classical method for determining soil salinity (soil sampling and ECe analysis) is unfeasible for high-resolution salinity mapping. Thus, the MGES significantly improves the efficiency for characterizing and mapping the spatial variability of ECa.

Case study 1 (Hondo de Espartosa): soil salinity mapping for determining the suitability of cropping patterns in a salt-affected field

Using the methodology previously described for sensor calibration, the following equation was obtained in this study area:

$$\ln ECe = 2.33 + 0.34\ z1$$

with R^2 (coefficient of determination) = 0.906, MSE (mean square error) = 0.0198, and *P* (probability value) = 0.0001. The calibration model explains 91% of the observed ECe variability. The absence of large residuals and the non-significant Moran spatial autocorrelation statistic confirms that this calibration equation allows for the accurate prediction of ECe from ECah.

The predicted ECe map (Fig. 2) shows that soil salinity is a relevant problem in this field. Based on the average profile ECe, only 1.7% of the area is classified as non-saline (ECe < 4 dS m^{-1}), whereas 19.5% is moderately saline (4 < ECe < 8), 70.8% is highly saline (8 < ECe < 16) and 8.0% of the field exceeds 16 dS m^{-1}. The most saline areas are located in the center of the field, which could be in part a consequence of field topography. According to the digital elevation model, there is some sloping from the Southeast towards the Northwest (Fig. 2), and the center of the field could be acting as a discharge area.

The very high soil salinity levels make this field unsuitable for most agricultural crops, since their expected yield losses (between 15% for canola to 87% for corn) are much higher than those acceptable for profitable yields. Thus, with a limit in yield loss of 20% as economically affordable, only canola, barley and durum wheat will be suitable in this field. The ECa mapping with MGES and its calibration to ECe values is an essential information for selecting the most suitable crops for the study area. An alternative to growing of agricultural crops could be the use of salt-tolerant, deep-rooted trees with the objective of lowering the groundwaters below the critical depth for soil salinization (i.e., bio-drainage; Heuperman *et al.,* 2002).

Assessing progressive remediation or salinization of this field will require performance of new surveys with time. Two minimum procedures will be required at each time (i) a new MGES survey (when the soil is at or near field capacity or the soil water content is similar to the one in the first survey), and (ii) the acquisition of new soil samples for calibration (conversion of ECa data into ECe values), maintaining the depths of sampling. New calibration equations will have to be developed, which in turn will be used for creating new salinity maps for salinity monitoring. The global shift and dynamic variation in salinity within time will be explained by a combination of the change in ECa data and changes in the regression models structure or parameter estimates. Qualitative comparisons between the original and new salinity maps will identify spatial changes in the salinity pattern. Quantitative changes in salinity with time will be identified by comparing (i) surface areas falling in the same ECe intervals, and (ii) average salinity levels in the field.

Case study 2 (Barranco de Lerma): ECa mapping and its relationship with drainage water salinity

The ECa map of the Barranco de Lerma basin (Fig. 3) indicates that soil salinity is not a relevant problem except in several localized areas close to some gullies. Thus, 92% of the basin has ECah values lower than 0.8 dS m^{-1} (i.e., lower than about 4 dS m^{-1} in terms of ECe). Nevertheless, salinity of the drainage waters (ECdw) tends to increase along the gullies, from low values of around 0.4 dS m^{-1} in the East, to values close to 5 dS m^{-1} in the North-West (Fig. 3). These ECdw values suggest that rainfall mobilizes towards the gullies some salts present in the soil or subsoil of the study area.

In order to evaluate the impact of soil salinity on drainage water salinity, a regression analysis was performed between the surface-weighted ECah* of each of the 25 watersheds and the ECdw measured at the exit of each watershed. Figure 4 shows that both variables were significantly correlated ($P < 0.001$) and that 57% of the ECdw variability could be explained by the ECah* variability. Figure 4 also shows that two observations had ECdw values much lower than those predicted by the regression equation. These observations with ECdw of 0.60 and 0.68 dS m^{-1} correspond to two sampling points located in the vicinity of the irrigation canal crossing the study area in the East (Fig. 3). Since the ECah* values in their watersheds were relatively high (0.40 and 0.43, respectively), the lower than expected ECdw were attributed to seepage of the irrigation canal and the subsequent dilution of their baseflows by the low-salinity irrigation water (EC of about 0.4 dS m^{-1}). If these outliers are deleted from the regression line, the new regression equation increases its coefficient of determination by 30% ($R^2 = 0.73$) without a significant change in the intercept and slope values.

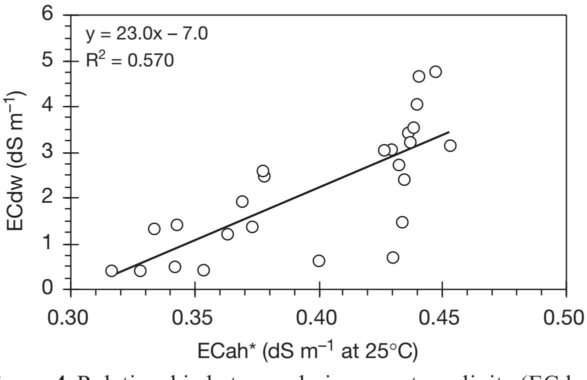

Figure 4. Relationship between drainage water salinity (ECdw) and surface-weighted apparent soil electrical conductivity (ECah*) for the 25 watersheds delimited in the Barranco de Lerma study area.

It is concluded that the ECa mapping of the study area is a sensible approach for delineating the salinity-source areas provoking the salinity of drainage waters. This analysis may be performed satisfactorily on the basis of ECa instead of ECe. Therefore, sensor calibration is not required at this preliminary stage, with the corresponding saving in time and resources derived from the soil sampling and analysis required in sensor calibration. Further work will asses if the ECdw-ECah* regression equation changes with the development of irrigation in the study area and will anticipate the impact of potential new salinity areas on drainage water salt concentrations.

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References

BRANDSMA A.S., KETELLAPPER R.H., 1979. Further evidence on alternative procedures for testing on spatial autocorrelation amongst regression disturbances. In: Exploratory and explanatory statistical analysis of spatial data (Bartels C.P.A., Ketellapper R.H., eds). Martinus Nijhoff, Hingham, MA, USA. pp. 113-136.

CARTER L.M., RHOADES J.D., CHESSON J.H., 1993. Mechanization of soil salinity assessment for mapping. ASAE Paper No. 931557. ASAE, St Joseph, MI, USA.

COM (2006) 232 final, 2006. Proposal for a Directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC. 30 pp.

CORWIN D.L., LESCH S.M., 2003. Application of soil electrical conductivity to precision agriculture; theory, principles and guidelines. Agron J 95, 455-471.

CORWIN D.L., LESCH S.M., 2005. Apparent soil electrical conductivity measurements in agriculture. Comp Electron Agric 46, 11-43. doi:10.1016/j.compag.2004.10.005.

EC, 2003. Extent, causes, pressures, strategies and actions that should be adopted to prevent and to combat salinization and sodification in Europe. European Commission, Directorate General Environment, Directorate B, Erosion Working Group (Task 5; Topic: Salinization and Sodification). 10 pp.

FAO, 2002. Crops and drops; making the best use of water agriculture. Food and Agriculture Organization of the United Nations, Rome.

GOBIERNO DE NAVARRA, 2001. Estudio agroclimático de Navarra (Spain). Departamento de Agricultura, Ganadería y Alimentación, Gobierno de Navarra, Pamplona (Navarra, Spain). [In Spanish].

HERRERO J., ARAGÜÉS R., 1988. Suelos afectados por salinidad en Aragón. Surcos de Aragón 9, 5-8. [In Spanish].

HEUPERMAN A.F., KAPOOR A.S., DENECKE H.W., 2002. Biodrainage-Principles, experiences and applications. International Programme for Technology and Research in Irrigation and Drainage (IPTRID), Food and Agriculture Organization (FAO) of the United Nations, Roma.

LESCH S.M., STRAUSS D.J., RHOADES J.D., 1995a. Spatial prediction of soil salinity using electromagnetic induction techniques: I. Statistical prediction models: a comparison of multiple linear regression and cokriging. Water Resour Res 31, 373-386. doi:10.1029/94WR02179.

LESCH S.M., STRAUSS D.J., RHOADES J.D., 1995b. Spatial prediction of soil salinity using electromagnetic induction techniques: II. An efficient spatial sampling algorithm suitable for multiple linear regression model identification and estimation. Water Resour Res 31, 387-398. doi:10.1029/94WR02180.

LESCH S.M., RHOADES J.D., CORWIN D.L., 2000. ESAP-95 version 2.01R. User manual and tutorial guide. Research Report Nº 146, June 2000. USDA-ARS. George E. Brown, Jr., Salinity Laboratory, Riverside, Ca, USA.

LESCH S.M., RHOADES J.D., CORWIN D.L., ROBINSON D.A., SUÁREZ D.L., 2002a. ESAP-RSSD version 2.30R. User manual and tutorial guide. Research Report 148, November 2002. USDA-ARS. George E. Brown, Jr., Salinity Laboratory, Riverside, Ca, USA.

LESCH S.M., RHOADES J.D., CORWIN D.L., ROBINSON D.A., SUÁREZ D.L., 2002b. ESAP-SaltMapper version 2.30R. User manual and tutorial guide. Research Report 149, December 2002. USDA-ARS. George E. Brown, Jr., Salinity Laboratory, Riverside, Ca, USA.

MAAS E.V., 1990. Crop salt tolerance. In: Agricultural salinity assessment and management. ASCE Manuals and reports on Engineering Practice No. 71, New York. pp. 262-304.

MARTÍNEZ-BELTRÁN J., MANZUR C.L., 2005. Overview of salinity problems in the world and FAO strategies to address the problem. Proceedings of the International Salinity Forum. Riverside, California, April 2005, pp. 311-313.

RHOADES J.D., 1993. Electrical conductivity methods for measuring and mapping soil salinity. In: Advances in agronomy 49 (Sparks D.L.,, ed.). Academic Press, San Diego, CA, USA. pp. 201-251. doi:10.1016/S0065-2113(08)60795-6.

RHOADES J.D., MANTEGHI N.A., SHOUSE P.J., ALVES W.J., 1989. Soil electrical conductivity and soil salinity: new formulations and calibrations. Soil Sci Soc Am J 53, 433-439.

RHOADES J.D., CHANDUVI F., LESCH S., 1999. Soil salinity assessment: methods and interpretation of electrical conductivity measurements. FAO Irrigation and Drainage Paper 57. Food and Agriculture Organization of the United Nations, Rome, Italy. 150 pp.

SOIL SURVEY STAFF, 1999. Soil taxonomy. A basic system of soil classification for making and interpreting soil surveys, 2nd ed. USDA Handbook 436. US Gov Printing Office, Washington, DC. 869 pp.

SPIES B., WOODGATE P., 2005. Salinity mapping methods in the Australian context. Commonwealth of Australia, Department of the Environment and Heritage, and Agriculture, Fisheries and Forestry. 234 pp.

STATGRAPHICS PLUS FOR WINDOWS 5.1., 2000. Statgraphics Plus for Windows: a Manugistics product. Statistical Graphics Corporation, Manugistics, Inc, Rockville, MD, USA.

SUDDUTH K.A., KITCHEN N.R., DRUMMOND S.T., 1999. Soil conductivity sensing on claypan soils: comparison of electromagnetic induction and direct methods. Proc Fourth International Conference on Precision Agriculture, St Paul, Minnesota (USA). pp. 979-990.

TRIANTAFILIS J., AHMED M.F., ODEH I.O.A., 2002. Application of a mobile electromagnetic sensing system (MESS) to assess cause and management of soil salinization in an irrigated cotton-growing field. Soil Use Man 18, 330-339. doi:10.1079/SUM2002139.

USSL STAFF, 1954. Diagnosis and improvement of saline and alkali soils. Agriculture Handbook 60 (Richards L.A., ed). USDA Washington, DC (Reprinted 1969). 160 pp.