EIP-AGRI Focus Group

Soil salinisation

MINIPAPER: Measuring, mapping and monitoring of soil salinity

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1 Introduction

Soil salinity is a major threat in agriculture, affecting a substantial land surface throughout the world, in both irrigated and dryland soil. Measurement of soil salinity is essential for effective management and planning of agricultural activity in salt-affected soils. For individual crops, localised measurements are required to optimise crop management. At field level and at larger scales, mapping of salinity is required to establish the most appropriate irrigation and soil management practices, to delineate crop management zones, and for regional land management. Monitoring is required to follow on-going salinisation/desalinisation over time and to ensure up-to-date delineation of crop management zones. This minipaper intends to contribute to the topics of the *Soil Salinisation Focal Group* by presenting the state-of-the-art about the methods for measuring, mapping and monitoring of soil salinity, as well as knowledge gaps, potential innovation, and needs for research about them.

2 State of the Art

2.1 Measurement of soil salinity

Soil salinity is the sum of dissolved salts in the soil. The concentration of dissolved salts is proportional to the capacity of soil to conduct electrical current. Methods based on the electrical conductivity (EC) of soil are practical approaches to measure soil salinity. Various approaches have been developed. The suitability of a given approach depends on the intended use of the measurement, the soil water content, the established methodology in the area, and the availability of specialised equipment. The most conventional methods for measuring soil salinity can be considered as belonging to two broad classes: (1) manual methods, for both the laboratory and field, and (2) proximal sensors for field measurement. Over recent decades, a number of approaches have been used; those presented here are some of the most used ones in current farming and land management practice.

2.1.1 Manual methods

Manual methods refer to those approaches in which EC is measured in an aqueous solution (extract solution, soil solution) using a conductivity meter and expressing it as dS m^{-1}. Because the EC of aqueous solutions increases with temperature, conductivity meters include a temperature sensor for temperature correction. Aqueous EC measurements, made with conductivity meters are standardised to 25°C, referred to as EC_{25}. Conventional manual methods measure EC_{25} of a solution obtained from the soil either in the laboratory under controlled conditions or in the field under field conditions. Detailed information on manual methods is available in Rhoades et al. (1999).

2.1.1.1 Manual laboratory methods (various soil water extracts)

The standard approach for assessment of soil salinity is the EC measurement of the extract obtained from a saturated soil paste, known as the “saturated extract” or “saturated soil-paste extract” (Rhoades et al., 1999). In the laboratory, sufficient de-ionised water is added to soil samples to reach saturation. Following equilibrium (4+ hours, or commonly, overnight), vacuum is applied to extract the soil water (saturated extract) using a vacuum pump. The EC of the extract is measured at 25°C, the resultant value is the EC_e (dS m^{-1}). This method has the advantages of being a reproducible method not affected by the soil water content. This enables EC_e values to be used as standardised values that are comparable for a wide range of soil water contents, and different soil types. Most agronomic advice for evaluating the degree of soil salinity (e.g. US Salinity Lab., 1954) and the sensitivity and response of crops to salinity is based on values of EC_e (e.g. Mass and Hoffman, 1977).

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EC_e values are the standard international reference for interpreting soil salinity. However, the preparation of the saturated extract is labour-intensive and time-consuming, and is not well-suited to processing large number of samples as may occur in commercial farming. Similarly, it is not well-suited for periodic sampling to follow the dynamics of soil salinity during crop growth. To overcome these practical limitations, alternative laboratory extraction procedures are often used, based on fixed ratios of soil and de-ionised water, for example 1:1, 1:2 or 1:5, and filtration with filter paper is used (Rhoades et al., 1999). The relative simplicity of these methods enables appreciably more rapid measurement. In all of these extraction procedures, air-dried soil is used, which is commonly sieved (2 mm), and the amount of soil is generally based on mass. An alternative extraction approach, enabling more rapid processing is the 1:2 soil to water volumes, used in the Netherlands, in which fresh soil is used and the amount of soil is measured by volume (Sonneveld and ven Elde, 1971). The regions or laboratories that use these alternative extraction methods have their own interpretation criteria.

2.1.1.2 Field-sampled soil solution

Ceramic cup suction samplers installed directly in the field enable samples of soil solution to be obtained from different soil depths and locations during the crop growth. Commonly, suction samplers are used to sample the soil solution where roots are most concentrated. The EC of the extracted soil solution or soil water (EC_{sw}) is measured with a hand-held EC-meter. EC_{sw} is a more realistic measure of salinity encountered by crop roots in the soil solution than EC_e (Rhoades et al., 1999). However, soil solution samples can only be obtained when the soil matric potential is in the range of about 0 to -60 kPa. Consequently, this method is most suitable for frequently irrigated crops or for measurements soon after irrigation or rainfall. Other considerations are that EC_{sw} is affected by soil water content (unlike EC_e), measurements are highly localised, the volume collected is influenced by soil texture (less volume in coarser soils), and reference values to interpret EC_{sw} are hardly available.

2.1.2 Proximal sensors for field measurement of EC_a

Proximal sensors refer to sensors that obtain data from the soil when they are in contact with the soil or close to it (within 2 m). In recent decades, a number of sensor types have been used for direct *in-situ* measurement of soil EC; these EC measurements are referred as “apparent” EC (EC_a) and expressed in dS m^{-1} (Rhoades et al., 1999; Visconti and de Paz, 2016). Whereas EC_e and EC_{sw} determine EC in solution extracted from soil, EC_a determines the depth-weighted average EC of a given volume of soil (“bulk soil EC”). EC_a measurements should not be performed on relatively dry soil (Rhoades et al., 1999) as an appreciable portion of the salts may not be dissolved. For soil water contents between field capacity and approximately half of that value, EC_a has been found to be relatively constant (Rhoades et al., 1999). Therefore, EC_a measurements should be performed at that range of soil water content. EC_a may also be affected by soil texture, density, and organic matter content, which should be taken into account when using EC_a to estimate soil salinity. EC_a values are instrument specific, i.e. specific to the particular type and model of sensor. Sensors types that are currently used for crop and land management applications are electrical resistivity sensors, dielectric sensors, and electromagnetic induction (EMI) sensors. Imbibition-type sensors and four-electrode resistivity sensors are now little used. EC measurement with sensors enables continuous or regular monitoring at different locations. Dielectric sensors are useful for on-going monitoring at different depths and specific locations. EMI sensors are useful for mapping spatial variation.

2.1.2.1 Electrical resistivity sensors

The 5E and GS3 sensors produced by METER, formally Decagon Devices (https://www.metergroup.com) are examples of the use of electrical resistivity sensors to measure EC_a. These sensors also measure volumetric soil water content using FDR (see section 2.2.2) and soil temperature using a thermistor (Visconti and de Paz, 2016).

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2.1.2.2. Dielectric sensors

Dielectric sensors using Time Domain Reflectometry (TDR), Amplitude Domain Reflectometry (ADR) or Frequency Domain Reflectometry (FDR) are commonly used to directly measure the volumetric soil water content (VSWC) in the field (Visconti and de Paz, 2016). Some models of these dielectric sensor types also measure EC_a. The procedures used for EC_a measurement and relevant sensors are described by Visconti and de Paz (2016). A range of TDR equipment can be used for both VSWC and EC_a measurement (Visconti and de Paz, 2016); these TDR systems are generally used for research applications. The versatile and robust Hydra Probe (https://www.stevenswater.com) is an ADR system that simultaneously provides VSWC and EC_a measurement, and is widely-used in soil monitoring networks throughout the USA. Some FDR sensors provide simultaneous measurement of VSWC and EC_a. A widely-used example is the WET sensor (https://www.delta-t.co.uk). The TriSCAN (https://sentektechnologies.com) measures salinity as Volumetric Ion Content (VIC) which is a proprietary method related to EC_a, but is not directly interchangeable with it.

2.1.2.3 Electromagnetic induction (EMI) sensors

Hand-held and tractor-pulled electromagnetic induction (EMI) sensors are commonly-used methods for *in-situ* field measurement of soil salinity as EC_a, based on geophysical techniques that considerably reduce the need for soil sampling (Rhoades et al., 1999; Corwin and Lesch, 2003). The most used sensors for agronomic applications are the EM38-RT and EM38-MK2 models from Geonics (www.geonics.com) and the 1S model from Dualem (www.dualem.com). EC_a measurements are made to depths of approximately 0.4 m to 2 m; the actual depth measured depends on the specific sensor and the orientation of its magnetic coils (horizontal or vertical) and the height of the sensor above the soil surface. Single coil EMI instruments such as the EM38-RT require two passes, with horizontal and vertical coil orientation, to measure to 1 m and to 2 m depths, respectively; while EM38-MK2 and Dualem sensors make both measurements simultaneously. For each measurement location, EC_a values for different soil depths provide information of the salinity profile (*normal*, *inverted*, *uniform*, i.e. increasing, decreasing, and constant with depth, respectively). The identification of inverted salinity profiles (i.e. decreasing with depth) is agronomically very useful as it suggests poor water management, e.g. insufficient irrigation or poor drainage. When EC_a is measured at multiple heights from the soil surface and in the two modes, the combined data sets can be analysed mathematically to obtain the bulk EC of the soil at various depth increments and to develop 2D and 3D maps of soil salinity; see case study 2 in section 5.

The main advantages of EMI sensors are they: (1) are lightweight, compact, non-invasive, and non-destructive method, (2) do not require contact with soil, (3) can be used in stony soils, (4) make rapid in-situ EC_a readings, and (5) characterise large soil volumes (about 2–3 m^3) thereby reducing small scale spatial variability. The main disadvantages are: (1) to correct to the reference temperature of 25°C, soil temperature must be measured at different depths at the time of EC_a measurement, (2) EC_a is affected by metallic objects closer than 1 m, (3) measurements are restricted to soil moisture between 0.5–1 of field-capacity (Rhoades et al., 1999), and (4) the requirement of calibration for conversion to EC_e values. EC_a data from EMI can be converted to EC_e values using site specific calibrations.

2.2 Relationships between different methods

Standard reference values for interpreting soil salinity as the degree of soil salinity and the effects on crop production are expressed as EC_e. There is a large body of widely-accepted information of reference EC_e values for soil salinity (e.g. US Soil Salinity Lab., 1954) and crop response (e.g. Mass and Hoffman, 1977). Consequently, there is a general requirement to convert EC measured with other procedures (other extract ratios, soil solution, EC_a with sensors) to EC_e. Some regions and local laboratories have their own reference values for a particular procedure such as the extract from an alternative soil to water ratio. With the increasing use of extracts from alternative soil-water ratios such as 1:5, more reference values will be increasingly available.

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2.2.1 Relationships between different laboratory methods

Conversion of EC values measured with one extraction procedure to another is affected by numerous physico-chemical factors such as mineral dissolution/precipitation, cation exchange, ion pair formation etc. that are influenced by the degree of dilution, time of equilibration, soil characteristics, soil drying and grinding etc. (Rhoades et al., 1999). Conversion factors have been derived; however, they are regarded as being location specific and not readily applicable to other locations (Rhoades et al., 1999). Factors and equations, for converting from $EC_{1:5}$ to EC_e were reviewed by Aragüés et al. (1986a) and de Paz and Thompson (2018a), and determined by Aragüés et al. (1986b). For equivalent comparisons, there was notable variation between some of these conversion factors and equations, indicating that no general equation could be derived (Aragüés et al., 1986a). Nevertheless, there were also clusters of similar simple linear equations, suggesting that for certain conditions that general "rules of thumb" may be applicable (Aragüés et al., 1986a). Equations and tabulated conversions for this conversion of $EC_{1:5}$ to EC_e for given regions were presented by de Paz and Thompson (2018a).

2.2.2 Relationships between laboratory methods and field-sampled soil solution

A general "rule of thumb" is that the soil water content of saturated soil is approximately double that of soil at field capacity. Applying it, EC_{sw} will be approximately double that of EC_e, assuming a straightforward dilution, and that the effects of the previously-mentioned physico-chemical factors are relatively minor. The approximate and variable nature of this conversion is apparent in the equations $EC_e = 0.32 * EC_{sw} + 0.56$ reported by Aragüés et al. (1986b) and $EC_{sw} = 2.1 * EC_e$ where EC_e is <10 dS m^{-1} reported by de Paz and Thompson (2018a).

2.2.3 Relationships between sensor-measured EC_a and EC_e measurements

Sensor measured EC_a values require conversion to EC_e values for evaluating the degree of soil salinity and for assessing the crop response to soil salinity. For dielectric sensors, the relevant scientific literature should be evaluated (e.g. de Paz and Thompson 2018b). Calibration of EC_a to EC_e is done by soil sampling; following EC_a measurement, representative soil samples are taken by auger and EC_e determined (Rhoades et al., 1999).

For EMI sensors, calibrations must be rigorously performed for each field and soil type, and for each date of measurement (in case of monitoring) as the measured EC_a values are influenced by texture, water content, etc. Generally, in saline soils, EC_a is more influenced by salinity than by other characteristics. When EC_a surveys are performed in saline fields with uniform texture and water content, EC_e can be estimated from EC_a data with a simple regression equation. Where soil texture, VSWC and organic matter content are significantly correlated with EC_a, they should be considered when calibrating EC_e-EC_a (e.g., through multiple linear regression methods, etc.). About 15–20 calibration sites per field should be selected that include the full range of EC_a values and cover the entire study area. Calibrations are conducted for a single soil depth or for soil depth intervals of a soil type. Soils with appreciable gypsum ($CaSO_4$) content can have atypical EC_e-EC_a calibration equations, because of the higher solubility of gypsum in the soil saturated extract (EC_e) than in the soil solution which will be measured as EC_a (Rhoades et al., 1999).

2.3 Mapping of soil salinity

2.3.1 Use of proximal sensors measuring EC_a for mapping soil salinity

Hand-held EMI sensors have been very useful for assessing, predicting and mapping soil salinity (Amezketa, 2006). However, for more efficient mapping of EC_a, portable EMI sensors are combined with Global Positioning Systems (GPS) and data-loggers, which are all incorporated with vehicles, such as small tractors (Rhoades et al., 1999; Spies and Woodgate, 2005; Urdanoz et al., 2008). These automated salinity mapping systems are

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known as *mobile and georeferenced electromagnetic induction sensors* (MGES). They have been successfully used over the last two decades, particularly in the USA, Australia and Spain. Early mobile MGES systems used analog sensors operating in a “stop-and-go” mode. The current digital systems operate in “on-the-go” mode. Commercial MGES systems are expensive and complex (Rhoades et al., 1999). Simpler and cheaper systems have been developed at local level (Urdanoz et al., 2008). Examples of two different locally-developed terrain MGES systems are shown in Figure 1; these systems were used for field- and basin-scale studies. Terrain MGES systems such as these are driven through the field while georeferenced EC_a measurement are made and stored using a fully automated “on-the-go” mode. For very extensive areas (thousands of hectares or higher), airborne EMI techniques are more suitable, and have been used, particularly, in Australia (Spies and Woodgate, 2005).

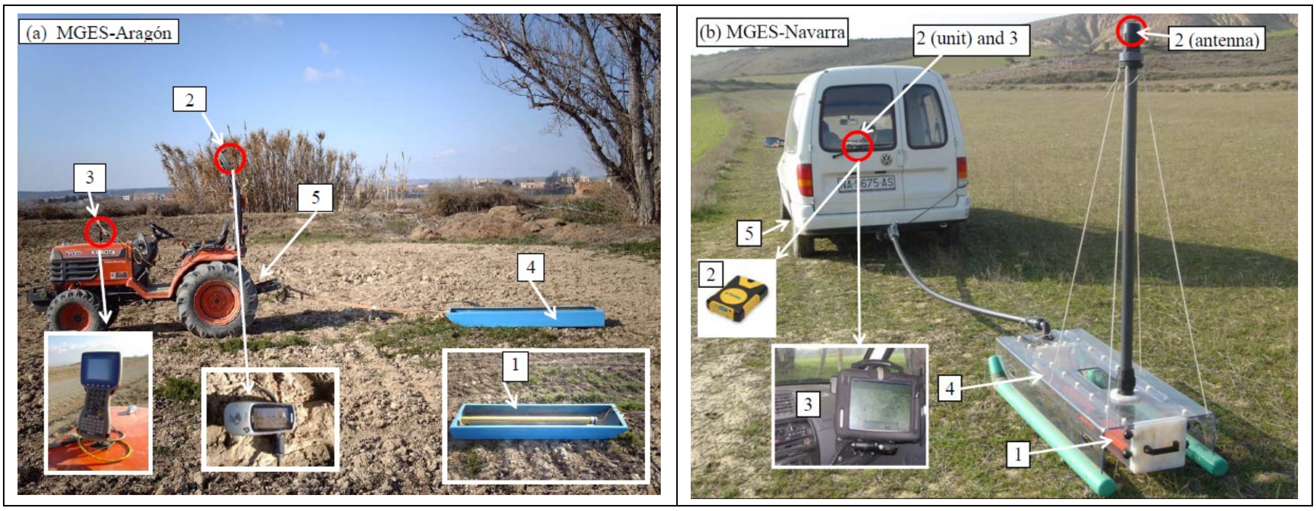

Figure 1. Two examples of MGES integrated by five basic components (Urdanoz et al., 2008): (1) electromagnetic sensor (Dualem-1S in (a) and EM38-RT in (b)), (2) GPS unit, (3) data acquisition system, (4) non-metallic sled and (5) vehicle.

The standard operating procedure for field-scale mapping of soil salinity involves five major steps: (1) an initial **intensive EC_a (dS m^{-1}) survey with MGES**, (2) **EC_a mapping** using geostatistical techniques and a GIS (Geographical Information System) for spatial analysis, (3) **soil sampling**, based on EC_a readings, with subsequent laboratory EC_e measurement, (4) **calibration to convert EC_a to EC_e values**, and (5) application of the calibration model to the EC_a map for **creating an EC_e map** (soil salinity map). GIS packages or similar applications such as *Surfer* or *ESAP* (Lesch et al., 2002) have been specifically developed to analyse, process and map information collected by MGES systems and are very useful for assessing and mapping soil salinity.

2.3.1.1 Conducting a MGES survey and EC_a mapping

The EC_a survey with MGES must be performed when the soil water content is close to field capacity, i.e., a few days after an irrigation or rain event. On-the-go measurements with a terrain MGES are conducted at an average vehicle speed of 5–10 km h^{-1}, following orthogonal grids of variable size; grid size depends on the surface area of the field and the resolution of the required map. The distance between transects can vary from several metres (2–10 m) for detailed studies of individual fields, to e.g., 75–100 m for basin-scale studies. For planning purposes, when driving a terrain MGES at a speed of 7 km h^{-1}, with 30 m between transects, an area of approximately 18 ha can be mapped in one hour. EC_a readings must be transformed to a reference temperature of 25°C, and then, through geostatistical techniques (for interpolation) and GIS converted to an EC_a map. This map provides a rapid, easy and inexpensive means of determining the spatial distribution of soil salinity.

2.3.1.2. Soil sampling and EC_e (and SAR_e) analysis

A reduced number of suitable calibration sites covering the full range of EC_a values over the whole study area must be selected, sampled at multiple-depths, and their EC_e analysed in laboratory. The Sodium Adsorption Ratio of the saturated extract (SAR_e) can also be determined at this stage, to enable mapping of soil sodicity.

2.3.1.3 EC_a-EC_e calibration and EC_e mapping

Calibration must be established for specific soil types/fields and water-content conditions, and then applied to the EC_a values to provide estimates of EC_e (EC_e map). The resulting EC_e map displays the spatial patterns of soil salinity, and can be used to identify and rank salinity affected areas according to soil salinity classifications (e.g. slightly-, moderately- and severely-affected). Detailed field-scale MGES surveys are useful for identifying sources/causes of salt-loading, and establishing proper management (including crop selection) and rehabilitation strategies. Irrigation district-scale MGES surveys are useful for crop selection and for irrigation water planning, for identifying saline recharge/discharge areas, and for prioritising salt-affected land for alternative land uses.

2.3.2 Remote sensing approaches for mapping soil salinity

Air-borne sensors (installed in helicopters, light aircraft, drones, etc.) and satellite-borne sensors can facilitate soil salinity mapping by reducing time-consuming and costly field surveys. Soil salinity can be assessed directly or indirectly through the reflectance (and ratios) of various bands of electromagnetic radiation obtained from multispectral or hyperspectral imagery from airborne or satellite platforms. However, the effectiveness is restricted by the spatial and spectral resolutions of the images, vegetation coverage, atmospheric effects, etc. These spectral data only provide information of the soil surface, and not from the soil profile, as only the soil surface is observed. Direct methods measure the spectral reflectance of the bare soil surface and can detect salts crusts. Indirect methods infer the presence of salts through use of selected indices or indicators (salinity indices, vegetation indices such as NDVI that can detect anomalies in crops vigour, the presence of halophytes, etc.), radiative transfer models, etc. Multi-year crop stress is an indicator of salinity in the root zone. Relevant electromagnetic spectrum ranges for salinity detection are: Visible, infrared (NIR, SWIR, MWIR), thermal-infrared (TIR) and microwave (radar bands C, P, L). Detailed information about remote sensing of soil salinisation can be found in Metternich and Zinck (2009). Remote sensing methods for salinity mapping are not yet fully developed (Mulder et al., 2011). Moreover, satellite images have usually not enough spatial and spectral resolutions for salinity detection at farm level. The limitation of remote sensing for detecting salinity in the soil profile can be overcome by integrating remote and proximal sensing data with soil surveys and sampling.

2.3.3 Spatial resolution of salinity maps must fit the scale of management decisions

Three levels of detail can be discerned: (1) very detailed maps at field or farm level (i.e. up to 100 m of spatial resolution) allow farmers to apply site specific management decisions (i.e. precision agriculture); (2) for grazing and extensive farming, medium detailed maps (between 100m and 500m approx.) are suitable, and (3) larger maps (>1km) provide global information on soil salinity that is key to identify and understand major global trends. The Harmonised World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2012) (≈1km) has information on soil salinity and sodicity for the topsoil (0–30 cm) and subsoil (30–100 cm) of 221 million grid cells.

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2.3.4 Country-wide maps of soil salinity in the EU and need for harmonised methods

No EU member states (MS) possess publicly-available, detailed, soil salinity maps of their salt-affected areas. Delineation of soil salinity and sodicity areas, which are major natural constraints on agriculture, was requested (not obligatory) to the MS by the European Commission (DG-AGRI) as the basis for special compensation for the farmers (Article 32 of EU Regulation 1305/2013). If these delineated maps have been prepared, they are not publicly available. Additionally, no harmonised methodology is available in Europe for their assessment (van Beek et al., 2010). It is necessary to develop a harmonised methodology for salinity mapping, to provide separate maps of soil salinity and sodicity, and to define criteria of their obsolescence. A European scale review/map of soil salinity is presented in Toth et al. (2008) and Daliakopoulos et al. (2016).

2.4 Temporal and spatial monitoring of soil salinity

Soil salinization is a dynamic process as dissolved salts are transported by water. This is particularly so in irrigated agriculture, but also in dryland salinity due to climate (seasonality, climate change effects). Consequently, soil salinity monitoring is required for salt-affected areas. Intra-annual or inter-annual changes can reflect on-going salinisation/desalinisation processes, and can also assess the efficiency of irrigation and farming practices for soil desalination. Monitoring the soil salinity of a field requires conducting MGES surveys over time. Qualitative (spatial changes in the salinity distribution pattern) and quantitative salinity changes are obtained by comparing subsequent salinity maps.

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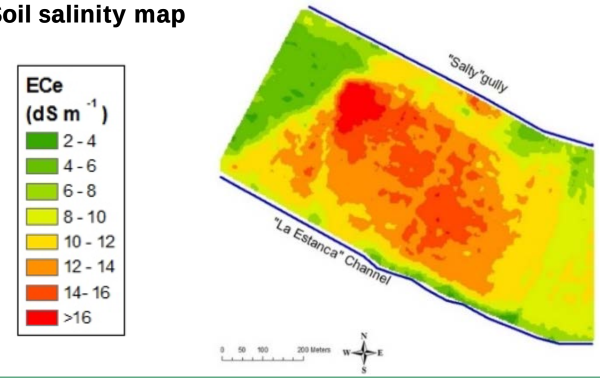
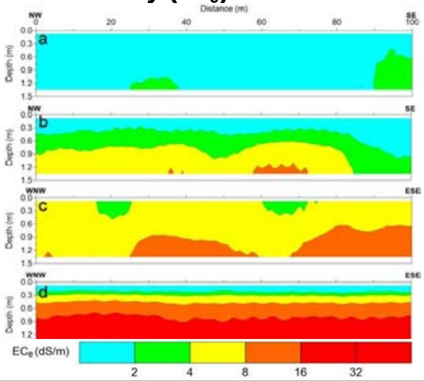
2.5 Case studies

Examples of case studies are presented below and detailed information in the bibliographic references.

<table>
<tr><th>EXAMPLES</th><th colspan="2">EXAMPLES OF METHODS AND / OR RESULTS</th><th>REF.</th></tr>
<tr>
<td>(1) Conducting soil salinity survey with MGES (EMI sensor) and mapping soil salinity

(study carried out in Navarre and Aragón, North of Spain)</td>
<td>
<table>
<tr><th colspan="2">GMES survey / soil sampling</th></tr>
<tr><th colspan="2">General characteristics</th></tr>
<tr><td colspan="2">Sprinkler irrigated field (43ha)</td></tr>
<tr><td colspan="2">MGES survey (EM38-RT)</td></tr>
<tr><td>Grid size (m)</td><td>14x2</td></tr>
<tr><td>Number of EC_a</td><td>11,721</td></tr>
<tr><td>EC_a readings ha^{-1}</td><td>273</td></tr>
<tr><td>Survey time (h)</td><td>4.1</td></tr>
<tr><td>Survey time ha^{-1}</td><td>6</td></tr>
<tr><th colspan="2">Soil sampling for calibration</th></tr>
<tr><td>Nº of calibration</td><td>27</td></tr>
<tr><td>Nº of calibration</td><td>0.63</td></tr>
<tr><td>Maximum depth</td><td>0.9</td></tr>
<tr><td>Nº of soil samples</td><td>81</td></tr>
</table>
</td>
<td>Soil salinity map

</td>
<td>Urdanoz et al. (2008)</td>
</tr>
<tr>
<td>(2) Determination and mapping salinity and sodicity with EMI in four soil transects (100 m long x 1.5m depth)

(study carried out at 4 sites near Lisbon, Portugal)</td>
<td>Soil salinity (EC_e) in 2D transects

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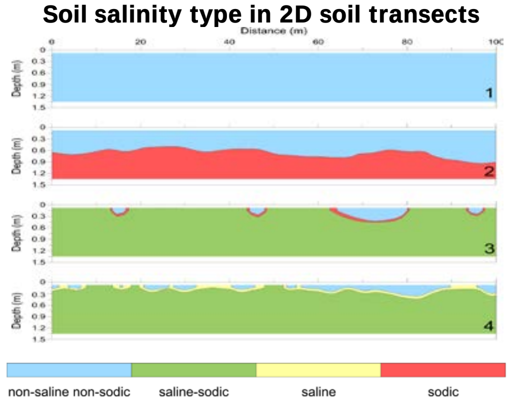
<td>Soil salinity type in 2D soil transects

</td>
<td>Farzamian et al. (2019)</td>
</tr>
<tr>
<td>(3) Spatial distribution of soil sodicity with EMI

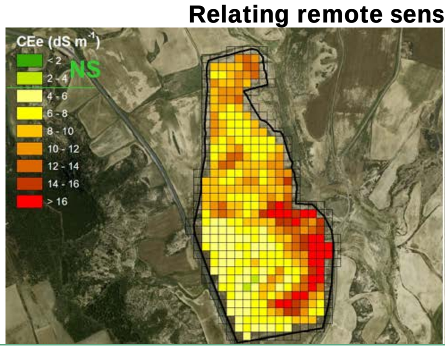
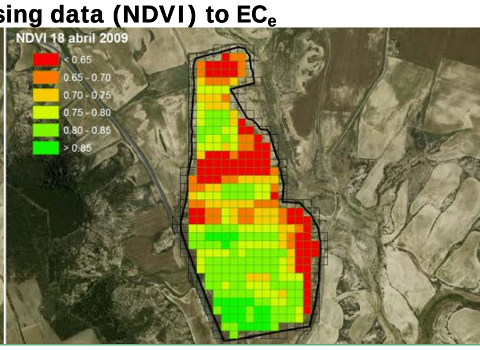
(study carried out in Navarre, North of Spain)</td>
<td>Salinity distribution

0m X (Easting) 80m</td>
<td>Sodicity distribution
190m Y Northing 0m

0m X (Easting) 80m

ECe (ave) (dSm^{-1}): <4; 4 – 8; 8 – 16; >16
SAR (ave) ($(mmol\ L^{-1})^{0.5}$): <5; 5 – 9; 9 – 13; >13

NOTE: EC_a measurements can be satisfactorily used for characterizing the spatial distribution of soil sodicity in saline-sodic soils if EC_e and SAR_e are significantly auto-correlated.</td>
<td>Amezketa (2007)</td>
</tr>
<tr>
<td>(4) Use of remote sensing data to detect soil salinity

(study carried out in Navarre and Aragón, North of Spain)</td>
<td colspan="2">Relating remote sensing data (NDVI) to EC_e


</td>
<td>Amezketa et al. (2011)</td>
</tr>
</table>

3 Knowledge gaps, potential innovation, and sustainability of innovations (problems and opportunities)

CATEGORY	KNOWLEDGE GAPS	POTENTIAL INNOVATIONS	SUSTAINABILITY OF INNOVATIONS	
			PROBLEMS	OPPORTUNITIES
Awareness of the soil salinity problem	Lack of awareness of the salinity problem is illustrated by the lack of current policy instruments considering soil salinisation as a threat	**1.** Develop data at EU level (extent, distribution, severity, impacts on water resources, transboundary impact, costs of "no action", etc.) to raise awareness for developing policies for preventing/ mitigating soil salinisation	Requires much work and funding for development of such data	Obtain up-to-date information of the extent of soil salinity problems and their consequences at EU level Awareness of administrators of salinity issues
Methods of measurement of soil salinity	Lack of universal equations between different EC measurements and EC_e	**2.** Develop calibration equations for soil types of different edaphic-climatic conditions	Lacking soil maps, in general, to identify different soil types	Extensive criteria/ reference values for evaluating salinity/ crop response
	Lack of universal equation for EC_a-EC_e			Analyse if general equations could be developed to save time and money
	Lack of cheap reliable sensors for salinity monitoring	**3.** Develop cheap, miniaturised EMI sensors to be installed in soil profile for on-going monitoring	Requires technology development	Potential for large improvement in soil salinity management
	Lack of knowledge of the concept/types of soil salinity profiles and their potentiality	**4.** Develop simple methods to identify inverted salinity profiles as a mean to identify areas with poor water management	Requires knowledge and technical support	
	Lack of harmonised methods	**5.** Develop guidelines on harmonised methods for mapping and monitoring soil salinity	Requires consensus among soil scientists	Data obtained with harmonised methods can be compared
Methods for discrimination of soil sodicity	EC_e and other EC measurements measure the total dissolved salts, but do not discriminate the type of salts/ions, particularly Na ion (soil sodicity)	**6.** Develop simple field methods to characterise soil sodicity	Requires technology development	Reduce current time-consuming methods Easier discrimination between salinity and sodicity (have diff. effects/management)
	Problems with definition of sodic soils: soils with ESP >15 or SAR_e > 13 (in general), but soils with ESP > 6 in Australia and Africa. Currently in EU: ESP≥6 in topsoil is considered as a limiting constrain for agricultural use (Terres et al. 2016)	**7.** Need to review the definition of sodic soils (from the point of view of their behaviour)	Lack of knowledge, in general, that the negative effect of soil sodicity is also dependent on the total dissolved salts (EC_e, other soil EC measurement, EC of irrigation water, etc.)	Clarify concept and behaviour of sodic soils
Methods for soil salinity mapping/ monitoring	Remote sensing (RS) methods are still immature (not well developed) to infer soil salinity in the soil surface (in absence of white crust) and in the root zone	**8.** Improve RS methods for salinity mapping at farm level	Satellite images with not enough spectral and spatial resolutions	Reducing time-consuming and costly field surveys for soil salinity mapping
		9. Develop protocols/methods for validation/calibration of RS data with ground truth soil salinity data (resolve scale gap)		
		10. Integrate technological solutions (mounted sensors, drones, robotics) to enhance ground-truthing capacity	Ground-truthing can be costly and labour intensive	
	Lack of soil salinization risk maps	**11.** Define clear criteria for identifying areas at salinisation risk	Lacking of required input data at required scale for modelling the risk	Be anticipated and ready to counteract soil salinization at specific areas
		12. Development of methods to infer and map critical areas at		

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		risk of salinisation at regional level: e.g. combination of multiyear RS data with other methods/data (MGES-EMI survey, GIS techniques, etc.) **13.** Develop user-friendly soil salinization risk maps	of salinization: frequent lack of soil maps, geological maps, irrigation water quality, groundwater level and quality, etc.	Develop soil salinization warnings of soil salinization risks
Methods for sodicity mapping	Lack of simple methods for quantifying and mapping soil sodicity	**14.** Develop simple methods for soil sodicity mapping		

4 Suggestions of ideas for innovative projects/Operational Groups

TITLE	DESCRIPTION	STAKEHOLDERS	EXPECTED RESULTS/IMPACT
1. Pre- and post-irrigation mapping of soil salinity with GMES techniques and relationship with irrigation/farming practices performed by farmers: Impro-vement of salinity management	Surveillance of soil salinity from just pre-irrigation (*t0- salinity maps*) and X years after irrigation started (repeat maps at tXy), and explain the changes with the field management performed by the farmers and with meteorological data (*Note: this idea can be extrapolated to areas with pre-irrigation salinity maps, or post-irrigation salinity maps at 2 times separated by some years,* t_x*-*t_y *years*)	Researchers, agronomists, farmers, irrigation districts, Department of Agriculture/Soils (local Governments)	Irrigation/farming practices responsible for salinisation and desalination; impact of management practices on soil salinity; identification of best practices and lessons learnt; improve salinity management; establishment of surveillance programs of soil salinity
2. Combined SMART irrigation and EC management at field scale	Combined use of both soil moisture and soil salinity sensors to simultaneously optimally manage both root zone soil water and soil salinity; testing different EC methods under smart agricultural solutions at field scale	Growers, researchers, advisors, developers of smart agriculture technologies	Development of combinations of technology and management to simultaneously optimally manage irrigation and salinity

5 Needs from practice and further research

5.1 Needs from practice

- Need of accurate inventory of salt-affected areas (extent, severity) at local, regional, national, and EU levels (required for field management, crops and irrigation water planning, identifying recharge/discharge of saline areas, prioritising areas for changing land-use, providing information for development of policies).
- Need of EU network of salt-affected soils for sharing data and knowledge (e.g., development of monitoring grids and data transfer tools to inventory information available in the existing farmer networks).
- Need of a concerted approach at national and European level for providing guidelines on harmonised methods for measure, map and monitor soil salinity.
- Need to provide separate maps of soil salinity and sodicity and define criteria of their obsolescence.
- Need for monitoring soil salinity, particularly in irrigated areas.
- Need of policy instruments for encouraging soil salinity mapping and monitoring: Develop policies/programmes on salinity surveillance.
- More widespread use of salinity sensors and smart/wireless communication systems for regional mapping
- Incorporation of soil salinity testing into routine (regular) agronomy soil testing in areas of emerging saline concern (e.g., coastal North Sea areas) where salinity testing has not been common before.
- Awareness campaigns for the negative consequences of soil salinisation.
- Overcome the lack of reference spectral data for soil salinity identification/mapping.
- Need for satellite images of higher spatial and spectral resolution to map soil salinity at farm level.

5.2 Further research

- Develop guidelines on harmonised standards methods for measuring, mapping and monitoring soil salinity.
- Integrating new technologies in mapping (drones, robotics, novel sensors and data upload systems).

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- Develop simple models for water dynamics and solute transport, i.e., to calculate water and salt balances.
- Identification of the best spectral single bands, band combination/ratios, and spectral indices to map salinity.
- Develop spectral libraries for soil salinity identification and for calibration of remote sensing data.
- Development of methods for automatic processing and extracting information from multi-year satellite data (through machine learning techniques, etc.), and for validation/calibration of RS data with ground truth soil salinity data (resolve the scale gap).
- New modelling approaches combining multiple sources data (RS, terrain attributes derived from DEM, geological maps, land use, meteorological data, irrigation water quality, groundwater level and quality, etc.) for mapping soil salinization and assessing salinity risk at regional levels.
- Develop models to scale soil salinity data from local to regional levels.
- Modelling salinization risk in critical areas considering different climate change scenarios.

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