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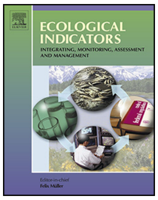

Comparative regional-scale soil salinity assessment with near-ground apparent electrical conductivity and remote sensing canopy reflectance

Elia Scudiero*, Todd H. Skaggs, Dennis L. Corwin

USDA-ARS, United States Salinity Laboratory, 450 West Big Springs Rd., Riverside, CA 92507-4617, USA

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ABSTRACT

Soil salinity is recognized worldwide as a major threat to agriculture, particularly in arid and semi-arid regions. Producers and decision makers need updated and accurate maps of salinity in agronomically and environmentally relevant ranges (i.e., <20 dS m^{-1}, when salinity is measured as electrical conductivity of the saturation extract, EC$_e$). State-of-the-art approaches for creating accurate EC$_e$ maps beyond field scale (i.e., 1 km^2) include: (i) Analysis Of Covariance (ANOCOVA) of near-ground measurements of apparent soil electrical conductivity (EC$_a$) and (ii) regression modeling of multi-year remote sensing canopy reflectance and other co-variates (e.g., crop type, annual rainfall). This study presents a comparison of the two approaches to establish their viability and utility. The approaches were tested using 22 fields (total 542 ha) located in California's western San Joaquin Valley. In 2013 EC$_a$-directed soil sampling resulted in the collection of 267 soil samples across the 22 fields, which were analyzed for EC$_e$, ranging from 0 to 38.6 dS m^{-1}. The ANOCOVA EC$_a$-EC$_e$ model returned a coefficient of determination (R^2) of 0.87 and root mean square prediction error (RMSPE) of 3.05 dS m^{-1}. For the remote sensing approach seven years (2007–2013) of Landsat 7 reflectance were considered. The remote sensing salinity model had R^2 = 0.73 and RMSPE = 3.63 dS m^{-1}. The robustness of the models was tested with a leave-one-field-out (*lofo*) cross-validation to assure maximum independence between training and validation datasets. For the ANOCOVA model, *lofo* cross-validation provided a range of scenarios in terms of RMSPE. The worst, median, and best fit scenarios provided global cross-validation R^2 of 0.52, 0.80, and 0.81, respectively. The *lofo* cross-validation for the remote sensing approach returned a R^2 of 0.65. The ANOCOVA approach performs particularly well at EC$_e$ values <10 dS m^{-1}, but requires extensive field work. Field work is reduced considerably with the remote sensing approach, but due to the larger errors at low EC$_e$ values, the methodology is less suitable for crop selection, and other practices that require accurate knowledge of salinity variation within a field, making it more useful for assessing trends in salinity across a regional scale. The two models proved to be viable solutions at large spatial scales, with the ANOCOVA approach more appropriate for multiple-field to landscape scales (1–10 km^2) and the remote sensing approach best for landscape to regional scales (>10 km^2).

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1. Introduction

Soil salinization diminishes the productivity of irrigated farmlands throughout the world (Ghassemi et al., 1995; Ivits et al., 2011; Singh, 2015). Of the cultivated lands worldwide, about 0.34 × 10^9 ha (23%) are estimated to be saline and another 0.56 × 10^9 ha (37%) are estimated to be sodic (Tanji and Wallender, 2012). In actuality, these estimates are educated guesses at best as no reliable quantitative inventories of soil salinity exist due to the dynamic and complex spatial and temporal nature of salinity, which make measurements at regional scale problematic.

Abbreviations: ANOCOVA, Analysis Of Covariance; CRSI, canopy response salinity index; EC$_a$, apparent soil electrical conductivity (dS m^{-1}); EC$_e$, electrical conductivity of the saturation extract (dS m^{-1}); EC$_a$H, apparent soil electrical conductivity measurement taken in the horizontal coil configuration with an electromagnetic induction conductivity meter; EC$_a$V, apparent soil electrical conductivity measurement taken in the vertical coil configuration with an electromagnetic induction conductivity meter; FSR, field specific regression; OLS, ordinary least square; MAE, mean absolute error; NRCS, natural resource conservation service; RMSPE, root mean square prediction error; WSJV, western San Joaquin Valley.

* Corresponding author.

E-mail addresses: elia.scudiero@ars.usda.gov, scudiero@dmsa.unipd.it (E. Scudiero).

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The U.S. Salinity Laboratory (U.S. Salinity Laboratory Staff, 1954) classifies agricultural soil salinities as: 0–2 dS m^{-1} (non-saline), 2–4 dS m^{-1} (slightly saline), 4–8 dS m^{-1} (moderately saline), 8–16 dS m^{-1} (strongly saline), and >16 dS m^{-1} (extremely saline), where salinity is quantified as the electrical conductivity of a saturated soil paste extract (EC_e, dS m^{-1}). In the agronomically and environmentally relevant ranges of soil salinity (i.e., <20–30 dS m^{-1}), the available regional-scale maps are often qualitative or unreliable (Lal et al., 2004; Lobell, 2010), and, therefore, provide little useful information for producers, land and water resource managers, extension specialists, or policy and decision makers. Methods of quantitatively mapping and monitoring soil salinity at regional to global scales are essential for providing information to land and water resource managers and decision makers faced with policy decisions responding to climate pattern changes and increased food demands that require alternative water sources (e.g., reuse of degraded water) and marginally productive land (e.g., saline-sodic soils).

Two approaches have been presented in the literature as reliable methods to map root-zone soil salinity over large spatial extents (i.e., >1 km^2): (i) the Analysis Of Covariance (ANOCOVA) technique and (ii) multi-year remote sensing techniques. The ANOCOVA technique (Corwin and Lesch, 2014) uses field measurements of apparent soil electrical conductivity (EC_a) as a proxy for soil salinity. Intensive geospatial measurements of EC_a can be acquired over an entire field quickly (e.g., thousands of measurements per day). According to the ANOCOVA technique the EC_a-salinity relationship can be represented with linear modeling. Once this relationship is calibrated over a sufficiently large set of fields, the ANOCOVA approach assumes that the slope coefficients of the EC_a-salinity relationship remain constant throughout the same region, whereas the intercept may vary from field-to-field because of different soil types and agronomic practices. The ANOCOVA technique maps soil salinity based on the EC_a survey data and a single soil sample taken from each field, which is needed to calculate the regression intercept. Alternatively, multi-year remote sensing of canopy reflectance can be used to map salinity at regional scale (Lobell et al., 2010). Freely available satellite data (e.g., Landsat reflectance provided by the U.S. Geological Survey Agency) can be used to model soil salinity with total coverage over the area of interest (e.g., Wu et al., 2014; Yahiaoui et al., 2015). A regression model relates soil salinity to multi-year remote sensing canopy reflectance, usually in the form of a ratio of wavelengths representing a salinity index, and other co-variates (e.g., fallow or cropped, crop type, annual rainfall).

The preferred method for mapping soil salinity at large (multiple-field to regional) scales likely depends on the intended audience and use of the salinity map, and on available resources. The objective of this study is to compare the two available methodologies with respect to accuracy, potential map uses, and required resources. The comparison, which highlights the strengths and weaknesses of the two approaches, will assist decision makers in determining which approach best meets their needs and matches their resources. It also provides scientists with direction for future research efforts that will fill knowledge gaps and improve the quality and efficiency of root-zone salinity mapping at large spatial extents.

2. Theoretical background

2.1. Apparent electrical conductivity estimations of soil salinity with Analysis Of Covariance (ANOCOVA)

Geospatial measurement of apparent (or bulk) soil electrical conductivity (EC_a) is a proximal sensor technique that plays a major role in salinity mapping at field scale (Corwin and Lesch, 2005a). An increase in the concentrations of ions (e.g., Cl^-, Na^+) in the soil solution increases EC_a. Other soil properties also influence EC_a, including texture, water content, bulk density, organic matter, and cation exchange capacity (Corwin and Lesch, 2005a). The EC_a measurements can be expressed as a multiplicative function of salinity, water content, and soil tortuosity (which depends on soil texture, particle pore distribution, density and particle geometry, and organic matter content). Several authors explored this relationship (e.g., Archie (1942) and Rhoades et al. (1976)), which can be generalized as

$$EC_e = \beta \times EM^{\alpha} \times \varepsilon^* \quad (1)$$

where α and β are coefficients that take into account the effects of soil tortuosity and water content; and ε^* is a (multiplicative) error component. In Eq. (1), the error component is the ratio between EC_e and the explanatory term of the equation (Tian et al., 2013).

After a logarithmic transformation of Eq. (1), the EC_a-EC_e relationship is:

$$\ln(EC_e) = \ln\left(\beta\right) + \alpha \times \ln(EC_a) + \varepsilon \quad (2)$$

where ε is a random (additive) error component, equal to ln(ε^*). Equation [2] can be parameterized using an ordinary least square approach (OLS), provided the underlying assumptions (e.g., residuals are normally distributed and spatially independent) are respected (Lesch and Corwin, 2008). Note that Eq. (2) is not applicable when soil is too dry because the water pathways for electrical conductivity are not continuous. As a rule of thumb, Corwin and Lesch (2013) suggest that volumetric water content should be at least 70% of field capacity when the EC_a survey is carried out.

Field-wide (e.g., 1–100 ha) soil salinity can be mapped using intense geospatial measurements (thousands to tens of thousands per field) calibrated with a limited number of soil sample locations (~6 to 100 per field) using field specific regressions (FSR) of Eq. (2) (Corwin and Lesch, 2005a):

$$\ln\left(EC_{e,ij}\right) = \gamma_{0,j} + \gamma_{1,j} \times \ln\left(EC_{a,ij}\right) + \varepsilon_{ij} \quad (3)$$

where γ_0 and γ_1 are the OLS regression coefficients and i refers to the location (i.e., latitude and longitude) of the soil samples used to parameterize the model for the field (j) under consideration. Eq. (3) can be used to map specific soil intervals (e.g., 0.6–0.9 m) and/or composite soil profiles (e.g., 0–1.2m). Using the FSR approach to map soil salinity at large spatial extents (i.e., >100 ha) may be unfeasible because the cost of collecting the number of soil samples needed to calibrate Eq. (3) over a large number of fields is prohibitive based on field-work labor and laboratory expenses.

Fortunately, as shown by Corwin and Lesch (2014), when EC_a is measured with volumetric water content at or near field capacity, the γ_1 coefficient can be considered constant across fields in the same region, whereas γ_0 changes from field to field because of differences in soil properties and agricultural management. Therefore, Corwin and Lesch (2014) formulated the ANOCOVA model to calibrate the EC_a-EC_e relationship:

$$\ln\left(EC_{e,ij}\right) = \gamma_{0,j} + \gamma_1 \times \ln\left(EC_{a,ij}\right) + \varepsilon_{ij} \quad (4)$$

in which the intercept parameter is uniquely estimated for each field, but the slope coefficient is assumed to be constant for a particular geographical region. Once Eq. (4) is parameterized over a number of calibration fields, then salinity can be mapped at a new field using an intense survey of EC_a and a single soil sample EC_e measurement (used to calculate γ_0 for a given field j). The ANOCOVA approach is a significant advance in comparison to the FSR approach in terms of soil sampling labor and laboratory analysis cost.