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Regional scale soil salinity evaluation using Landsat 7, western San Joaquin Valley, California, USA

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A B S T R A C T

Despite decades of research in soil mapping, characterizing the spatial variability of soil salinity across large regions remains a crucial challenge. This work explores the potential use of Landsat 7 (L7) satellite reflectance data (30 × 30 m resolution) to facilitate salinity mapping. Reflectance data spanning a seven-year period (2007–2013) were obtained for western San Joaquin Valley, California (ca. 1.5×10^6 ha), over five soil Orders (Aridisols, Entisols, Inceptisols, Mollisols, and Vertisols). Two ground-truth datasets were considered: 267 direct measurements of salinity (one per L7 pixel) from soil samples (EC_e), and 4891 indirect salinity values (EC_e^*) estimated from the relationships of EC_e with geospatial (on average 16 per L7 pixel) electromagnetic induction measurements. The EC_e^* ground-truth dataset was characterized by stronger relationship with the L7 reflectance, with the multi-year averages of the L7 data showing R^2 up to 0.43. The correlations between L7 data and EC_e^* were significantly influenced by rainfall (stronger in dry years than in rainy years), soil properties (weaker in finer soils), and crop type (stronger when soil salinity was over crop stress tolerance threshold). The results suggest that a fusion of the L7 multi-year reflectance data with information on meteorological conditions, crop type, and soil texture could lead to a reliable salinity prediction model for the entire western San Joaquin Valley. Land resource managers, producers, agriculture consultants, extension specialists, and Natural Resource Conservation Service field staff are the beneficiaries of regional-scale maps of soil salinity.

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1. Introduction

Soil salinization diminishes the productivity of irrigated farmlands throughout the world (Ghassemi et al., 1995; Ivits et al., 2013). 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 inventories of soil salinity exist due to the dynamic and complex spatial and temporal nature of salinity, which make measurements at regional scale problematic. The available regional 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 to provide land and water resource managers with the information needed to make recommendations to decision makers faced with policy decisions responding to climate pattern changes and increased food demands that require alternative water (e.g., reuse of degraded water) and land (e.g., reclamation of non-productive saline-sodic soils) sources.

Agriculturally rich areas, such as California's San Joaquin Valley, are economically impacted with lost revenues of tens to hundreds of millions of dollars each year due to reduced crop yield from salinity (Johnston et al., 2012). The west side of the San Joaquin Valley (WSJV) is particularly susceptible to the accumulation of salinity due to shallow water tables and native levels of salts (Letey, 2000). Maps inventorying salinity and monitoring the spatio-temporal changes in salinity for the WSJV are vital to the management of salinity and allocation of limited water resources, particularly during recurring periods of drought. Recent advances in the use of satellite imagery (Metternicht and Zinck, 2003; Caccetta et al., 2010; Furby et al., 2010; Lobell et al., 2010; Singh et al., 2010) and electromagnetic induction (Corwin and Lesch, 2014) have made positive strides in regional-scale salinity assessment.

Ground-based geospatial measurements of apparent electrical conductivity (EC_a), from electromagnetic induction, can be obtained relatively quickly and can be used as a proxy for soil salinity (Corwin and Lesch, 2013). Typically, for a field-scale (i.e., tens of hectares) salinity assessment a small number of soil salinity measurements determined from electrical conductivity of the saturation extract (EC_e) are made in conjunction with a larger EC_a survey so that a relationship between EC_a and EC_e can be determined (Lesch et al., 1992; Triantafilis et al.,

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2000). Corwin and Lesch (2014) proposed a spatial linear regression technique to describe the relationships between salinity and EC_a, based on the analysis of covariance, over very large areas (i.e., tens of thousands of hectares). Once such a relationship is established, a unique regression slope can be used throughout a region, whereas the intercept values would vary at a smaller scale (e.g., field scale), reducing (up to the 60%) the number of soil samples needed to map an entire region.

The size of an area that can be surveyed using ground-based instrumentation is, however, limited due to practical considerations, which leads to consideration of remote sensing. There is great potential in the use of remote sensing for assessing and mapping soil salinity (Lobell, 2010; Allbed and Kumar, 2013). In agricultural areas, the most accurate quantitative remote sensing salinity estimations across a regional scale have been achieved by studying crop canopy reflectance (Lobell et al., 2010). Good results have also been obtained studying bare-soil reflectance, but mainly on lands with very high salinities that cannot be tolerated by most crops (Metternicht and Zinck, 2003; Allbed and Kumar, 2013). Canopy reflectance has been used to represent crop status throughout the growing season and to predict yield (Mulla, 2013). The intra-annual variations in crop reflectance depend on factors influencing plant growth through each year, and are, therefore, a means of monitoring vegetation health rather than discriminating between different stress types (Scudiero et al., 2014). Nevertheless, previous studies showed that landscape features that are relatively stable in time (such as soil salinity) can be emphasized using multi-year reflectance data (Lobell et al., 2010). In fact, using multiple-year satellite data generally improves the reflectance–salinity relationships compared to those observed for a single-year (Lobell et al., 2007, 2010; Furby et al., 2010; Dang et al., 2011; Scudiero et al., 2014). Scudiero et al. (2014) showed that that areas affected by soil salinity are generally characterized by lower temporal variability of canopy reflectance than areas with healthy vegetation, or areas suffering from other stresses that are less stable in time (e.g., water stress, pests…). The research of Lobell et al. (2010) indicated that the multi-year analysis of MODIS (National Aeronautics and Space Administration Agency, USA) reflectance integrated by information on crop cover, could explain large portions (up to 53%) of the spatial variability of soil salinity in the Red River Valley, North Dakota and Minnesota, USA. Unfortunately, MODIS data has very coarse spatial resolution (250 × 250 m), which does not generally allow proper land management at the sub-field scale.

In the United States, regional studies at spatial resolutions high enough to be used by producers (i.e., field or sub-field scale) have not been carried out using remote sensing data. Canopy reflectance obtained from the Landsat 7 (L7) satellite sensor (National Aeronautics and Space Administration Agency and US Geological Survey, USA) could be potentially used for this purpose as characterized by moderately high spatial resolution (900 m^2). In other countries L7 surface reflectance has been used for salinity assessment by various authors (e.g., Furby et al., 2010; Taghizadeh-Mehrjardi et al., 2014) in the past years, often on soils characterized by very high salinity values. In the USA, to our knowledge, the multispectral data from the L7 satellite has not been tested for use in soil salinity assessment on agricultural land, especially at low and moderate salinity levels, where most crops can still grow.

The objective of this study was to explore the use of multi-year Landsat 7 canopy reflectance data for regional-scale salinity assessment in the WSJV. To do so, reflectance–salinity relationships were analyzed over a 7-year period at regional and field scales, using the six Landsat 7 spectral bands and selected vegetation indices. Additionally, the study aimed to understand the spatio-temporal variability of the relationship between canopy reflectance and soil salinity, and to identify possible explanatory variables for a salinity assessment model utilizing L7 reflectance and other ancillary data, such as information on meteorological conditions and soil type.

2. Materials and methods

2.1. Western San Joaquin Valley

The Central Valley of California, which includes the San Joaquin Valley, the Sacramento Valley, and the Sacramento-San Joaquin Delta, produces about 25% of USA's table food on only 1% of the nation's farmland (Cone, 1997). The San Joaquin Valley lies south of the Sacramento–San Joaquin River Delta in California's Central Valley stretching 354 km in length and 64–97 km in width (Fig. 1a). Irrigated land comprises 2.3 $\times 10^6$ ha of the San Joaquin Valley. Saline and saline–sodic soils are estimated to cover 8.9×10^5 ha in the San Joaquin Valley, of which most are found in the WSJV (Backlund and Hoppes, 1984). The major crops grown include grapes, cotton, nuts, citrus, garlic, tomatoes, and alfalfa. Cattle and sheep ranching and dairy farming are also important to the valley's agricultural productivity. The soils of the WSJV are derived from alluvium originating from the coastal mountains. The alluvium contains high concentrations of salts since the coastal mountains were once below sea level and uplifted to their present state (Letey, 2000).

The selection of the WSJV as the study site was based on two factors: (i) the tremendous agricultural productivity of this region and the impact that salinity has on that productivity and (ii) the need for a current reliable inventory of salinity to enable water resource managers to make informed water and salinity management decisions, particularly during droughts.

Twenty-two fields across the WSJV were selected (Fig. 1) to provide ground-truth soil salinity data.

2.2. Landsat 7 Surface Reflectance Climate Data Record

The Landsat 7 (L7) satellite sensor (National Aeronautics and Space Administration Agency and US Geological Survey, USA) provides reflectance imagery with a 30 × 30 m resolution over six spectral bands, namely: blue (B, 450–520 nm), green (G, 520–600 nm), red (R, 630–690 nm), near-infrared (NIR, 770–900 nm), shortwave infrared 1 (IR1, 1550–1750 nm), and shortwave infrared 2 (IR2, 2090–2350 nm). The Landsat 7 Climate Data Record (CDR) surface reflectance was used in this study. The L7 CDR is atmospherically corrected through the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) according to Masek et al. (2006). The WSJV is covered by five L7 acquisition areas (Fig. 1). Scenes were obtained from January 2007 through December 2013. A total number of 366 scenes with cloud coverage $<10\%$ were considered. The seven years of L7 data consisted of about 13–27 cloudless scenes per year over each ground-truth study site (Table 1). Most of the data was available for the spring, summer, and early fall months, whereas less than 23% of the scenes were from the months of January, February, March, November, and December.

Several vegetation indices were calculated using the L7 spectral bands as suggested by Mulla (2013), Li et al. (2013), and Jiang et al. (2008). Five indices were selected because of their past performances and popularity in the literature. The selected indices were (Table 2): Normalized Difference Vegetation Index, NDVI (Rouse et al., 1973); Enhanced Vegetation Index, EVI (Huete et al., 2002), where the aerosol and soil correcting parameters g, c_1, c_2, and l are set to 2.5, 6, -7.5, and 1, respectively; Salinity Index, SI (Aldakheel et al., 2005); Green Atmospherically Resistant Vegetation Index, GARI (Gitelson et al., 1996), where $\gamma = 0.9$ is a parameter that improves atmospheric correction; and a new index developed in this study, the Canopy Response Salinity Index, CRSI.

The NDVI is well-known and widely used in remote sensing studies (Jackson et al., 2004; Jiang et al., 2008). Lobell et al. (2010) similarly found that the EVI could describe up to half of the spatial variability in soil salinity in a regional-scale salinity assessment using MODIS data. The SI has also been found useful for predicting soil salinity and sodicity (Aldakheel et al., 2005; Odeh and Onus, 2008). The GARI was formulated to enhance the sensing of green vegetation (Gitelson et al., 1996) and