Computers and Electronics in Agriculture 119 (2015) 241–253

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Determining soil salinity and plant biomass response for a farmed coastal cropland using the electromagnetic induction method

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ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form 19 May 2015
Accepted 25 October 2015

Keywords:
Soil salinity
Plant biomass
Coastal
Electromagnetic induction
Apparent electrical conductivity

ABSTRACT

Apparent electrical conductivity (EC_a) measured by electromagnetic induction (EM) instruments has been successfully used as an ancillary variable to estimate soil salinity from field to watershed scales. It is particularly useful in the case of coastal farming area where reliable estimates of soil salinity aid farmers and researchers in understanding the development of salinization and establishing appropriate management practices. The objectives of this research were to estimate soil salinity (EC_e) using intensive EM survey data and prediction equations relating soil salinity to EC_a, to determine the optimal data interval in EM survey and to validate the prediction reliability using plant biomass response to soil salinity. This study was conducted in a typical coastal rain-fed farmland in north Jiangsu Province, China. The results indicated that apparent electrical conductivity showed significant correlation with EC_e and EM readings from the horizontal coil orientation can be used as the sole predictor in a linear mixed model. Field EM survey data exhibited directional trend resulting from the impact of anthropogenic activities on soil salinity. An optimal sampling interval of 16 m in the survey transect essentially meets the need of spatial prediction when field EM survey is performed. Soil salinity increased with depth and higher soil salinity mainly occurs in areas where rice was previously planted, particularly in lower-lying regions and areas adjacent to the aquaculture plant. Plant biomass is negatively related to both, measured and estimated soil salinity. The relation to measured soil salinity was closer than to estimated soil salinity. Boundary line analysis shows that root zone salinity (EC_e) causes a 4.4% and 6.4% plant biomass reduction per dS/m for rice and cotton, respectively. Such results allowed us to conclude that a larger data interval of EM survey than the present could produce satisfactory estimation accuracy of field soil salinity, and the relationship between soil salinity (or EC_a data) and plant biomass could help to derive site specific yield goals and management practices in the farmed coastal cropland.

1. Introduction

Soil salinity is a frequent problem for agricultural production in coastal farmlands. This is the case not only in China but also across the world (Shahid, 2013). Driven by the strong evaporation demand of the air, salt is consequently brought to the soil surface through capillary rise in the dry season. Besides this natural process, salinization maybe 'anthropogenic', as irrigation schemes in these areas often lack matching drainage facilities. Salinity associated with the presence of a very shallow, saline water table and marine sediments has caused considerable annual crop yield reductions to farmers in coastal regions (Guan et al., 2001).

Understanding the characteristics of soil salinity is important for agriculture management (Corwin and Lesch, 2003). Thus, soil salinity and its indices, for instance apparent electrical conductivity or resistivity measured by geoelectrical instruments such as ARP 03, CM-138, EM38, EM38-DD, EM38-MK2 and Veris 3100 (Gebbers et al., 2009), are useful to farmers and researchers who are interested in identifying areas in the field where soil salinity might be problematic to crop growth. Owing to its low weight, high efficiency and being non-invasive, EMI instruments for assessing and monitoring the origin and development of soil salinity conditions have received considerable attention in the last two decades (Rhoades, 1992; McBratney et al., 2000; Sudduth et al., 2005; Moore et al., 2011). Compared with other instruments, the

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http://dx.doi.org/10.1016/j.compag.2015.10.020
0168-1699/

disadvantage of the EMI methods is its sensitivity to ambient noise and sensitive to deeper soil layers (Daniels et al., 2008). Previous studies of calibration approaches relating EMI measurement to soil salinity are numerous (Corwin and Rhoades, 1984; Rhoades et al., 1990; Triantafilis et al., 2000; Herrero et al., 2011).

In order to delineate the spatial soil salinity, geostatistical are needed to estimate soil salinity at unsampled locations due to the high spatial variability of soil salinity. Geostatistical methods have been successfully adopted to map soil salinity by calibrating EMI measurements to soil salinity. The related literature describes several approaches (Corwin and Plant, 2005). Among these, a multiple linear regression model was used for spatial prediction of soil salinity in contrast to the commonly recommended ordinary kriging method (Lesch et al., 1995). Walter et al. (2001) examined the performance of spatial prediction of topsoil salinity using local ordinary kriging with local variograms versus whole-area variogram. In an exhaustive comparison between five geostatistical models for predicting field soil salinity across an irrigated cotton field (Triantafilis et al., 2001). Corwin and Lesch (2005) characterized the spatial variability of soil salinity and other physicochemical properties using apparent soil electrical conductivity. Electromagnetic induction has gained popularity in precision agriculture, such as characterization of soil clay content at the field (Triantafilis and Lesch, 2005), improvement of soil mapping (Zhu et al., 2010), identification of manure accumulation area and soil constraints to crop yield (Dang et al., 2011), and assessment of potential nutrient build-up (Cordeiro et al., 2011).

The EMI instruments and the mobile EMI system have been widely used to measure soil EC_a with data intervals ranging between 5 m and approximately 2 km from the field to watershed scales (Triantafilis and Lesch, 2005; Woodbury et al., 2009; Yao and Yang, 2010; Aragüés et al., 2011). Recently, precise delineation of field soil salinity with high benefit vs. cost, and the appraisal and modeling of related agricultural managements on crop growth, salt transport and water usage have been reported (de Clercq et al., 2009; Herrero et al., 2011; Ganjegunte et al., 2012). Despite the high efficiency of data acquisition for EMI instrument, there is also a need to determine optimal intervals for generating field data considering the time-cost for data collection and mapping accuracy. The selection of data interval largely depended on the spatial variability of soil attributes, and the information on the optimal sampling interval has been sought by comparing the semi-variograms (Adhikari et al., 2011) and/or interpolated maps of geo-referenced data collected at different data intervals (Liu et al., 2010; Yao et al., 2014a). Many algorithmic methods were also used to assess the influence of sampling schemes on the estimation precision in previous reports (Pettitt and McBratney, 1993; Brus et al., 2006; Li et al., 2007).

However, there are limited studies which have discussed the effect of sampling interval on prediction accuracy using intensive EM survey data in the marine–terrestrial interlaced region of the coastal zone. In this study, apparent electrical conductivity (EC_a) obtained by intensive field survey with a mobile EMI system was used as an ancillary variable to indicate soil salinity. Statistical comparisons were performed among various EMI data intervals which were achieved by uniformly selecting different proportions of EC_a from the raw EMI dataset. The prediction accuracy was further validated by relating predicted and measured soil salinity to crop above-ground biomass. The primary objectives of this paper included: (i) delineating field scale soil salinity using apparent electrical conductivity measured by EM38 as ancillary variable, (ii) determining an optimal sampling interval in field EM survey by examining the effectiveness of various EC_a datasets and, (iii) assessing the prediction reliability by identifying the relationship between plant biomass and soil salinity with boundary line method.

2. Materials and methods

2.1. Study region description

The study was conducted on Jinhai Farm, which was reclaimed from a tidal flat in 1999 and is located in the southeast of Dafeng City, north Jiangsu Province, China (Fig. 1). The farm was approximately 5 km away from the coastline of China Yellow Sea and the topography of the farm was flat with an average elevation of 1.5 m. The climate is subtropical with large seasonal fluctuations in temperature and precipitation. The mean monthly air temperature ranges from 1.9 °C in January to 27.2 °C in June with an average annual air temperature of 14.9 °C. The mean annual precipitation is 1058.4 mm with approximately 70% of annual rainfall occurring in June through September. The cold, dry, season is from October to March and the hot, wet, season is from April to September. The predominant soil is silt loam, identified as a loamy, mixed, hyperthermic, Aquic Halaquepts according to the soil taxonomy (Soil Survey Staff, 2010).

The study region consisted of 25 terraces which are separated by open drain ditches (Fig. 2). The open drainage system, with 25 open collector drains and discharging in a south-easterly direction, is 1.2 m in depth and 4.2 m in width on average at a spacing of 100 m. The irrigation system was installed in 2001 with an open irrigation canal located in the middle of each terrace. In each terrace, field ditches of 300 mm width and 150 mm depth spaced about 3 m apart were ploughed by a planter along with the sowing. The topography of the study area permitted gravity outflow of the discharge of the open collector drains into the open main drain, which headed northeastward. Soil salinity was known to be a significant problem in this farm and large areas of salt-affected land was abandoned due to a very saline shallow water table (average electrolytic conductivity EC of 13.1 dS/m and water table of 1.2–2.0 m). The soil of the farm covers a variety of salinity conditions and its soils are representative for large areas of coastal saline soils of Jiangsu Province.

2.2. Field management history

The study field (i.e. Field 7) shown in Fig. 1 is adjacent to the aquaculture plant in the north (i.e. Field 3) and cultivated fields (i.e. Field 8–9) in the south and east. Two crop rotation systems including rice–rape rotation and cotton–barley rotation, representing the most commonly used rotation systems in coastal farming areas, were used in the study field (Fig. 2). Using conventional soil fertility and pest management practices, the study field was cultivated with rice (*Oryza sativa* L.) – rape (*Brassica campestris* L.) rotation at the eastern portion, were high soil salinity was observed and paddy rice was planted to leach soil salinity under flooded condition. The western area of relatively low soil salinity was cultivated with cotton (*Gossypium* spp.) – barley (*Hordeum vulgare* L.) rotations. There were no organic matter inputs other than crop residues. The crop growth varied greatly across the study field with some locations abandoned for cultivation. Except in the rice season, the study field was rain-fed during cotton, barley and rape cultivation as the abundant river water and shallow groundwater was too saline for irrigation. The irrigation water used for paddy rice was pumped from underground wells of approximately 350–400 m depth with average electrolytic conductivity of 0.35 dS/m. Farmers regularly suffered from approximately 30–60% yield losses due to excessive surface soil salinity, especially in the dry season.

2.3. Soil sampling and soil pit excavation

Soil sampling protocols for the calibration of EM38 (EMI instrument type EM38, Geonics Limited, Ontario, Canada) for soil salinity assessment have been widely used for field studies (Rhoades et al.,