Apparent Soil Electrical Conductivity as an Indicator of Failed Subsurface Drains

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Abstract.

It is estimated that 2,000 ha of cropland are taken out of production daily worldwide due to salinization and sodification. Salinity is estimated to result in economic losses of $27.3 billion U.S. dollars annually. Our project aimed to develop techniques for quantifying the severity of soil-water salinity and impacts on crop production in the Lower Arkansas River Valley (LARV) in Colorado. The Fairmont Drainage District (FDD) study site in the LARV is a furrow-irrigated, tile-drained area of about 200 ha that suffers from salinity-affected soils due to shallow water tables resulting from inefficient irrigation practices and inadequate drainage. The objective of this study was to test the utility of soil apparent electrical conductivity (EC_a) measurements in identifying salinity hot spots in the field that indicate shallow water tables potentially caused by failed tile drains. Two fields in the FDD were selected for this study. The fields were surveyed in 2018 with a Geonics EM38-MK2 electromagnetic induction meter connected to a GPS unit to create EC_a maps. Corn (Zea mays, L.) grain yield samples were also taken in 2018 and correlated with soil EC_a. Maps of relative yield (Y_r) were then generated to show the spatial variability of corn grain yield in the two fields. The EC_a values ranged from 0.3 to 3.1 dS/m while Y_r ranged from 12.7% to 100%. Areas with high EC_a coincided with low Y_r values, indicating salinity hot spots with shallow water tables and inadequate drainage (i.e., failed tile drains). Preliminary results indicated that soil EC_a can be used to locate potential tile drain failures and salinity hot spots in irrigated fields.

Keywords.
salinity, shallow water table, relative yield, corn, furrow irrigation, Colorado, Arkansas River Valley

Introduction

Salt-affected and waterlogged soils exist as a growing global problem for agricultural production. These are defined as soils in which salts are in enough quantity to interfere with normal plant growth. The Harmonized World Soil Database (Nachtergaele et al., 2009) estimates the global extent of salt-affected land to be 1128 Mha, 60% of which is saline, 26% is sodic, and the remaining 14% is saline sodic. It is estimated that 2000 ha worldwide are taken out of production every day due to salinization and sodification (Nellemann, 2009; Qadir et al., 2014). This salinity impact was estimated to have an economic impact of $27.3 billion U.S. dollars annually (Qadir et al., 2014). These economic and environmental issues will only be magnified as the area of salt-affected soils expands each year as intensive irrigation practices continue globally.

Salt tolerance of a crop is traditionally described through plotting a crop's relative yield as a continuous function of soil salinity. Relative yield (Y_r) is used to circumvent differences in absolute yield (Y) due to differences in crop species, cultivar, ambient environment, soil fertility, pest damage, and factors other than salinity. The conventional method to convert Y into Y_r involves scaling each observation of Y by the maximum yield observed (Y_m) (Grieve et al., 2013). Various models have been attempted to accurately describe this phenomenon (Steppuhn et al., 2005). Each model, although different in form, require the average root zone salinity (C), where C can be expressed as solute concentration (C_s), osmotic potential (Ψ_o), saturated paste electrical conductivity (EC_e), or the electrical conductivity of irrigation water (EC_w).

One of the most popular methods used for the quantification of soil salinity on field and regional scales is through electromagnetic induction (EMI) techniques that calibrate apparent soil electrical conductivity (EC_a) to other edaphic physical and chemical properties. In cases where EC_a correlates with a soil property of interest, an EC_a – directed sampling strategy has been found successful in quantifying the spatial distribution and variability of that soil property, all while minimizing the number of sample locations, keeping the lab and labor costs to a minimum (Corwin et al., 2003a; Shaner et al., 2008). Furthermore, it has been shown that if EC_a correlates with crop yield, these directed sampling approaches can be used to identify soil properties that are causing yield variability, and thus direct management decisions for remediation (Corwin et al., 2003b).

In fields with shallow water tables that are drained by subsurface tiles, the spatial variability of EC_a and Y_r could be an indicator of salinity hot spots caused by failures in subsurface tiles. Failures in tile drainage may be caused by a collapse of a tile section or clogging by debris. These failures may cause localized increases in water table elevation and subsequent uplflux of salts or water logging of the root zone immediately after irrigation events.The lack of drainage also hinders effective leaching of salts from the root zone.The objective of this study was to test the utility of soil apparent electrical conductivity (EC_a) measurements in identifying salinity hot spots in the field that indicate shallow water tables potentially caused by failed tile drains.

Materials and Methods

Study Site Description

Soil salinity as an issue in the Lower Arkansas River Valley (LARV) in southeastern Colorado originated in the 1970s due to the increase in river diversions for the use of irrigation water, a lack of efficient irrigation systems (which leads to a severe over application of water), and a decrease in the use of groundwater as a source for irrigation. These practices have led to an increase in the height of the water table within the LARV, pushing salts up into the root zones of many crops (Gates et al., 2002). Salts have negative impacts on crop yields throughout the valley; research and intervention are needed to develop more sustainable water use practices.

A sub-region of the LARV, called the Fairmont Drainage District (FDD), (37°58'56.2" N;

103°38'38.5" W; Fig 1), was identified as a suitable area of study for observing and quantifying the magnitude of salinity effects in gypsiferous soils. Two study fields were selected for more detailed observation since they contained a range of estimated EC_a values which were representative of the FDD, were irrigated, and contained corn (i.e. the most salt-sensitive crop found in the FDD). The FDD itself refers to an area of 200 hectares having a drainage tile network installed in the early 20th century as a result of the Colorado Drainage District Act (CO Rev Stat § 37-28-101). The intent of installing drainage tiles in the FDD was to reduce waterlogging caused by a shallow water table. Despite this, salt presence continues to negatively affect the agronomic systems in the region.

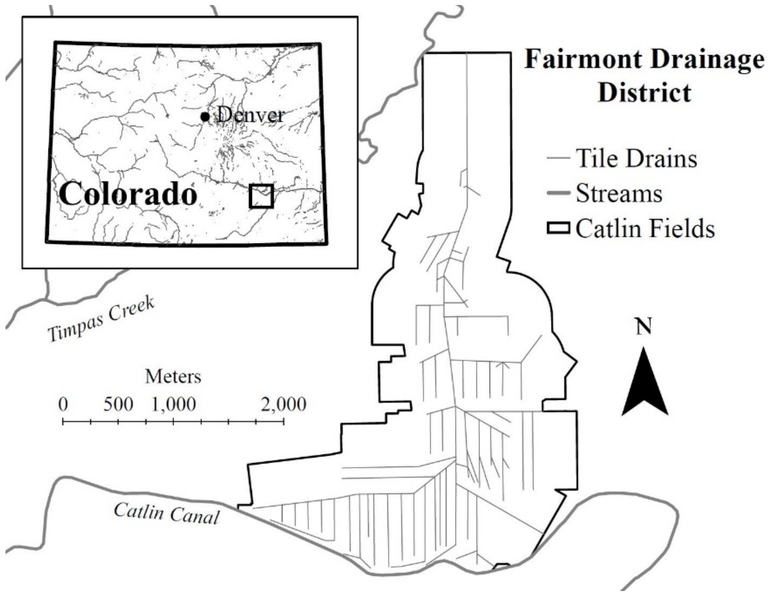

Fig 1. The FDD in the LARV with the layout of the tile drains.

The FDD contains approximately 20 different fields averaging 10 ha each. In this context, a field is defined as a homogenously managed piece of land devoted to the growth of a singular crop for commercial value. The dominant crops in the region consist of alfalfa (*Medicago sativa* L.) with 65% coverage, corn (*Zea Mays* L.) with 20% coverage, and winter wheat (*Triticum aestivum* L.) with 10% coverage. The remaining 5% of land is fallow or rangeland (not harvested for economic value). Irrigation methods consist of siphon tube irrigation down furrows and center pivot sprinkler irrigation, with application rates varying based on specific field management. Soil textures range from Silty Clay Loam to Clay Loam.

Electromagnetic Induction Surveys for Field Characterization of EC_a and Yield

In 2018, EMI surveys were carried out using mobile equipment (i.e. EM38-MK2, Trimble™ GPS system, and Juniper Allegro CX for datalogging) on 2 corn fields within the FDD prior to corn planting (approx. early May). The EM38-MK2 provided a continuous stream of EC_a measurements (one reading every 4 seconds) at 0-0.75 m (EM_h) and 0-1.5 m (EM_v) depths simultaneously. This averaged approximately 500 locations of EC_a measurement in each field. Model-based sampling design via the Electromagnetic Sampling Analysis and Prediction model (ESAP, ver. 2.35) was used to locate soil and yield sampling points in each field. ESAP uses a response surface sampling design (RSSD) strategy which, in essence, creates a 3-D surface of the EC_a measurements and, based on the range and variation, selects locations that characterize the EC_a variation while maximizing the distances between adjacent sampling locations (Lesch et al., 2002). Surface maps of EC_a were generated using ordinary kriging in ArcGIS (ESRI, Inc.). Areas of elevated EC_a values were identified as potential salinity hot spots caused by failed tile drains.

ESAP-RSSD was used once again in conjunction with EC_a survey data to determine ideal sampling locations for maize yield. Thirty-eight (38) locations were identified in each field, resulting in a total of 76 samples. At each location, a one meter by 0.76 m plot was sectioned off for cob selection. This amounted to seven cobs per plot for yield analysis. Samples were oven dried at 70°C for 14 days before being shucked and weighed to determine marketable yield. After yields were determined, Y_r was calculated by averaging the top three yields (to identify a reasonable yield unaffected by salinity), dividing each point by this average, and multiplying by 100.

Corn Yield Model Selection and Evaluation

Y_r was predicted using a traditional model: the modified discount function (Steppuhn et al., 2005), as well as two alternative statistical models: a sigmoidal four parameter logistic (4PL) model, and single variate linear regression (Table 1). Each model was tested using EC_a as the input variable.

Table 1. Summary of salinity tolerance models used to predict relative yield losses in the Fairmont Drainage District using soil bulk apparent electrical conductivities (EC_a).

Model	Model Form	Input
Sigmoidal Four Parameter Logistic (4pl) Model	$\hat{Y}_r = d + \frac{a-d}{1+\left(\frac{x}{c}\right)^{\mathrm{b}}}$	EC_a
Modified Discount Function	$\hat{Y}_r = \frac{1}{1+\left(\frac{C}{C_{50}}\right)^{\exp(sC_{50})}}$	EC_a
Linear Regression	$\hat{Y}_{r,i} = \beta_0 + \beta_1 \mathrm{C}_i + \varepsilon_i$	EC_a

Where $\hat{Y}_r$ is model predicted relative yield (%), $a,\ b,\ c,\ d,\ s,\ \beta_0$, and β_1 are empirically fit shaping parameters, C is average root zone salinity (can be expressed as EC, osmotic potential, or solution concentration), C_{50} is C at $Y_r = 0.5$, C_t is the maximum value of C without yield reduction, $C_0$is the lowest value of C where $Y_r = 0\%$, m is the absolute value of the declining slope in Y_r, i is the sample site within a field.

The goodness of fit (GOF) for each model was evaluated in R studio using the HydroGOF package using root mean squared error (RMSE), root mean squared prediction error (RMSPE), and index of agreement (IOA). RMSE and RMSPE were used to evaluate error in terms of yield units, but RMSPE is a measurement of the model's prediction error using a leave-one-point out approach for cross-validation. IOA was used to evaluate model agreement with observations. A value of 0 indicates no fit, while 1 indicates a perfect fit.

RESULTS AND DISCUSSION

EC_a Surveys

The EC_a values in the two corn fields ranged from 0.3 to 3.1 dS/m (Fig 2). Elevated EC_a readings were observed in the southeast portion of field F1 and central portion of field F2. These portions of the fields closely coincided with areas of depressed corn yields (see next section). These observations provided indirect evidence of failures in the subsurface tile drains at these locations. Site visits to investigate the soil and tile drain conditions at these locations confirmed that some tiles in field F1 were broken and required repairs (Fig 3). The farmer removed the broken tiles and replaced them with 12-inch PVC pipe.

In field F2, elevated EC_a readings at the south-central edge were caused by a tile drainage manhole (junction) that would frequently overflow due to overirrigation in adjacent fields. A recommendation to reduce the surface irrigation amounts in the adjacent fields was given. This would prevent the tile junction from being overwhelmed with excessive tile flow. Subsequent EC_a surveys in the following year (2019) revealed that the salinity hot spots remained. It may take several seasons of leaching to flush the excess salts from the hot spots.

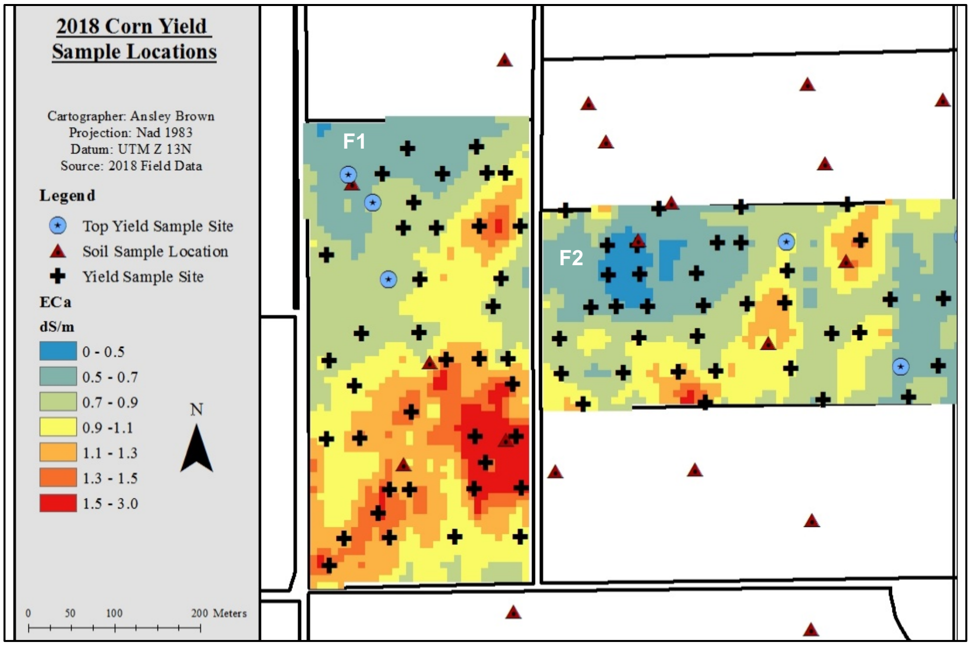

Fig 2. EC$_a$ map of the two corn fields (F1 and F2) showing locations of corn yield sampling.

Fig 3. Photo of a manhole at the southeast section of field F1 (left panel) and the adjoining tile drain that collapsed (right panel).

Corn Yield

Corn yield model evaluation results are summarized in Table 2. The three models based on EC$_a$ were able to predict Y$_r$ with similar accuracies. The 4PL model resulted in the least errors and highest IOA. The soil EC$_a$ was shown to be useful for modeling the spatial variability of Y$_r$. Furthermore, it was shown that the RMSE and RMSPE values generated are small enough to indicate that the model could be viable for sub-regional yield mapping and informing location-specific management decisions (e.g., repair of tile drains).

Table 2. Summary of goodness of fits results using soil bulk apparent electrical conductivities (EC_a) to predict relative yield losses (Y_r; %).

Model	Input Variable	RMSE %	RMSPE %	IOA n/a
4PL	EC_a	16.71	17.02	0.74
Modified Discount	EC_a	21.37	21.48	0.71
Linear Regression	EC_a	18.06	18.29	0.66

Where 4PL is sigmoidal four parameter logistic model, RMSE is root mean squared error, RMSPE is root mean squared prediction error, and IOA is index of agreement.

Visual fitting of the three models with EC_a inputs compared to observed Y_r is shown in Figure 4. Although the 4PL model captures the general trend of the data well, much variability exists around each Y_r prediction. This may be due to yield variability caused by factors other than soil salinity. Some of these factors may include: i) differences in corn variety salinity and drought tolerance, ii) differences in field-to-field irrigation and fertilizer management, and iii) spatial differences in soil physicochemical properties.

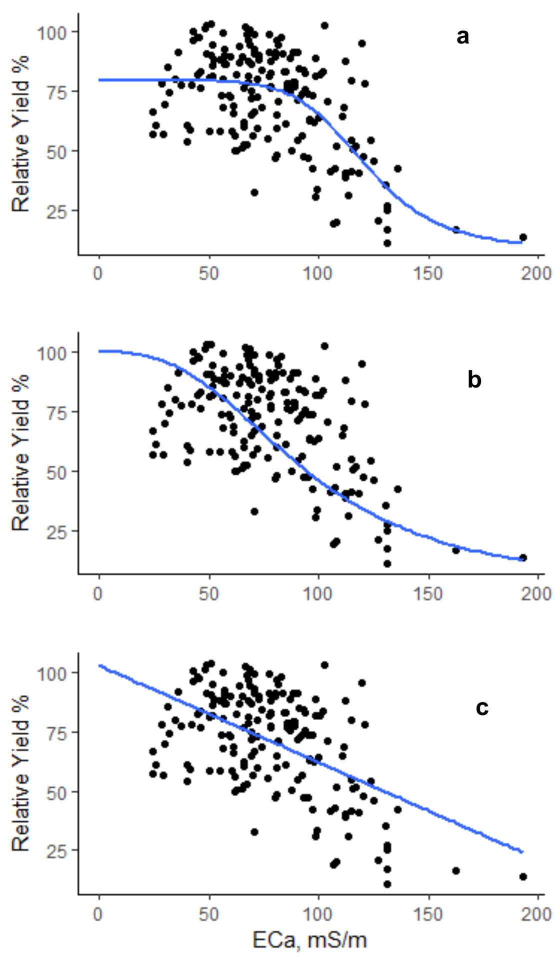

Fig 4. Relative yield as a function of EC_a using (a) sigmoidal 4PL, (b) modified discount, and (c) linear regression functions.

As mentioned in the previous section, the corn yield maps (Fig 5) were consistent with EC_a patterns (Fig 2). Depressed yields in the southeast section of field F1 and south-central section of field F2 coincided with elevated EC_a readings. Selective soil sampling at those sections (data not shown) revealed that the EC of saturated paste extract (EC_e) were as high as 4 to 12 dS/m. Those EC_e levels were above the salinity tolerance threshold of 1.7 dS/m for corn (Rhoades et al., 1992).

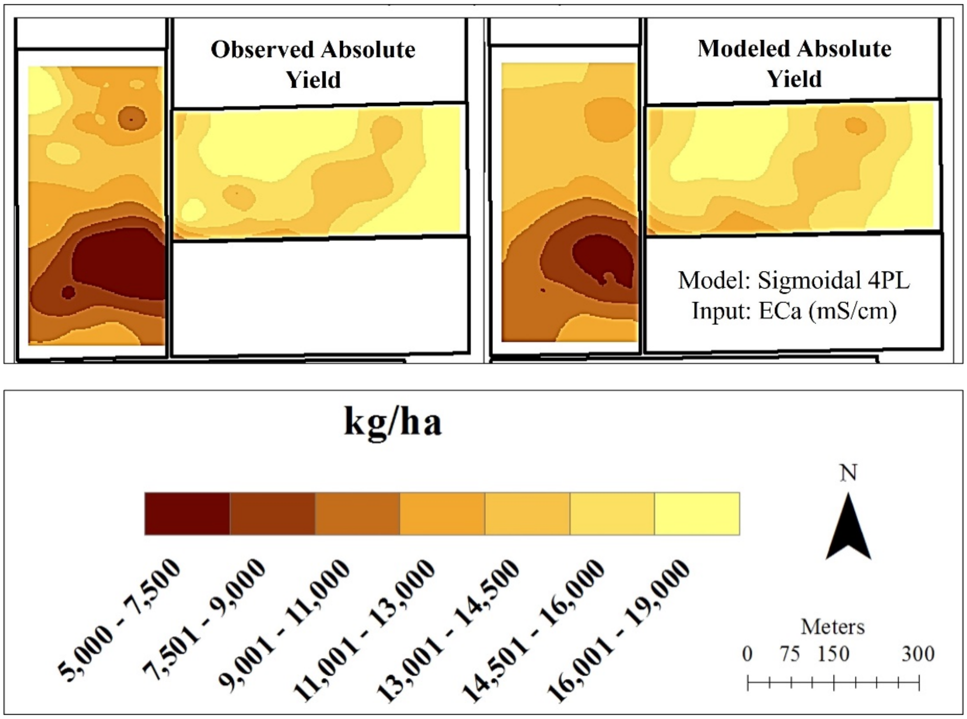

Fig 5. Observed and modeled corn yield maps in 2018.

Summary

Preliminary results from this study provided evidence that soil EC_a can be effectively used to identify salinity hot spots and related failures in tile drains. A sigmoidal 4PL model for corn yield as a function of EC_a could be a useful tool for characterizing spatial yield variability in fields with highly variable EC_a. However, the relationship between crop yield and EC_a may not be temporally stable across years and may require seasonal calibration. Further tests of these approaches on other tile-drained fields are needed to verify transferability of techniques.

Acknowledgments

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