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Computers and Electronics in Agriculture 46 (2005) 379–397

Computers and electronics in agriculture

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Development of practical site-specific management methods for reclaiming salt-affected soil

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Abstract

Sustaining irrigated agricultural production systems in semi-arid and arid regions requires consideration of with saline and sodic soil conditions. The spatial variability of these conditions makes soil reclamation an ideal practice in which to apply site-specific management (SSM). We discuss an application of SSM in which preliminary measurements of apparent soil electrical conductivity (EC_a), supplemented by EC_a-directed soil sampling, are used to construct a GIS map of salinity zones on which site-specific amendment application can be based. Our primary objective was to develop a field-implementable methodology for site-specific soil amendment application. The focus of the program was on cotton production, although the method should be applicable to other crops. A second objective was to establish experiments to test the effectiveness of this program. Evaluating the effectiveness of a sprinkler application for the first irrigation was incorporated as a part of this program in hopes of reducing variability due to poor germination. This study consisted of two commercial fields located in the San Joaquin Valley of California. Based on the consideration that EC_a is directly related to electrical conductivity from soil saturation paste extract (EC_e) for known saline-sodic conditions,

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Abbreviations: DPPC, dual pathway parallel conductance; EC_a, apparent soil electrical conductivity; EC_e, electrical conductivity from soil saturation paste extract; EMI, electromagnetic induction; ESP, exchangeable sodium percentage; GIS, geographic information system; SAR, sodium absorption ratio; SSM, site-specific management

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doi:10.1016/j.compag.2004.11.008

we developed a four-step method for site-specific salinity management in commercial fields. The steps included the following: (1) generation of an EC_a map; (2) directed soil sampling for EC_e; (3) determination of the estimated amendment requirement as a function of location in the field; and (4) integration of the individual amendment requirements into a practical spatial pattern for amendment application. Cotton yield monitors were utilized to indicate spatial yield variation throughout the replicated plots instead of aggregated yield values.

Because of the high levels of variability in these commercial fields and the time required for amendments to have a substantial effect, we can provide only short-term results of these experiments. In both of the experiments no significant differences existed between the irrigation and amendment treatments ($p > 0.05$), but increased yield trends supported the benefit of sprinkler application of the first irrigation. A Scheffe test of the cotton yield monitor data indicated significant yield differences between in-plot treatment zones.

Keywords: Salinity; Electrical conductivity; Electromagnetic induction; EM38; Saline-sodic soils; Soil reclamation

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1. Introduction

Salinization is one of the most serious problems confronting sustainable agriculture in irrigated production systems in semi-arid and arid regions. The problem may be caused by importation of dissolved salts in irrigation water, existing high salt levels in the soil due to ancient marine deposits or prior playa areas, or a combination of the two. The effects of poor drainage, concentration of indigenous salts, and elevated water table tend to exacerbate this problem by moving these salts into the root zone and potentially to the surface.

A considerable portion of the west side of the San Joaquin Valley, California is salt affected or may become salt affected (Letey, 2000). Managing soil salinity involves several aspects. Two of the most important are disposing of saline drainage water and reclaiming fields whose productivity is limited by salinity (Richards, 1954; Rhoades et al., 1988, 1997; Goyal et al., 1999; Mitchell et al., 2000).

The most appropriate reclamation procedure depends on the nature of the ionic chemistry affecting the soil. Salt-affected soils are traditionally divided into three broad categories depending on the extent to which they are saline or sodic (also called alkali) (Richards, 1954). These categories are based upon the electrical conductivity of the saturation paste extract (EC_e), exchangeable sodium percentage (ESP), and pH (Richards, 1954). These categories are defined as: (i) saline (i.e., EC_e greater than $4\,dS\,m^{-1}$, ESP less than 15 and pH less than 8.5); (ii) saline-sodic (i.e., EC_e greater than $4\,dS\,m^{-1}$, ESP greater than 15 and pH less than 8.5), and (iii) sodic (i.e., EC_e greater than $4\,dS\,m^{-1}$, ESP greater than 15 and pH greater than 8.5). A different approach is necessary to reclaim each category. Establishing adequate drainage and providing adequate low sodium water to leach the salts from the system may reclaim saline soils, but saline-sodic and sodic soils, which are characterized by high levels of monovalent sodium, usually need the application of appropriate amendments to aid in reclamation (Richards, 1954).

The desired effect of the amendments is a cation exchange of calcium for sodium, which permits subsequent leaching of the exchanged sodium through the application of low sodium water. Therefore, the amendments must supply calcium, either directly or indirectly. The most effective and economical means of doing this depends on the soil chemistry. If the soil is low in carbonate, then the calcium must be supplied directly. The most common amendment in this case is gypsum, although in some cases (generally those of low pH), lime may also be used. If the soil has sufficient calcium carbonate, then this may be used as a source of the calcium. In this case, sulfuric acid may be applied. It reacts with calcium carbonate to form gypsum, which then supplies exchangeable calcium. Alternatively, elemental sulfur may be applied. Elemental sulfur must be incorporated into the soil and then oxidized by *Thiobacillus* and or other related bacteria to form sulfuric acid; the sulfuric acid in turn reacts to form gypsum. The chemistry of most salt-affected soils on the west side of the San Joaquin Valley permits the use of either, gypsum, sulfur, or sulfuric acid in reclamation.

Because of the need to remove salts through leaching, the salinity properties of the soil and the nature of the reclamation are highly affected by field drainage and elevated water tables. In general, salinity and sodicity are not uniformly distributed in a field, but rather exhibit a heterogeneous distribution. The tendency of saline and sodic conditions to be spatially variable makes soil reclamation an ideal practice for applying site-specific management (SSM). Site-specific management is the management of an agricultural crop at a spatial scale smaller than that of the individual field (Plant et al., 2000). The principle behind SSM is that in many fields the crop's environment varies substantially from one part of the field to another. If these variations can be properly quantified, then management practices may be adjusted to provide appropriate response to conditions at different locations in the field.

A problem with assessing soil salinity at a high spatial resolution is the cost associated with determining soil salinity from EC_e. However, EC_e can be estimated by apparent soil electrical (EC_a) measured directly in the field. This correlation of salinity (EC_e) to EC_a can be explained by the dual pathway parallel conductance (DPPC) model introduced by Rhoades et al. (1989). This model attributes the major contribution to EC_a to conductance in the large water-filled pores, which contain the majority of the dissolved salts, with a relatively small contribution of the exchangeable cation associated with the soil clay particles. The most common commercially available EC_a measuring sensors are the Veris 3100, an invasive four-electrode ER (electrical resistivity) sensor, and Geonics EM38, a non-invasive electromagnetic induction (EMI) sensor (Corwin and Lesch, 2003; Lesch et al., 2005). A description of the theory and operation of these sensors has been previously given by McNeill (1980) and Hendrickx et al. (2002).

These portable instruments may be used to rapidly measure EC_a with a high level of spatial resolution. In this study we used the non-invasive EMI (Geonics EM38). These data may be used to direct soil sampling for purposes of measuring EC_e and sodium absorption ratio (SAR), which can be used as a more easily measured indicator of ESP (Rhoades and Miyamoto, 1990). The combined EC_a data and soil sample data may then be integrated into a geographic information system (GIS) to develop maps of estimated EC_e and SAR. In this paper we focus on the reclamation of fields that are known from prior soil samples taken for normal agronomic evaluation to contain saline-sodic areas. The most economical, as well as the most conservative, assumption is that EC_a is directly related to EC_e (Rhoades et al., 1997). With this assumption a map of EC_a may be used to guide the site-specific application of amendments by estimating the amendment application rate necessary to achieve a level of salinity and sodicity not detrimental to cotton yield. Richards (1954) gives formulas for this estimation. The application of modern electronic and information technology in this manner to achieve SSM is called precision agriculture (Lowenberg-DeBoer and Erickson, 2000). Evaluation of methods of precision agriculture must be done on commercial fields rather than on homogenous field plots in order to test their usefulness in the presence of natural spatial variation in field conditions.

Crop response to the osmotic and toxic effects of soil salinity varies by species. Tolerance of the crop also depends on the crop's developmental stage when it is exposed to saline conditions. In this study we focus on soil management practices related to the production of cotton (*Gossypium hirsutum* L.), though the method may be applied to other cropping systems. Our primary objective was to develop a methodology for a practical, field-implementable site-specific application amendment program. A second objective was to carry out experiments to test the effectiveness of this program. Evaluating the effectiveness of a sprinkler application for the first irrigation was incorporated as a part of this program in hopes of reducing variability due to poorly germinating cotton seed. The advantage of sprinkler irrigation is the relative uniform leaching of salts to a depth below the emerging seed; thus, allowing greater stand establishment (Hanson et al., 1993; Hake et al., 1996; Rhoades et al., 1997). One of the effects of salinity on soil structure is to cause crusting at the soil surface. Cotton has relatively weak capacity to emerge in the soil conditions of the San Joaquin Valley, and thus is sensitive to the soil crusting (Hake et al., 1996). However, it is relatively salt tolerant once established. Therefore, early sprinkler irrigation should in principle improve cotton yield in moderately saline and saline-sodic soils.

2. Materials and methods

2.1. Site description

The study sites consist of two commercial fields located in the San Joaquin Valley of California (Fig. 1). One is located near Mendota (longitude 120.4346°W, latitude 36.7762°N, Fresno County) and will be denoted field 1; the second is located near Lemoore (longitude 119.9455°W, latitude 36.2143°N, Kings County) and will be denoted field 2. Field 1 is composed of Tranquility soils, which are members of the fine, smectitic, thermic Sodic Haploxererts. Soils in field 2 are predominantly Lethent silty clay loam (fine, montmorillonitic, themic Typic Natragids) and Panoche (fine-loamy, mixed (calcareous) thermic Typic Torriothents). Field 1 measures approximately 74 ha. Field 2 is a standard quarter section, measuring 65 ha (approximately 792 m on a side). Mean annual precipitation is approximately 210 mm, almost all of which occurs during the winter. Normal commercial practices for cotton (Hake et al., 1996) were followed, including pest management and supplemental fertilization.

2.2. Site-specific amendment program

A commercially viable site-specific management program must increase profitability through a combination of increased yields and reduced input costs sufficient to offset the increased costs associated with the site-specific management. In the case of site-specific application of soil amendments, in which the alternative to site-specific management is the

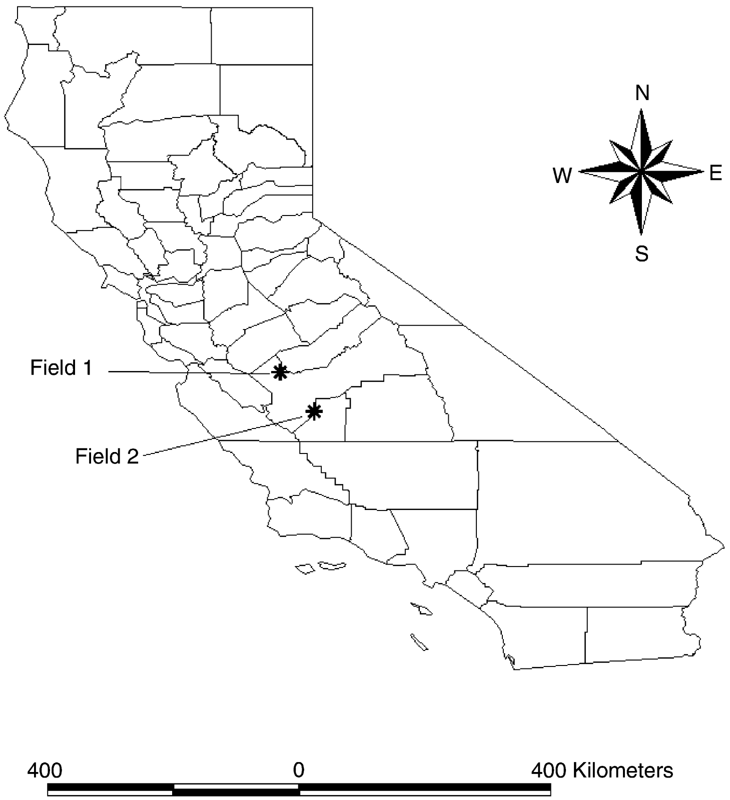

Fig. 1. Map of California showing the locations of field 1 near Mendota (Fresno County) and field 2 near Lemoore (Kings County).

uniform application of amendment at a fixed rate, the reduced costs are associated with not applying the amendment in areas in which it is not needed. Therefore, the sum of the costs associated with gathering the information on the distribution of salinity plus to any extra equipment costs associated with variable rate application cannot exceed the value of the saved amendment. This places a severe constraint on the amount of information that can be collected and imposes the need to make certain simplifying assumptions in estimating the distribution of salt effects.

The assumption we chose to make was to consider EC_a to be directly related to EC_e. That is, we neglected other potential contributors to EC_a such as soil texture, water content, bulk density, and temperature. Our reasoning was that this simplifies the procedure for the grower, reduces costs, and is conservative in the sense that, in a field known to be salt affected, it may identify some locations as needing amendment when they do not, but it is much less likely to fail to identify areas in need of treatment. Apparent soil electrical conductivity is relatively inexpensive to measure; therefore, an EC_a map, supplemented by directed soil sampling for EC_e, provides a spatially precise and agronomically conservative application plan. We judge that the savings associated with further reductions in amendment application would not be justified by the costs associated with more precisely determining the spatial distribution of salt effects.

Based on these considerations we developed a four-step method for site-specific salinity management in commercial fields. The steps are the following:

Step 1. *Generation of an EC_a map*. The first step is a straightforward one that in a commercial setting will ordinarily be carried out using either a direct-contact conductivity sensor, such as the Veris 3100, or a soil inductance sensor, such as the Geonics EM38, sampling at a sufficient density to capture the important conductance spatial patterns in the field.

Step 2. *Directed soil sampling for EC_e*. In order to estimate EC_e based on EC_a a collection of soil samples must be collected that will permit an estimate of the relation between EC_e and EC_a for this particular field. There are a number of potential approaches. We selected the method of Lesch et al. (1995a), which has proven very effective in a number of related applications. This method is implemented in the ESAP-95 computer program (Lesch et al., 2000), which develops a recommended soil sampling pattern based on a preliminary EC_a map and develops an estimated relation between EC_a and EC_e once the soil samples have been collected in this pattern.

Step 3. Determine the estimated amendment requirement as a function of location in the field. This step is accomplished in two sub-stages. The first is to calculate the amount of sodium to be replaced at each location based on measured soil properties. Data from the soil samples may be used to calculate the SAR at a given location according to the equation:

$$\mathrm{SAR} = \mathrm{meq\,Na}^{+}\sqrt{(\mathrm{meq\,Ca}^{2+} + \mathrm{meq\,Mg}^{2+})/2} \qquad (1)$$

where meq of Na^+, Ca^{2+}, and Mg^{2+} are determined from the saturation paste extract of the soil samples. The amount of Na^+ to be replaced to achieve a desired SAR is then given by:

$$\mathrm{meq\,Na}^{+}_{(\mathrm{r})} = X\,(\mathrm{desired\,SAR\,value}) \times \sqrt{(\mathrm{meq\,Ca}^{2+} + \mathrm{meq\,Mg}^{2+})/2} \qquad (2)$$

where $\mathrm{meq\,Na}^{+}_{(\mathrm{r})}$: meq of Na^+ to be replaced. The meq of Na^+ to be exchanged ($\mathrm{meq\,Na}^{+}_{(\mathrm{e})}$) is then derived by:

$$\mathrm{meq\,Na}^{+}_{(\mathrm{e})} = {}^{*}\mathrm{meq\,Na}^{+}_{(\mathrm{d})} - \mathrm{meq\,Na}^{+}_{(\mathrm{r})} \qquad (3)$$

where ${}^{*}\mathrm{meq\,Na}^{+}_{(\mathrm{d})}$: meq of Na^+ determined by saturation paste extract.

The second stage of step (3) is to calculate the amount of amendment necessary to apply at each location in order to replace this quantity of sodium. The amount of exchangeable sodium needed can be converted into the amount of soil amendment needed based on the data given by Richards (1954):

$\mathrm{meq\,Na}^{+}_{(\mathrm{e})} \times 0.9$ for gypsum
$\mathrm{meq\,Na}^{+}_{(\mathrm{e})} \times 0.49$ for sulfuric acid
$\mathrm{meq\,Na}^{+}_{(\mathrm{e})} \times 0.16$ for sulfur

Step 4. Integrate the individual amendment requirements into a practical spatial pattern for amendment application. The creation of the actual application map from the rate by location map of step (3) generally involves simplification into contiguous areas of a given application rate to accommodate farm operations. The number and size of such areas is dependent on the application equipment. Although in principle a mathematical algorithm could be used to generate these different application zones, for the present we generated these maps by eye.

2.3. EM38 survey

Apparent soil electrical conductivity measurements were made in each field using a Geonics EM38 induction meter (Geonics Ltd., Mississauga, Ont., Canada). Readings were taken in the vertical (denoted EM_v) and horizontal (denoted EM_h) modes. The EM_v reading penetrates to a depth of approximately 1.2–1.5 m, while the EM_h reading penetrates to approximately 0.60–0.75 m (McKenzie et al., 1997; McNeill, 1992). Preliminary EM38 readings were taken in February 1999 in field 1 using a regular grid pattern (60 m × 60 m) from 226 locations and in April 2000 in field 2 using a regular grid pattern (60 m × 60 m) with 195 locations. These surveys were scheduled 4–5 days after a rain event or pre-irrigation in order to minimize spatial variation of water content for the EM38 survey. The surveys were also scheduled in the morning in an attempt to reduce variation of the air and diurnal ground temperature near the surface of the soil (Fox and Hatfield, 1983). The EM38 meter was calibrated prior to the start of each survey and a sensitivity check of the instrument was preformed after every 20th survey location. The calibration and sensitivity checks were in accordance to Geonics EM38 ground conductivity meter operating manual.

Preliminary trials indicated that the EM_v EC_a spatial distribution generally provided the best visual correlation with yield distribution. Raw data EM_v EC_a readings from field 1 (1999) and field 2 (2000) surveys were interpolated via kriging to generate maps of EC_a data distribution (Figs. 2 and 3). Kriging has been shown to create very good interpolations for soil properties when enough data points are collected ($N \geq 50$) (Kravchenko and Bullock, 1999). The maps were used to visually identify the best location within each field to conduct amendment and modified irrigation experiments, namely, those areas within field 1 and field 2 having the greatest EM_v EC_a spatial variation. These experimental areas selected are the boxed areas seen in Figs. 2 and 3. An additional 136 EM38 survey locations (17 locations for each plot) were collected in June 2000 within the selected experimental area for field 1. This was due to extreme EM_v EC_a variation observed in the west end of this field during the initial survey 1999 (Fig. 2). Fig. 4 shows the kriged interpolated map of the EM_v EC_a of the data obtained from this survey. The extreme EM_v EC_a variation for this portion of the field was attributed to drainage tiles that, even though they had not been serviced for approximately 20 years, were still exerting a strong influence on soil drainage. These variations due to drainage tile influences are consistent with other investigators have observed (Rhoades et al., 1997). No such artificially induced variation was present in field 2. However, due to irrigation practices and natural soil variation the EM_v EC_a raw data showed the potential of segregating this field into four management zones, which are arranged from north to south. Fig. 5 shows these naturally occurring zones.

2.4. Soil sample collection and analysis

The ESAP-95 program (Lesch et al., 1995a, 1995b, 2000) was used to process the EM38 survey data and generate sampling plans for calibration soil core extraction. The algorithm in this program selects a limited set of calibration sites with desirable spatial and statistical characteristics by analyzing survey site location information with response surface design techniques (Lesch et al., 1995a, 1995b, 2000). Sixteen optimal sampling locations were identified for field 1 (Fig. 2) and 12 for field 2 (Fig. 3). Soil samples were collected from each site at depths of 0–30, 30–60, 60–90, and 90–120 cm for field 1 and 0–30, 30–60, and 60–90 cm for field 2. Commercial laboratories analyzed the saturation paste extract of these soil samples for EC_e, Ca^{2+}, Mg^{2+}, Na^+, and SAR in accordance with the procedures listed in the western states laboratory proficiency testing program, soil and plant analytical methods (Miller et al., 1997). The soil data were then used to determine the gypsum, sulfur, and sulfuric acid requirement to amend the various locations within each field. At each selected experimental area within both fields an additional group of soil samples were collected. These additional soil samples were collected to give a greater soil analysis resolution in those areas selected. Gypsum prescription maps were then generated in ArcView version

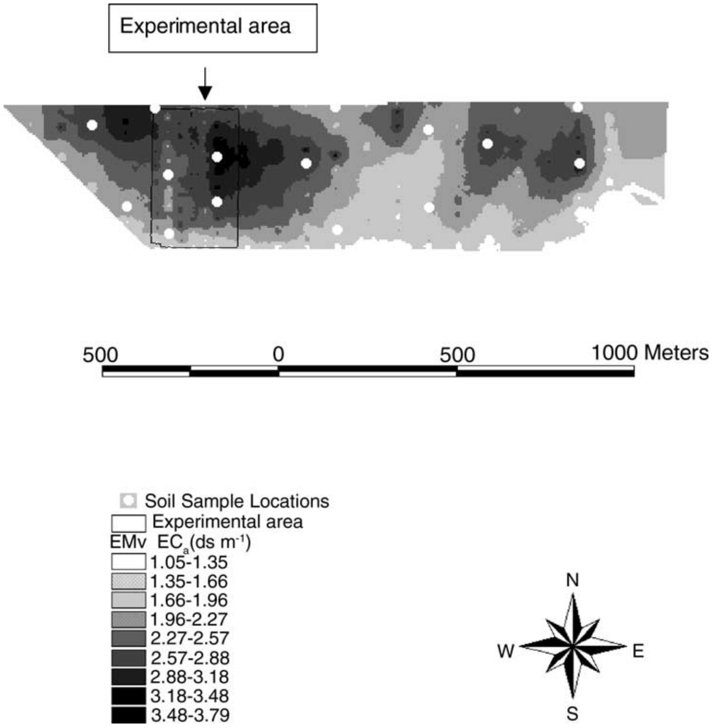

Fig. 2. Diagram of field 1 showing soil sample locations established from developed preliminary EC_a data and showing interpolated EM_v EC_a data. The rectangular region located with the field is the experimental site. The numbers correspond to the numbering system of the preliminary data.

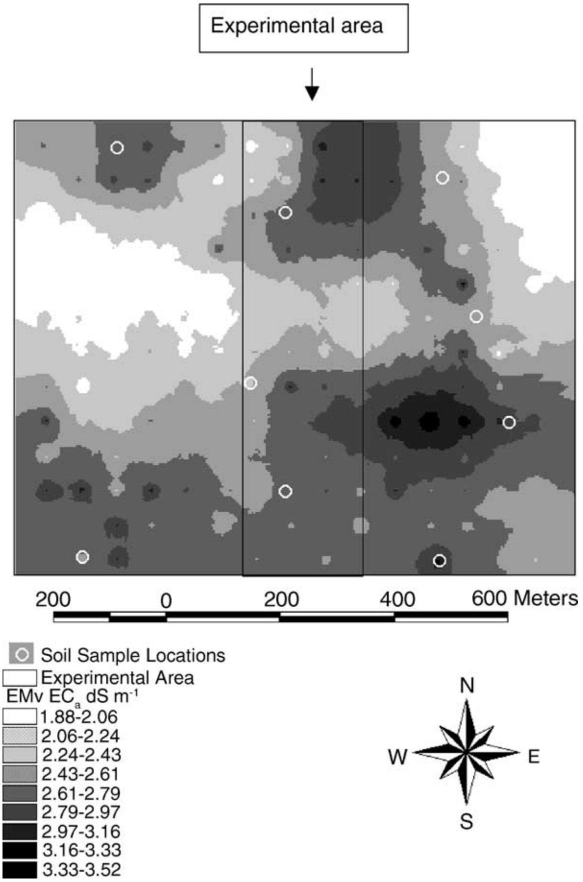

Fig. 3. Diagram of field 2 showing soil sample locations established from developed preliminary EC$_a$ data and showing interpolated EM$_v$ EC$_a$ data. The rectangular region located with the field is the experimental site. The numbers correspond to the numbering system of the preliminary data.

3.2 (ESRI, Redlands, CA) using an inverse distance weighted interpolation as described below.

2.5. Experimental design

The experiment conducted in 2000 in field 1 was laid out as a split plot design replicated in four blocks with the main plot treatments consisting of the two methods, sprinkler or furrow irrigation, applied for the first two irrigations (subsequent irrigation was by furrow for both treatments) and subplot treatments consisting of amendment type (gypsum, sulfur, and untreated control). Each plot consisted of eight rows of 76 cm beds (Fig. 4). The experiment conducted in 2001 in field 2 was laid out as a randomized complete block with four blocks containing five treatment plots. These treatments consisted of two uniform, two

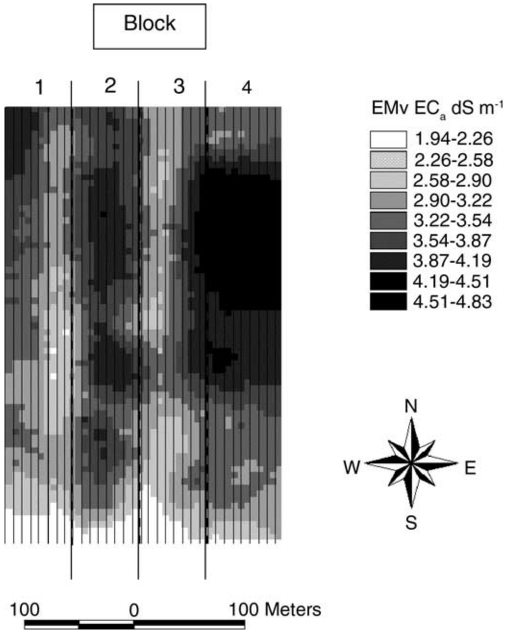

Fig. 4. Map of interpolated values of the EM_v EC_a readings resulting from an intensive survey carried out in the experimental area of field 1. The light areas in blocks 1 and 3 correspond to the locations of drain tiles as inferred from EC_a data.

variable amendment application rates (with the application rates changing in each zone), and one untreated control. Each plot for this field consisted of eight rows on 96.5 cm beds. Variable-rate treatments were developed according to the site-specific management program described in the preceding section. The experimental factors for the two experiments are as follows.

2.6. *Field 1*

The treatments consisted of three soil amendments with either a modified sprinkler or furrow irrigation. They are designated as follows:

1. Control F: with furrow irrigation.
2. Control S: sprinkler irrigation for the first two irrigations followed by furrow irrigation.
3. Gypsum F: 2.9 Mg ha^{-1} of gypsum @ 70%, with furrow irrigation.
4. Gypsum S: 2.9 Mg ha^{-1} of gypsum @ 70%, sprinkler irrigation for the first two irrigations followed by furrow irrigation.
5. Sulfur F: 4.4 Mg ha^{-1} of sulfur, with furrow irrigation.
6. Sulfur S: 4.4 Mg ha^{-1} of sulfur, sprinkler irrigation for the first two irrigations followed by furrow irrigation.
7. Sulfuric acid F: 2241 kg ha^{-1} sulfuric acid, with furrow irrigation.

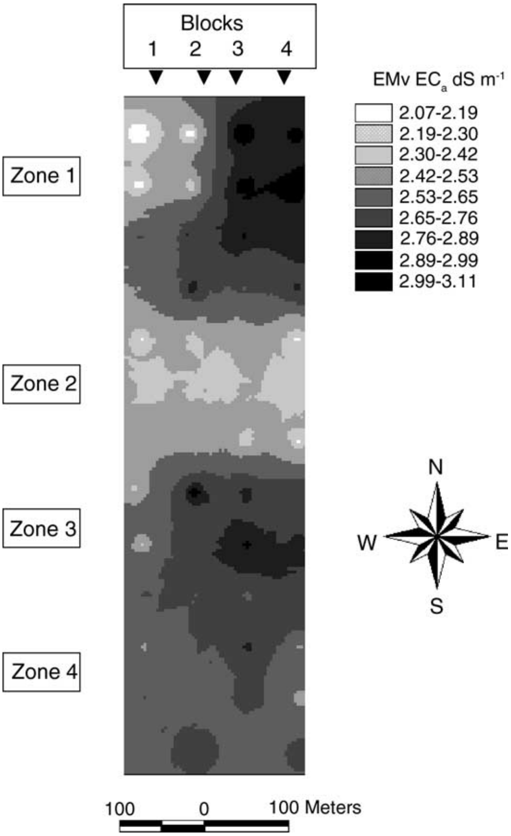

Fig. 5. Map of interpolated values of EM_v EC_a in field 2, showing the four zones corresponding to north–south variation in EC_a.

8. Sulfuric acid S: 2241 kg ha^{-1} of sulfuric acid, sprinkler irrigation for the first two irrigation followed by furrow irrigation.

2.7. Field 2

The treatments consisted of the following:

1. A uniform 13.5 Mg ha^{-1} application rate of gypsum (60%). Gypsum (60%): refers to the mean dry weight of gypsum ($CaSO_4 \cdot 2H_2O$) content calculated from a sulfate sulfur analysis performed on six randomly collected gypsum samples used for this trial.
2. A variable application rate of gypsum (60%). Each variable-rate gypsum plot was separated into four zones. These zones were determined from the predicted EC_e and gypsum amendment maps. The zones were numbered 1 through 4 with zone 1 located at the north end of the field and zone 4 at the south end. The applied rates for zone 1 and 3 were 40 Mg ha^{-1} (60% gypsum), while zones 2 and 4 were 26 Mg ha^{-1} (60% gypsum).

3. A uniform application rate of 1120 kg ha^{-1} of sulfuric acid.
4. A variable-rate application of sulfuric acid. Each variable rate sulfuric acid plot was also separated into four zones similar to treatment #2. Zones 1 and 3 had application rates of 3362 kg ha^{-1} and zones 2 and 4 had application rates of 2241 kg ha^{-1}.
5. A control with no amendment applied.

Note that treatments 2 and 4 involve a variable-rate application of inputs. From the perspective of the experimental design, however, they are regarded as a single treatment, since an objective of the experiment is to compare fixed and variable input application. In this context, the experimental unit is the plot.

2.8. Cotton seed yields

At harvest the plot yields were measured at both experimental locations. This was done by loading the total harvest for each plot into a movable bin (called a boll buggy) and weighing the boll buggy before and after loading. Yield monitoring data were also collected for both experimental areas in field 1 and field 2 using an Ag Leader yield monitor (Ag Leader Technology, Ames, IA) mounted on a commercial picker. Due to problems with the commercial picker in field 1, only a small portion of the experimental area was harvested with the yield monitor; thus, only the boll buggy weights were utilized. Prior to data collection for field 2 the yield monitor was calibrated by harvesting six 96.5-cm rows. Yield monitor values were then compared to boll buggy weights in order to establish a correction coefficient. This correction coefficient was then entered into the monitor software to correct for the difference between the two. After the initial calibration the yield monitor was not adjusted during the remainder of the harvesting. The 2001 yield data within the experimental area were collected from the middle four rows of each plot to eliminate possible influences of treatments from adjacent plots. The yield monitor data, although not required for the replicated experiment, provides an indication of the spatial yield variation throughout the plot, instead of an aggregated yield value as obtained by the boll buggy weights.

2.9. Geographic information system and statistical analysis

Spatial data were analyzed using ArcView, version 3.2 (ESRI, Redlands, CA) and ESAP-95 (Lesch et al., 2000). A kriging script for ArcView 3.2 was used to generate interpolated maps from the EM_v, because of the greater number of data values for this factor. Inverse distance weighted (IDW) interpolation with power 2 was used on the soil sample data due to the limited number of samples. The ESAP-95 program is based on a comprehensive methodology introduced by Lesch et al. (1995a, 1995b). This methodology uses a stochastic/dynamic modeling approach to predict soil salinity (EC_e) from EC_a survey data.

SAS, Version 8.0 (SAS Institute, Cary, NC) was used in the statistical evaluation of the data. Scheffe's test was used as a pairwise comparison for the irrigation and soil amendments. Scheffe's test is compatible with the overall ANOVA *F*-test in that it never declares a contrast significant if the overall *F*-test is non-significant. The test controls the maximum experimental error rate (MEER) for any set of contrasts including pairwise comparisons and may be used for “data snooping” (Steel et al., 1997). In this study the test was used to study the effects of the drain tiles in field 1.

3. Results

3.1. Field 1

Analysis of variance for the cotton seed yield (kg ha^{-1}) in field 1 (Table 1) indicated a p-value of 0.4357 for each amendment treatment (Table 2). There was also a high p-value of 0.3038 between the types of irrigation. However, there was a significant block × irrigation interaction ($p > 0.0189$). In examining Table 1 a trend can be seen with higher yield for all plots receiving the modified sprinkler irrigation as compared to furrow irrigation treatment. Statistical significance is not attained because of the high level of plot-to-plot variability. A transect from west to east of the plots (Fig. 6) shows the influence of drainage tiles on $\mathrm{EM_v}$ $\mathrm{EC_a}$ readings and cotton seed yield. The lower $\mathrm{EM_v}$ $\mathrm{EC_a}$ values in (Fig. 6a) correspond to the higher yield value seen in (Fig. 6b). The tiles align with the experimental layout, with blocks 1 and 3 containing the tiles (Fig. 4). Fig. 3 indicates the pronounced, but highly localized, effect of the tiles on $\mathrm{EC_a}$.

Table 1
Plot yield data for irrigation and amendment trial in field 1

	Cotton seed weight (kg ha^{-1})					
	Control F	Control S	Gypsum F	Gypsum S	Sulfur F	Sulfur S
Block 1	1541	3242	1962	4363	1601	3382
Block 2	1341	1741	1381	1661	1361	2261
Block 3	3142	3149	2062	3362	1922	3202
Block 4	1942	2642	2682	2342	1822	1981
Mean	1991.6	2693.7	2021.6	2932.2	1676.3	2706.6
S.D.	806.8	687.6	532.6	1182.6	249.3	689.6
CV	40.5	25.5	26.3	40.3	14.9	25.5

S.D.: standard deviation; CV: coefficient of variation.

Table 2
Split plot analysis of variance results for yield response to treatments, irrigation, and block in the data of Table 1 (field 1)

Source	d.f.	Sum of squares	Mean square	F-value	Pr > F
Block	3	5,145,624	1,715,208	1.91	0.1071
Irrigation type	1	4,654,323	4,654,323	5.19	0.3038
Block × irrigation type	3	2,690,346	896,782	4.90	0.0189
Amendment	2	326,124	163,062	0.89	0.4357
Irrigation type × amendment	2	110,194	55,097	0.30	0.7454
Error	12	2,195,675	182,973		

The error term for block and irrigation type is block × irrigation type. d.f.: degrees of freedom.

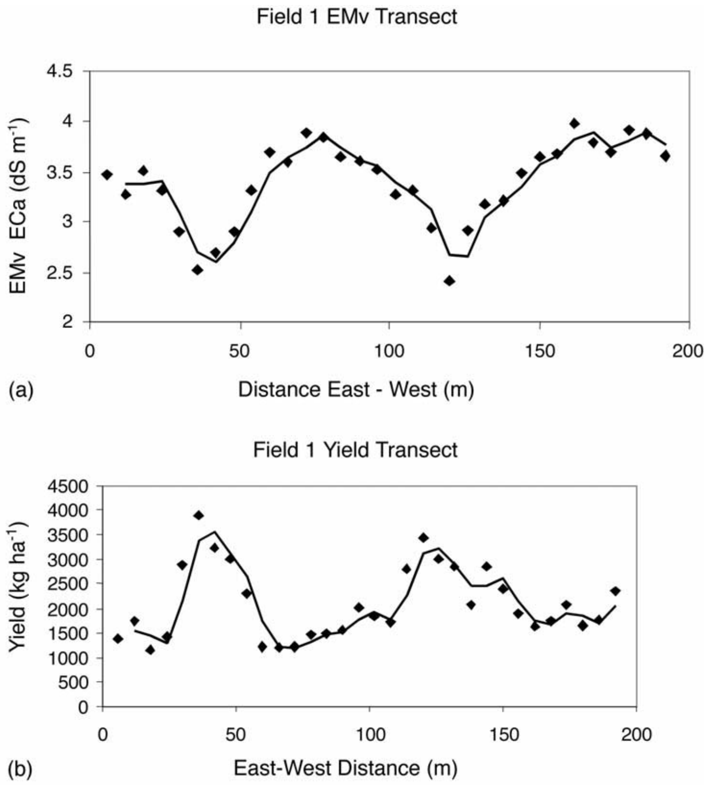

Fig. 6. Measurements of (a) EM_v EC_a and (b) cotton seed yield along a west-to-east transect in field 1.

Based upon the trend seen in Table 1 and the results in Table 2, a Scheffe test was performed on the block data (Table 3). There was a significant yield difference between the pair 1 and 3 of blocks and the pair 2 and 4. Although there was not a significant yield response to irrigation treatment (Table 2) there was a strong trend toward increased yield in the sprinkler-irrigated treatment (Table 1). A Scheffe analysis was performed to compare the pair of blocks 1 and 3 against the pair 2 and 4 (Table 4). This test indicated a significant difference between the sprinkler and the furrow irrigation treatments for blocks 1 and 3, but not for blocks 2 and 4.

Table 3
Scheffe comparison of the blocks in the data of Table 2 means with the same letter are not significantly different (field 1)

Scheffe grouping		Mean	*N*	Block
	A	2806.5	6	3
B	A	2681.8	6	1
B		2235.2	6	4
		1624.3	6	2

Table 4
Scheffe comparison of blocks 1 with 3 and 2 with 4 from data in Table 2

Blocks 1 and 3				Blocks 2 and 4			
Scheffe grouping	Mean	*N*	Irr	Scheffe grouping	Mean	*N*	Irr
A	3450.0	6	2	A	2104.7	6	2
				A			
B	2038.3	6	1	A	1754.8	6	1

Means with the same letter are not significantly different (field 1). Irr 1: furrow irrigation; Irr 2: sprinkler irrigation.

3.2. Field 2

Fig. 7 shows a map of the individual plots of field 2. The plots are numbered 1–20 moving from west to east. The variable application rate treatments can be seen as those whose rates vary from zone to zone. A comparison was made of total plot yield as measured by the yield monitor and that measured by the boll buggy for each experimental plot. Yield monitor weight of plots 1 through 14 (blocks 1 through 3) were all within 10% of boll buggy weight, whereas yield monitor weight for plots 15 through 20 (1 plot of block 3 plus block 4) were from 122 to 133% of boll buggy weight (Table 5). These latter plots were the first to be harvested, and we believe that this discrepancy resulted primarily from incorrect calibration. The yield monitor data revealed that a few of the plots included data outside the experimental area, while other plots had multiple data entries at the same location within the plot. All data entries outside the plot and multiple entries at the same spatial location

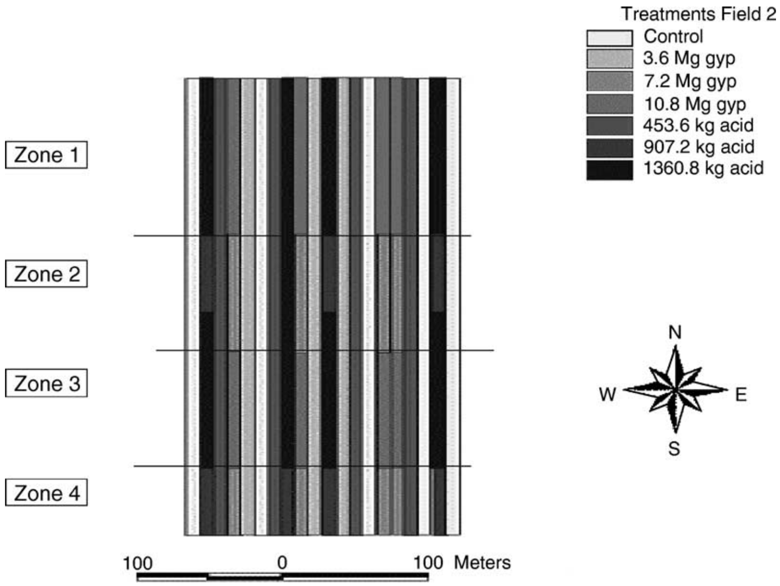

Fig. 7. Diagram of the experimental plot showing each zone and plot location for each treatment. (Gypsum rates based on 100% gypsum.)

Table 5
Comparison of yield monitor and boll buggy yield measurements (kg cotton seed plot^{-1})

Unadjusted (%)				Adjusted (%)			
Plot#	Monitor	Buggy	Buggy	Plot#	Monitor	Buggy	Buggy
1	1408	1341	105.0	1	1406	1341	104.8
2	1569	1629	96.3	2	1564	1629	96.0
3	1484	1610	92.2	3	1476	1610	91.6
4	1697	1594	106.5	4	1694	1594	106.3
5	1653	1584	104.4	5	1637	1584	103.4
6	1479	1474	100.3	6	1493	1474	101.3
7	1599	1510	105.9	7	1599	1510	105.9
8	1724	1627	106.0	8	1698	1627	104.4
9	1608	1521	105.7	9	1554	1521	102.2
10	1364	1454	93.8	10	1393	1454	95.8
11	1749	1612	108.5	11	1750	1612	108.6
12	1404	1503	93.4	12	1391	1503	92.5
13	1390	1512	91.9	13	1389	1512	91.9
14	1540	1505	102.4	14	1528	1505	101.6
15	1965	1486	132.2	15	1955	1486	131.5
16	1799	1441	124.9	16	1794	1441	124.5
17	2176	1633	133.2	17	2177	1633	133.3
18	2018	1538	131.2	18	1667	1538	108.4
19	2110	1586	133.1	19	2042	1586	128.8
20	1980	1612	122.8	20	1970	1612	122.2
Mean	1686	1539		Mean	1659	1539	
S.D.	251	78		S.D.	231	78	
CV	14.9	5.1		CV	13.9	5.1	

S.D.: standard deviation; CV: coefficient of variation.

were removed in order to standardize the data. Table 6 shows the results of the correction process.

No significant difference was found among plot yields (as measured by the boll buggy) for the treatments (Table 6), although there were trends in the treatment response (Table 7). There is a trend of increasing yield with the variable rate application of sulfuric acid (treatment 4) and the variable rate of gypsum (treatment 2) as compared with uniform application rates (treatments 1 and 3) or the control treatment 5.

Table 6
ANOVA for plot yield (as measured by boll buggy) response to treatment and block in field 2 (randomized complete block design)

Source	d.f.	Sum of squares	Mean square	*F*-value	Pr > *F*
Block	3	33,941	11,314	0.43	0.74
Treatment	4	206,604	51,651	1.94	0.17
Error	12	319,065	26,589		
Total	19	559,610			

d.f.: degrees of freedom.

Table 7
Scheffe test ANOVA of corrected yield monitor data for treatment, block, and management zones (kg cotton seed ha^{-1}), field 2

Treatment	Mean	Group	Block	Mean	Group	Zone	Mean	Group
4	4370	A	2	4158	A	2	4375	A
2	4081	A	1	4156	A	1	4289	A
3	4039	A	3	4021	A	4	3868	B
1	3974	A	4	3988	A	3	3790	B
5	3940	A						

Means with the same letter are not significantly different ($p \leq 0.05$). Analyzed as a repeated measures design in the treatment zone. Treatment 1: uniform application of gypsum; treatment 2: variable application rate of gypsum; treatment 3: uniform application of sulfuric acid; treatment 4: variable application rate of sulfuric acid; treatment 5: control. Zone 1: north; zone 2: north central; zone 3: south central; zone 4: south portion of the experimental area (Fig. 6).

Using only aggregated boll buggy cotton seed weight for each plot could potentially mask effects of the variable-rate treatments used in field 2. To determine if potential effects were being masked, a Scheffe analysis for cotton seed yield was carried out on the yield monitor data with the plots separated into the four management application zones (Fig. 7). These management zones for the Scheffe analysis were treated as a repeated measure. The northern two zones showed a significant difference when compared to the southern two zones (Table 7). A slight trend of increasing yield is seen with the variable-rate application of sulfuric acid (treatment 4) and the variable-rate application of gypsum (treatment 2).

4. Discussion and conclusions

Our objective was to develop and test a practical, field-implementable method for site-specific management of soil salinity and sodicity. The primary economic constraint to such a method is that the costs associated with the procedure cannot exceed the value of the saved amendment. We chose to resolve this by relying primarily on measurements of bulk soil electrical conductivity, which may result in some amendment being applied where it is not needed, but at least will not result in missing areas that actually need reclamation.

The lack of significant differences seen in analyzing the various treatments was likely due in part to the high level of spatial variability present in the commercial fields in which the experiments were carried out. The existence of this variability is the primary motivation for the use of site-specific crop management methods, and our results indicate that traditional field plots harvested with an aggregate yield method (i.e., boll buggy) may not be appropriate for evaluating the response variable on a site-specific crop management experiment. This difference was apparent when comparing the ability to evaluate field 1 with only the boll buggy and field 2 with a yield monitor.

Although in field 2 there was no significant difference in yield response to the amendment treatments, treatment 4 (variable rate sulfuric acid) was consistently the highest yielding treatment. Yield monitor data indicated a significant yield difference between the two northern zones (1 and 2) as compared to the two southern zones (3 and 4) (Table 7). This is encouraging because zone 1 was the most affected by salinity problems, according to the

EM38 and soil surveys performed in 2000 and 2001 (Figs. 2 and 4). The trend observed with the variable rate application of sulfuric acid may be in part due to the rapid reaction with the soil and residue gypsum from previous applications (6.7 Mg ha^{-1} in September, 1998, and November, 1999). In addition, the effects of gypsum may not be evident in the first year following application due the particle size, purity of the gypsum, and water quality.

Although the primary objective of this study was to develop a methodology for a site-specific soil amendment application program, the experiment in field 1 also examined the effects of modifying irrigation by applying the first irrigation via sprinkler. This practice is increasingly used in the San Joaquin Valley and was used in all plots in field 2, in which the water in the first two irrigations was applied by sprinkler. Both fields in this experiment are located in the Westlands Water District, which is experiencing a severe problem of disposal of saline drainage water. The results in Table 4 showed that blocks 1 and 3, which were located over the drainage tiles, had a significant difference between the sprinkler and furrow irrigation, while blocks 2 and 4, not located over the tiles, had no significant difference. This suggests the importance of drainage in the reclamation efforts of saline-sodic fields. While not evaluated in this study the ratio of the EM_h EC_a and EM_v EC_a has been shown to indicate water applications uniformity or lack of uniformity (Rhoades et al., 1997; Corwin and Lesch, 2003), which can be influenced by drainage characteristic. Evaluating drainage characteristics using this methodology maybe helpful in the soil reclamation efforts.

Acknowledgements

This research was partially support by the Cotton Incorporated and Sunland Analytical Lab Inc. We are grateful to the J and J Farms and Sheely Farms for permission to carry out our research in their fields. We are very grateful to Dennis Corwin for the many hours spent planning, organizing, and editing this special issue.

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