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Site-specific management in salt-affected sugar beet fields using electromagnetic induction

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Abstract

An assessment of field-scale variation and the characterization of correlated crop response are the first steps in evaluating the potential for variable-rate technologies and other techniques used in site-specific management (SSM). The responses of sugar beets to salinity and to residual and applied soil N were studied at sites in California's Imperial and San Joaquin Valleys to evaluate the potential of electromagnetic induction (EMI) techniques for SSM. Electromagnetic induction was used to create geo-referenced assessments of apparent soil electrical conductivity (EC_a) and correlated soil properties in salt-affected fields in the Imperial (IV) and San Joaquin (SJV) Valleys. Soils at the two sites were primarily fine, smectitic (calcareous) thermic, vertic Torifluvents and Fluvequents, respectively. Two crops were grown in the IV and one in the SJV. Root and gross sugar yields were evaluated at field scale using a yield monitor and in subplots centered on soil sampling locations chosen using ESAP-95 (v. 2.01) software that were harvested by hand. Average subplot root yields differed from field-scale averages derived from the yield monitor by less than 4% for all three crops. In the IV field, average salinity increased with depth, indicating leaching of salts. The natural logs of electrical conductivity of the saturation paste extract (EC_e) and saturation percentage (SP) were strongly correlated with measured EC_a ($r = 0.97$ and $r = 0.86$, respectively) and nitrate was moderately correlated ($r = 0.55$). Root and sugar yields declined at the higher salinity levels from 18.0 to 8.0 mg ha^{-1}. The SJV site was poorly drained and leaching was not apparent. EC_e was strongly correlated with EC_a ($r = 0.94$), but SP was not ($r = 0.20$). Gross sugar yields apparently were influenced by SP rather than by EC_e

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Abbreviations: EC_a, apparent soil electrical conductivity; EC_e, electrical conductivity of the saturation extract; EMI, electromagnetic induction; GIS, geographic information system; GPS, global positioning systems; SSM, site specific management; IV, Imperial Valley; SJV, San Joaquin Valley

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and varied from 2.9 to 14.1 mg ha^{-1}. Where crop growth and yield are influenced by salinity, EMI is useful for estimating optimum fertilizer N application rates and for identifying areas of the field that will have unprofitable yields. Irrigation might be withheld from these areas and the water saved for other beneficial uses.

Keywords: GIS; Apparent soil electrical conductivity; Electromagnetic induction; Site-specific crop management; Salinity; Sugar beet

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1. Introduction

Site-specific management (SSM) is the attempt to improve crop production by managing diversity at the field-scale using new data collection and information management technologies (Plant, 2001). These include systematic soil and model-based sampling, yield monitoring, remote sensing, and spatially oriented data analysis techniques (Pierce and Nowak, 1999; NRC, 1997). There are many uncertainties about the use and value of these technologies including (i) how accurately significant soil or crop properties can be measured, (ii) whether accurate interpolation from those measurements can be made (McBratney and Pringle, 1999; Shatar and McBratney, 1999), (iii) whether sufficient variation is present at the scale of interest, (iv) whether that variation is of agronomic use and can be managed with the equipment available, and (v) whether SSM will be economically worthwhile (Pierce and Nowak, 1999; Bullock et al., 1998; Lowenberg-Deboor and Boehlje, 1996).

Work on SSM originated in the Midwest region of the United States and most of the work that has been carried out to date has been done there, particularly on corn, soybean, and sugar beet fields. Some of the most successful applications of SSM reported so far may involve sugar beet production (Reitmeir et al., 1999; Cattanach et al., 1996). Remotely sensed crop images of preceding wheat crops were used successfully to reduce variation in sugar beet yields following the wheat. Different areas in the field with varying residual N fertility were identified from images of the wheat crop and subsequently sampled to 1.5 m in depth. Soil test N levels were used to variably apply fertilizer N to the following beet crop. Sugar yields were made more uniform and higher on average than in neighboring fields managed uniformly. The success of this approach to sugar beet fertility management was based on the existence of different levels of residual N within a field that were identified accurately and then managed using a traditional input (N fertilizer). Crop response to N variation is understood and has economic effects: sugar concentrations are reduced when N availability is too great (Hills and Ulrich, 1971). More concisely, the variation had an interpretable structure (Gotaway et al., 1997) and was responsive to traditional management practices.

The use of SSM in the arid Southwest is more recent. There are several important differences between the irrigated agriculture practiced in the Southwest and the rain-fed, temperate agriculture of the Midwest. Most important is the use of irrigation. Water is provided more or less in a timely and sufficient manner to crops and the severe effects of periodic drought are eliminated. Huggins and Alderfer (1995) reported that 67% of the variation in yield across years and sites in a long-term trial in the Midwest was due to temporal variation, compared to 10–15% due to spatial variation within the field. Because of irrigation, a larger amount of variation may be correlated with spatial variation in fields. Rather than drought, moisture-related yield effects are due more to non-uniformity, which is a combination of irrigation technology and soil properties, including texture, drainage, and salinity. Erosion is less of a concern because most irrigated fields are leveled. Other important differences include a wider range of crops produced than in the Midwest, and in some locations salinity is a problem.

One of the ways to determine field-scale variation of soil physical and chemical properties is geo-referenced measurements of apparent soil electrical conductivity, EC_a (Rhoades et al., 1999a,b; Corwin and Lesch, 2003; Corwin et al., 2003a). Soil EC_a has been used frequently to characterize field variability for application to precision agriculture (Jaynes et al., 1993, 1995; Sudduth et al., 1995; Kitchen et al., 1999; Corwin and Lesch, 2003). Geo-referenced soil EC_a measurements have been shown to provide a means to identify edaphic factors influencing crop yield (Corwin et al., 2003a). However, the correlation between crop yield and EC_a may be inconsistent because of interactions with other soil properties, seasonal variation, and management factors that confound the influence of a single state variable such as EC_a (Corwin et al., 2003b). Field-scale yield variation has not been widely characterized in the Southwest. Plant et al. (1999) evaluated the performance of wheat in California's San Joaquin Valley. Corwin et al. (2003b) found that leaching fraction, salinity (EC_e, electrical conductivity of the saturation extract), saturation percentage (SP), available water, and pH accounted for roughly 60% of the yield variation for seed cotton in a 32.4-ha field in the SJV. Plant et al. (2000) have evaluated the relationship between remote sensing, soil salinity, and cotton yield.

In California's Imperial and San Joaquin Valleys, horticultural and perennial crops increasingly are planted on better, more uniform soils. But the most responsive locations to SSM will likely be those with the largest amount of variation, where lower valued field crops tend to be produced. In general, crop responses under these conditions are less well understood than on better soils, and are less predictably responsive to management (De Wit, 1992; Corwin et al., 2003b). Site-specific management techniques might be of use, but their successful adoption may be dependent on poorly characterized crop response.

Sugar beets are a salt-tolerant crop that are grown frequently in salt-affected fields. Yield declines above an EC_e of approximately 7 $\mathrm{dS\,m^{-1}}$ but plants are more sensitive as seedlings (Maas, 1990). Most salt tolerance data have been established using small plots where salinity was the primary factor varied. Typically salt was applied to a non-saline field (Shalhevet, 1994). Farm fields usually differ from these conditions. In fields a number of soil chemical and physical properties are linked to salinity, but may change across the field at varying rates (Kaffka et al., 1999). Others may not be correlated at all or vary due to management.

An assessment of field-scale variation and the characterization of correlated crop response are the first steps in evaluating the potential for variable rate technologies and other techniques used in SSM. The responses of sugar beets to salinity, and to residual and applied soil N were studied at sites in California's Imperial and San Joaquin Valleys. The objectives of this study were: (i) to investigate the complex relationship between geo-referenced EC_a measurements, correlated soil properties, and crop yield (specifically sugar beets) on salt-affected soils and (ii) to evaluate the use of geo-referenced EC_a measurements as a way to apply site specific management technology, including yield and profit estimation.

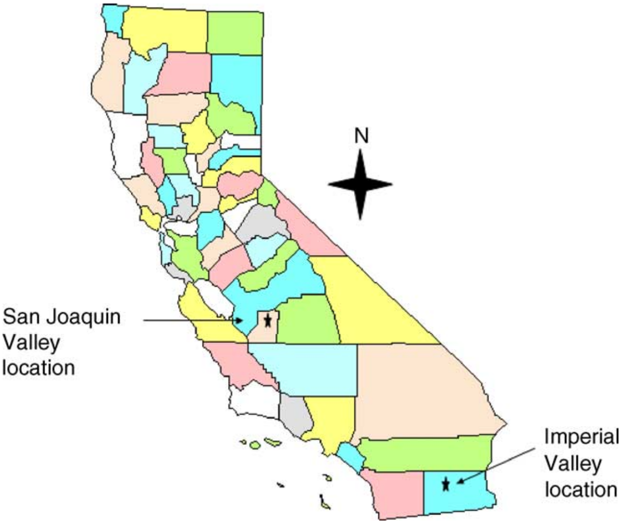

Fig. 1. Map of California showing the location of the San Joaquin Valley and Imperial Valley field sites.

2. Materials and methods

2.1. Description of the study sites

Two farm fields planted with sugar beets were identified in regions of California that have salt-affected soils. One was in the Imperial Valley (IV) near Brawley, the other was located in the western San Joaquin Valley (SJV) near Stratford (Fig. 1 and Table 1). The IV site was furrow irrigated. It is underlain with a series of tile drain lines at approximately 2 m in depth. Two sugar beet crops, rotated with winter wheat, were studied. The first crop was grown on approximately 60% of the field (34 ha), regarded as the more productive portion, while the second crop was produced on the entire 58-ha field. The SJV site was located along the western edge of the old Tulare Lake bed and was underlain with tile drains at a

Table 1
Field management information

	Imperial Valley (IV), lat: 33.02247818, long: −115.38786397	Kings County (KC), lat: 36.17469370, long: −119.86119920
Area (ha)	33.6/58	60
Soil type (s)	Imperial-Glenbar silty clay loam and Imperial clay loam: fine, smectitic, (calcareous), hypothermic vertic Torifluvent	Wellbank clay: fine, silty, mixed (calcareous), thermic, aeric Fluvequent; Houser clay: fine, smectiitc (calcareous) thermic, vertic Fluvequent
Planting date	19 September 1998; 20 September 2000	5 November 1998
Harvest date	22–23 May 1999, 1–6 June 2001	9–15 September 1999
Fertilization (kg N/ha)	225	112

depth of 1.1 m. It lies in a region with some of the most saline-sodic soils used for crop production in California. It was sprinkler irrigated. Details about planting, harvest, and crop management are summarized in Table 1.

2.2. *Intensive EC_a survey*

Both mobile EMI and fixed-array resistivity equipment provide maps of EC_a that can be used to direct soil sampling for the purpose of characterizing the spatial variability of those soil properties that influence the EC_a measurement (Lesch et al., 2000; Corwin and Lesch, 2003; Corwin et al., 2003a,b). At the IV site, the initial intensive EC_a survey was conducted in August 1998 following a pre-plant irrigation to bring the study site to field capacity but before field preparation and planting. Pre-irrigation also facilitates salinity assessment (Lesch et al., 1995a; Rhoades, 1992; Rhoades et al., 1999b; Corwin et al., 2003a,b). The fixed-array electrodes were set to measure EC_a to a depth of 1.2–1.5 m. Mobile EMI equipment measures soil to approximately the same depth. Each EC_a measurement was geo-referenced using a GPS. In August 2000, the entire field at the IV site was surveyed, including the portion previously assessed in 1998. At the IV site in 2000, 1255 EMI measurements were collected (Fig. 2a). At the SJV site, 3179 EC_a measurements were taken across the 58-ha study area (Fig. 2b).

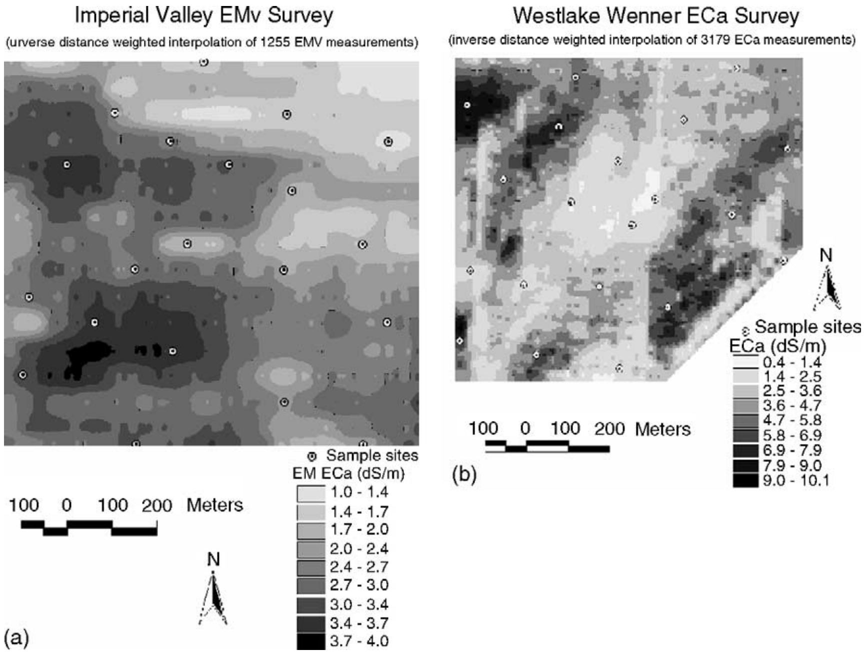

Fig. 2. Maps of EC_a surveys of (a) IV site where EM_v (0–1.6 m) was mapped (irrigation water flowed from east to west) and (b) SJV site where EC_a (0–1.1 m) was mapped.

2.3. Soil sampling design and sample collection

Once the intensive EC_a survey was conducted at each site, the ESAP-95 (v. 2.01) software package developed by Lesch et al. (1995a,b, 2000) was used with EC_a survey data to select the locations where soil cores were taken. Using a model-based sampling strategy, soil sample locations were selected that reflected the observed variation in EC_a, while simultaneously maximizing the spatial uniformity of the sampling design across the study area (Fig. 2a and b). A detailed discussion of the application of a model-based sampling strategy using EC_a survey data can be found in Lesch et al. (1995b) and Lesch (this issue).

At both the SJV and IV sites, soil cores were taken with a Giddings drill rig. In 1998, cores at the IV site were taken at 0.45-m increments to a depth of 1.8 m. In fall 1999, cores were taken to 1 m in depth at 0.3-m increments, while in 2001 after harvest samples were collected to 1.8 m in 0.3-m increments. At the SJV site, cores were taken at 0.3-m increments to a depth of 1.5 m. Cores could not be taken at the 1.5–1.8 m because the water table in the SJV field fluctuated between 1.5 and 1.8 m. The soil sample at this depth was saturated, causing it to run out of the core tube before reaching the soil surface. At each sampling, one set of core samples was taken at the IV site, while two sets were taken at the SJV site. The duplicate cores were taken within 7.5–10 cm of one another. One set of soil cores was taken for bulk density determination (Blake and Hartge, 1986), and another set was taken for soil chemical and physical property analysis. The single set of core samples for the IV site was used only for soil chemical and physical property analysis.

2.4. Soil chemical and physical analyses

At the IV site, soil samples were analyzed for pH, NO_3-N, EC_e, sodium adsorption ratio (SAR), % sand, silt, and clay; and saturation percentage (SP). At the SJV site, soils were analyzed for bulk density, NO_3-N, EC_e, and SP. Solution extracts were taken from prepared saturation pastes according to Rhoades et al. (1992). The saturation extracts were analyzed following procedures outlined in Agronomy Monograph No. 9 (Page et al., 1982). Particle-size distribution was measured using the hydrometer method (Gee and Bauder, 1986).

2.5. GIS and map preparation

All spatial data were entered into a geographic information system (GIS), (ESRI, ArcView 3.1, Redlands, CA). Interpolated maps of the soil physicochemical properties were prepared by using inverse distance weighting of the measurements. Some previous studies comparing interpolation methods for mapping soil properties have found kriging better (Laslett et al., 1987; Warrick et al., 1988; Leenaers et al., 1990; Kravchenko and Bullock, 1999), while others have shown inverse distance weighting to be superior (Weber and Englund, 1992; Wollenhaupt et al., 1994; Gotway et al., 1996). Inverse distance weighting was selected as the preferred method of interpolation because it was more accurate than kriging based on the use of the mean squared error as the primary criterion for comparison.

2.6. Sugar beet yield monitoring and data management

Spatial distributions of sugar beet yield were measured with a Harvest Master yield monitor fit with a global positioning system (GPS). The GPS unit used was a Trimble 132 Ag GPS. Yield sensors used a load cell to weigh sugar beet roots as they were transferred to a truck for removal from the field. Weights were recorded 7 m from the point of harvest so adjustments for this lag distance were accounted in creating yield maps. The GPS receiver accuracy was within >1 m of horizontal accuracy. The spatial sugar beet yield data were collected during May 1999 and June 2001 for the IV site and during September 1999 for the SJV site. Interpolated yield maps were created using ArcView 3.1 software after data smoothing.

2.7. Crop quality and yield assessment

At the same locations where soils were sampled, small plots were created to observe and then harvest sugar beet plants for yield and root quality. Sugar beet root quality cannot be measured directly with a yield monitor, so hand sampling was required. Soil sample locations chosen by the ESAP software program were used for this purpose. At harvest of the entire field, small plots (four rows 12.7-m long) centered on each soil sample location (Fig. 2a and b) were harvested in both fields and plant population, yield, and root quality (sucrose and impurities) were determined. Roots were analyzed for sugar content and impurities at the Spreckels Sugar laboratories in Brawley and Tracey, California. The entire fields were harvested with a commercial sugar beet harvester using a Harvest Master yield monitor.

In the second trial in the IV on all the plots, two rows were treated with gypsum (9 mg ha^{-1} equivalent) applied directly over the row at planting. The gypsum was used to reduce the effects of salinity on soil crusting to determine if this use improved sugar beet emergence. The effects of additional N fertilizer also were studied. Adding N fertilizer does not overcome the limitations of soil salinity on plant growth (Shalehevet, 1994), but sugar beet root quality is influenced by N (Hills and Ulrich, 1971). Nitrogen fertilizer (90 kg ha^{-1}) was added to half of the plots after emergence and crop establishment. Electrical conductivity of the saturation extract was used as a stratification variable to divide the plots. The 20 hand-sampled locations were divided in half, with each half including approximately similar variability in soil properties and comparably distributed throughout the field. This method of division allowed each set of plots to encompass the observed variation in EC_e combined with any effects of location, and allowed N treatments to be randomized by groups of plots or blocks. The attempt to carry out experiments with agronomic inputs at field scale is relatively new (Plant, 2001). A number of undeveloped statistical issues are raised by this effort, including how to avoid formal bias and its meaning. These questions require further research and development, but are beyond the scope of this paper.

The variable costs associated with sugar beet production were calculated for the IV site for 2000–2001. Based on subplot gross sugar yields (determined by root fresh weight yield multiplied by their respective sucrose percentages), the returns over variable costs were calculated based on contract prices received that year for sugar beets and records of variable costs for the field kept by the cooperating growers in the IV. Costs and returns were compared at the field scale and areas of the field falling below the break-even price were identified. A map of predicted gross sugar yield was created using predicted yields and EC_e based on plot yield data carried out with Arc View 3.1 software.

2.8. *Data analyses*

Plots were located at soil sample locations so plot yield data could be used for analyzing the relationship between soil properties and crop yield. The results from soil cores taken in the center of each plot were considered representative of the whole plot. For the 2000–2001 trial in the IV site, ANOVA and a single degree of freedom contrast test (Littell et al., 2002) were used to test for the effects of gypsum on the number of emerging seedlings in measured areas of the rows and fertilizer N treatments on root yield and sugar content. For the purpose of analysis, gypsum treatments were regarded as subplots and N was analyzed as differences between groups of plots or blocks. If there were no significant differences, results from the entire plot were combined. OLS regression was used to determine the relationships between soil properties and crop yield and quality characteristics. Yield maps were used to estimate field-scale root yield averages, and the areas of the field within five yield ranges using ArcView software were calculated. The average plot yield and range were compared to the field average yield and the range of yields recorded by the yield monitor.

Correlations among soil properties based on soil cores were made using ESAP-95 (v. 2.01) software (Lesch et al., 2000) software and confidence intervals derived using log-ratio approximations (Graybill, 1976).

3. Results

3.1. *Field soil characteristics*

Apparent soil electrical conductivity (EC_a) varied greatly at the field scale at both sites (Fig. 2a and b). At the IV site, EC_e averaged over the profile depth varied from 2.3 to 21.0 dS m^{-1} at the 20 sample locations (Table 2a). Salinity was influenced in part by irrigation patterns, increasing from the irrigation water source at the furrow head end of the field (east) towards the furrow tail end, and by soil physical properties, particularly SP or clay content. Lower SP areas near the tail end of the field had higher EC_a values than those near the head end (Fig. 2a), an irrigation related effect (Rhoades et al., 1997a). This pattern was confounded with variation in average profile SP, particularly in the deeper profile layers sampled. Apparent soil electrical conductivity and SP values corresponded approximately to soil map units reported in the NRCS survey for that location (Zimmereman, 1981). The greater the average SP, the greater the average EC_a value (Table 3). Salinity increased with depth at most sample locations, implying that leaching is occurring (Fig. 3a). In one plot location with the highest average EC_e and lowest crop yield, the profile was inverted (Fig. 3c).

At the SJV site, average profile EC_e varied from 3.1 to 24 dS m^{-1}. A large portion of the field was very saline (Table 2). These soils are marginal for crop production for all but the most salt-tolerant crops. Values of EC_e were lower in general in the first foot, otherwise the soil profile tended to be approximately uniformly saline with depth (Fig. 3b). This suggests

Table 2
Mean and range statistics of soil physical and chemical properties

Soil property	N	Mean	Maximum	Minimum	Range	S.D.	S.E.	Co-efficient of variation	Skewness	Kurtosis
(a) (0–1.8 m) for IV site, June 2001										
Depth (0–0.3 m)										
pH	20	7.54	7.9	7.2	0.7	0.19	0.04	2.49	0.06	−0.12
EC_e (dS m^{-1})	20	10.24	27.6	2.28	25.32	7.21	1.61	70.4	0.93	0.39
% Sand	20	7.2	17.0	4.0	13.0	2.98	0.67	41.5	2.32	6.09
% Silt	20	48.7	52.0	41.0	11.0	2.72	0.61	5.6	−1.61	2.90
% Clay	20	44.1	47.0	42.0	5.0	1.62	0.36	3.7	0.73	−0.62
SP	20	56.85	62.0	51.0	11.0	2.80	0.63	4.92	−0.03	−0.02
SAR	20	10.1	35	3	32.0	8.15	1.82	80.7	1.80	3.63
Cl ($mmol_c$ L^{-1})	20	25.81	80.8	4.5	76.3	23.0	5.15	89.8	1.40	1.33
NO_3-N (mg L^{-1})	20	29.14	155.4	3.5	151.9	43.25	9.67	148.4	2.59	5.81
Depth (0.3–0.6 m)										
pH	20	7.65	7.9	7.5	0.4	0.14	0.03	1.82	0.26	−1.53
EC_e (dS m^{-1})	20	9.31	20.4	1.46	18.94	6.13	1.37	65.9	0.18	−1.18
% Sand	20	7.35	25.0	3.0	22.0	4.86	1.09	66.1	2.79	9.30
% Silt	20	49.1	55.0	40.0	15.0	3.78	0.84	7.70	−0.54	0.28
% Clay	20	43.6	50.0	35.0	15.0	3.23	0.72	7.42	−0.62	1.73
SP	20	58.1	67.0	51.0	16.0	3.63	0.81	6.25	0.51	0.77
SAR	20	10.85	29.0	3.0	26.0	7.10	1.59	65.4	0.95	0.57
Cl ($mmol_c$ L^{-1})	20	16.09	63.0	1.8	61.2	16.37	3.66	101.79	1.56	2.28
NO_3-N (mg L^{-1})	20	10.41	71.4	2.2	69.2	15.92	3.56	152.95	3.45	12.43
Depth (0.6–0.9 m)										
pH	20	7.68	7.9	7.2	0.7	0.19	0.04	2.45	−0.95	0.84
EC_e (dS m^{-1})	20	11.59	19.0	1.47	17.53	6.12	1.37	52.81	−0.47	−1.12
% Sand	20	8.05	28.0	3.0	25.0	5.61	1.25	69.63	2.51	8.32
% Silt	20	51.3	56.0	43.0	13.0	3.18	0.71	6.20	−0.74	0.89
% Clay	20	40.65	47.0	29.0	18.0	4.51	1.01	11.10	−1.03	1.09
SP	20	63.4	73.0	46.0	27.0	7.16	1.60	11.30	−0.72	0.07
SAR	20	12.7	28.0	2.0	26.0	7.33	1.64	57.75	0.23	−0.88
Cl ($mmol_c$ L^{-1})	20	16.48	49.4	1.9	47.5	14.12	3.16	85.70	0.90	−0.04
NO_3^-N (mg L^{-1})	20	3.93	27.1	1.2	25.9	5.69	1.27	144.97	3.96	16.40
Depth (0.9–1.2 m)										
pH	20	7.74	7.9	7.5	0.4	0.13	0.03	1.69	−0.73	−0.054
EC_e (dS m^{-1})	20	12.50	20.9	1.35	19.55	6.61	1.48	52.8	−0.51	−1.11
% Sand	20	9.45	35.0	1.0	34.0	9.51	2.23	100.65	1.88	3.14
% Silt	20	50.55	58.0	35.0	23.0	6.90	1.54	13.65	−1.14	0.69
% Clay	20	40.0	50.0	30.0	20.0	5.15	1.15	12.88	−0.51	0.26
SP	20	62.60	72.0	44.0	28.0	7.07	1.58	11.29	−1.33	1.57
SAR	20	15.25	30.0	3.0	27.0	7.59	1.70	49.75	−0.07	−0.83
Cl ($mmol_c$ L^{-1})	20	21.08	57.7	1.6	56.1	18.87	4.22	89.51	0.85	−0.49
NO_3-N (mg L^{-1})	20	2.31	11.8	1.0	10.8	2.50	0.56	108.1	3.36	11.95
Depth (1.2–1.5 m)										
pH	20	7.74	7.9	7.3	0.6	0.15	0.04	1.98	−1.22	2.22
EC_e (dS m^{-1})	20	13.03	22.1	1.92	20.0	6.02	1.38	46.2	−0.45	−0.69
% Sand	20	17.0	67.0	3.0	64.0	17.37	3.99	102.19	1.78	2.86
% Silt	20	44.3	58.0	16.0	42.0	10.57	2.43	23.86	−1.44	1.83
% Clay	20	38.68	47.0	17.0	30.0	7.50	1.72	19.38	−1.63	2.87
SP	20	60.26	73.0	34.0	39.0	13.11	3.01	21.75	−0.99	−0.28
SAR	20	16.68	29.0	4.0	25.0	7.90	1.81	47.32	−0.43	−1.07
Cl ($mmol_c$ L^{-1})	20	24.5	68.2	1.7	66.5	21.91	5.03	89.43	0.77	−0.77
NO_3-N (mg L^{-1})	20	2.28	7.4	0.8	6.6	1.81	0.41	79.02	1.89	3.17
Depth (1.5–1.8 m)										
pH	19	7.79	8.0	7.6	0.4	0.13	0.03	1.68	−0.22	−0.93
EC_e (dS m^{-1})	19	12.02	22.0	1.35	20.0	6.21	1.43	51.66	−0.15	−0.90
% Sand	19	30.35	85.0	5.0	80.0	25.79	5.92	85.08	1.26	0.63
% Silt	19	37.58	57.0	6.0	51.0	15.06	3.46	40.10	−1.14	0.49
% Clay	19	32.11	45.0	9.0	36.0	11.01	2.52	34.28	−1.22	0.63
SP	19	53.84	83.0	30.0	53.0	14.79	3.39	27.47	−0.07	−0.50
SAR	19	16.32	26.0	2.0	24.0	8.49	1.95	52.01	−0.60	−1.40

Table 2 (*Continued*)

Soil property	*N*	Mean	Maximum	Minimum	Range	S.D.	S.E.	Co-efficient of variation	Skewness	Kurtosis
Cl (mmol$_c$ L^{-1})	19	27.18	73.5	2.2	71.3	23.11	5.30	85.02	0.83	−0.30
NO$_3$-N (mg L^{-1})	19	2.67	5.8	0.90	4.9	1.53	0.35	57.59	0.44	−1.02
(b) At 0–1.5 m for SJV site, March 1999										
Depth (0–0.3 m)										
EC$_e$ (dS m^{-1})	20	6.34	14.7	1.66	13.1	3.56	0.82	56.2	0.88	0.11
SP	20	80.4	102.8	68.9	33.9	10.6	2.43	13.2	0.89	−0.35
Δ_b	20	1.0	1.12	0.87	0.25	0.07	0.016	6.82	0.10	−0.28
NO$_3$-N (mg L^{-1})	20	48.3	94.1	15.2	78.9	18.5	4.24	38.3	0.47	0.91
Depth (0.3–0.6 m)										
EC$_e$ (dS m^{-1})	19	10.7	22.3	1.41	20.9	6.89	1.57	63.7	0.18	−1.21
SP	19	85.4	106.6	61.8	44.8	13.64	3.12	16.0	0.12	−1.23
Δ_b	19	0.98	1.13	0.56	0.57	0.146	0.033	14.9	−1.64	2.70
NO$_3$-N (mg L^{-1})	19	66.7	141.1	23.2	117.9	39.6	9.08	59.4	0.88	−0.82
Depth (0.6–0.9 m)										
EC$_e$ (dS m^{-1})	20	13.6	26.7	1.52	25.2	8.06	1.85	59.2	−0.15	−1.38
SP	20	86.6	120.4	43.6	76.7	21.0	4.81	24.2	−0.09	−0.75
Δ_b	20	0.972	1.15	0.65	0.50	0.131	0.03	13.5	−1.10	1.29
NO$_3$-N (mg L^{-1})	20	70.5	183.0	13.0	170.0	58.9	13.5	83.5	0.83	−0.85
Depth (0.9–1.2 m)										
EC$_e$ (dS m^{-1})	20	15.1	30.9	2.8	28.1	7.7	1.77	51.3	0.00	−0.69
SP	20	91.8	122.3	70.6	51.8	16.6	3.81	18.7	0.14	−1.40
Δ_b	20	0.956	1.21	0.62	0.59	62.9	0.035	15.9	−0.78	0.71
NO$_3$-N (mg L^{-1})	20	79.3	206.4	14.1	192.4	0.152	14.4	79.4	0.72	−0.75
Depth (1.2–1.5 m)										
EC$_e$ (dS m^{-1})	20	14.2	26.2	3.51	22.7	6.5	1.49	45.6	−0.03	−1.01
SP	20	90.9	114.4	69.0	45.4	15.3	3.51	16.8	0.01	−1.557
Δ_b	20	0.875	1.12	0.668	0.45	52.4	0.042	17.2	0.10	−1.12
NO$_3$-N (mg L^{-1})	20	84.2	192.1	16.5	175.7	0.15	12.1	62.3	0.53	

Table 3
Soil property correlation matrix and 95% confidence intervals

IV	ln(EC$_a$)	ln(EC$_e$)	SP	ln(NO$_3$)
1998 (*n* = 16)				
ln(EC$_a$)	1.000	0.97 (0.91, 0.99)	0.86 (0.63, 0.95)	0.55 (0.06, 0.95)
ln(EC$_e$)		1.00	0.80 (0.50, 0.93)	0.45 (−0.07, 0.78)
SP			1.00	0.53 (0.04, 0.82)
ln(NO$_3$)				1.00
2001 (*n* = 20)				
ln(EC$_a$)	1.000	0.95 (0.87, 0.98)	0.71 (0.38, 0.88)	0.58 (0.18, 0.82)
ln(EC$_e$)		1.00	0.75 (0.45, 0.90)	0.59 (0.19, 0.82)
SP			1.00	0.55 (0.13, 0.80)
ln(NO$_3$)				1.00
SJV	ln(EC$_a$)	ln(EC$_e$)	SP	ln(NO$_3$)
1999 (*n* = 20)				
ln(EC$_a$)	1.000	0.94 (0.85, 0.98)	0.20 (−0.28, 0.60)	0.79 (0.53, 0.91)
ln(EC$_e$)		1.00	0.05 (−0.41, 0.49)	0.78 (0.51, 0.91)
SP			1.00	−0.30 (−0.66, 0.17)
ln(NO$_3$)				1.00

EC$_a$: bulk average electrical conductivity estimated from field survey data; EC$_e$: electrical conductivity of the saturation extraction, estimated from soil samples; SP: saturation percentage; NO$_3$: nitrate.

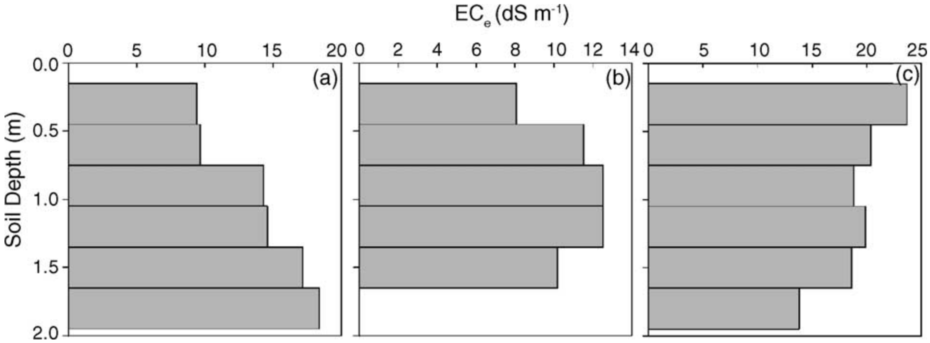

Fig. 3. EC_e ($dS\,m^{-1}$) by soil depth for selected soil sample locations at the IV and SJV sites: (a) typical profile conditions for the majority of sties at the IV site where increasing salinity with depth indicates leaching is occurring, (b) typical profile conditions for the SJV sites where no leaching is occurring, and (c) inverted soil profile at the most saline and lowest yielding location at the IV site, which indicates poor drainage due to high clay content (high SP).

that leaching was not occurring throughout the measured profile or that perched, saline water was a problem.

Apparent soil electrical conductivity was strongly correlated with EC_e (expressed as natural logs, Lesch et al., 1995b) (Table 3). At the IV site, NO_3-N was moderately well correlated with SP and EC_e. In 2001 after harvest, surface values of NO_3-N were greatest, in part due to the extra N fertilizer applied at some locations, but values deeper in the profile were much smaller (Table 2). At all sample times, shallow profile NO_3-N values were extremely variable, while the average profile ln(NO_3-N) was moderately well correlated with ln(EC_e) and ln(EC_a) (Table 3). In contrast, at the SJV site, ln(NO_3-N) and ln(EC_e) were more strongly correlated in the profile, except in the top 30 cm of soil (Table 3). Bulk average NO_3-N values ranged from 20 to 160 $mg\,kg^{-1}$ in the surface 1.5–1.8 m of soil (Table 2). It is unclear why such large amounts of N were present. Saturation percentage was not correlated with EC_a or NO_3-N (Table 3). Lower SP values were observed in the southeast portion of the field.

3.2. *Crop performance*

3.2.1. *Gypsum use*

Seedling numbers tended to increase slightly with the use of gypsum, but were not significantly affected by gypsum treatments ($p = 0.15$). The use of gypsum increased the average number of seedlings by only 4% and effects were inconsistent. Irrigation water in the IV is mildly saline (1.2–1.5 $dS\,m^{-1}$) so infiltration tends to be maintained, while soils were not particularly sodic, a soil condition where gypsum might be of greater use (Ayers and Westcott, 1985).

3.2.2. *Root and sugar yields (IV)*

Yield monitor maps reflect a wide range of root weights in both locations (Fig. 4a and b). At the IV site, sugar beet root yields and sucrose content on average were very good for the

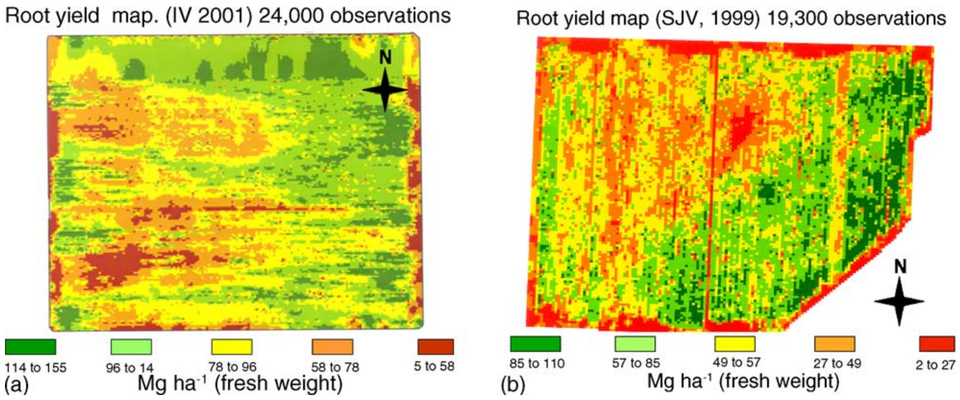

Fig. 4. (a) Root yield map in the Imperial Valley (mg fresh weight per ha) based on data collected with a Harvest Master monitor. Yields were lowest in the southwest end of the field. (b) Interpolated root yield map based on data collected with a Harvest Master monitor. Yields were lowest in the center of the field, and highest along the south and southeast edge.

May–June harvest dates in both years (Table 4). A comparison of yield maps (Fig. 4a and b) with EC_a maps (Fig. 2a and b) suggests a close correlation between salinity and yield at the IV site, but a poor correlation between salinity and yield at the SJV site. Average yields based on plot samples differed from field average yield derived from the yield monitor data by 4% or less (Table 4). The range of yields observed in plots harvested by hand likely reflects more closely the true range observed in each field, compared to the much larger range derived from the yield monitor.

Table 4
Yields, sucrose percent, and ranges observed at each location

	IV (1999)	IV (2001)	SJV (1999)
Plot mean yield (mg ha^{-1})	83.3	90.9	58.7
Plot range (mg ha^{-1})	69.9–99.5	59.4–111.6	15.7–92.7
Plot mean sucrose concentration (mg kg^{-1})	17.8	16.3	16.7
Plot sucrose range (mg kg^{-1})	164–191	132–179	150–187
Plot sugar yield (kg ha^{-1})	14830	14820	9710
Plot gross sugar yield range (kg ha^{-1})	13360–17720	8120–17970	2890–14180
Yield monitor mean (mg ha^{-1})	82.0	87.6	57.8
Yield monitor range (mg ha^{-1}), ha harvested within that range; percent of total area harvested in that category (percent of field)	4–58 (1.2 ha); 3.5%	4.5–58.2; 7.8%	2.2–27 (6 ha); 10.4%
	58–72 (0.9 ha); 2.5%	58.2–78.4; 29.2%	27–49 (13.2 ha); 22.8%
	72–85 (3.7 ha); 16.4%	78.4–96.3; 30%	49–57 (20 ha); 35.6%
	85–98.6 (15.1 ha); 43.8%	96.3–114.2; 23.8%	57–85 (16 ha); 27.3%
	98.6–134 (5.8 ha); 16.7%	114.2–154.6; 8.8%	85–110 (4.5 ha); 7.8%

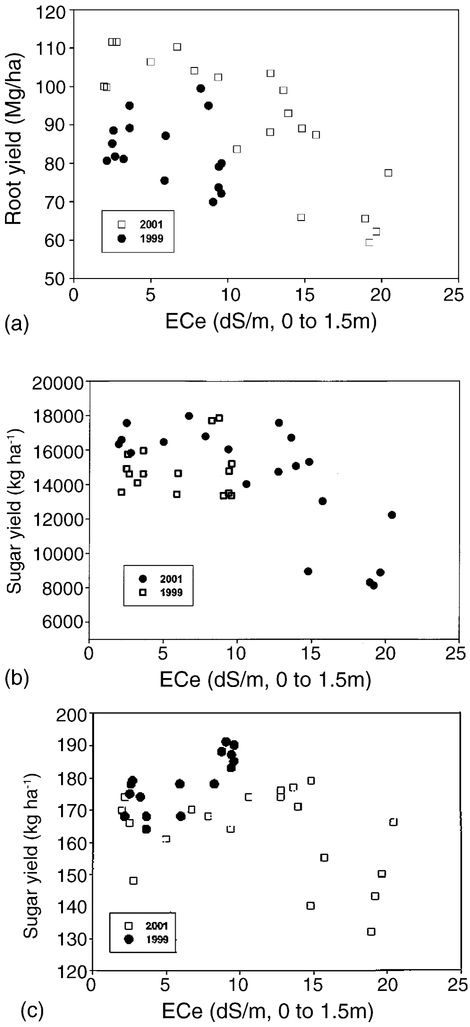

Fig. 5. (a) Root yield vs. EC_e for both the 1999 and 2001 harvests at the IV site. (b) Gross sugar yield from both harvests in 1999 and 2001 at eh IV site (data are from plot harvests). (c) Sugar concentration vs. EC_e for both the 1999 and 2001 harvest at the IV site (data are from plot harvests).

Root yields, sugar concentrations, and sugar yields for both years are plotted with EC_e in Fig. 5. In 1998–1999, there was no correlation among these properties when beets were grown in the better portion of the field while in 2000–2001 when less productive areas were included, some correlations improved. For example, the relationship between sugar yield (kg ha^{-1}) and EC_e (dS m^{-1}) in the 1998–1999 season was not significant ($R^2 = 0.004$); while in 2001 it was (sugar yield = 16, 287.9 + 269.3 EC_e − 31.4 EC_e^2, $R^2 = 0.704$, Fig. 5b). The decline in root fresh weights and gross sugar yields follows the pattern predicted by Maas (1990) though the threshold value appears higher (approximately 9–10 dS m^{-1}) at

Table 5
Regression relationships and parameter estimates (S.E.)

	Equation				Model F-test
IV (1998–1999) ($n = 16$)					
Root yield (mg ha^{-1})	85.4	+ 0.0373SP	− $0.963EC_e$	− $0.185NO_3$	($F = 0.37$, $p = 0.773$)
		(0.518)	(1.32)	(1.343)	
Sugar yield (kg ha^{-1})	13248	+ 26.67SP	− $24.9EC_e$	− $6.76NO_3$	($F = 0.05$, $p = 0.986$)
		(88.84)	(225.1)	(229.7)	
Sugar concentration (mg kg^{-1})	158.3	− 0.171SP	− $1.929EC_e$	− $0.422NO_3$	($F = 13.25$, $p = 0.0007$)
		(0.342)	(0.869)	(0.896)	
IV (2000–2001) ($n = 20$)					
Root yield (mg ha^{-1})	88.6	+ 0.506SP	− $2.51EC_e$	− $0.049NO_3$	($F = 18.37$, $p = 0.0001$)
		(0.712)	(0.535)	(0.136)	
Sugar yield (kg ha^{-1})	16375	+ 43.9SP	− $428.5EC_e$	− $2.14NO_3$	($F = 12.90$, $p = 0.0001$)
		(143.0)	(107.4)	(27.0)	
Sugar concentration (mg kg^{-1})	189.2	− 0.322SP	− $0.675EC_e$	+ $0.042NO_3$	($F = 1.85$, $p = 0.156$)
		(0.798)	(0.599)	(0.151)	
SJV (1998–1999) ($n = 20$)					
Root yield (mg ha^{-1})	114.5	− 0.663SP	+ $0.484EC_e$	− $0.0636NO_3$	($F = 13.58$, $p = 0.0001$)
		(0.105)	(0.382)	(0.0483)	
Sugar yield (kg ha^{-1})	17868	− 96.7SP	+ $77.5EC_e$	− $10.91NO_3$	($F = 12.61$, $p = 0.0001$)
		(15.82)	(57.7)	(7.30)	
Sugar concentration (mg kg^{-1})	145.7	+ 0.247SP	+ $0.004EC_e$	+ $0.004NO_3$	($F = 3.89$, $p = 0.031$)
		(0.062)	(0.225)	(0.029)	

this location based on average profile salinity (Fig. 5a). The relationship between yield and factors other than salinity at some plot locations is apparent in the figure as well from some of the outlying data points (Shalhevet, 1994). Sucrose concentration over much of the EC_e range was not affected by salinity. Low concentrations at a few locations with high EC_e levels may also have been affected by higher NO_3 levels present during the growing season, which typically reduce sugar content (Fig. 5c).

Corwin et al. (2003a) determined that cotton yields from a saline field in the SJV were most closely correlated with salinity, leaching fraction, soil moisture (estimated from either SP or clay content), and pH. Similar analyses are reported in Table 5 for all three site-years. Root fresh weight and gross sugar yields overall were negatively correlated with increasing salinity based on subplot samples collected by hand, but sugar concentration was not (Table 5).

3.2.3. *Root yields and soil properties (SJV)*

At the SJV site results were different. The range in plot yields was much larger than in the IV, from approximately 15.7–92.7 mg ha^{-1}, average root and sugar yields were much lower than at the IV site, while sucrose content was comparable (Table 4). Root and sugar yields were correlated with EC_e and soil NO_3, but the most significant correlation was with SP (root yield (mg ha^{-1}) = 167.7–1.26 SP, $R^2 = 0.61$; Fig. 6, Table 5). Despite tile drainage being present, soil texture apparently restricted root growth in most of this field. Also, despite extremely large amounts of nitrate in the soil, sugar concentrations in roots were

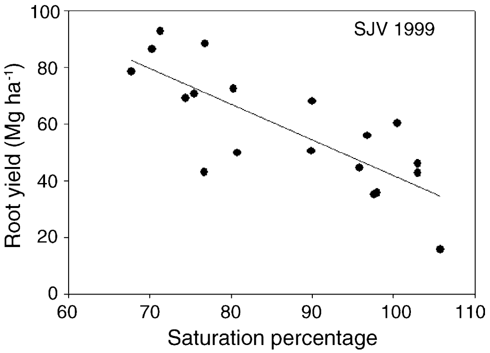

Fig. 6. Correlation between root yield and SP at the SJV site.

higher than might otherwise be expected (Hills and Ulrich, 1971). The presence of ammonia-N can interfere with nitrate uptake by roots under anaerobic conditions, and chloride and other ions can compete with nitrate uptake and induce nitrate efflux from roots (Aslam et al., 1984). Saturation percentage was negatively correlated with soil NO_3 (Table 3) suggesting that denitrification was occurring in saturated portions of the soil profile. Under anoxic conditions, root growth and nutrient uptake are restricted.

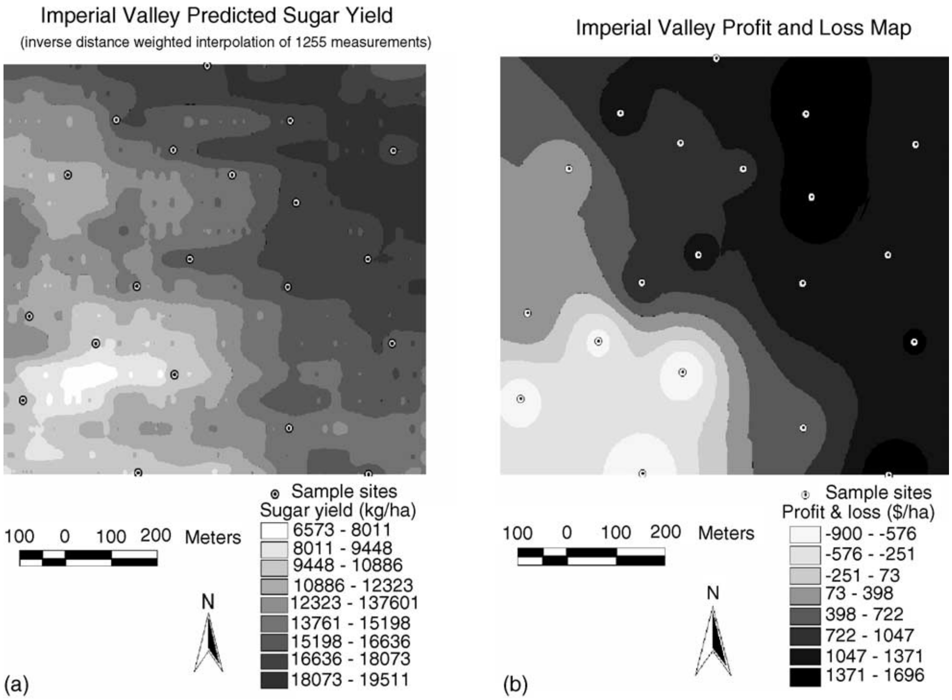

Fig. 7. Maps of the IV site in 2001 showing (a) predicted gross sugar yields and (b) predicted profit and loss.

3.3. Economic returns

Income is derived from the sale of sugar based on a formula negotiated by the California Beet Growers Association and the sugar company. This formula is calculated using root yields and sugar percent, with the higher sugar percentages worth more money on a per ton basis. Based on predicted gross sugar yields in the 2000–2001 crop at the IV site, some areas of the field produced gross sugar yields below the variable costs of production, particularly near the tail end of the field (Fig. 7). The estimated cost of production in 2000–2001 at the IV site was US\$ 3073 ha^{-1}. At average sugar concentrations, this equalled 74 mg ha^{-1} of beets or 11.76 mg of gross sugar per ha (based on US\$ 41.00 per mg roots at 163 mg kg^{-1} sucrose). If all fixed costs were included, the area falling below the profitable yield level would increase.

4. Discussion

4.1. The detection of manageable variation (IV)

Apparent soil electrical conductivity values were accurately mapped using the techniques of Rhoades et al. (1997b). The close correlation between $\mathrm{EC_a}$ and $\mathrm{EC_e}$ observed in this study has been reported repeatedly (Corwin and Lesch, 2003; Rhoades et al., 1999b; Rhoades et al., 1997b). These techniques are accurate, precise, fast, and relatively inexpensive.

4.1.1. Imperial Valley

Salinity as measured by $\mathrm{EC_e}$ varied over the range of 2–21 dS m^{-1} at the IV site (Table 2). At greater $\mathrm{EC_e}$ values, sugar beet yield is predicted to be and was adversely affected (Maas, 1990). Salinity was correlated with field position, i.e., salinity was higher at the end of the irrigation furrows, but also was correlated with SP at depth. When larger values of SP were measured at depth, salinity increased throughout the profile. Conversely, lower SP in the lower half of the profile was also correlated with lower salinity levels throughout the profile, except in locations at the tail end of the field, which received larger amounts of salts due to the transport of salt carried by irrigation water moving in that direction. Nitrate was correlated with $\mathrm{EC_e}$ deeper in the soil profile, but differences in residual profile $\mathrm{NO_3}$-N content were mostly small by harvest, with the result that profile residual $\mathrm{NO_3}$-N differences did not adversely affect sugar content in roots at most locations.

Variable-rate N application may have been useful in areas of the field where yields were restricted by salinity, reducing the crop's uptake of N and its potential to respond to fertilizer N. The application of additional fertilizer N to half of the subplots allowed for an assessment of this practice. In the best drained (lowest average SP), least saline portions of the field, additional N increased root yields (for N: root yield = $98.3 + 1.68\mathrm{EC_e} - 0.15\mathrm{EC_e}^2$, $R^2 = 0.86$; for N: root yield = $111.0 + 0.41\mathrm{EC_e} - 0.16\mathrm{EC_e}^2$, $R^2 = 0.86$; Fig. 8a) but not gross sugar yields (for N: gross sugar yield = $16.1 + 0.33\mathrm{EC_e} - 0.03\mathrm{EC_e}^2$, $R^2 = 0.72$; for N: gross sugar yield = $15.2 + 0.63\mathrm{EC_e} - 0.05\mathrm{EC_e}^2$, $R^2 = 0.75$; Fig. 8b), while in the less well drained, more saline portion of the field, root and sugar yields declined when additional N was applied. Applying variable rates of N fertilizer based on potential root yield derived from

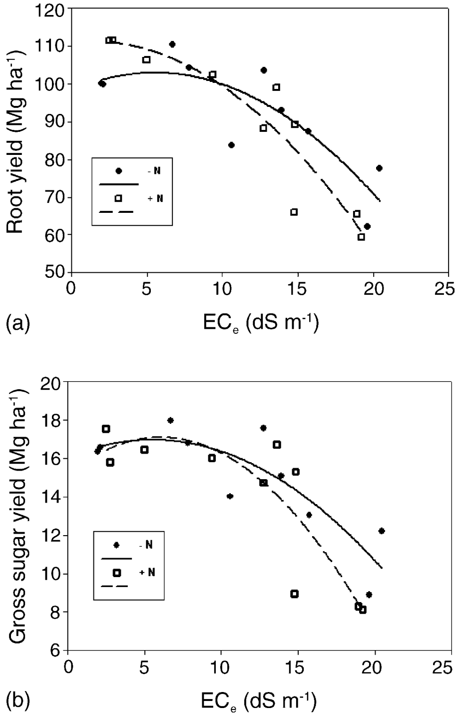

Fig. 8. Graph of the IV site showing (a) root yields vs. salinity (EC_e) compared by N treatments and (b) gross sugar yields vs. salinity compared by N treatments.

predicted or previously estimated crop growth–EC_e relationships would be a profitable practice at such salt-affected locations within fields.

4.1.2. San Joaquin Valley

The range of variation in average EC_e at the SJV site was very large (from 3 to greater than 24 dS m^{-1}). Beets tolerated the high EC_e levels found in portions of this field because the use of sprinkler irrigation throughout the season likely created transient, more tolerable levels of salinity in at least the first 30–60 cm of the profile (Fig. 3b). Nonetheless, the performance of sugar beets under such highly saline conditions was unexpected and exceeded their reported salinity tolerance (Maas, 1990). Soil measurements made early in the growing season apparently did not estimate the effective salinity experienced by the crop for the entire growing season under sprinkler irrigation (Shalhevet, 1994). Also, in soils with gypsum and other sulphate salts, plants will tolerate about 2 dS m^{-1} higher salinity than otherwise (Maas, 1990).

The correlation at the SJV site between yield and SP (Fig. 6 and Table 5) was more important than that between yield and EC_e. Yield predictions based on EC_e would not have been helpful at this site, suggesting that an understanding of the relationship among soil properties and EMI measurement is essential. Similarly, the large amounts of soil NO_3-N present were not as important as expected (Hills and Ulrich, 1971).

The management of difficult or marginal soils and crop response under such conditions is poorly understood and therefore unpredictable. The correlations between root and sugar yield and SP were unexpected, but in retrospect can be understood by hypothesizing a relationship between soil drainage and chronic anoxic conditions in the root zone. Beets grew best where soils had lower SP, and where soils were presumably less anoxic. Infiltration was likely better in the more well drained areas, improving crop water supply. Root systems were able to develop. But even in the better portions of the field, root uptake of NO_3-N apparently was restricted sufficiently to allow beets to accumulate economic sugar concentrations.

4.2. Predicting yield and profit

Lowenberg-Deboor and Swinton (1997) reviewed a number of economic analyses of precision farming. These were largely from the mid-western USA. Most were partial or incomplete. Of the well-conducted studies, most suggested that these techniques would not be profitable. In their own analysis of site-specific fertilization, the authors reported that the use of variable-rate technology was unprofitable because of the large capital cost for equipment and the short amortization period assumed for its purchase (due to rapid technological obsolescence). They also suggested that larger scale farms and fields were more likely to be profitable than small-scale uses, because of economies of scale. Variation in salinity can be mapped accurately and a large amount of information collected at low cost. Where fields are saline and crops respond to that salinity, SSM may be used profitably. Sugar beet growers have the added advantage of knowing with reasonable certainty the price they will receive for their crop because of the profit-sharing contract used and reliable price predictions at planting, reducing the amount of uncertainty associated with prediction.

Yields varied nearly two-fold at the IV site in 2000–2001, and by nearly five-fold at the SJV site. Portions of the fields with yields much below the mean were unprofitable to farm at both locations. Yield patterns and amounts were comparable for both crop-years at the IV site. Soil salinity and correlated properties are slow to change or stable over time making them practical for assessing field variation. Since results are unlikely to change quickly, a single detailed assessment could be of use for a number of crops. Conversely, they are also difficult to influence through normal agricultural management. But at a minimum, if potential yields are reasonably predictable, and crop prices can be anticipated, then predictions can be made about which portions of the field will be unprofitable to farm and these can be avoided, improving overall profitability. Additionally, fertilizer rates could be adjusted based on yield predictions using salinity measurements where correlations with salinity have been observed or predicted, if the cost of variable-rate application is not too great. At the IV site in 2000–2001, predicted yield loss compared to a non-saline field using ESAP-95 (v. 2.01) software (Lesch et al., 1995c) based on EC_e which includes the crop loss model proposed by Maas (1990) was 22.5% compared to 18.5% calculated using subplot data. But because yield was not correlated with EC_e at the SJV site due to adverse drainage characteristics (limited leaching), prediction based on EC_e would not have been effective.

4.3. Environmental uses

In the arid western USA, water is limiting for agricultural, urban, and environmental uses. It is not rational to use water to produce crops at an economic loss, but it can be difficult to anticipate ahead of time whether a crop will be profitable in a given year. Soil properties like salinity, if correlated closely with yield, can provide a basis for prediction that might be useful for irrigation decisions. Irrigating less of a field may be more profitable overall than farming the entire field, depending on the patterns of salt distribution present (Fig. 7a). In such cases, it would be more profitable to farm less land while saving the irrigation water otherwise used unprofitably for other purposes. This presupposes, however, that irrigation can be managed at a field scale in ways that allow unprofitable areas to be left un-irrigated.

Nitrate leaching from fertilized fields is a nationwide problem that might also be addressed through SSM based on the use of EMI techniques. It is difficult to sample sufficiently in many instances to allow for an accurate estimate of field variability, especially if nitrate is located deeper in the profile. For sugar beets, nitrate deep in the soil profile can lead to reduced sugar concentrations in roots (Kaffka et al., 1999). Nitrate may act as a simple salt below the biologically active portion of the soil profile. Where nitrate and salinity are correlated, higher salinity values can be used as a means of identifying likely locations in the profile to sample for residual NO_3-N. The soil mapping techniques of Rhoades et al. (1997b) have the advantage of being inexpensive, accurate, and precise, especially in comparison to attempts to describe NO_3-N variation directly through grid sampling or random sampling. The use of model-based sampling strategies (Lesch et al., 1995b; Lesch, this issue) to identify an appropriate range of sampling locations based on spatial dispersion and modeled relationships between EMI measurements and soil salinity will make sampling for nitrate at depth in the profile a more reasonable process where such correlations are known to exist or are thought to be likely. The use of EMI to evaluate variation in soil residual nitrate may make field-scale assessment for this purpose far less expensive and much more practical and accurate than other ground-based attempts reported previously.

5. Conclusions

At the IV site, field-scale salinity was correlated with soil physical characteristics like SP, but also increased in the direction of irrigation water flow. EMI techniques accurately and efficiently mapped field-scale variation in salinity. In this same field, because tile drainage was effective and leaching was occurring, sugar beet yield was correlated with salinity. Root and gross sugar yield at the field scale followed the pattern predicted by Maas (1990) based on work carried out under carefully controlled, experiment station conditions. Actual yields in the most saline portions of the field were 18.5% lower than in the highest yielding portion compared to a predicted 22.5% based on the Mass model used in the ESAP software (Lesch et al., 2000). ESAP software, together with EC_a data collected using EMI techniques, provided an efficient means to estimate field average yield from plot locations selected using the software, subsample the sugarbeet crop for quality, and carry out an effective crop fertilization experiment.

At the IV site, nitrate accumulated more in locations in the field where drainage was impaired and was positively correlated with salinity deeper in the soil profile. Adding additional N as fertilizer to these sites did not increase root yield but reduced gross sugar yield compared to portions of plots receiving no additional fertilizer N. EMI techniques provide accurate and inexpensive maps of salinity and correlated soil properties. When salinity and nitrate content are correlated, EMI techniques should be useful in identifying locations in fields where nitrate may have accumulated at depth and can guide soil sampling. These maps, together with predictions about crop response, can be used to guide fertilization using variable rate management practices. Additionally, if prices can be anticipated with reasonable accuracy ahead of time, growers may be able to identify portions of the field which it would be unprofitable to farm, increasing profit and saving resources like irrigation water otherwise used without benefit. For sugarbeet growers in the IV, prices are predictable, and soil salinity properties are slow to change. Yield and economic return predictions may provide an alternative way to save irrigation water compared to fallowing entire fields by fallowing only those portions of fields that are uneconomic to farm.

In the SJV field, where drainage was impaired, there was no correlation between salinity and yield. Yield was positively correlated with SP. Despite large amounts of residual nitrate, nitrate had little influence on root quality or yield. There, the use of EMI and ESAP software did not predict crop performance, but was helpful in identifying yield limitation due to SP. It remains difficult to predict crop performance under disadvantageous soil conditions. The SJV field provides an example of conditions where current methods of measurement and yield prediction are inadequate.

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