DELINEATING SITE-SPECIFIC CROP MANAGEMENT UNITS: PRECISION AGRICULTURE APPLICATION IN GIS

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Abstract

Crop yield is influenced by soil-related, anthropogenic, topographic, biological, and meteorological factors that are highly spatially variable. Because of the complex spatial interaction of these factors, GIS and other advanced information technologies (e.g., spatial statistics, remote sensing, crop-yield response models) are essential tools in precision agriculture. Site-specific crop management refers to the application of precision agriculture to crop production. A fundamental aspect of site-specific crop management is the delineation of site-specific management units (SSMUs), which are spatial domains where soil properties can be managed similarly to optimize crop yield. In a study conducted by USDA-ARS scientists at the George E. Brown Jr. Salinity Laboratory, ArcView, electromagnetic induction, spatial statistics, and regression analysis were used to identify soil-related factors influencing crop (i.e., cotton) yield within an 80-acre field in California's San Joaquin Valley. The developed maps and crop-yield response model provided the essential information for site-specific crop management recommendations.

Introduction

Conventional agriculture treats an entire field uniformly with respect to the application of fertilizer, pesticides, soil amendments, or other inputs. However, soil is spatially heterogeneous, with most soil chemical and physical properties varying significantly within just a meter. Soil spatial heterogeneity is one of several factors that cause within-field variation in crop yield. Other spatially and/or temporally variable factors influencing within-field variation in crop yield include man-related (e.g., irrigation management, compaction due to equipment, etc.), biological (e.g., disease, pests, etc.), meteorological (e.g., humidity, rainfall, wind, etc.), and topographical (e.g., slope, aspect, etc.) influences. The inability of conventional farming to address within-field variations in these factors not only has a detrimental economic impact due to reduced yield in certain areas of a field, but also detrimentally impacts the environment due to over applications of agrochemicals and wastes finite resources.

Precision agriculture, or more appropriately site-specific crop management, has been proposed as a means of managing the spatial variability of edaphic (i.e., soil related), anthropogenic, topographical, biological, and meteorological factors that influence crop yield with the aim of increasing profitability, increasing crop productivity, sustaining the soil-plant environment, optimizing inputs, and/or minimizing detrimental environmental impacts. Site-specific management units (SSMUs) are spatial domains of soil that can be managed similarly to optimize yield by accounting for variability. The spatial variability of edaphic factors is a consequence of pedogenic and anthropogenic influences, which produce variation in soil physical and chemical properties within agricultural fields that affect crop productivity. A variety of soil physical and chemical properties are known to influence crop productivity, including plant-available water; infiltration; permeability; soil texture and structure; soil depth; restrictive soil layers; organic matter; chemical constituents such as fertilizers, pesticides, trace elements, and toxic ions; meteorology; and landscape features such as microelevation and topography (Black, 1968; Thornley and Johnson, 1990; Hanks and Ritchie, 1991; Tanji, 1996). In the arid southwestern USA the primary soil properties influencing crop yield are salinity, soil texture and structure, plant-available water, trace elements (particularly boron), nutrient deficiency, and ion toxicity from Na^+ and Cl^- (Tanji, 1996).

Bullock and Bullock (2000) indicate that efficient methods for accurately measuring within-field variations in soil physical and chemical properties are important for site-specific crop management. Because apparent soil electrical conductivity (EC_a) is influenced by a variety of soil physical and chemical properties (i.e., salinity, water content, texture, bulk density, organic matter, and temperature) and is a reliable measurement that is easy to take, geospatial measurements of EC_a have become one of the most frequently used measurements to characterize field variability for agricultural applications (Corwin and Lesch, 2003). Spatial measurements of EC_a have been used to characterize soil salinity and nutrients such as NO_3^- (Halvorson and Rhoades, 1976; Rhoades and Halvorson, 1977; Cameron et al., 1981; Williams and Baker, 1982; Greenhouse and Slaine, 1983; Williams and Hoey, 1987; Brune and Doolittle, 1990; Hendrickx et al., 1992; Lesch et al., 1992, 1995a, 1995b, 1998; Rhoades 1992a, 1993; Cannon et al., 1994; Nettleton et al., 1994; Drommerhausen et al., 1995; Mankin et al., 1997; Eigenberg et al., 1998, 2002; Eigenberg and Nienaber, 1998, 1999, 2001; Rhoades et al., 1999a, 1999b; Mankin and Karthikeyan, 2002; Corwin et al., 2003a, 2003b), water content (Kachanoski et al., 1988, 1990; Vaughan et al., 1995; Khakural et al., 1998; Morgan et al., 2000; Freeland, 2001; Corwin et al., 2003a, 2003b), texture-related properties (Williams and Hoey, 1987; Jaynes et al., 1993; Stroh et al., 1993; Sudduth and Kitchen, 1993; Doolittle et al., 1994, 2002; Rhoades et al., 1999b; Kitchen et al., 1996; Boettinger et al., 1997; Scanlon et al., 1999; Inman et al., 2001; Triantafilis et al., 2001; Anderson-Cook et al., 2002; Brevik and Fenton, 2002; Corwin et al., 2003b), bulk density related properties such as compaction (Rhoades et al., 1999b; Gorucu et al., 2001; Corwin et al., 2003b), leaching (Slavich and Yang, 1990; Corwin et al., 1999b; Rhoades et al., 1999b) and organic matter related properties (Greenhouse and Slaine , 1983, 1986; Nyquist and Blair, 1991; Jaynes, 1996; Bowling et al., 1997; Brune et al., 1999).

Most recently, geo-referenced EC_a measurements have been correlated to associated yield-monitoring data with mixed results (Jaynes et al., 1993; Sudduth et al., 1995; Kitchen et al., 1999; Johnson et al., 2001; Corwin et al., 2003b). These mixed results are due, in part, to a misunderstanding of the relationship between EC_a measurements and variations in crop yield. As pointed out by Corwin and Lesch (2003), crop yield inconsistently correlates with EC_a due to the influence of soil properties (e.g., salinity, water content, texture, etc.) that are being measured by EC_a, which may or may not influence yield within a particular field, and because a temporal component of yield variability is poorly captured by a state variable such as EC_a. Corwin and Lesch (2005a) provide a recent review of the application of geo-referenced EC_a measurements in agriculture with particular attention to EC_a measurements for precision agriculture applications.

Geospatial measurements of EC_a are a powerful tool in site-specific management when combined with GIS, spatial statistics, and crop-yield monitoring. It is hypothesized that in instances where EC_a correlates with crop yield, spatial EC_a information can be used to direct a soil sampling plan that identifies sites that adequately reflect the range and variability of various soil properties thought to influence crop yield. The objective of this study is to integrate spatial statistics, GIS, geophysical techniques, and a crop-yield response model (i) to identify edaphic properties that influence cotton yield and (ii) to use this spatial information to delineate SSMUs with associated management recommendations for irrigated cotton. This paper draws from previous work conducted and published by Corwin and colleagues (Corwin and Lesch, 2003, 2005b; Corwin et al., 2003b).

Materials and Methods

A 32.4-ha field located in the Broadview Water District on the west side of California's San Joaquin Valley was used as the study site (Fig. 1). Broadview Water District is located approximately 100 km west of Fresno, CA. The soil at the site is slightly alkaline and has good surface and subsurface drainage (Harradine, 1950). The subsoil is thick, friable, calcareous, and easily penetrated by roots and water.

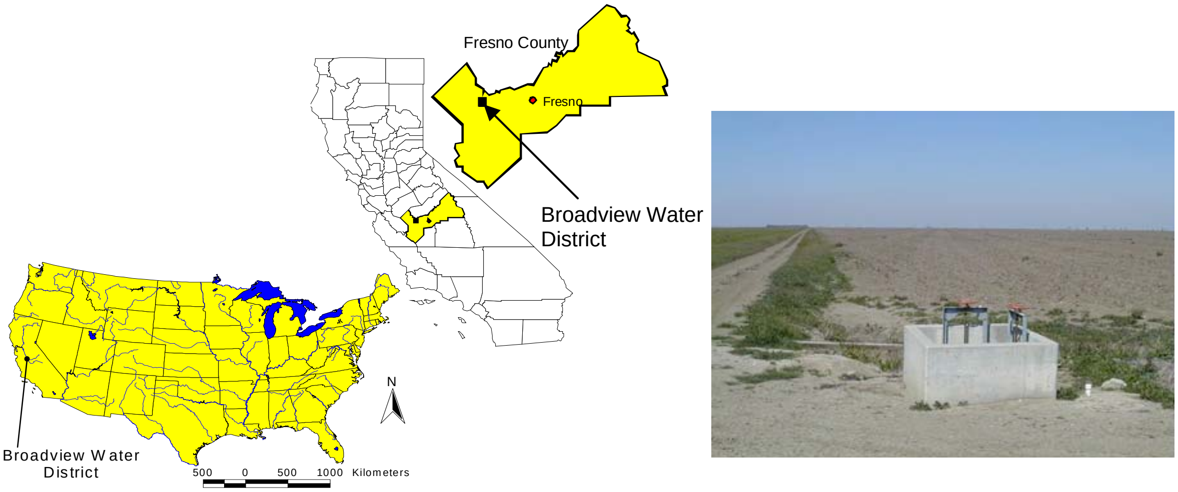
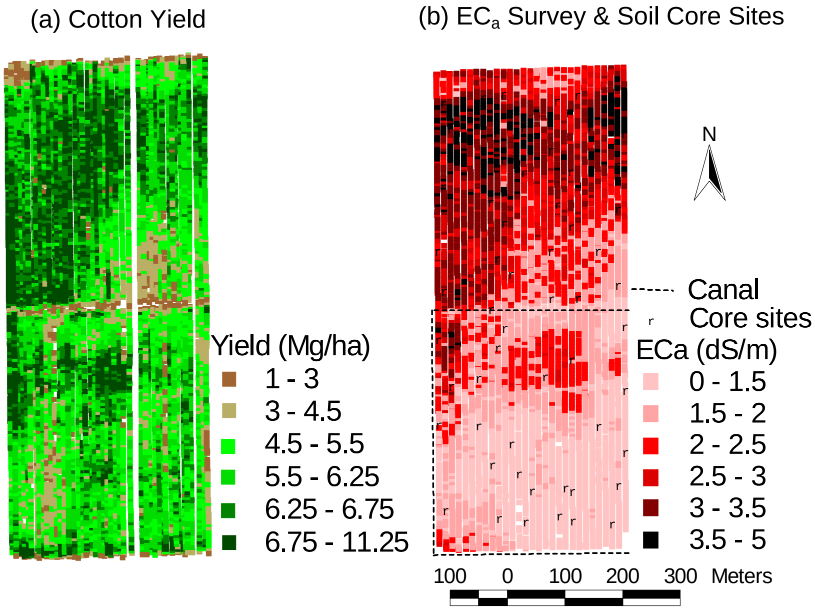


Figure 1. Map showing the location of the study site and photo of southwest corner of 32.4-ha field.

Spatial variation of cotton yield was measured at the study site in August 1999 using a four-row cotton picker equipped with a yield sensor and global positioning system (GPS). A total of 7706 cotton yield readings were collected (Fig. 2a). Each yield observation represented a total area of approximately 42 m^2. From August 1999 to April 2000 the field was fallow.

On March 2000 an intensive EC_a survey (Fig. 2b) was collected using mobile fixed-array electrical resistivity (ER, Fig. 3) and mobile electromagnetic induction (EMI, Fig. 4) equipment developed by Rhoades and colleagues at the GEBJ Salinity Laboratory (Rhoades, 1992a, 1992b; Carter et al., 1993).


(a) Cotton Yield

(b) EC_a Survey & Soil Core Sites

Figure 2. Maps of (a) cotton yield and (b) EC_a measurements including the locations of the 60 soil core sites. *Source:* modified from Corwin et al. (2003b) with permission.

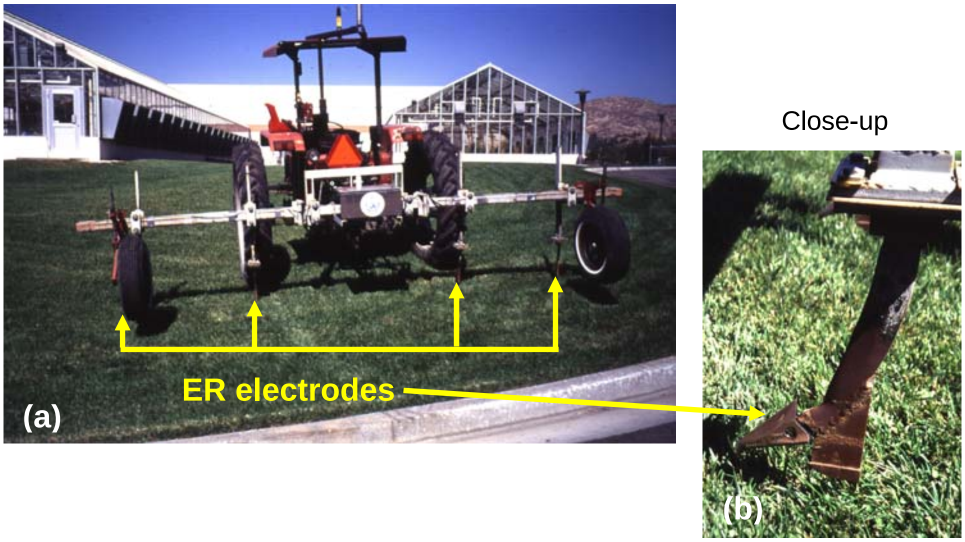


Figure 3. Mobile GPS-based electrical resistivity (ER) equipment showing (a) fixed-array tool bar holding four ER electrodes and (b) a close-up of one of the ER electrodes.

Figure 4. Mobile GPS-based electromagnetic induction (EMI) equipment showing (a) a side view of the entire rig and (b) a close-up of the sled holding the EMI unit.

The methods and materials used in the EC_a survey were those subsequently published as a set of guidelines and protocols by Corwin and Lesch (2003, 2005b). The protocols consist of 7 basic steps: (i) site description and EC_a survey design, (ii) EC_a data collection with GPS-based EC_a equipment (see Figs. 3 and 4), (iii) soil sample design directed by EC_a spatial data, (iv) soil core sampling at specified sites, (v) laboratory analysis of soil physical and chemical properties defined by project objectives, (vi) spatial statistical analysis to determine the properties influencing EC_a, and (vii) GIS database development and graphic display of spatial distribution of soil properties. The EC_a survey followed a sprinkler irrigation to bring the soil at the study site to field capacity. The fixed-array ER electrodes were spaced to measure EC_a to a depth of 1.5 m. Over 4000 EC_a measurements were collected (Fig. 2b).

Following the EC_a survey, soil samples were collected at 60 locations. The data from the EC_a survey were used to direct the selection of soil sample sites. The ESAP-95 version 2.01 software package developed by Lesch et al. (1995a, 1995b, 2000) at the GEBJ Salinity Laboratory was used to establish the locations where soil cores were taken based on the EC_a survey data. The software used a model-based response-surface sampling strategy to locate the 60 sites. These sites reflected the observed spatial variability in EC_a while simultaneously maximizing the spatial uniformity of the sampling design across the study area. Figure 2b visually displays the distribution of EC_a survey data in relation to the locations of the 60 core sites. Duplicate soil core samples were taken at each site at 0.3-m increments to a depth of 1.8 m: 0-0.3, 0.3-0.6, 0.6-0.9, 0.9-1.2, 1.2-1.5, and 1.5-1.8 m. The duplicate sets of cores were taken within 7.5 to 10 cm of one another. One set of cores was used for water content and bulk density (Blake and Hartage, 1996) and the other set was used to measure soil physical and chemical properties thought to influence cotton yield [i.e., pH, B, nitrate nitrogen (NO_3-N), Cl^-, salinity (EC_e), leaching fraction (LF), gravimetric water content (θ_g), bulk density (ρ_b), % clay, and saturation percentage (SP)]. All samples were stored and analyzed for physical and chemical properties following the methods outlines in Agronomy Monograph No. 9 (Page et al., 1982).

Statistical analyses were conducted using SAS software (SAS Institute, 1999). The statistical analyses consisted of 3 stages: (i) determination of the correlation between EC_a and cotton yield using data from the 60 sites, (ii) exploratory statistical analysis to identify the significant soil properties influencing cotton yield, and (iii) development of a crop-yield response model based on ordinary least squares regression adjusted for spatial autocorrelation with restricted maximum likelihood.

Because the location of EC_a and cotton yield measurements did not exactly overlap, ordinary kriging was used to determine the expected cotton yield at the 60 sites. The spatial correlation structure of yield was modeled with an isotropic variogram. The following fitted exponential variogram was used to describe the spatial structure at the study site:

$$v(\delta) = (0.76)^2 + (1.08)^2\,[1 - \exp(-D/109.3)] \qquad [1]$$

where D is the lag distance.

All spatial data were compiled, organized, manipulated, and displayed within a geographic information system (GIS). ESRI's ArcView 3.3 was the commercial GIS software used. Kriging was selected as the preferred method of interpolation because in all cases it outperformed inverse distance weighting based on comparisons using jackknifing.

Results and Discussion

Correlation between Cotton Yield and EC_a

The fitted variogram model (Eq. [1]) was used in an ordinary kriging approach to estimate cotton yield at the 60 sites. The correlation of EC_a to yield at the 60 sites was 0.51. The moderate correlation between yield and EC_a suggests that some soil property(ies) influencing EC_a measurements may also influence cotton yield making an EC_a-directed soil sampling strategy a potentially viable approach at this site. The similarity of the spatial distributions of EC_a measurements and cotton yield in Fig. 2 visually confirms the reasonably close relationship of EC_a to yield (R^2=0.51).

Exploratory Statistical Analysis

Exploratory statistical analysis was conducted to determine the significant soil properties influencing cotton yield and to establish the general form of the cotton yield response model. The exploratory statistical analysis consisted of three stages: (i) a preliminary multiple linear regression (MLR) analysis, (ii) a correlation analysis, and (ii) scatter plots of yield versus potentially significant soil properties. The preliminary multiple linear regression analysis and correlation analysis were both used to establish the significant soil properties influencing cotton yield, while the scatter plots were used to formulate the general form of the cotton yield response model. Both preliminary MLR and correlation analysis showed that the 0-1.5 m depth increment resulted in the best correlations and best fit of the data; consequently, the 0-1.5 depth increment was considered to correspond to the active root zone.

The preliminary MLR analysis indicated that the following soil properties were most significantly related to cotton yield: EC_e, LF, pH, % clay, θ_g, and ρ_b. Table 1 shows the correlation analysis between EC_a and soil properties and between yield and soil properties. Table 1 reveals that the correlation coefficients between EC_a and θ_g, EC_e, B, % clay, ρ_b, Cl^-, LF, and SP were significant at the 0.01 level. The correlation coefficients were 0.79, 0.87, 0.88, 0.76, -0.38, 0.61, -0.50, and 0.77, respectively, indicating that the correlation between EC_a and the properties of θ_g, EC_e, B, % clay, and SP are highly correlated. However, B is a property not measured by EC_a. Rather, the high correlation of B to EC_a is an artifact due to its close correspondence to salinity (i.e., EC_e). The correlation coefficient between EC_e and B was 0.96. The high correlation of EC_a to both percentage clay and SP is expected because it reflects the influence of texture on the EC_a reading. The correlation of percentage clay and SP was very high (r = 0.99). So, in this particular field EC_a is highly correlated with salinity, θ_g, and texture. Table 1 also indicates the correlation between cotton yield and soil properties with the highest correlation occurring with salinity (EC_e).

Physicochemical property[†]	Fixed-array ER EC_a[‡]	Cotton yield[§]
θ_g	0.79**	0.42**
EC_e	0.87**	0.53**
B	0.88**	0.50**
pH	0.33*	-0.01
% clay	0.76**	0.36*
ρ_b	-0.38**	-0.29*
NO_3-N	0.22	-0.03
Cl^-	0.61**	0.25*
LF[¶]	-0.50**	-0.49**
SP	0.77**	0.38*

* Significant at the $P \leq 0.05$ level. ** Significant at the $P \leq 0.01$ level.

[†] Averaged over 0-1.5 m. [‡] Based on 60 observations. [§] Based on 59 observations. [¶] Leaching fraction = (Cl^- concentration of irrigation water) / (Cl^- concentration of saturation extract at the 1.2-1.5 m depth increment at each site adjusted to the water content at 1.2-1.5 m).

Table 1. Simple correlation coefficients between EC_a and soil physicochemical properties and between cotton yield soil physicochemical properties. *Source:* modified from Corwin et al. (2003b) with permission.

A scatter plot of EC_e and yield indicates a quadratic relationship where yield increases up to a salinity of 7.17 dS m^{-1} and then decreases (Fig. 5a). The scatter plot of LF and yield shows a negative, curvilinear relationship (Fig. 5b). Yield shows a minimal response to LF below 0.4 and falls off rapidly for LF > 0.4.

Clay percentage, pH, θ_g, and ρ_b appear to be linearly related to yield to various degrees (Figs. 5c, 5d, 5e, and 5f, respectively). Even though there was clearly no correlation between yield and pH (r = -0.01; see Fig. 5d), pH became significant in the presence of the other variables, which became apparent in both the preliminary multiple linear regression analysis and in the final yield response model.

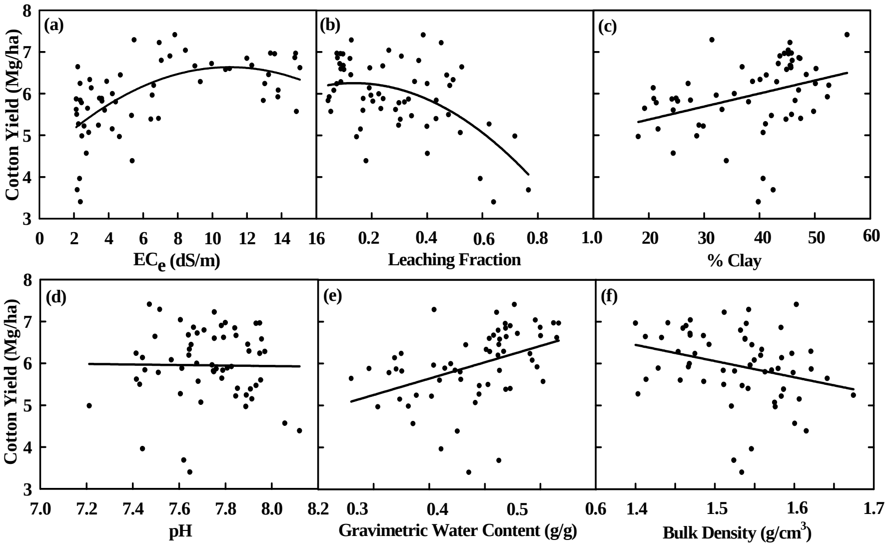


Figure 5. Scatter plots of soil properties and cotton yield: (a) electrical conductivity of the saturation extract (EC_e, dS m^{-1}), (b) leaching fraction, (c) percentage clay, (d) pH, (e) gravimetric water content, and (f) bulk density (Mg m^{-3}). *Source:* Corwin et al. (2003b) with permission.

Based on the exploratory statistical analysis it became evident that the general form of the cotton yield response model was:

$$Y = \beta_0 + \beta_1(EC_e) + \beta_2(EC_e)^2 + \beta_3(LF)^2 + \beta_4(pH) + \beta_5(\%\ clay) + \beta_6(\theta_g) + \beta_7(\rho_b) + \varepsilon \qquad [2]$$

where, based on the scatter plots of Fig. 5, the relationships between cotton yield (Y) and pH, percentage clay, θ_g, and ρ_b are assumed linear; the relationship between yield and EC_e is assumed to be quadratic; the relationship between yield and LF is assumed to be curvilinear; β_0, β_1, β_2, . . . , β_7 are the regression model parameters; and ε represents the random error component.

Cotton Yield Response Model Development

Ordinary least squares regression based on Eq. [2] resulted in the following response model:

$$Y = 20.90 + 0.38(EC_e) - 0.02(EC_e)^2 - 3.51(LF)^2 - 2.22(pH) + 9.27(\theta_g) + \varepsilon \qquad [3]$$

where the non-significant *t* test for % clay and ρ_b indicated that these soil properties did not contribute to the yield predictions in a statistically meaningful manner and dropped out of the regression model, while all other parameters were significant near or below the 0.05 level. The R^2 value for Eq. [3] is 0.61 indicating that 61% of the estimated spatial yield variation is successfully described by Eq. [3]. However, the residual variogram plot indicates that the errors are spatially correlated, which implies that Eq. [3] must be adjusted for spatial autocorrelation.

Using a restricted maximum likelihood approach to adjust for spatial autocorrelation, the most robust and parsimonious yield response model for cotton was Eq. (4):

$$Y = 19.28 + 0.22(\mathrm{EC_e}) - 0.02(\mathrm{EC_e})^2 - 4.42(\mathrm{LF})^2 - 1.99(\mathrm{pH}) + 6.93(\theta_g) + \varepsilon \qquad [4]$$

A comparison of the measured and the simulated cotton yields at the locations where directed soil samples were taken shows close agreement. Figure 6 shows the observed versus predicted cotton yield estimates from Eq. [4]. Figure 6 suggests that the estimated regression relationship has been reasonably successful at reproducing the predicted yield estimates with an R^2 value of 0.57.

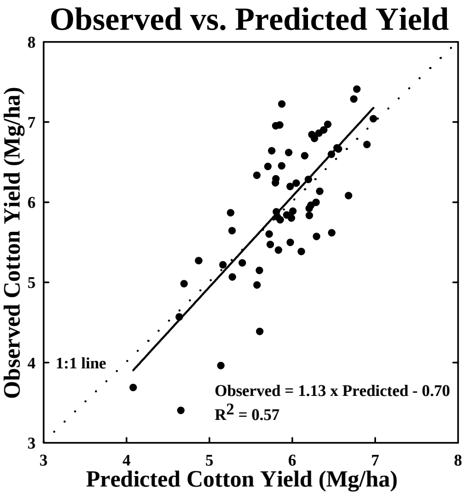


Figure 6. Observed vs. predicted cotton yield estimates using Eq. [4]. Dotted line is a 1:1 relationship. *Source:* Corwin et al. (2003b) with permission.

A visual comparison of the measured and simulated spatial yield distributions of cotton shows a reasonably close spatial association between interpolated measured (Fig. 7b) and predicted (Fig. 7c) maps.

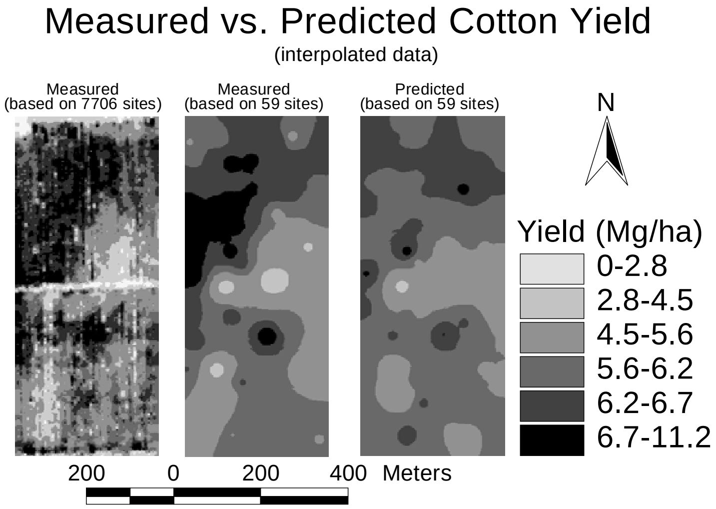


Figure 7. Comparison of (a) measured cotton yield based on 7706 yield measurements, (b) kriged data at 59 sites for measured cotton yield, and (c) kriged data at 59 sites for predicted cotton yields based on Eq. [4]. *Source:* Corwin et al. (2003b) with permission.

Sensitivity analysis reveals that LF is the single most significant factor influencing cotton yield with the degree of predicted yield sensitivity to one standard deviation change resulting in a percentage yield reduction for EC_e, LF, pH, and θ_g of 4.6%, 9.6%, 5.8%, and 5.1%, respectively.

Conclusions

Based on Eq. [4], Fig. 5, and knowledge of the interaction of the significant factors influencing cotton yield in the Broadview Water District, four recommendations can be made to improve cotton productivity at the study site:

1. reduce the LF in highly leached areas (i.e., areas where LF > 0.5),
2. reduce salinity by increased leaching in areas where the average root zone (0-1.5 m) salinity is > 7.17 dS m^{-1},
3. increase the plant-available water in coarse-texture areas by more frequent irrigation,
4. and reduce the pH where pH > 7.9.

Figure 8 indicates the areas pertaining to the above recommendations. All four recommendations can be accomplished by improving water application scheduling and distribution and by site-specific application of soil amendments. The use of variable-rate irrigation technology at this site would enable the site-specific application of irrigation water at the times and locations needed to optimize yield.

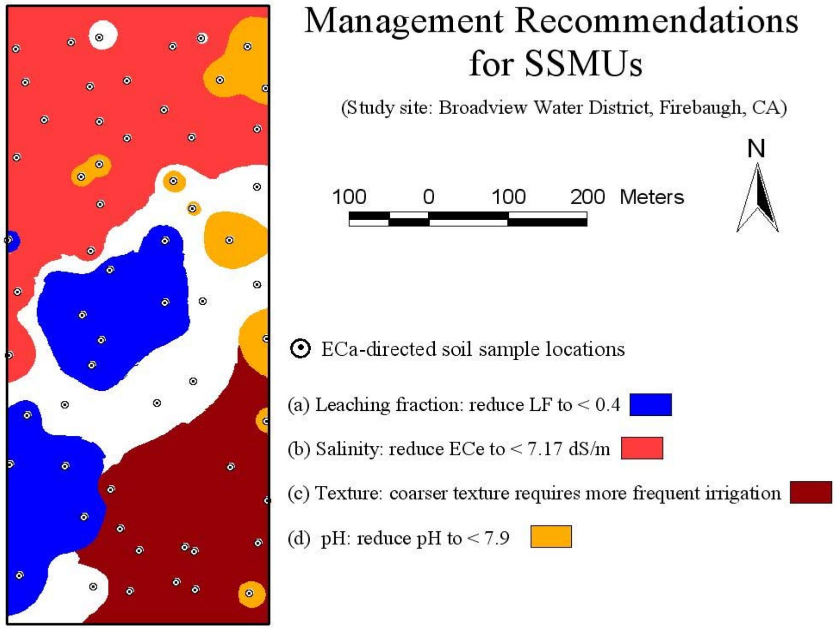


Figure 8. Site-specific management units for a 32.4-ha cotton field in the Broadview Water District of central California's San Joaquin Valley. Recommendations are associated with the SSMUs for (a) leaching fraction, (b) salinity, (c) texture, and (d) pH. *Source:* Corwin and Lesch (2005a) with permission.

Hypothetically, when crop yield correlates with EC_a, then spatial distributions of EC_a provide a means of determining edaphic properties that influence yield. This hypothesis was evaluated and found to hold true. A yield map could provide the same capability as an EC_a map, but yield monitoring has not been developed for all crops, so an EC_a map provides an acceptable alternative. Furthermore, an EC_a map provides information specific to the spatial distribution of edaphic properties, whereas a yield map reflects the influence of numerous additional factors.

Even though EC_a-directed soil sampling provides a viable means of identifying some soil properties that influence within-field variation of yield, it is only one piece of a complicated puzzle of interacting factors that result in observed within-field crop variation. Crop yield is influenced by complex interactions of meteorological (e.g., temperature, humidity, wind, etc.), biological (e.g., pests, earthworms, etc.), anthropogenic (management related), and edaphic (e.g., salinity, soil pH, water content, etc.) factors. Furthermore, precision agriculture requires more than just a myopic look at crop productivity. It must balance sustainability, profitability, crop productivity, optimization of inputs, and minimization of environmental impacts. Nevertheless, the presented approach is a step forward since it provides spatial information for use in site-specific soil and crop management.

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