Revised Draft Report:

Statistical Assessment of the Relationship between Marketable Lettuce Yield, Soil Salinity, and the Depth to Water Table across the South Gila and Yuma County Water Users Authority Water Districts (YCWUA).

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Executive Summary

This report summarizes a statistical analysis of the of the relationship between marketable lettuce yield, soil salinity, apparent field-average leaching fractions and the depth to water table across the South Gila and YCWUA Water Districts. The data presented in this report are based on a stratified random sampling of 19 lettuce fields throughout these two districts and includes detailed measurements of marketable lettuce yield (Iceburg and Romaine varieties), soil salinity, leaching fractions, and field average depth to water table estimates. This analysis has been performed as part of the ARS research agreement # 5310-13610-013-15S, an inter-agency agreement between the U.S. Bureau of Reclamation (Yuma Area Office), the Yuma Agricultural Center (University of Arizona), and the USDA-ARS George E. Brown Jr. Salinity Laboratory to provide a statistical analysis of the expected economic damages (with respect to lettuce production) due to soil salinity, leaching practices, and/or shallow water table conditions throughout these districts.

The statistical analyses presented here indicate that on average, marketable Iceburg and/or Romaine lettuce yields decrease by 4.77 Mg/ha per unit increase in soil salinity (EC_e, dS/m, weighted 0-60 cm depth), once the soil salinity exceeds about 0.7 dS/m. Note that this estimated salt-threshold value is 0.6 dS/m lower than (and statistically different from) the 1.3 dS/m threshold level typically reported in the crop science literature (Shannon & Grieve; 1999). Additionally, these analyses suggest that both under- and over-leaching decreases the field average marketable yields and that excessive over-leaching practice appear to be more problematic throughout the two districts. For example, in a typical over-leached field within the S. Gila or YCWUA districts, about 72 % of the total estimated yield loss appears to be due to excessive leaching. None of the analyses presented here indicate that the water table level effects either the field average or site specific salinity level(s), leaching fraction(s), and/or marketable yield(s), provided that the depth of the water table > 7.5 ft.

On average, the expected yield loss in a typical S. Gila or Yuma lettuce field is calculated to be 10.14 Mg/ha, with an approximate 95% confidence interval of 4.0 Mg/ha to 16.3 Mg/ha. We estimate that about 6.58 Mg/ha of this expected loss is due to sub-optimal leaching practices (primarily over-leaching), while the remaining 3.56 Mg/ha loss can be attributed to excessive salinity levels. Assuming a $406 gross dollar value figure (for 1 Mg of lettuce) and the reported 14,449 Ha area production estimate, the total dollar loss estimate across these two districts during the 2004 lettuce growing season was 59.5 million dollars (with an approximate 95% confidence interval of 23.6 to 95.4 million dollars).

1.0 Introduction

This report summarizes a statistical analysis of the of the relationship between marketable lettuce yield, soil salinity, apparent field-average leaching fractions, and the depth to water table across the South Gila and YCWUA water districts. The data presented in this report are based on a stratified random sampling of 19 lettuce fields during the 2004 and 2005 growing seasons throughout these two districts. This data includes detailed measurements of marketable lettuce yield (Iceburg and Romaine varieties), soil salinity, leaching fractions, and field average depth to water table estimates.

The primary purpose of this study was to provide statistically derived sample information on lettuce yields and soil salinity levels throughout these two districts which in turn could be used to quantify economic damages. Specifically, the four goals of this study were to (i) assess and quantify the influence (if any) of shallow water table conditions on both site specific and field average marketable lettuce yields, (ii) determine the relationships (if any) between the apparent water table level and the observed soil salinity and leaching fraction data, (iii) specify and estimate lettuce salt tolerance models that quantify the yield losses due to soil salinity (and/or other relevant soil properties), and (iv) provide a statistically based estimate of the total dollar loss in lettuce yield due to excessive soil salinity levels and/or leaching practices across these two districts.

This report contains six sections. Section 2 describes the field selection and field surveying and sampling protocols used during the study. Section 3 presents an exploratory statistical analysis of the study data, using field average estimates of the relevant variables. Section 4 then presents the confirmatory statistical analyses, based on the site specific soil property and yield loss measurements. A lettuce yield salt-tolerance equation and a yield / salt-tolerance / leaching fraction equation are also developed and presented in this section. Finally, field average and district-wide total dollar loss estimates are presented in Section 5 and a summary of findings are given in Section 6.

2.0 Sampling Protocols

2.1 Field Selection

The original field selection protocol followed a stratified random sampling plan. Specifically, 8 to 10 lettuce fields within the S. Gila and Yuma County Water Users Association (YCWUA) districts were to be selected as close as possible to a random selection of 4-6 shallow (< 8 feet) and deep (> 12 feet) water table monitoring wells; note that the apparent depth to water table represented the stratification variable in the sampling plan. Table 2.1 shows the Reclamation well identification names (Well Codes) that were randomly selected from the full set of wells classified as exhibiting either shallow or deep annual water table levels, respectively. The S. Gila well averages were based on their January 2002 – October 2003 monthly well readings, since the S. Gila sampling plan was developed in November 2003. In contrast, the YCWUA well averages were based on their January 2003 – June 2004 monthly well readings (the YCWUA sampling plan was not developed until July 2004).

The initial intent of the sampling protocol was to restrict the selection of lettuce fields to within 0.25 miles of each selected well, thereby ensuring adequate stratification across shallow and deep water table conditions. Unfortunately, this criterion proved to be impossible to satisfy for about half of the S. Gila fields and nearly all of the YCWUA fields. Thus, in addition to classifying each field included in the sampling design with respect to its closest (shallow or deep) target well, a kriging analysis was used to predict the average water table depth beneath each field using the complete set of well data from each district. Linear trend, universal kriging equations were fit to the averaged depth to water table data (based on the August 2003 through July 2004 monthly readings) for each district separately; these fitted equations were then in turn used to predict the average depth to water table at the center of each sampled field (Schabenberger & Gotway, 2005; Wackernagel, 1998). Tables 2.2 and 2.3 show the REML (restricted maximum likelihood) parameter estimates and model statistics for the Yuma and S. Gila universal kriging equations, respectively. Table 2.4 shows the corresponding predicted average depth to water table (Mean DWT) and associated prediction standard error. Note also that Table 2.4 shows the centroid (center) coordinates of each field, the corresponding field code and lettuce variety present in the field (during the survey), the independently determined depth to water table classification code (Field Class) based on the closest water table monitoring well, and the number of site specific yield samples acquired from each field.

Although all of the randomly selected target shallow wells in S. Gila and Yuma exhibit average depth to water table levels < 6 feet (Table 2.1), the kriging predictions shown in Table 2.4 suggest that all of the sampled fields exhibit average water table levels in excess of 7 feet. Specifically, the kriging predictions range from 7.7 to 14.4 feet, with an average standard error of about 2.5 feet. Due to the fact that at least 8 of the 19 selected fields fell more than one mile away from the nearest target well, the mean DWT predictions shown in Table 2.4 are probably more accurate than the corresponding S/D field classification code. However, note that both (depth to water table) indexes are examined in the statistical analyses presented in sections 3 and 4, respectively.

2.2 Within-field Sampling Protocols

In all, 10 fields in the S. Gila district and 9 fields in the YCWUA district were surveyed and sampled between December 2003 and April 2005. After obtaining landowner permission, an EM38 electrical conductivity survey was initially performed in each field. Twelve specific locations within each field were then selected for soil sampling and follow-up yield monitoring, based upon the results of the EM survey data (Lesch, 2005; Lesch et al., 2005). The ESAP software was used for all EM data processing and within field, sample site selection (Lesch et al., 2000). Four 30 cm soil samples were collected at each sample site (0-30, 30-60, 60-90, and 90-120 cm sample depths) and analyzed for soil salinity (EC_e, dS/m), saturation percentage (SP, %), gravimetric soil water content (θ_g, kg/kg), and chloride content (Cl, meq/L). These initial surveying and sampling operations were performed between December 2003 through

February 2004 in S. Gila and November 2004 through February 2005 in Yuma, respectively.

Yield samples at the corresponding soil sample locations were collected immediately before (or sometimes during) the lettuce harvest operations within each field (i.e., from March to April 2004 in S. Gila and from January to March 2005 in Yuma). At the time of harvest, lettuce heads from ten feet of bed were acquired from both sides of each soil sample location. The heads acquired from these 20-ft strips were then individually weighed and the site-specific marketable yield estimates were determined after grading for quality.

In the analyses that follow, root zone averaged salinity (EC_e) and soil texture variables have been defined using a 70 % / 30 % weighted average of the 0-30 and 30-60 cm EC_e and SP samples, respectively. (With respect to lettuce, we have defined the "lettuce root zone" to consist of the top 60 cm of soil, with 70% of the roots concentrated in the top 30 cm.) Additionally, the apparent leaching fraction has been estimated from the 90-120 cm chloride concentration using the following formula (Rhoades et al, 1999):

$$LF = \min\left[\frac{2.95}{Cl_e\left(\dfrac{\rho B \cdot SP}{100 \cdot \theta_g}\right)}, 1\right] \qquad (2.1)$$

where the bulk density (ρB) has been estimated from the SP as ρB = 1.73 – 0.0067(SP). In Eqn. (2.1), a value of 2.95 meq/L has been used for the average chloride concentration of Colorado River water, based on the irrigation water sample concentrations reported in Lesch, Corwin, and Suarez (June 2004: Reclamation Report #60-5310-2-337). Note that we have defined the bottom of the "general root zone" to be 1.2 m (rather than 0.6 m), since other deep-rooted crops (such as wheat) have been historically grown in many of these surveyed fields during the summer months. Finally, note that in sections 3 and 4 soil "texture" is expressed as % clay content where the % clay is defined as % clay = SP – 15.

2.3 Additional sampling notes / complications

Although every effort was made to acquire a full set of yield samples from each field, this was not always possible (due primarily to belated notification from some land owners concerning their harvesting schedules). As shown in Table 2.4, 1-4 sample sites were lost due to commercial harvesting operations in eight fields (*g01, g02, g03, g08, y03, y06, y07,* and *y09*), 6 sample sites were lost in field *y05*, and all of the yield sample sites were lost in field *y02* (this latter land owner harvested his entire field without ever notifying the Yuma Agricultural Center).

Some additional complications were encountered in fields *y01* and *g08*. In *y01*, confusion over the original soil sampling design inadvertently lead to the acquisition of yield samples at non-collocated sample sites (i.e., the soil samples and yield samples were taken from different positions in this one field). In *g08*, the land owner elected to grow a Green leaf lettuce variety (rather than Iceburg or Romaine). While we have elected to keep both of these fields in the final study, the above issues preclude them from being included in the statistical analysis presented in section 4.

Finally, it should be noted that a three-row planting scheme was employed in field *g05* (all other fields used a two-row planting scheme). Hence, in an effect to correct for the higher than normal yield levels from this field, all of the site specific marketable yield measurements from *g05* have been divided by 1.5 in the subsequent statistical analyses.

Table 2.1. YCWUA and S. Gila stratified random sample well locations and average depth to water table information.

YCWUA Wells: Stratified Random Sampling Locations

Selected Deep Wells:

Obs	Well Code	UTM-east	UTM-north	Ave DWT (ft)	Std Dev DWT (ft)
1	12S-6W	714291	3603796	14.08	0.32
2	14S-10W	707942	3600422	15.63	0.28
3	1S-4W	717063	3621664	11.84	0.47
4	2S-6_1/2W	713105	3619980	17.00	0.44
5	8S-8_1/2W	710151	3610214	21.57	0.36
6	9S-7W	712601	3608575	12.22	0.16

Selected Shallow Wells:

Obs	Well Code	UTM-east	UTM-north	Ave DWT (ft)	Std Dev DWT (ft)
7	10_1/2S-5W	715901	3606266	5.78	1.14
8	11S-5_1/2W	715102	3605437	5.56	1.50
9	11_1/2S-7_1/4W	712282	3604568	5.44	1.10
10	1S-5W	715491	3621616	6.51	0.69
11	5S-5_1/2W	714821	3615115	3.61	0.28
12	7S-1_3/8W	721579	3612055	3.25	0.24

South Gila Wells: Stratified Random Sampling Locations

Selected Deep Wells:

Obs	Well Code	UTM-east	UTM-north	Ave DWT (ft)	Std Dev DWT (ft)
1	1_1/2S-1_1/2E	725945	3621058	14.99	1.17
2	1_5/8S-3_1/2E	729201	3620942	15.41	1.27
3	2S-6_1/2E	734050	3620541	13.91	0.53
4	1/8S-10_1/4E	740188	3623830	12.75	0.48

Selected Shallow Wells:

Obs	Well Code	UTM-east	UTM-north	Ave DWT (ft)	Std Dev DWT (ft)
5	1_1/2S-2_1/2E	727560	3621111	5.25	1.19
6	3S-4_1/4E	730431	3618778	5.56	2.22
7	1/2S-7_1/2E	735570	3622963	3.41	0.39
8	3/4S-10_1/2E	740435	3622798	6.59	0.60

Table 2.2. Parameter estimates and statistics for the estimated Yuma universal kriging model.

Spatial GLS Model: 2003-04 Average DWT (YCWUA)

Covariance Structure	Isotropic Spatial Spherical
Estimation Method	REML
Covariance Parameters	3
Model Parameters	3 {u, x, y: 1st order trend surface}

Covariance Parameter Estimates

Cov Parm	Label	Estimate	95% Confidence Lower	95% Confidence Upper
Variance	Partial Sill	23.451	14.052	46.829
SP(SPH)	Range (1000m)	12.762	10.510	15.828
Residual	Nugget	4.423	3.055	6.975

-2 Res Log Likelihood 668.6

Likelihood Ratio Test (for significant spatial structure)

DF	Chi-Square	Pr > ChiSq
2	57.9	0.0001

Linear Trend Parameter Estimates

Effect	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept	742.3	840.4	129	0.88	0.3787
X (1000m)	-0.7509	0.3967	129	-1.89	0.0606
Y (1000m)	-0.0533	0.2552	129	-0.21	0.8348

Table 2.3. Parameter estimates and statistics for the estimated S. Gila universal kriging model.

Spatial GLS Model: 2003-04 Average DWT (S. Gila)

Covariance Structure	Isotropic Spatial Spherical
Estimation Method	REML
Covariance Parameters	3
Model Parameters	3 {u, x, y: 1st order trend surface}

Covariance Parameter Estimates

Cov Parm	Label	Estimate	95% Confidence Lower	95% Confidence Upper
Variance	Partial Sill	6.709	4.668	10.464
SP(SPH)	Range (1000m)	1.583	1.229	2.116
Residual	Nugget	0.958	0.438	3.492

-2 Res Log Likelihood 404.3

Likelihood Ratio Test (for significant spatial structure)

DF	Chi-Square	Pr > ChiSq
2	27.3	0.0001

Linear Trend Parameter Estimates

Effect	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept	2440.4	1061.7	84	2.30	0.0240
X (1000m)	0.0361	0.0948	84	0.38	0.7043
Y (1000m)	-0.6781	0.2971	84	-2.28	0.0250

Table 2.4. Summary information for the S. Gila and Yuma surveyed fields, including (i) lettuce variety, (ii) field codes and coordinates, (iii) kriging predicted depth to water table and standard error, (iv) field classification (shallow or deep water table), and (v) number of site specific yield samples successfully acquired in each field.

Lettuce Variety	Field Code	UTM Coordinates (east)	(north)	Prd DWT (ft)	Std Dev (ft)	Field Class	Number of Yield Samples
Romaine	g01	727598	3621090	10.24	2.45	S	8
Romaine	g02	727185	3621368	10.19	2.45	S	9
Romaine	g03	726418	3620255	11.67	1.95	D	9
Iceburg	g04	733577	3620055	13.99	2.12	D	12
Romaine	g05	731353	3620943	12.23	2.26	D	12
Iceburg	g06	731617	3621236	11.07	2.43	D	12
Iceburg	g07	734126	3620814	14.40	1.91	D	12
Grnleaf	g08	739936	3622893	8.86	2.31	S	10
Romaine	g09	725764	3621348	11.74	2.12	D	12
Romaine	g10	727608	3620806	11.23	2.31	S	12
Iceburg	y01	708810	3604179	11.99	2.97	D	12
Iceburg	y03	715226	3621092	7.72	2.62	S	8
Iceburg	y04	713974	3602981	10.92	2.92	S	12
Iceburg	y05	714449	3603380	11.30	2.84	S	6
Iceburg	y06	715721	3604639	9.85	2.79	S	9
Romaine	y07	712411	3601735	11.16	2.97	S	8
Iceburg	y08	713352	3600599	12.82	3.25	D	12
Romaine	y09	711291	3602105	10.83	2.67	D	10

Note: field y02 is not listed, since no yield samples were acquired...

3.0 Exploratory Statistical Analyses: Field Averaged Data

This section presents an exploratory statistical analysis of the relationships between the field average estimates of marketable yield, soil salinity, leaching fraction, estimated % clay content, and water table depth. Note that these field average estimates (for all properties except the water table depth) have been calculated by averaging the available site specific sample data within each field.

Table 3.1 presents the basic summary statistics for these five variables; these statistics summarize the field average data associated with the 18 fields where yield samples were acquired. These 18 fields exhibited a mean EC_e estimate of 1.44 dS/m, a mean leaching fraction of 0.44, and mean % clay content of 31.5 %, and a mean depth to water table of 11.2 feet. The corresponding average marketable yield for these 18 fields was 42.3 Mg/ha. Table 3.1 also shows the calculated Pearson correlation coefficients (and associated p-values) between the marketable yield and remaining four variables, and the depth to water table versus the three soil properties (salinity, LF, and clay content), respectively. Note that only one of these seven calculated correlation coefficients (yield versus LF) is statistically significant below the 0.05 level ($r = -0.498$, $p = 0.0354$).

Figures 3.1 through 3.6 show the scatter plots associated with the first six pair-wise correlation estimates reported in Table 3.1. Specifically, Figures 3.1 through 3.4 show the scatter plots of marketable yield versus EC_e, LF, % clay, and the depth to water table data, while Figures 3.5 and 3.6 display the EC_e and LF versus depth to water table scatter plots, respectively. Again, the only discernable pattern in any of these figures appears to be that the field average yields tend to decrease once the LF > 0.4. Surprisingly, there does not appear to be any discernable relationship between yield and salinity, at least when the data is analyzed on a field average basis. However, note also that on this basis the observed 1.4 dS/m range in salinity is very small and hence the averaging effect is most likely obscuring site specific yield / salinity effects. (Evidence to support this latter conclusion is presented in section 4.)

The preceding analysis used the average depth to water table estimates derived from the kriging equations. Table 3.2 presents a second exploratory analysis of the relationships between the water table classification code (i.e., deep or shallow) and the marketable yield (and other relevant soil properties). In Table 3.2 the yield, salinity, leaching fraction, and (for reference) kriging estimated depth to water table averages and standard deviations are shown by classification code. Additionally, the t-test results associated with this classification scheme are presented at the bottom of Table 3.2. Although the field average yield estimate decreases from 47.3 to 37.3 Mg/ha for fields classified as exhibiting deep versus shallow water tables, this decrease is not statistically significant ($t = 1.72$, $p = 0.1056$). Additionally, the changes in the average EC_e (1.49 versus 1.39 dS/m) and leaching fraction (0.41 versus 0.47) are negligible and clearly non-significant. The only statistically significant change is in the kriging estimated depth to water table (12.30 versus 10.16 feet; $t = 3.72$, $p = 0.0018$), which of course simply confirms that the kriging predictions concur with the dichotomous classification coding scheme.

Overall, these analyses show that the field average yield, EC_e, and LF data are statistically uncorrelated with both the kriging estimated depth to water table predictions and the depth to water table classification codes. In turn, this result suggests that if the water table is > 7.5 feet deep, then the apparent water table depth does not influence these other variables (i.e., the marketable yield, soil salinity, or apparent leaching fraction), at least when analyzed on a field average basis.

Table 3.1 Summary statistics and selected correlation estimates for the field averaged marketable yield, EC_e, LF, % clay, and depth to water table data.

Variable	Label
mECe	Field average ECe (dS/m)
mLFc	Field average leaching fraction
mClay	Field average % clay (%: estimated from SP)
DWT	Field average water table depth (ft: estimated)
mYield	Field average yield (Mg/ha)

Simple Statistics

Variable	N	Mean	Std Dev	Minimum	Maximum
mECe	18	1.442	0.394	0.826	2.184
mLFc	18	0.440	0.172	0.110	0.735
mClay	18	31.518	10.115	13.767	55.635
DWT	18	11.234	1.616	7.720	14.400
mYield	18	42.308	12.985	17.087	61.593

Pearson Correlation Coefficients, N = 18
Prob > |r| under H0: Rho=0

	mYield	DWT
mECe	0.1324	0.0956
p-value	p=0.6004	p=0.7058
mLFc	-0.4981	-0.2062
p-value	p=0.0354	p=0.4117
mClay	0.0180	-0.0847
p-value	p=0.9434	p=0.7382
DWT	0.2898	
p-value	p=0.2435	

Table 3.2 Calculated means, standard errors, and t-test results for the field averaged marketable yield, EC_e, LF, and depth to water table data, when stratified by the water table classification code.

Summary Statistics: Fields located near Deep wells (ave WTD > 12 ft)

Variable	Label	N	Mean	Std Dev
mYield	Yield (Mg/ha)	9	47.281	9.329
mECe	ECe (dS/m)	9	1.490	0.477
mLFc	Leaching Fraction	9	0.409	0.160
DWT	Water Table Depth (ft: estimated)	9	12.304	1.226

Summary Statistics: Fields located near Shallow wells (ave WTD < 8 ft)

Variable	Label	N	Mean	Std Dev
mYield	Yield (Mg/ha)	9	37.334	14.684
mECe	ECe (dS/m)	9	1.394	0.313
mLFc	Leaching Fraction	9	0.471	0.188
DWT	Water Table Depth (ft: estimated)	9	10.163	1.213

t-test Results: Deep/Shallow well classification

Variable	Label	t-score	p-value
mYield	Yield (Mg/ha)	1.72	0.1056
mECe	ECe (dS/m)	0.51	0.6189
mLFc	Leaching Fraction	-0.75	0.4653
DWT	Water Table Depth (ft: estimated)	3.72	0.0018

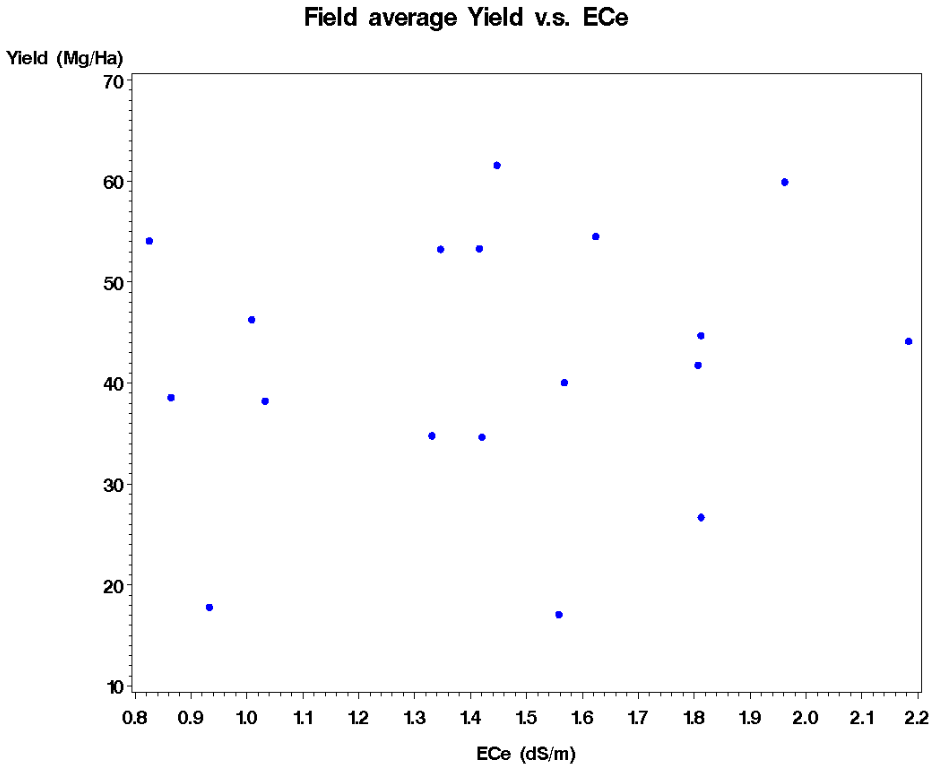

Figure 3.1. Field average marketable yield versus soil salinity.

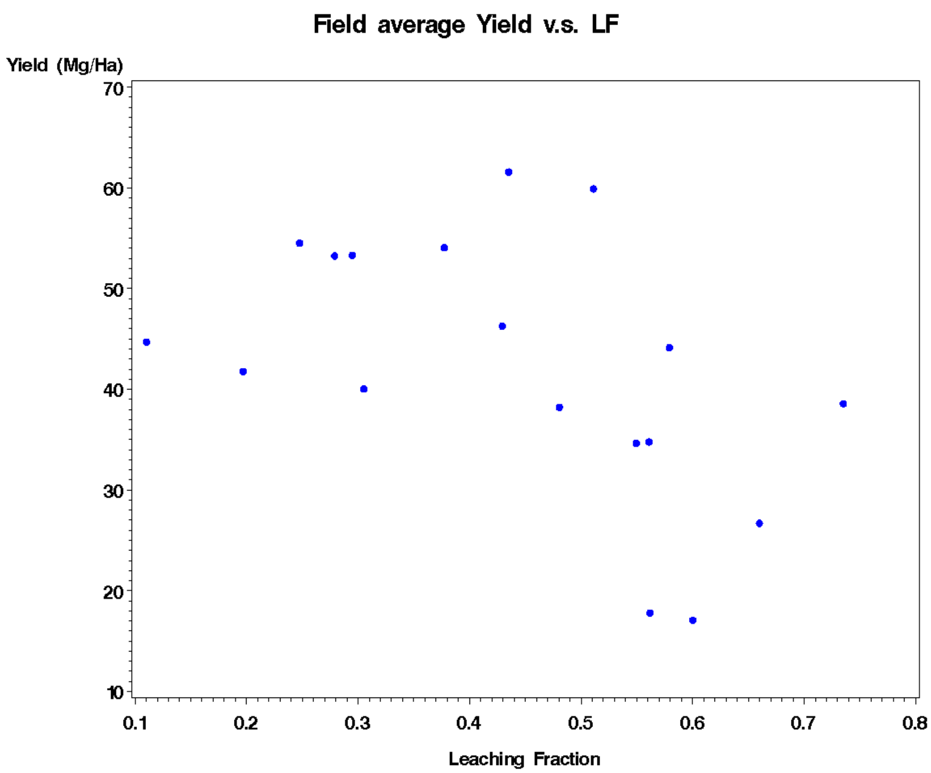

Figure 3.2. Field average marketable yield versus leaching fraction.

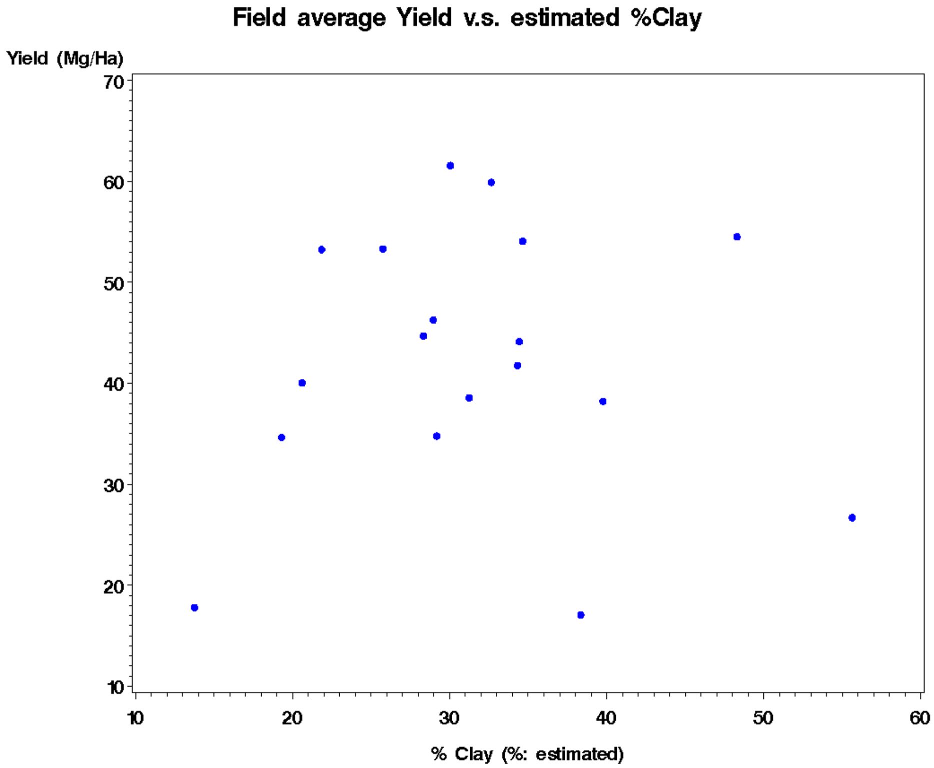

Figure 3.3. Field average marketable yield versus estimated % Clay.

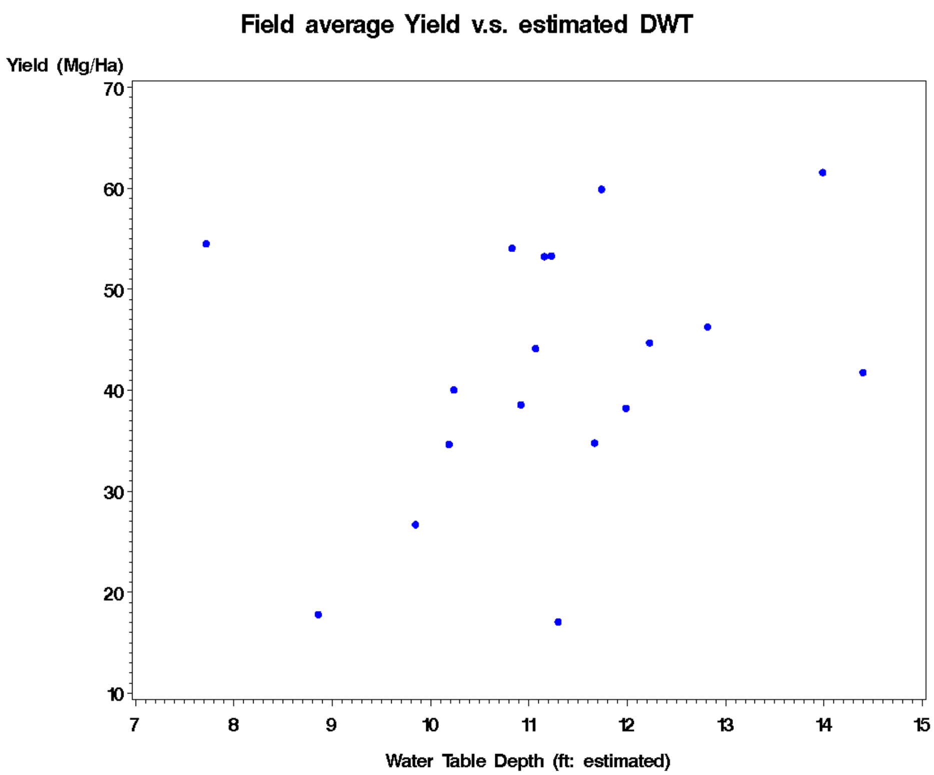

Figure 3.4. Field average marketable yield versus estimated depth to water table.

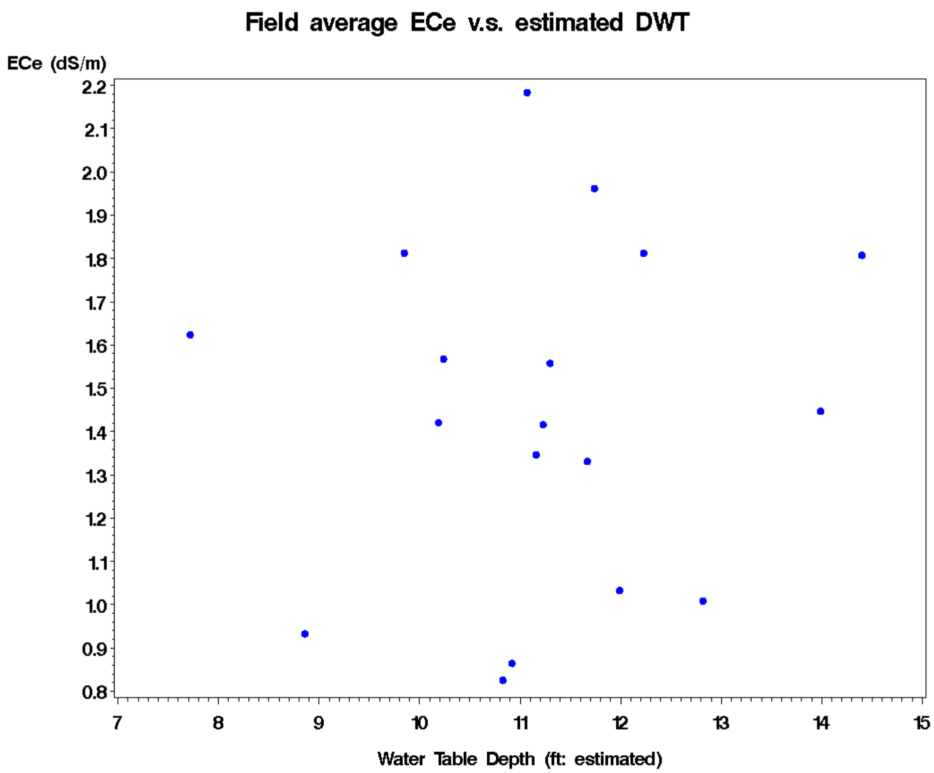

Figure 3.5. Field average soil salinity versus estimated depth to water table.

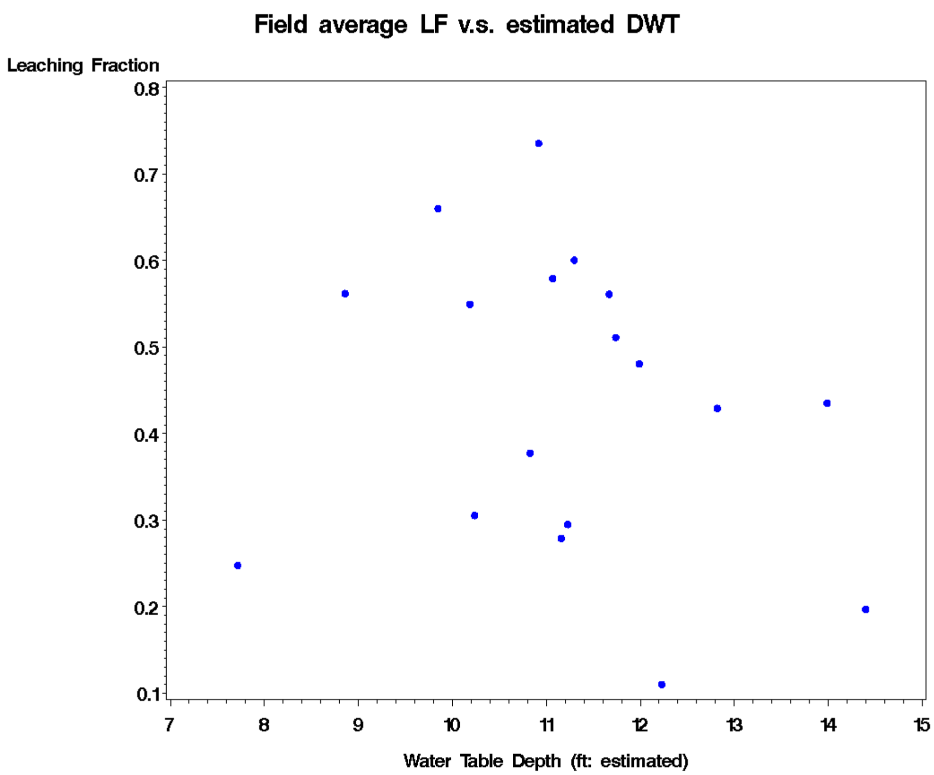

Figure 3.6. Field average leaching fraction versus estimated depth to water table.

4.0 Site Specific Yield Response Models

Three types of site specific yield response equations are estimated and analyzed in this section. The first set of equations represent mixed linear models (MLM) that relate the site specific marketable yield estimates to all of the various soil, crop, and depth to water table covariate factors examined in this study. These first equations are used to test for what effects (if any) each of the soil, crop, and/or depth to water table variables have on the yield response levels. The second equation represents a simplified analysis of covariance (ANOCOVA) model that predicts the yield to be a function of just two variables, (threshold adjusted) soil salinity and (unspecified) field management effects. This second model represents a generalized version of a field-based salt tolerance equation that specifically describes the fields analyzed in this study. The third equation represents another MLM that simultaneously describes the effects that the apparent site-specific salinity and field-average leaching fraction levels have on the marketable yields. This latter equation will be used in section 5 to produce district wide estimates of yield losses due to these two covariate factors.

4.1 The Multiple Soil-Property Mixed Linear Models (MLM)

Two multiple soil-property mixed linear models were initially estimated using the site specific data observations from 16 of the 18 fields discussed in section 3 (Littell et al., 1996; McCulloch & Searle, 2001). These models were defined as follows:

$$\begin{aligned} y_{ij} = \beta_0 + \beta_1(adjECe) + \beta_2(Crop) + \beta_3(adjECe \cdot Crop) + \beta_4(LF) + \beta_5(LF^2) \\ + \beta_6(\%Clay) + \beta_7(DWT) + \eta_j + \varepsilon_{ij} \qquad (4.1) \\ for\ \eta_j \sim N(0,\theta^2),\ \varepsilon_{ij} \sim N(0,\sigma^2) \end{aligned}$$

and

$$\begin{aligned} y_{ij} = \beta_0 + \beta_1(adjECe) + \beta_2(Crop) + \beta_3(adjECe \cdot Crop) + \beta_4(LF) + \beta_5(LF^2) \\ + \beta_6(\%Clay) + \beta_7(F_{class}) + \eta_j + \varepsilon_{ij} \qquad (4.2) \\ for\ \eta_j \sim N(0,\theta^2),\ \varepsilon_{ij} \sim N(0,\sigma^2) \end{aligned}$$

These two equations are identical except with respect to the employed depth to water table regression variable (4.1 uses the continuous kriging prediction, while 4.2 uses the field classification code).

In both equations, y_{ij} represents the marketable yield observed at the i^{th} site within the j^{th} field, while η_j and ε_{ij} represent the between field and within field error components, respectively. Additionally, the regression variables are defined as follows:

adjECe:	max[EC_e – 1.3, 0]
Crop:	1 if Romaine variety, 0 if Iceburg variety
LF:	calculated leaching fraction (Eqn 2.1)
%Clay:	SP – 15
DWT:	kriging estimated depth to water table (see Table 1.4)
F_{class}:	1 if deep water table classification, 0 if shallow

The threshold adjusted salinity (adjECe) variable has been defined in accordance with previously published literature which states that the threshold point for salinity effects on lettuce yield is 1.3 dS/m (Shannon & Grieve, 1999). As indicated above, the Crop and F_{class} variables represent indicator (0/1) variables, while all remaining variables are continuous. The inclusion of the Crop variable and adjECe x Crop interaction term allow for the possibility of different salt tolerance slope estimates and average yield estimates (for the Iceburg and Romaine varieties). Additionally, both linear and quadratic leaching fraction effects have been included in both models in order to account for the possible non-linear LF effect seen in Figure 3.2.

Equations (4.1) and (4.2) represent reasonable statistical models for simultaneously describing the joint effects of the site-specific salinity level, crop variety, leaching fraction, and soil texture effects and (field average) depth to water table effects on the observed marketable yield measurements. Note that all data associated with fields *g08* and *y01* have been excluded from both modeling analyses. The data associated with *g08* has been excluded due to the *a typical* lettuce variety (Green leaf) encountered in this field. As discussed previously (in Section 2), the yield monitoring sites in field *y01* did not correspond to the soil sampling locations, hence no data from this field could be used in the estimation of either MLM.

Table 4.1 presents the MLM estimation results and parameter estimates for Eqn. (4.1). The compound symmetry error structure is highly significant; the between-field variance estimate (154.9) is three times larger than the within-field estimate (52.3). The adjECe parameter estimate is also highly significant ($t = -4.01$, $p = 0.0001$), but somewhat surprisingly this is the only regression model parameter that appears to be significantly different from 0. The contrast F-tests shown at the bottom of Table 4.1 indicate that both the leaching effect and the variety effect are non-significant. Likewise, the pClay and DWT parameter estimates are also non-significant. Hence, these mixed linear modeling results imply that only the soil salinity affects the site-specific marketable yields.

Table 4.2 presents the MLM estimation results and parameter estimates for Eqn. (4.2). In nearly all respects, the results shown in Table 4.2 are statistically equivalent to the Table 4.1 results. The compound symmetry error structure is again highly significant; the between-field variance estimate (134.3) is about 2.5 times larger than the within-field estimate (52.3). The adjECe parameter estimate is again highly significant ($t = -4.02$, $p = 0.0001$) and is again the only significant regression model parameter estimate. The contrast F-tests shown at the bottom of Table 4.2 still show that both the leaching and variety effects are non-significant. Likewise, the pClay parameter estimate and the (indicator) depth to water table classification variable are also non-significant.

Taken together, these results show that neither depth to water table index influences the site-specific marketable yields in a statistically significant manner. These results also suggest that the soil salinity represents the only <u>site-specific</u> soil property influencing the marketable yields (note that the site-specific leaching fraction effects are clearly non-significant in both models). Thus, the site-specific marketable yield estimates acquired from these 16 fields appear to be a function of the site-specific soil salinity levels and differences in (field specific) management practices across fields.

The lack of a statistically significant leaching fraction effect is rather surprising, given the earlier results shown in section 3. To explore this issue further, the site-specific LF variable in Eqn. (4.1) was replaced with the following threshold adjusted, field average LF variable:

$$adjmLF = \max\left[LF_{j,ave} - 0.4,\ 0\right]$$
$$\text{where } LF_{j,ave} = \frac{1}{n_i}\sum_{i=1}^{n_i} LF_{i,j} \qquad (4.3)$$

This modified equation was then re-fit to the site specific marketable yield data; the resulting MLM estimation results and new parameter estimates are shown in Table 4.3. Interestingly, the parameter associated with this field average LF index is statistically significant ($t = -2.35$, $p = 0.0201$). These results suggest that irrigation efficiency (as measured by the field average leaching fraction) represents one of the "field specific" management practices influencing the average marketable yields.

4.2 The ANOCOVA Model

Based on the previous modeling results, a simplified salt tolerance model was adopted. This simplified ANOCOVA model was specified as

$$y_{ij} = \beta_{0j} + \beta_1(adjECe) + \varepsilon_{ij} \qquad (4.4)$$

were the β_{0j} parameters represent unique field effects (i.e., management variation between fields) and the remaining variables are defined as before. The field specific intercepts account for the between-field variation effects, hence the residual errors are assumed to be uncorrelated within each field in this model. As before, the adjusted ECe variable was based on an *a priori* assumed salinity threshold value of 1.3 dS/m.

Table 4.4 presents the ANOCOVA model estimation results and parameter estimates for Eqn. (4.4). This model produced an R^2 of 0.724 and a root MSE estimate of 7.26 Mg/ha. Both the threshold adjusted salinity effect and field specific intercept effects are highly significant ($p < 0.0001$ for both F-tests), but the latter effects appear to account for the great majority of the explained variation (0.655 versus 0.069 for the adjECe). The field specific intercept estimates can be interpreted as the average marketable yields expected (from each field) in the absence of any salinity effects; note that these yields are quite variable (for a low of 20.1 Mg/ha to a high of 63.1 Mg/ha). The adjusted salinity parameter estimate ($\beta_1 = -4.81$) implies that for each unit increase in the lettuce root-zone soil salinity level (above 1.3 dS/m), these fields exhibited an average a 4.81 Mg/ha reduction in marketable yield. Based on the average yield estimate of 45.9 Mg/ha (average intercept value for the 16 fields), the % reduction in yield per unit increase in salinity (above 1.3 dS/m) can be estimated as 4.81/45.9 = 10.5%. This estimate is slightly lower than the literature reported reduction estimate of 13% (Shannon & Grieve, 1999).

Figure 4.1 shows the predicted versus observed site specific marketable yields for the 16 fields used in Eqn. (4.4). As shown by this plot, the ANOCOVA model predicts the site specific yields reasonably well.

In the preceding analysis, an *a priori* value of 1.3 dS/m was assumed to represent the correct threshold value. To check the validity of this assumption, Eqn. (4.4) was refit as a stochastic linear spline ANOCOVA equation where the threshold value was treated as an additional unknown parameter and estimated from the marketable yield data (Freund & Littell, 1991). In this stochastic spline equation, the optimized (minimum mean square error) model produced a threshold estimate of 0.69 dS/m and a new threshold adjusted salinity estimate of -3.94 (standard error = 0.96). Unfortunately, the standard error of the threshold estimate can not be computed in the usual manner, but both the threshold and slope estimates appear to have noticeably changed. Additionally, in this optimized model the calculated percent reduction in yield due to salinity is only 8.3%, but the apparent threshold level has been reduced by 0.6 dS/m.

In the next section we examine how each threshold level effects the composite yield / salt tolerance / LF model and show that the 0.69 dS/m optimized estimate is significantly different from 1.3 dS/m.

4.3 The composite Yield / Salt Tolerance / Leaching Fraction MLM

As noted above, the field specific yield effects were quite variable, but at least some of this variability is related to the apparent field average leaching fraction. To better determine the exact degree of this average LF effect, the following simplified salt tolerance / mean quadratic LF model was specified:

$$\begin{aligned} y_{ij} &= \beta_0 + \beta_1(adjECe) + \beta_2(mLF) + \beta_3(mLF^2) + \eta_j + \varepsilon_{ij} \\ &\quad for\ \ \eta_j \sim N(0,\theta^2),\ \ \varepsilon_{ij} \sim N(0,\sigma^2) \end{aligned} \tag{4.5}$$

Eqn. (4.5) again represents a mixed linear model with two error terms (a between-field and within-field component). However, this model postulates that only the site-specific adjusted salinity levels and field average LF levels effect the (site-specific) marketable yields. Additionally, this model assumes that the mean LF effect is non-linear (quadratic), and thus can be used to determine a LF point estimate which corresponds to the maximum yield potential. Note that this latter estimate can be found by differentiating (4.5) with respect to the LF parameters and setting the resulting equation equal to 0; i.e.,

$$optLF = -\hat{\beta}_2 / (2\hat{\beta}_3) \quad for\ \ \hat{\beta}_2 > 0,\ \hat{\beta}_3 < 0. \tag{4.6}$$

The upper portions of Tables 4.5 and 4.6 present the corresponding mixed linear model estimation results and parameter estimates for Eqn. (4.5), using assumed salt tolerance threshold values of 1.30 and 0.69 dS/m, respectively. The individual linear and quadratic LF parameter estimates exhibit non-significant t-tests, but the joint parameter F-tests (which test if both parameters are simultaneously 0) are significant below the 0.05 level in both cases (F = 3.42, p = 0.0353 for T=1.30 dS/m and F = 3.53, p =0.0319 for T = 0.69 dS/m). Additionally, regardless of the assumed threshold value (1.3 or 0.69), the maximum yield level occurs at a leaching fraction of approximately 0.3.

Given this apparent non-linear LF effect, an adjusted leaching fraction variable was next defined as

$$adjqLF = \left(LF_{j,ave} - 0.3\right)^2 \tag{4.7}$$

and then a revised salt tolerance / LF model was specified as

$$\begin{gathered} y_{ij} = \beta_0 + \beta_1(adjECe) + \beta_2(adjqLF) + \eta_j + \varepsilon_{ij} \\ for\ \ \eta_j \sim N(0,\theta^2),\ \ \varepsilon_{ij} \sim N(0,\sigma^2) \end{gathered} \tag{4.8}$$

Note that the *adjqLF* variable has been used in Eqn. (4.8) in order to “linearize” the quadratic effect (which in turn allows us to simplify the calculation of the associated confidence interval for this non-linear LF effect).

The lower portions of Tables 4.5 and 4.6 list the corresponding mixed linear model estimation results and parameter estimates for Eqn. (4.8). As previously stated, this model simultaneously quantifies the yield loss due to both the adjusted salinity and under- or over-leaching effects. The β_1 salinity parameter estimates of -4.85 and -4.77 Mg/ha are very similar to one another, and thus appear to be approximately invariant to the choice of the salt tolerance threshold value. The quadratic leaching fraction parameter estimates are also approximately equal. However, the -2LL (residual log likelihood) score for the T=0.69 dS/m model is 4.6 units lower (i.e., 1159.6 – 1155.0 = 4.6). If we tentatively assume that Eqn. (4.8) has been optimized using this lower threshold value, then a test of T=1.3 (versus $T < 1.3$) can be performed by comparing this difference (in the -2LL scores) to a Chi-square distribution with 1 degree of freedom. This test produces a p-value of $p = 0.032$, suggesting that the optimized threshold value of 0.69 dS/m is significantly different from the (literature cited) 1.3 threshold value.

The threshold adjusted salinity parameter estimate shown at the bottom of Table 4.6 suggests that every 1 unit increase in EC_e (above 0.69 dS/m) results in a 4.77 Mg/ha yield loss. The β_2 LF parameter estimate of -123.1 is actually quantifying a quadratic yield loss effect that becomes progressively worse as the field average leaching fraction moves away from 0.3. For example, a field average LF level of 0.2 or 0.4 results in a projected yield loss of just 1.23 Mg/ha, but a 0.1 or 0.5 LF level translates into a yield loss of 4.92 Mg/ha, etc.

Conservative 95% confidence intervals for both parameter estimates can be calculated as $\beta_j \pm 2\times\text{StdErr}(\beta_j)$. For the adjusted salinity parameter estimate, the corresponding confidence interval is (-6.73, -2.81); i.e., 2.81 Mg/ha to 6.73 Mg/ha yield loss per unit increase in salinity. Likewise, the 95% confidence interval for the adjusted LF parameter estimate is (-214.9, -31.3).

The calculated correlation between the observed versus Eqn. (4.8) predicted yield loss estimates is 0.522. This correlation estimate is noticeably lower than the 0.851 correlation produced by the ANOCOVA model; the difference being due to the way in which the two models are defined. As shown in Table 4.4, the ANOCOVA model uses 16 distinct intercept parameters to model the 16 specific mean field yield loss levels (in contrast, the MLM uses only 3 regression model parameters). Thus, although the field average LF levels describe some of the observed between field variation in lettuce yield, this factor clearly does not account for all of the (management induced) variation.

4.4 Site specific salinity and leaching fraction relationship(s) to the field average depth to water table estimates

The field average ECe and LF data (analyzed in section 3) displayed no apparent relationship to the kriging predicted depth to water table estimates. Figures 4.2 and 4.3 show the equivalent site specific ECe and LF plots, respectively. Again, neither plot suggests that the estimated field average water table levels influence either the site specific salinity levels or leaching fraction estimates. The calculated correlation estimates shown in Table 4.7 confirm this lack of influence; neither correlation coefficient is significantly different from 0.

These results offer further evidence that when the water table is > 7.5 feet deep, the apparent water table depth does not influence either the (site specific) soil salinity or apparent leaching fraction.

Table 4.1 Mixed linear model estimation results and parameter estimates for Eqn. (4.1).

Covariance Structure	Variance Components
Estimation Method	REML
Covariance Parameters	2

Covariance Parameter Estimates

Cov Parm	Label	Estimate	95% Confidence Lower	95% Confidence Upper
Field	between-field	154.94	79.44	425.05
Residual	within-field	52.27	41.99	66.87

-2 Res Log Likelihood 1134.6

Likelihood Ratio Test (for compound symmetry covariance structure)

DF	Chi-square	Pr > ChiSq
1	126.7	0.0001

Regression Model Parameter Estimates

Effect	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept	40.802	25.886	13	1.58	0.1390
adjECe	-5.130	1.281	143	-4.01	<.0001
Crop	2.392	6.654	143	0.36	0.7197
adjECe*Crop	2.389	2.867	143	0.83	0.4061
LF	-1.914	10.099	143	-0.19	0.8499
LF*LF	3.847	8.748	143	0.44	0.6607
pClay	-0.187	0.124	143	-1.50	0.1352
DWT	0.835	2.089	143	0.40	0.6899

Parameter Lables

adjECe	adjusted ECe (max[ECe-1.3,0])
Crop	indicator variable (1 if Romaine variety, 0 otherwise)
adjECe*Crop	interaction term (between adjECe and Crop indicator variable)
LF	leaching fraction (linear term)
LF*LF	leaching fraction (quadratic term)
pClay	% clay (estimated as pClay = SP - 15)
DWT	field mean depth to water table (kriging estimate)

Secondary Contrasts (F-tests)

Label	Num DF	Den DF	F Value	Pr > F	Hypothesis test
leaching fraction	2	143	0.52	0.5959	LF=0 & LF*LF=0
crop difference	2	143	0.47	0.6238	Crop=0 & adjECe*Crop=0

Table 4.2 Mixed linear model estimation results and parameter estimates for Eqn. (4.2).

Covariance Structure	Variance Components
Estimation Method	REML
Covariance Parameters	2

Covariance Parameter Estimates

Cov Parm	Label	Estimate	95% Confidence Lower	Upper
Field	between-field	134.29	68.68	370.46
Residual	within-field	52.26	41.98	66.85

-2 Res Log Likelihood 1130.6

Likelihood Ratio Test (for compound symmetry covariance structure)

DF	Chi-square	Pr > ChiSq
1	117.9	0.0001

Regression Model Parameter Estimates

Effect	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept	46.216	7.565	13	6.11	<.0001
adjECe	-5.142	1.279	143	-4.02	<.0001
Crop	2.077	6.173	143	0.34	0.7369
adjECe*Crop	2.382	2.863	143	0.83	0.4067
LF	-2.061	10.077	143	-0.20	0.8382
LF*LF	3.967	8.736	143	0.45	0.6505
pClay	-0.189	0.122	143	-1.55	0.1239
Fclass	8.627	5.913	143	1.46	0.1467

Parameter Lables

adjECe	adjusted ECe (max[ECe-1.3,0])
Crop	indicator variable (1 if Romaine variety, 0 otherwise)
adjECe*Crop	interaction term (between adjECe and Crop indicator variable)
LF	leaching fraction (linear term)
LF*LF	leaching fraction (quadratic term)
pClay	% clay (estimated as pClay = SP - 15)
Fclass	field classification (shallow WT = 0, deep WT = 1)

Secondary Contrasts (F-tests)

Label	Num DF	Den DF	F Value	Pr > F	Hypothesis test
leaching fraction	2	143	0.52	0.5944	LF=0 & LF*LF=0
crop difference	2	143	0.46	0.6295	Crop=0 & adjECe*Crop=0

Table 4.3 Modified mixed linear model estimation results and parameter estimates For Eqn. (4.1), using the field average adjmLF variable in place of the site specific linear and quadratic LF variables.

Covariance Structure	Variance Components
Estimation Method	REML
Covariance Parameters	2

Covariance Parameter Estimates

Cov Parm	Label	Estimate	95% Confidence Lower	95% Confidence Upper
Field	between-field	109.01	54.30	319.85
Residual	within-field	52.09	41.91	66.52

-2 Res Log Likelihood 1132.2

Likelihood Ratio Test (for compound symmetry covariance structure)

DF	Chi-square	Pr > ChiSq
1	105.3	0.0001

Regression Model Parameter Estimates

Effect	Estimate	Standard Error	DF	t Value	Pr > |t|	
Intercept	63.627	23.677	12	2.69	0.0198	
adjECe	-5.371	1.256	145	-4.28	<.0001	
Crop	-3.547	6.132	145	-0.58	0.5638	
adjECe*Crop	2.698	2.825	145	0.96	0.3411	
adjmLF	-65.414	27.835	145	-2.35	0.0201	<- sig below 0.05
pClay	-0.197	0.121	145	-1.64	0.1039	
DWT	-0.336	1.827	145	-0.18	0.8546	

Table 4.4 ANOCOVA model estimation results and parameter estimates for Eqn. (4.3), using a salt tolerance threshold value of 1.3 dS/m.

```
Threshold/Slope Salt Tolerance Model
Fixed Effects Model: with unique Threshold Estimates (by Field)

Class         Levels    Values
Field             16    g01 g02 g03 g04 g05 g06 g07 g09 g10
                        y03 y04 y05 y06 y07 y08 y09


Dependent Variable: Yield (Mg/Ha)
                                        Sum of
  Source                       DF       Squares   Mean Square    F Value    Pr > F

  Model                        16     20352.766      1272.048      24.15    <.0001
  Error                       147      7742.257        52.668
  Corrected Total             163     28095.023

  R-Square   Coeff Var   Root MSE  yield Mean
     0.724      16.019      7.257      45.306


Threshold(s) & Slope Effects:

  Source    DF     Type I SS   % ExV   Type III SS   Mean Square    F Value    Pr > F

  adjECe     1      1405.640   0.069       946.191       946.191      17.97    <.0001
  Field     15     18947.126   0.655     18947.126      1161.026      23.98    <.0001

                           Standard
  Parameter    Estimate       Error    t Value    Pr > |t|

  field g01      41.768       2.598      16.08      <.0001
  field g02      36.174       2.445      14.79      <.0001
  field g03      35.266       2.421      14.56      <.0001
  field g04      62.800       2.114      29.70      <.0001
  field g05      47.277       2.180      21.68      <.0001
  field g06      48.393       2.322      20.84      <.0001
  field g07      44.425       2.185      20.33      <.0001
  field g09      63.100       2.225      28.35      <.0001
  field g10      54.307       2.107      25.77      <.0001
  field y03      57.306       2.506      22.86      <.0001
  field y04      38.590       2.095      18.42      <.0001
  field y05      20.050       3.044       6.59      <.0001
  field y06      30.271       2.560      11.82      <.0001
  field y07      54.114       2.573      21.03      <.0001
  field y08      46.472       2.095      22.18      <.0001
  field y09      54.076       2.294      23.56      <.0001

  adjECe         -4.808       1.134      -4.24      <.0001
```

Table 4.5 Mixed linear model estimation results and parameter estimates for Eqns. (4.5) and (4.8), using a salt tolerance threshold of 1.30 dS/m.

Covariance Structure	Variance Components
Estimation Method	REML
Covariance Parameters	2
Number of Models	2 (Eqns 4.5 and 4.8)
Salt Tolerance Threshold	1.30 dS/m

Eqn 4.5: Regression Model Parameter Estimates

Effect	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept	39.936	14.547	13	2.75	0.0167
adjECe	-4.833	1.127	147	-4.29	<.0001
mLF	79.396	74.275	147	1.07	0.2868
mLF*mLF	-130.61	85.840	147	-1.52	0.1303

Joint Parameter Test (of mLF=0 & mLF*mLF=0):

Num DF	Dem DF	F Value	Pr > F
2	147	3.42	0.0353

Estimate of Optimal LF (with respect to maximizing Yield):

Optimum LF = 79.396/(2*130.61) = 0.304

Eqn 4.8: Regression Model Parameter Estimates

Effect	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept	51.297	3.242	14	15.82	<.0001
adjECe	-4.850	1.126	147	-4.31	<.0001
qmLF	-120.66	46.018	147	-2.62	0.0097

-2 Res Log Likelihood (using ML Estimation): 1159.6

Table 4.6 Mixed linear model estimation results and parameter estimates for Eqns. (4.5) and (4.8), using a salt tolerance threshold of 0.69 dS/m.

Covariance Structure	Variance Components
Estimation Method	REML
Covariance Parameters	2
Number of Models	2 (Eqns 4.5 and 4.8)
Salt Tolerance Threshold	0.69 dS/m

Eqn 4.5: Regression Model Parameter Estimates

Effect	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept	42.486	14.572	13	2.92	0.0120
adjECe	-4.757	0.980	147	-4.85	<.0001
mLF	78.256	74.263	147	1.05	0.2937
mLF*mLF	-130.18	85.823	147	-1.52	0.1315

Joint Parameter Test (of mLF=0 & mLF*mLF=0):

Num DF	Dem DF	F Value	Pr > F
2	147	3.53	0.0319

Estimate of Optimal LF (with respect to maximizing Yield):

Optimum LF = 78.256/(2*130.18) = 0.301

Eqn 4.8: Regression Model Parameter Estimates

Effect	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept	53.565	3.313	14	16.17	<.0001
adjECe	-4.774	0.980	147	-4.87	<.0001
qmLF	-123.07	45.912	147	-2.68	0.0082

-2 Res Log Likelihood (using ML Estimation): 1155.0

Table 4.7 Summary statistics and selected correlation estimates for the site specific salinity (ECe) and leaching fraction (LF) data, versus field average depth to water table data.

Variable	Label
sECe	Site specific ECe (dS/m)
sLF	Site specific Leaching Fraction
DWT	Field average Depth to Water Table(ft: estimated)

Simple Statistics

Variable	N	Mean	Std Dev	Minimum	Maximum
DWT	192	11.335	1.546	7.720	14.400
ECe	192	1.499	0.686	0.250	3.967
LF	192	0.430	0.281	0.033	1.000

Pearson Correlation Coefficients, N = 192
Prob > |r| under H0: Rho=0

	sECe	sLF
DWT	0.0026	-0.1009
p-value	p=0.9713	p=0.1636

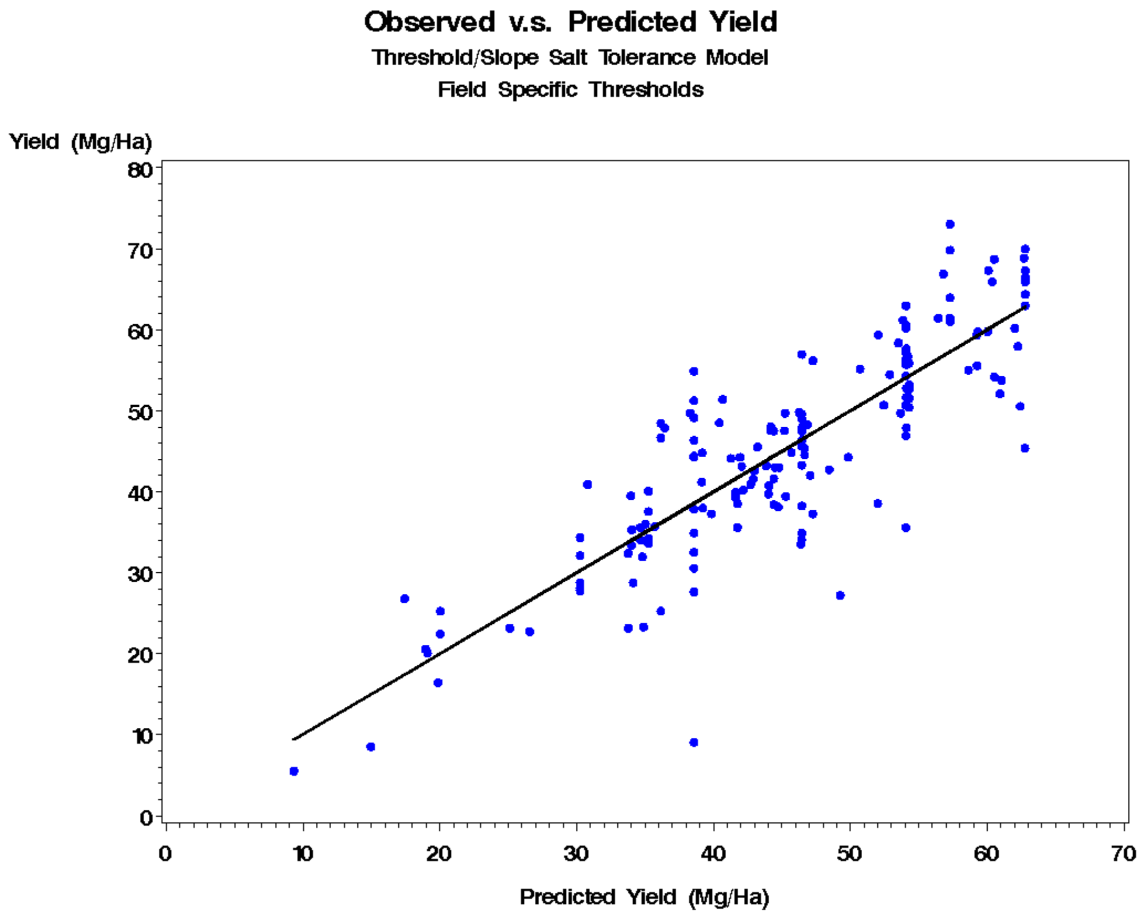

Figure 4.1 Observed versus ANOCOVA model predicted site specific marketable yield (for the ANOCOVA model using an assumed salt tolerance threshold of 1.30 dS/m).

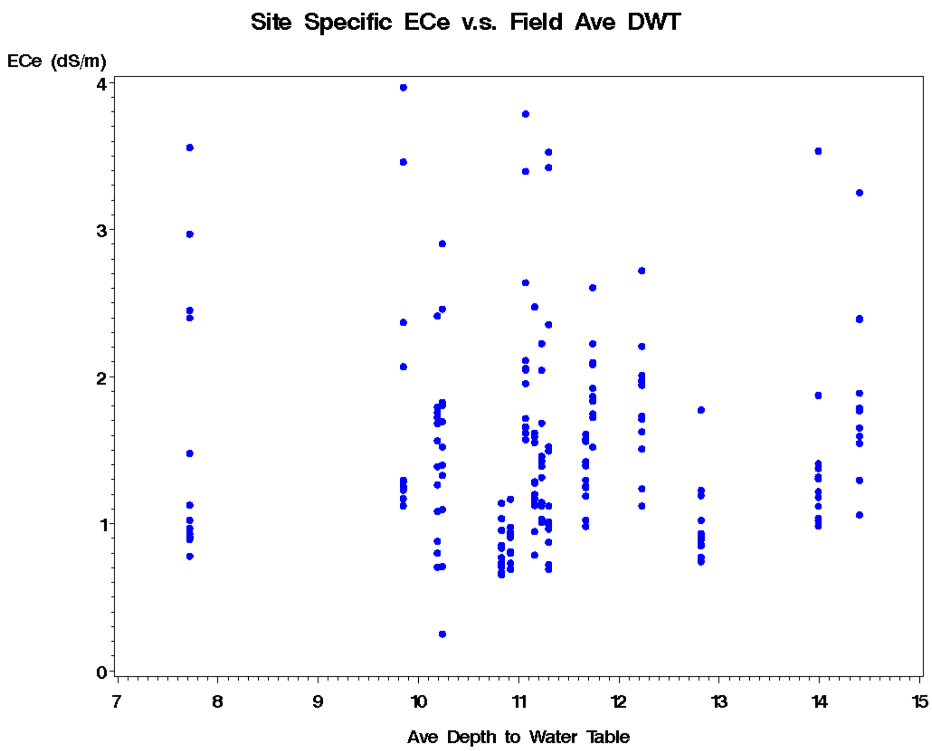

Figure 4.2 Site specific salinity data versus field average depth to water table estimates.

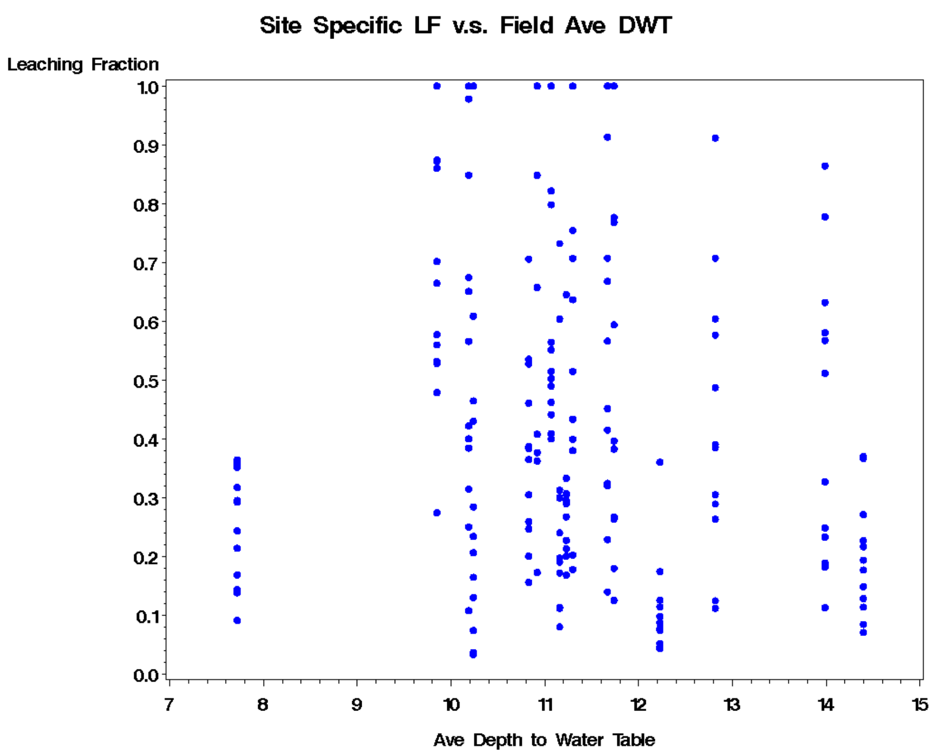

Figure 4.3 Site specific leaching fraction data versus field average depth to water table estimates.

5.0 District Wide Yield & Total Dollar Loss Estimates

5.1 Estimated yield loss in a typical field

The mixed linear modeling results presented in section 4 (Eqn. 4.8) produced a marketable yield loss estimate of 4.77 Mg/ha per unit increase in EC_e (above 0.7 dS/m). Additionally, this ML model predicts a non-linear yield loss effect for field average LF levels either above or below 0.3.

Using Eqn. (4.8), the expected yield loss (EYL: Mg/ha) for a typical lettuce field under various leaching scenarios in the S. Gila or YCWUA district can be calculated as

$$EYL = -\beta_1\mu_1 - \beta_2\mu_2 \qquad (5.1)$$

where μ_1 and μ_2 represent the average values of the threshold adjusted site-specific salinity and quadratic field-average leaching fractions for a specific leaching scenario. Estimates for β_1 and β_2 are shown in the lower portion of Table 4.6; estimates for μ_1 and μ_2 need to be computed directly from the soil sample calibration data. For this report, we have chosen to compute estimates for the following three scenarios:

(i) a typical under-leached scenario,

(ii) a typical over-leached scenario, and

(iii) the average leaching scenario.

Average yield loss estimates for scenarios (i) and (ii) were calculated by first dividing the soil sample data from the 19 fields into two distinct groups of under- and over-leached fields (based on the computed field average leaching fraction estimates). Next, the μ_1 and μ_2 estimates were computed as

$$\hat{\mu}_1 = (1/N_l)\sum_{i=1}^{N_l} \max[ECe_i - 0.69, 0]$$
$$Var(\hat{\mu}_1) = (1/m_l)S_{b1}^2 + (1/N_l)S_{w1}^2 \qquad (5.2)$$
$$\hat{\mu}_2 = (1/m_l)\sum_{j=1}^{m_l} \left\{LF_{j,ave} - 0.3\right\}^2$$
$$Var(\hat{\mu}_2) = (1/m_l)S_{b2}^2$$

where N_l and m_l represent the number of individual soil samples and fields falling into a specific leaching scenario, S_{b1}^2 and S_{w1}^2 represent the empirical between- and within-field adjusted salinity variance estimates and S_{b2}^2 represents the empirical between-field adjusted leaching fraction variance estimate. Note that these variance estimates reflect the clustered nature of the sampling design (Lohr, 1999). The average yield loss estimates were then derived using Eqn. (5.1).

To derive the average yield loss estimate under scenario (iii), a weighted average of scenarios (i) and (ii) was computed. The corresponding weights were defined to be proportional to the number of fields falling within each group; i.e.,

$$EYL_{(iii)} = \left(\frac{m_{(i)}}{m_{(i)} + m_{(ii)}}\right)EYL_{(i)} + \left(\frac{m_{(ii)}}{m_{(i)} + m_{(ii)}}\right)EYL_{(ii)} \qquad (5.3)$$

In Eqn. (4.8), the empirical correlation between the β_1 and β_2 parameter estimates was found to be essentially 0 ($r = 0.020$). Likewise, the empirical correlation between the adjusted salinity and leaching fraction estimates was also essentially 0 across all 19 fields. Thus, assuming that these various parameters are jointly independent, a straight-forward application of the 1st Order Delta Method can be used to derive the approximate variance for the expected yield loss estimates under scenarios (i) and (ii) (Casella & Berger, 2002); i.e.,

$$Var(EYL) \approx \hat{\mu}_1^2 Var(\hat{\beta}_1) + \hat{\beta}_1^2 Var(\hat{\mu}_1) + \hat{\mu}_2^2 Var(\hat{\beta}_2) + \hat{\beta}_2^2 Var(\hat{\mu}_2) \qquad (5.4)$$

Note that these (scenario (i) and (ii)) variance estimates can then be appropriately combined to produce an approximate variance estimate for scenario (iii), etc.

As previous stated, the mean and standard error estimates for the regression model parameters can be obtained from the lower portion of Table 4.6. Table 5.1 below shows the corresponding calculated μ_1 and μ_2 means and standard errors used to construct the EYL estimates for the average under- and over-leaching scenarios, respectively.

Table 5.1. Mean and standard error estimates for the adjusted salinity and quadratic LF effects; used in Eqns. (5.1) and (5.4) to estimate the EYL effects for scenarios (i) and (ii).

Scenario	# of Fields	# of Samples	$\hat{\mu}_1$	$SE(\hat{\mu}_1)$	$\hat{\mu}_2$	$SE(\hat{\mu}_2)$
Under-leached	5	60	0.91142	0.34373	0.00994	0.00677
Over-leached	14	166	0.69017	0.38854	0.06531	0.01410

Based on these estimates, the expected yield loss for a typical under-leached lettuce field in the S. Gila or YCWUA district is 5.62 Mg/ha, with an approximate 95% confidence interval of 1.4 Mg/ha to 9.8 Mg/ha, respectively. The corresponding yield loss components due to excessive soil salinity and under-leaching are 4.34 Mg/ha and 1.29 Mg/ha, respectively. In this under-leaching scenario, about 77% of the projected yield loss in a typical lettuce field is due to salinity. In contrast, the expected yield loss for a typical over-leached lettuce field in the S. Gila or YCWUA district is calculated to be 11.75 Mg/ha, with an approximate 95% confidence interval of 3.6 Mg/ha to 19.9 Mg/ha, respectively. The corresponding yield loss components due to excessive soil salinity and over-leaching are 3.28 Mg/ha and 8.47 Mg/ha, respectively. Thus, in this over-leaching scenario, about 72% of the projected yield loss in a typical lettuce field is due to excessive leaching practices.

On average, the expected yield loss in a typical S. Gila or Yuma lettuce field is calculated to be 10.14 Mg/ha, with an approximate 95% confidence interval of 4.0 Mg/ha to 16.3 Mg/ha. About 6.58 Mg/ha of this expected loss is due to sub-optimal leaching practices (primarily over-leaching), while the remaining 3.56 Mg/ha loss can be attributed to excessive salinity levels.

5.2 Total dollar loss estimates for Lettuce

According to the 2004 crop and water data statistics reported to the Reclamation, the S. Gila and YCWUA districts supported 14,449 Ha (35,694 Ac) of lettuce during the 2004 winter growing season. By combining this information with a gross dollar value for the lettuce yield ($/Mg), a total dollar loss estimate can be produced.

Over the last seven years (1998-2004), the value of lettuce per cwt (100 lbs) has ranged from $12.20 to $38.70, with an average value of $18.40. Assuming that it is reasonable to use the 7-year average price as a typical gross dollar value, 1 Mg of lettuce would have a value of about $406. Thus, given this gross dollar value and total area, a total dollar loss for the two districts can be calculated as

$$\text{TDL} = \text{Cost (\$/Mg)} \times \text{EYL (Mg/Ha)} \times \text{Total Area (Ha)} \qquad (5.5)$$

Using the $406 gross dollar value figure and 14,449 Ha estimate, the total dollar loss estimate across these two districts for the 2004 lettuce growing season was 59.5 million dollars (with an approximate 95% confidence interval of 23.6 to 95.4 million dollars, assuming that the $18.40 average value figure is exact). Note that this 59.5 million dollar loss represents the combined effects of a 20.9 million dollar loss due to excessive salinity levels and an 38.6 million dollar loss due to sub-optimal leaching practices.

5.3 *Apparent leaching fractions across the S. Gila & Yuma districts*

As shown in Table 5.1, 14 of the 19 surveyed fields exhibited calculated field average leaching fractions > 0.3. Table 5.2 below shows a more detailed breakdown of these observed LF estimates by district, using a 4-level LF classification scheme.

Table 5.2. Number of fields in various LF ranges, by district.

	LF < 0.2	0.2 < LF < 0.4	0.4 < LF < 0.6	LF > 0.6
S. Gila	2	2	6	0
YCWUA	0	3	2	4

It is clear from Table 5.2 that a majority of the surveyed fields in both districts exhibited field average LF estimates > 0.4.

The LF estimates for these 19 surveyed fields ranged from 0.11 to 0.74, with a calculated average LF value (across these two districts) of 0.45 (standard error = 0.04). For the S. Gila and YCWUA districts specifically, the calculated average LF estimates were 0.41 and 0.49, respectively. We note in passing that although the average Yuma LF estimate appears to be higher, it is not statistically different from the S. Gila estimate according to a two-sample *t*-test ($t = 1.05$, $p = 0.3103$).

6.0 Summary of Findings

The results from the statistical analyses presented in sections 3, 4, and 5 address the four project objectives presented in the Introduction. To motivate this discussion, recall that these individual objectives were as follows:

(1) To determine the degree of influence that the water table levels exhibit on both the site specific and field average marketable yields.

(2) To determine what relationships exist between the water table levels and the observed site specific and field average soil salinity and leaching fraction levels.

(3) To determine a statistically based salt tolerance model for predicting marketable yield losses due to soil salinity (and/or other soil properties and management practices).

(4) To provide a statistically based estimate of the total dollar loss in lettuce yield due to excessive soil salinity levels and/or leaching practices across the S. Gila and YCWUA districts.

Objective 1:

As shown by the analyses presented in sections 3 and 4, there appears to be no discernable relationship between the kriging predicted field average water table levels and either the field average or site specific marketable yield levels. Additionally, there appears to be no discernable relationship between the shallow versus deep classification codes (based on the nearest Reclamation monitoring well) and either the field average or site specific marketable yield levels. Thus, the shallow water table levels examined in this study do not appear to decrease the marketable yield in any statistically significant sense.

This being said, it should be noted that the shallowest kriging predicted water table level was 7.7 ft, and 15 of the 18 fields sampled for marketable yields exhibited (kriging predicted) water table levels > 10 ft. Normally, water table levels in excess of 8 ft are not thought to substantially influence the soil root-zone, so in this sense these results are not surprising. Additionally, the lack of any fields exhibiting critically shallow water table levels (< 6 ft) precludes us from drawing any conclusions about marketable yield losses under such high risk water table conditions.

Objective 2:

Again, as shown by the statistical analyses presented in sections 3 and 4, neither the kriging predicted or well classification water table index appears to be statistically correlated with the (field average or site specific) soil salinity or leaching fraction measurements. Again, given that the majority of fields appear to exhibit water table levels in excess of 10 ft, these results are neither surprising nor unexpected.

Objective 3:

The results for the ANOCOVA and mixed linear salt tolerance equations are discussed in detail in section 4. The ANOCOVA model includes field specific intercept estimates that account for between-field differences in management practices and a common (threshold adjusted) salinity parameter. This model produces noticeably different salinity parameter estimates which depend upon the specified threshold value. In contrast, the composite salinity / LF mixed linear model produced a very similar adjusted salinity parameter estimates (β_1 = -4.77 for T=0.69; -4.85 for T=1.30) with nearly equivalent standard errors. This latter model also quantifies the non-linear leaching effect for both under- and over-leaching scenarios. A -2LL Chi-square test suggests that the 0.69 dS/m salt-threshold model produces the best fit to the observed lettuce yield data. This model predicts that for each unit increase in the root-zone soil salinity level (above 0.69 dS/m), there will be on average a 4.77 Mg/ha reduction in marketable yield.

As shown by the preliminary mixed linear modeling results (Eqns. 4.1 and 4.2), the soil salinity appears to be the only *site specific* soil property influencing the marketable yields. However, the adjusted, *field average* leaching fraction variable was also found to be significantly correlated with both the field average and site specific yield levels (see Tables 3.1, 4.3, 4.5, 4.6 and Figure 3.2). Thus, we can also conclude that sub-optimal irrigation represents one of the detrimental management practices that appears to be reducing the marketable lettuce yields across the S. Gila and YCWUA districts.
As discussed in section 5, this effect is actually more significant than the current salinity hazard in the typical over-leached field, since nearly 72% of the projected yield loss in such a field appears to be due to excessive leaching.

It is well known that excessive leaching tends to strip away the beneficial nutrients needed for optimal plant growth. However, the magnitude of this leaching effect is somewhat surprising (at least in comparison to the salinity effect). More specifically, this data strongly suggests that the typical leaching strategy currently being practiced within these districts (for controlling soil salinity) is actually detrimental to the overall profit margin. In this study, fields with higher than normal leaching fractions ($LF_{ave} > .45$) did not exhibit consistently low salinity levels. However, these same fields did consistently exhibit lower marketable yield levels. Thus, this survey data clearly refutes the idea that the salinity hazard in these districts can be mitigated by simply using more water.

Objective 4:

Based on the analysis presented in section 5, the expected yield loss for a typical under-leached lettuce field in the S. Gila or YCWUA district is 5.62 Mg/ha, with an approximate 95% confidence interval of 1.4 Mg/ha to 9.8 Mg/ha. About 4.34 Mg/ha of this loss appears to be due to excessive salinity levels. The expected yield loss for a typical over-leached lettuce field in the S. Gila or YCWUA district is calculated to be 11.75 Mg/ha, with an approximate 95% confidence interval of 3.6 Mg/ha to 19.9 Mg/ha, respectively. However, about 3.28 Mg/ha of this loss again appears to be due to excessive salinity levels. Thus, very little reduction in the salinity hazard appears to have been achieved. In contrast, the yield loss incurred due to sub-optimal leaching increases from 1.28 Mg/ha to 8.47 Mg/ha. Additionally, in this over-leaching scenario, about 72% of the projected yield loss in a typical lettuce field is due to excessive leaching practices.

On average, the expected yield loss in a typical S. Gila or Yuma lettuce field is calculated to be 10.14 Mg/ha, with an approximate 95% confidence interval of 4.0 Mg/ha to 16.3 Mg/ha. We estimate that about 6.58 Mg/ha of this expected loss is due to sub-optimal leaching practices (primarily over-leaching), while the remaining 3.56 Mg/ha loss can be attributed to excessive salinity levels. Thus, assuming a $406 gross dollar value figure (for 1 Mg of lettuce) and the reported 14,449 Ha area production estimate, the total dollar loss estimate across these two districts during the 2004 lettuce growing season was 59.5 million dollars (with an approximate 95% confidence interval of 23.6 to 95.4 million dollars, assuming that the $18.40 average value figure is exact. This 59.5 million dollar loss represents the combined effects of a 20.9 million dollar loss due to excessive salinity levels and an 38.6 million dollar loss due to sub-optimal leaching practices.

Given that the potential field average lettuce yield is 53.6 Mg/ha (as predicted by Eqn. 4.8, see Table 4.6), the total achievable gross dollar value of lettuce production in the S. Gila and YCWUA districts is approximately 314.4 million dollars (assuming no losses due to salinity or excessive leaching, and an average dollar value of $18.40 per cwt). Assuming this study data is representative of the current (district-wide) salinity hazards and leaching practices, the current realized gross dollar value of lettuce production is 314.4 – 59.5 = 254.9 million dollars. Thus, the growers in these two districts are effectively incurring about a 19 % reduction in potential yield due to their salinity and irrigation management practices.

Additional Comments:

Since excessive leaching practices appear to be causing significant yield losses, improving the general irrigation management practices within these two districts certainly seems warranted. More specifically, growers should find it financially advantageous to adopt irrigation practices that improve the uniformity and/or reduce the aerial extent of excessively leached zones. However, we wish to clearly state that this study data by itself does not answer the "optimal leaching fraction" question. For example, even though the yield data analyzed in this study suggests that the optimal leaching fraction is around 0.3, this estimate does not necessarily imply that irrigation volumes of 30% above the expected ET are ideal. To conclusively answer this latter question, one needs to also examine the actual water balance data (since issues like bypass and/or tail water run-off also need to be accounted for).

Note withstanding the above limitations, the field average leaching fraction estimates can still be used in a relative sense to provide a rough estimate of the percentage of under- and over-leached lettuce fields across the two districts. For example, supose that field average LF estimates < 0.2 represent under-leached fields and LF estimates > 0.4 represent over-leached fields. Then this survey data suggests that about 11 % of the fields across these two districts are currently under-leached and about 63 % of the fields are over-leached. As pointed out already, these over-leached fields do not appear to exhibit significantly reduced salinity levels. However, they do tend to exhibit increased variability in the site-specific LF measurements, implying that the leaching is highly non-uniform within these fields.

Finally, it is worth re-iterating that the current LCRSAN surveying techniques are ideally suited for supplying rapid and reliable inventory information to the growers throughout these two districts. This surveying technology can be used to accurately map the within-field salinity pattern and also quantify the apparent leaching uniformity. Such information can in turn be used to adjust the current irrigation practice(s), which in principle should result in the more optimal use of the available water resources.

7.0 References

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