INDIRECT ESTIMATES OF SOIL ELECTRICAL CONDUCTIVITY FOR IMPROVED PREDICTION OF WHEAT GRAIN YIELD

By

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TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

APPENDIX

Figure Page

Table Page

Indirect Estimates of Soil Electrical Conductivity for Improved Prediction of Yield

Abstract

A system of midseason yield prediction of winter wheat grain yield based on sensed plant growth properties has been established. However, little research has been conducted to determine the relationship of grain yield, sensed plant data, and soil electrical conductivity (EC). This study was carried out to determine if soil EC is useful in better predicting wheat grain yield. During 2001 and 2002, measurements of soil EC, normalized difference vegetative index (NDVI), and grain yield were taken on five long-term soil fertility experiments across Oklahoma. Results indicated that soil EC was not better than NDVI at predicting grain yield at any location or year. A combination of soil EC and NDVI was also less correlated with grain yield than NDVI alone. Therefore, this study showed that pseudo-static soil EC measurements were not useful for predicting dynamic winter wheat grain yields.

Introduction

Application of variable rate technologies (VRT) for agricultural production are becoming more apparent. Increased fertilizer costs, growing environmental concerns, and pressure to increase production on less land have resulted in a need for alternatives to current management schemes. Identification of yield level and fertilization based on this expected yield is an important aspect of nutrient management which should result in higher use efficiencies and less environmental impact.

Methods for obtaining representative soil samples have been developed over many years. The most widely used method involves obtaining 15-20 soil samples which are then mixed together to obtain a representative sample for the field. One common example of this method is that provided by Zhang and Johnson (1998). This method assumes field-level heterogeneity. This assumption is validated by a visual observation of a field of wheat with some degree of soil nitrogen heterogeneity which shows that the response to soil variables (in this case, nitrogen) is very different from one section of the field to another. However, according to Solie et al. (1999), the variability of selected parameters such as total soil N, extractable P and K, organic C and pH was found to be significant at the meter to sub-meter level. This leads one to the conclusion that while the most common methods of treating soil variability, while better than nothing, may need refinement.

Current work evaluating nitrogen (N) use in winter wheat uses canopy reflectance to estimate final grain yield (Lukina et al., 2001). A normalized difference vegetation index (NDVI), which has been shown to be strongly correlated with N uptake, is obtained at Feekes 5. This combined with a consideration of environmental conditions conducive to plant growth measured as days from planting to sensing where growing degree days (GDD) are >0, results in an reliable estimate of final grain yield. In-season estimate of yield (INSEY) is calculated as follows:

INSEY = (NDVI/days from planting to sensing where GDD>0)

The equation can however be improved upon. Identification of soil parameters such as soil moisture capacity and soil texture could be added to the existing INSEY equation to improve yield prediction, provided that this kind of data can be collected at the same resolution.

Kachanoski et al. (1988) have shown that field scale measurements of electrical conductivity (EC) are strongly correlated to soil moisture holding capacity and Williams and Hoey (1987) demonstrate the correlation of EC with soil textural properties. The objective of this work is to measure bulk soil EC at the field level using the Veris EC instrument and to evaluate the correlation of grain yield with EC. The existing yield prediction equation will be infused with this information to determine if inclusion of EC data improves yield prediction.

Literature Review

Soil and plant laboratory testing has been agricultural scientists' main tool for "seeing" the nature of a particular soil or plant. Whether it be pH, cation exchange capacity, N, NO_3-N, phosphorus (P), potassium (K), micronutrients or a number of other factors, soil and plant lab testing has been and will continue to be useful.

Until recently, variability of soil parameters such as NO_3-N, Organic Carbon, PO_4-P, Soil Water Content, and K have been unknown. Several studies have been conducted within the past 10 years to determine the resolution at which there is significant difference in soil test parameters.

However, advancements in technology, and the skill to interpret the data that certain technologies will yield, has opened a whole new science of non-destructive, non-intrusive diagnostic tools. Of those tools, the one of interest here is the spectral reflectance readings on plants and their correlation to yield data. Lukina et al. (2001) made substantial progress in this area by reporting on a method to determine fertilizer N rates using estimates of early-season plant N uptake and potential yield determined from in-season spectral reflectance measurements collected between January and April. The red (671 ± 6nm) and near infrared (780 ± 6nm) reflectance readings were collected from 9 winter wheat experiments that were used to refine estimates of early-season plant N uptake at or near Feekes growth stage 5 and from 16 experiments to refine estimates of potential grain yield. The values for the reflectance readings were used in a normalized difference vegetation index (NDVI) to correct errors due to cloud cover, shadows and sun angle. NDVI is calculated as follows: $NDVI = [(NIR_{ref}/NIR_{inc}) - (Red_{ref}/Red_{inc})] / [(NIR_{ref}/NIR_{inc}) + (Red_{ref}/Red_{inc})]$, where NIR_{ref} and Red_{ref} = magnitude of reflected light, and NIR_{inc} and Red_{inc} = magnitude of the incident light. For the early season plant N uptake experiments, $1m^2$ plots were immediately hand clipped after sensing and analyzed for total N. Potential grain yield experiments were sensed in 4m^2 areas during the growing season, then grain was harvested and recorded from those areas. The results of this study indicated that NDVI was an excellent predictor of early season N uptake and that NDVI was also positively correlated with final grain yield. This work also focused on an index known as in-season estimated yield (INSEY) computed by the equation NDVI from Feekes 4 to 6/days from planting to sensing where growing degree days are >0. (GDD = $[(T_{min} + T_{max})/2 - 4.4^\circ C]$ (T_{min} and T_{max} being recorded from daily data). The ability to predict potential grain yield was then used in the nitrogen fertilization optimization algorithm (NFOA) which would produce an N fertilization rate based on predicted need. The potential for field application of this technology is great. However, the INSEY equation stands to be improved.

The basis for treating the soil at such a small scale is found in the fact that many soil parameters vary greatly at the meter and submeter level (Solie et al.,1999; Raun et al., 1998). In these studies, soils were sampled at a very minute scale (0.3- by 0.3-m) over a 2.13 by 21.33m area. The resulting soil test parameters such as total soil N, extractable P and K, organic C and pH were found to have large differences over small distances (< 0.3m).

Geologists and other scientists have been using soil EC measurements during the 20th century for finding archeological sites, pollution borders, and bedrock locations and type. However, the literature for agricultural use of soil EC measurements is quite "recent" (1970's), meaning that scientists are just beginning to learn about and correlate the EC data that they can record. Most recent articles on agricultural soil EC have referenced Williams and Hoey (1987) where it was discovered that both total soluble salts and <2µm clay material was correlated with apparent EC values. Since then other soil properties have been measured including depth to claypan (Doolittle et al. 1994), soil water storage capacity (Kachanoski et al. 1988), saline-seep areas (Halvorson and Rhoades 1974), cation exchange capacity (McBride et al. 1990), and herbicide behavior in the soil (Jaynes et al. 1994). Kitchen et al. (1999) investigated the soil EC/claypan/yield relationship. This study noted that topsoil thickness was related to a transformed EC ($1/EC_a$) and that there was a significant relationship between EC_a (apparent EC) and grain yield. However, they were quick to append that climate, crop type, and specific field information was also needed to explain the interaction between EC_a and potential yield. It appears that the interaction between EC_a, rooting zone depth, and crop yield is the main conclusion of their work.

The reproducibility of Veris 3100 EC readings over multiple years is very important. In a paper presented at the Wisconsin Fertilizer, Aglime and Pest Management Conference in 2001, Tom Doerge cited Lund et al., 1999 that the soil EC patterns obtained from a field are stable over time, and do not change significantly. Doerge goes on to note that relative accuracy is maintained unless some major soil movement by man or nature occurs. The usefulness of the Veris 3100 EC instrument is built on the ability of the system to reproduce similar results (field patterns, maps, *etc.*) from year to year. This is also important to the farmer in that if he obtains an EC map with the Veris instrument and is told that the data he receives is fairly accurate for a number of years, he will most likely make management decisions with that data. Should the data prove to be unreliable from year to year, the farmer will be faced with having to obtain a new set of Veris data, or continue making management decisions with the inaccurate measurements. However, if the Veris instrument data (and their patterns) are found to be statistically the same from year to year, the return on investment to the farmer could be very good.

Objective

The primary objective of this study was to improve the INSEY equation by use of EC data obtained from the fields. Raun et al. (1998) have shown that there is significant soil test variability among <1m^2 areas. The work noted before has correlated EC with various soil parameters including depth to claypan, soil water storage capacity, saline-seep areas, and CEC. Therefore, the EC data gathered using the Veris instrument should yield a set of data for each field that indirectly integrates differences in several soil parameters. This would in turn explain potential problems encountered by making fertilizer recommendations/applications by plant-sensing only, without direct reference to various soil parameters. For example, if the application of nitrogen is made based upon a predicted yield in winter wheat, and after the date that it is applied, area rainfall is much less than average, predicted yield may then be taxed based upon a calibrated EC reading that accounts for clayey texture.

Materials and Methods

This study was concerned with 5 long-term soil fertility study sites in Stillwater (222, 301, AA NUE), Perkins (N & P), and Haskell (801). (See Table 1 for soil characteristics at these locations) At each of these sites, soil EC readings were taken with a Veris 3100 EC Soil Mapping instrument during the summers of 2001 and 2002. Before the 2002 readings were taken, the instrument was tested with an Instrument Test Load and Implement Test Box to ensure that it was functioning properly. The Veris instrument uses 6 rotating soil-contacting discs placed approximately 6cm in the soil. One pair of discs (discs 1 and 5) passes an AC current (at 150 Hz, open circuit voltage of 25 volts) into the soil, while the other two pairs measure the drop of the current (See Figure 1). The Veris 3100 is capable of measuring both a shallow EC (0 - 30.5cm) and a deep EC (0 – 91.4cm). The EC data taken from the readout is in mS m^{-1} with no need for any calculation. The data was geo-referenced using a Trimble AgGPS with differential correction (DGPS). Speed across the field was approximately 4.8 kph, giving 1 sample for every 1.5m, and swaths were the distance of the Veris cart (2.3m).

This data was integrated into a field map for visual and statistical comparisons with plot plans using SSToolbox programs. The various

DGPS referenced points and EC data were converted into a surface grid of 4 by 4m over the whole of each site using the inverse distance function. A surface grid was made for shallow 2001, deep 2001, shallow 2002, and deep 2002 readings at each site employing an inverse distance function. The EC data used in statistical analysis were obtained by several steps. First, GPS readings were taken to determine the exact place of the YP plots since the data were taken over the whole field with no reference to a plot map. Once the YP plots were accounted for, the Veris readings were selected within the YP area to obtain an average value for either the surface grids, or the specific data points. Contour maps for visual and statistical comparison of 2001 and 2002 Veris readings were also produced and analyzed.

Soil samples of each yield potential plot within each different experiment were taken before fertilization in the fall of 2001 and analyzed for organic C, pH, EC, NH_4-N, NO_3-N, P, K and total N. Following harvest, stepwise regression was used with these variables to identify the best predictor of yield with either single variables or a set of variables.

Winter wheat (*Triticum aestivum* L.) was planted in these fields at 78 kg ha $^{-1}$ with 0.19m row spacing, NDVI readings were taken at Feekes 4, 5, and between 6 and 7. These spectral measurements were taken from the yield potential (YP) plots in each experiment. YP plots were 2 x 2m within larger existing long-term experimental plots. Separate NDVI readings were taken on these plots and they were harvested separate from the larger plots. The reflectance measurements were taken in two bands, RED (671 ± 6nm) and near infrared ((NIR) 780 ± 6nm) bandwidths (Stone et al., 1996). To obtain the In Season Estimate of Yield (INSEY) equation, Growing Degree Days (GDD) were calculated as follows: $GDD=[(T_{min} + T_{max})/2-4.4°C]$. The equation is represented as follows: INSEY = NDVI (Feekes 4 to 6)/days from planting where GDD>0. (Raun *et al.*, 2002). Statistical analysis using NDVI, INSEY, and yield with EC were used to begin to evaluate the use of Veris EC data in improving the prediction of yield. (SAS Institute, 1999). Weather data was also collected in 2002 for the week prior to taking the EC measurements. (See Table 2).

Results and Discussion

Veris Reproducibility

The collection of data from the Veris EC instrument was completed in 2002. One of the first things observed with this data was that patterns seen in the experiment in one year were also observed in the next, though at differing intensities (See Figure 2), and although the patterns were similar, definite differences were present when studied at a small scale. Though the year-to-year likeness was the case in most of the experiments, there were exceptions as in Figure 3, which shows range differences in the 2001 and 2002 Veris deep EC at the Efaw 301 site. At this site there were some dissimilar trends within the two contour plots as can be seen at the higher Veris deep EC locations in the upper center section. In this section, the high values are most likely due to very high rates of sewage sludge applied as nitrogen treatments in the fall. It was also noted that the Veris deep EC readings in that area during 2002 were more varied than the previous year.

To determine whether the patterns were significantly different, statistical analysis was done on four of the experiment sites. The data from these sites was made into a surface of 4 by 4m grids using an inverse distance function. The resulting sets of data for both shallow and deep were graphed, regressed on one another, and analyzed to determine if the slope was equal to one. If it did not equal one, that would infer that from one year to the next the data was not static, but only represented significant patterns in the field. The results from this analysis can be seen in Figures 4 and 5. Although the graphs definitely display a year to year trend, the statistical analysis shows that the slope of both lines was significantly different from 1 (PR > t, 0.01), especially for the Veris shallow readings. This suggests that from 2001 to 2002 the Veris readings changed relative to each other. This would perhaps lead one to call into question the reproducibility of the Veris EC readings over a long period of time. This would perhaps indicate why a key point was made by Doerge (2001) that the *patterns* of EC that are the most stable, while the various *points* might not be significantly the same between years. However, if a static variable is to be used over a period of say 10 years for managing inputs, it needs to be unaffected by time. These results clearly show that the Veris readings were significantly altered from one year to the next, even though the readings remained highly correlated with each other.

The Veris data were also tested for normality and the results indicate that over locations and years, not one location or year was normally distributed. Several of the sites had left skewed distributions, and one site (Efaw 301, 2001, deep EC) had a bi-modal distribution.

Soil Test Data Relationships

Initial 15 cm deep soil test data and lab results from 2001 are represented in Table 1. Simple linear regression analysis was performed on organic C, pH, Lab EC (µS/m), NH_4-N, NO_3-N, P, K, total N, Veris shallow, Veris deep and grain yield (see Table 3). One interesting observation was that the EC readings obtained from the lab (via saturated paste extract) were not related to grain yield. It is important to note that the Veris EC instrument integrates combined effects of soil parameters such as water content, clay content, and salts in solution, whereas the lab EC reading is strictly a measurement of dissolved salts or salinity. Lab EC itself was not significantly related to yield. However, the Veris shallow reading was correlated with the lab EC with a coefficient of 0.48. Also, the Veris deep reading was not related to the lab EC. The most significant correlation of soil test data with yield was NO_3-N (coeffecient of 0.936). The reason behind this is most likely due to the application of high N rates in the Haskell 801 long-term fertility experiment in which the plots receiving high N rates have severely reduced yields. It was noted also that significant correlations existed between yield and NH_4-N, K, and pH.

Grain Yield and Veris Readings

The relationship between Veris readings and grain yield could be important, even though many other independent variables may be helpful in refining yield prediction models. In the beginning steps of this research, the relationship between simple Veris shallow or deep readings was observed graphically and statistically. The linear relationship between Veris shallow and deep readings with grain yield are illustrated for all years in Figures 6 and 7. Neither Veris shallow nor deep readings were correlated with grain yield. However, though there was no consistent correlation over sites, there were two site-years that were significant: 222 shallow Veris EC with Grain Yield, and 801 both shallow and deep Veris EC with Grain Yield (see Table 4). Regarding the 801 site in Haskell, OK, with an increase in Veris EC, there was a decrease in yield. This was mainly due to the high rates of applied N on several plots in the experiment that has caused dramatic yield reductions due to excessive salt accumulation.

Surface Response Models

In Figures 8 and 9 the quadratic surface response model for NDVI and Veris shallow readings in 2001 and 2002 are illustrated. Surface response models were evaluated using shallow and deep Veris readings and other independent variables that included NDVI and various transformations of

Veris shallow and deep readings to better predict wheat grain yield. For both years the model was highly significant, but as seen in Figures 7 and 8, they were vastly different. The response in grain yield to changes in NDVI and Veris shallow was altered from one year to the next, thus restricting their temporal use.

The other independent variables evaluated in surface response models were: Veris deep, Veris shallow*Veris deep, Veris shallow/Veris deep, Veris deep/Veris shallow, Relative Veris shallow/Relative Veris deep. Relative Veris shallow and Relative Veris deep consisted of 1) dividing all data points at a specific site by the maximum reading, or 2) dividing all data points at a specific site by the minimum reading. The rationale behind Relative Veris calculations was to provide a transformation that would take into account the differences around the mean, thus in a sense, normalizing the data. All of these transformations showed less significant trends, and none yielded a better model than Veris shallow and NDVI with grain yield.

Stepwise Regression Analysis

Soil test data, Veris EC readings, NDVI and INSEY readings over all sites and years were all entered into a stepwise regression procedure to obtain possible variables that would improve the prediction of yield. Those variables that were found to best predict yield were NDVI, soil NO_3-N and Veris deep EC. The following equation using those three variables was obtained: Yield = -1.418 – 0.0037 (deep) – 0.0066 (NO3-N) + 6.811

(NDVI). This equation had an R^2 of 0.71. Although it was stated before that Veris deep readings were not correlated with grain yield, it appears that the deep readings did improve grain yield prediction a small amount.

Problems Encountered

One problem that was encountered during the data collection was the relative spatial coarseness at which the Veris EC instrument takes readings. For instance, the YP plots are 2 x 2m whereas the Veris EC toolbar was 2.3m in width. Since the surface grid made by the Veris EC instrument exists at a 4 x 4m resolution and the YP plots exist at a 2 x 2m resolution, for any surface made in SSToolbox the bulk EC for a YP plot needed to be interpolated often from several cells of the surface grid. Regarding predicting yield with Veris EC, this is the reasoning behind using the various 'points' obtained from the Veris instrument via the DGPS readings rather than the EC data obtained by the surface grids. The actual data points within (or nearest to) the YP plot provided the useable bulk EC data for determining if EC data helps improve yield prediction. The surface grids were however used for Veris reproducibility determination.

Another difficulty encountered was the lack of soils data taken at the time of the Veris EC readings. It would have been advantageous to have the YP soil samples in conjunction with the Veris EC readings all taken at the same time. However, there were routine soil samples taken in 2001 which were used to explore the connection between Veris EC, soil data and yield.

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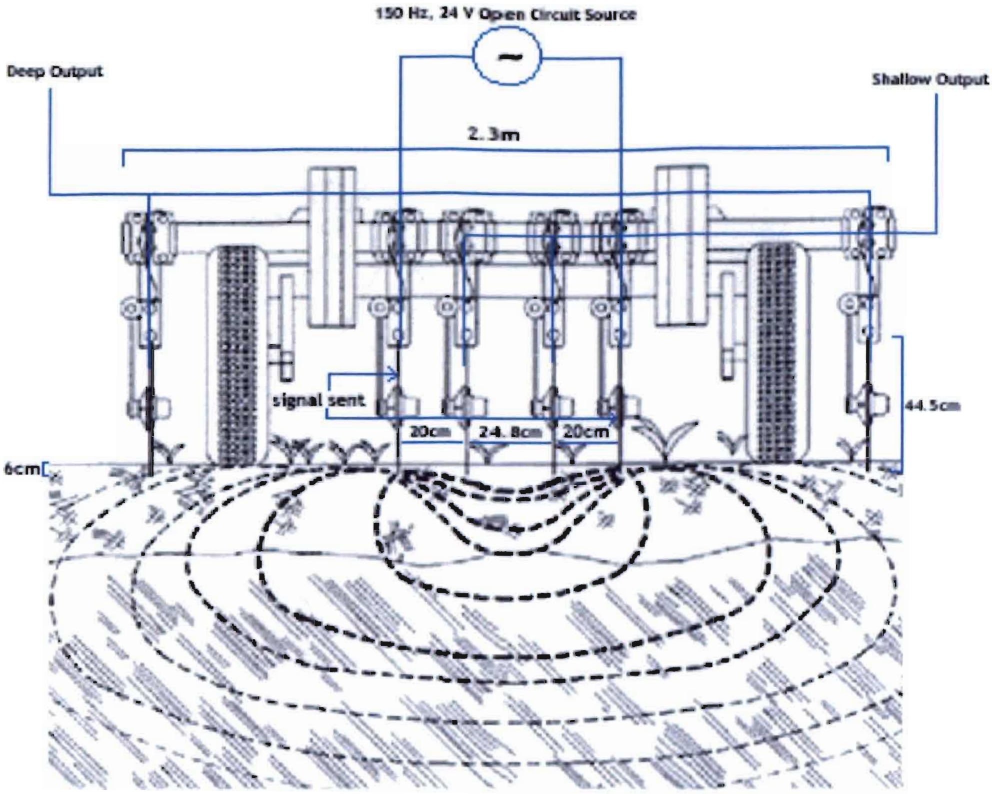
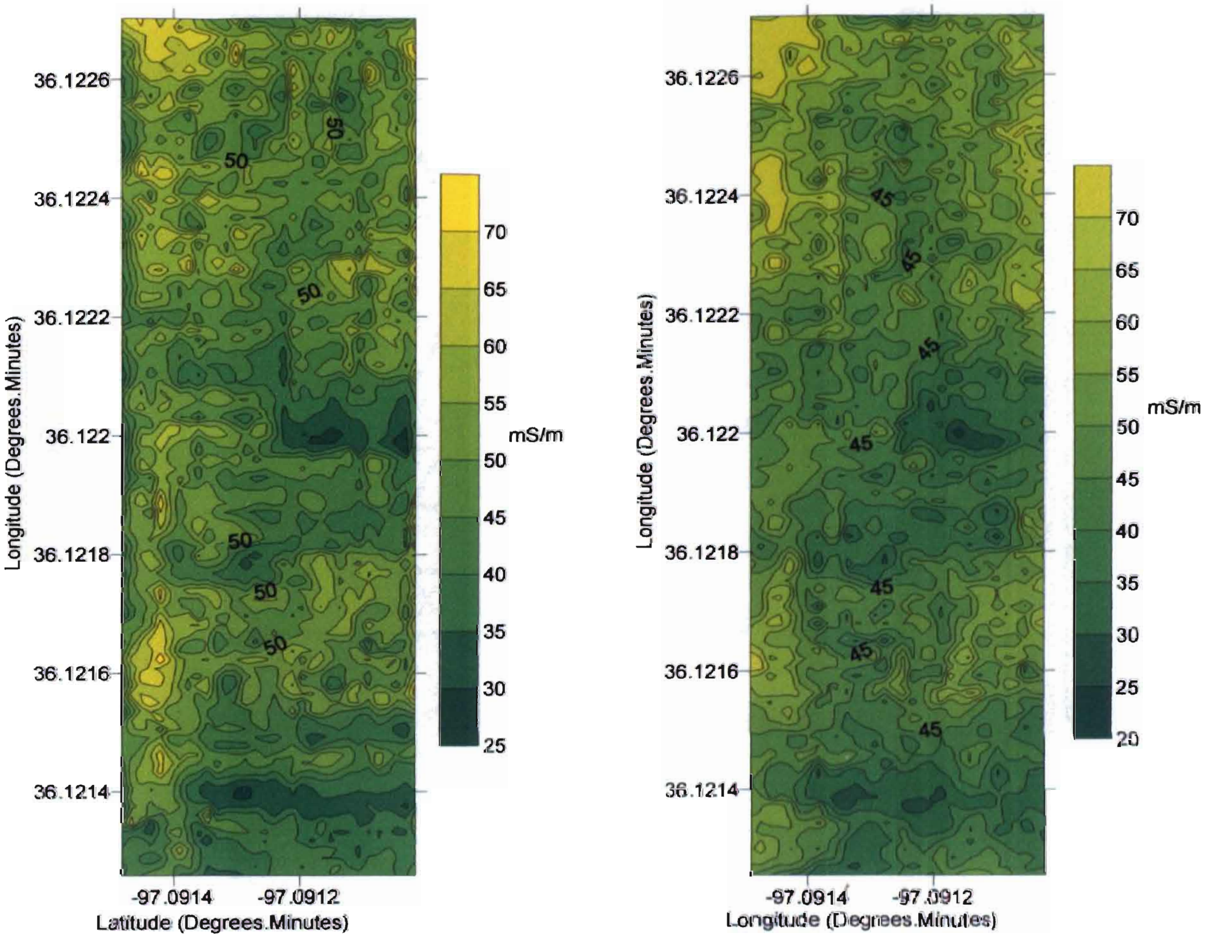


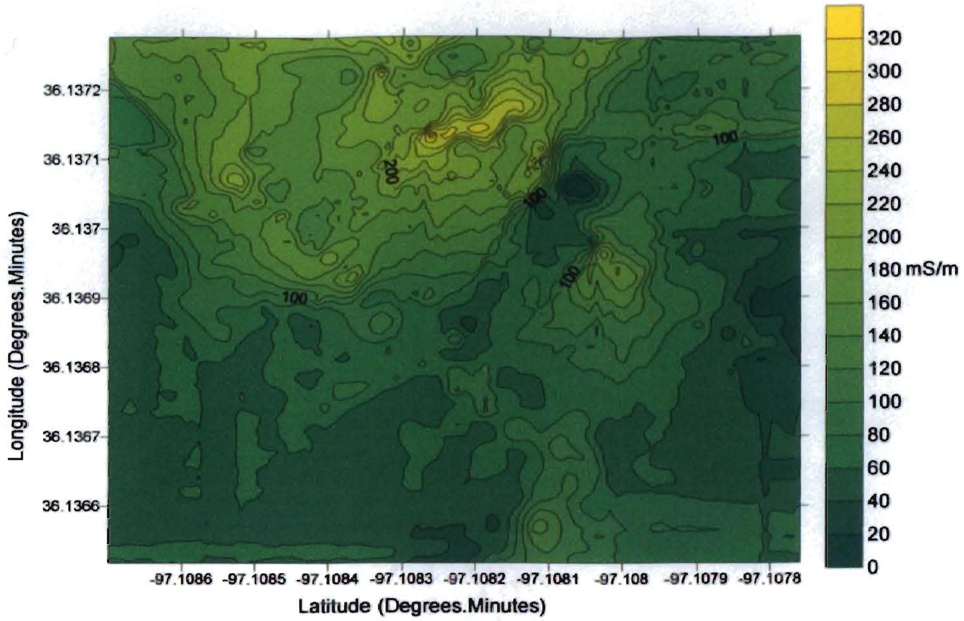
Figure 1. The array of discs on the Veris EC instrument along with electrical current layout. (www.veristech.com/faq.htm)



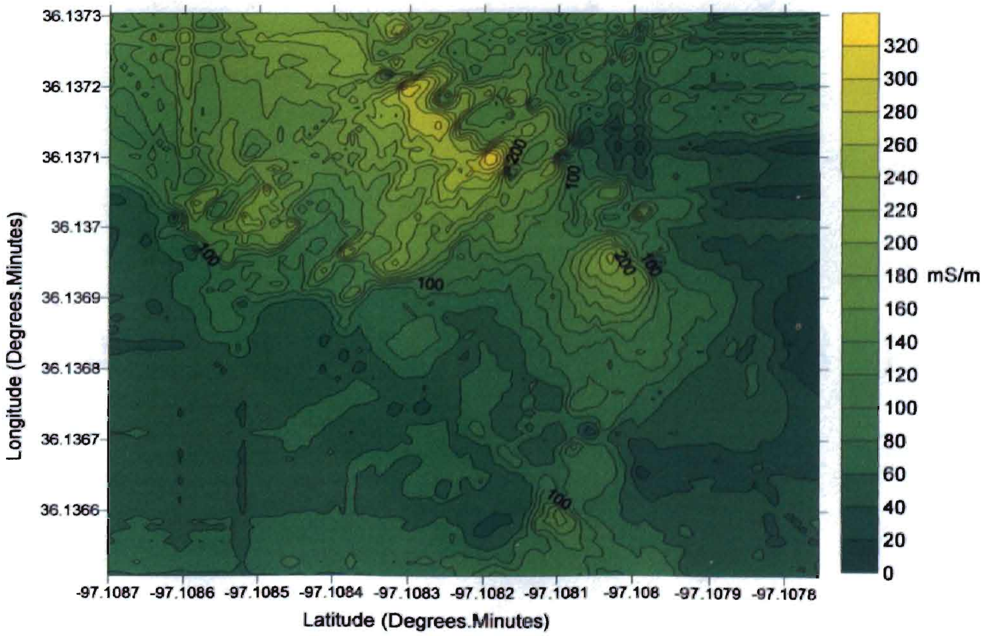
2002 Veris shallow EC

2001 Veris shallow EC

Figure 2. Veris shallow EC contour maps from 2001 and 2002, Stillwater, Oklahoma 222 site.



2001 Veris deep EC



2002 Veris deep EC

Figure 3. Veris deep EC contour maps from 2001 and 2002, Stillwater, Oklahoma Efaw 301 site.

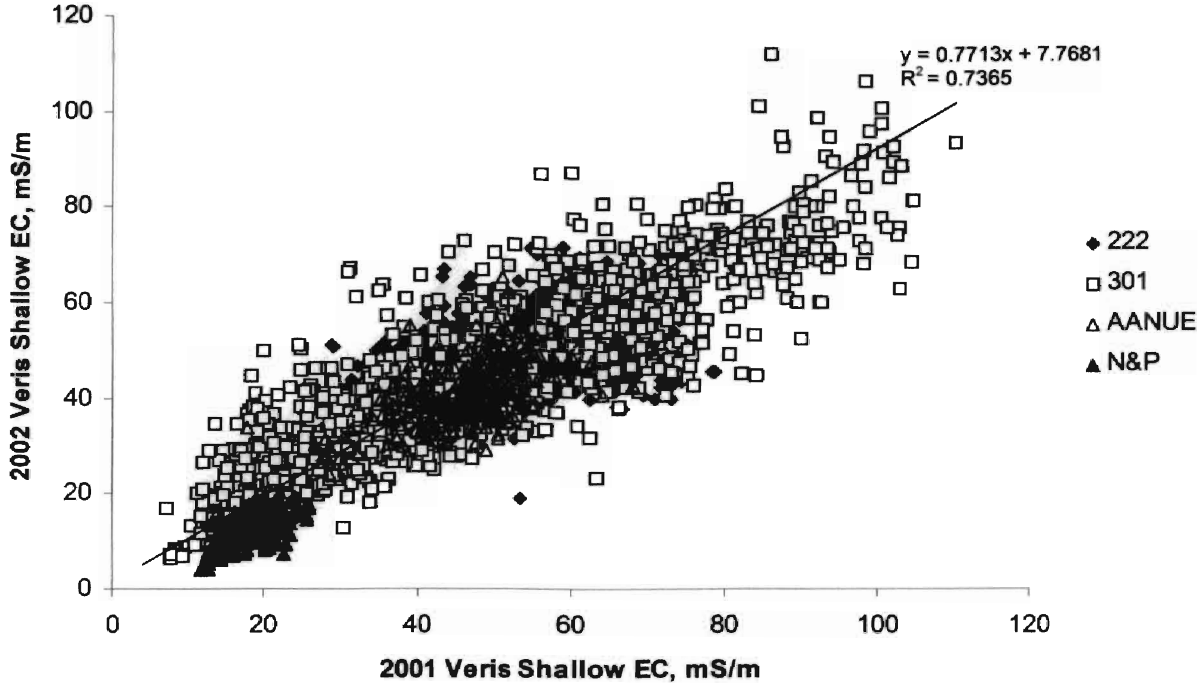


Figure 4. The relationship between 2001 and 2002 Veris shallow readings at Stillwater 222, Efaw 301, Efaw AANUE, and Perkins N&P, Oklahoma.

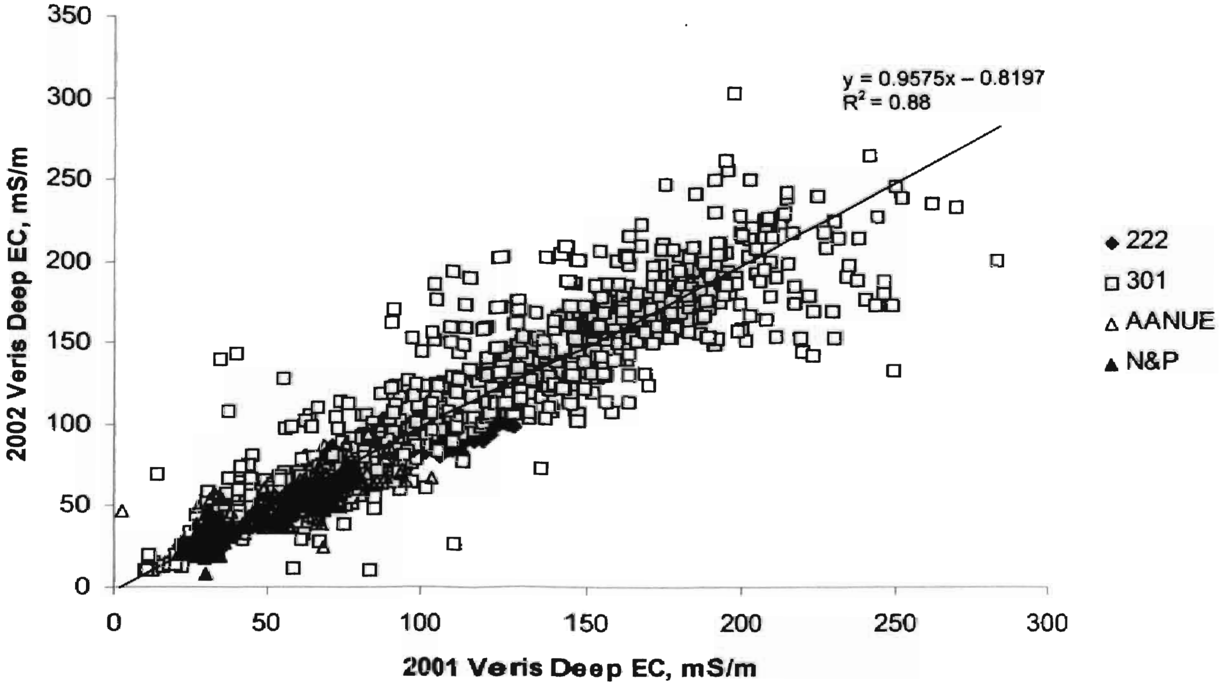


Figure 5. The relationship between 2001 and 2002 Veris deep readings at Stillwater 222, Efaw 301, Efaw AANUE and Perkins N&P, Oklahoma.

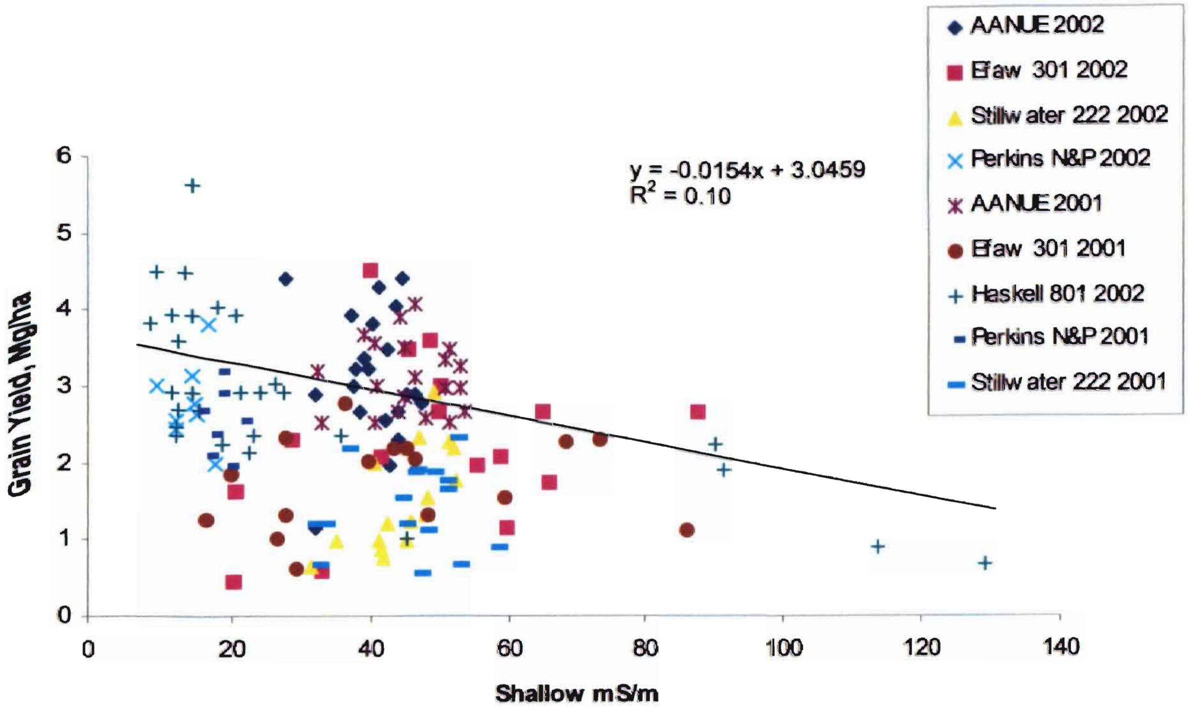


Figure 6. Relationship between Veris shallow EC and grain yield at Perkins N&P, Stillwater 222, Efaw 301, Efaw AANUE and Haskell 801, Oklahoma, 2001-2002.

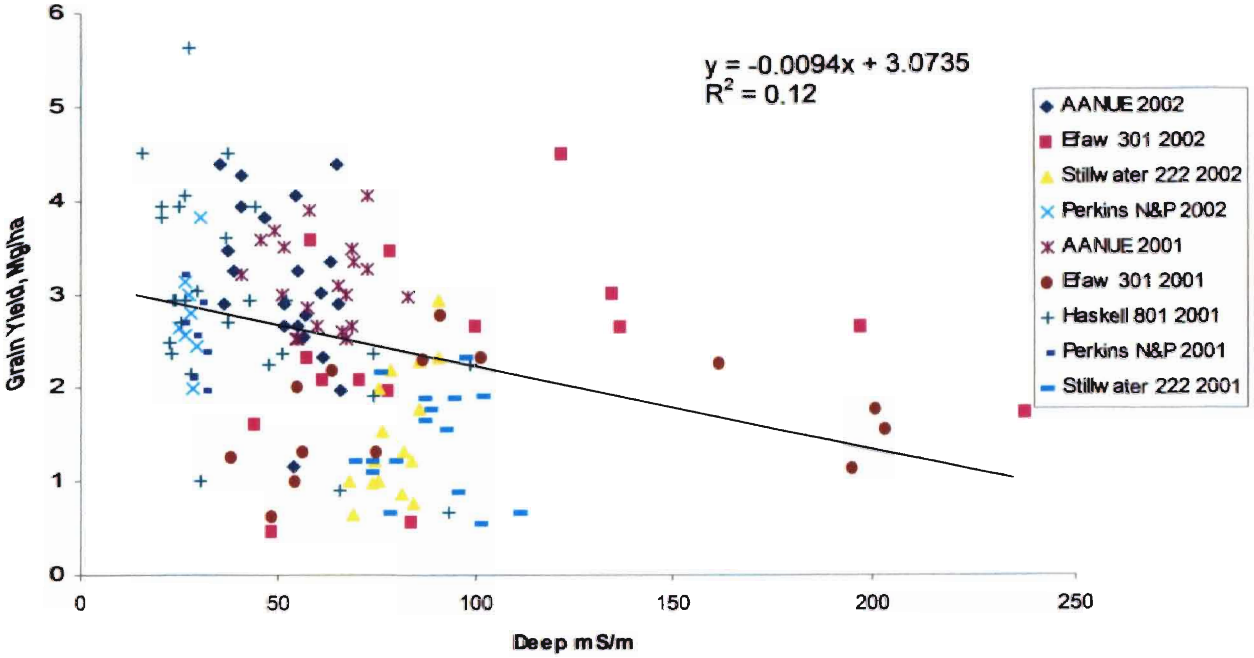


Figure 7. Relationship between Veris deep EC and grain yield at Perkins N&P, Stillwater 222, Efaw 301, Efaw AANUE and Haskell 801, Oklahoma, 2001-2002.

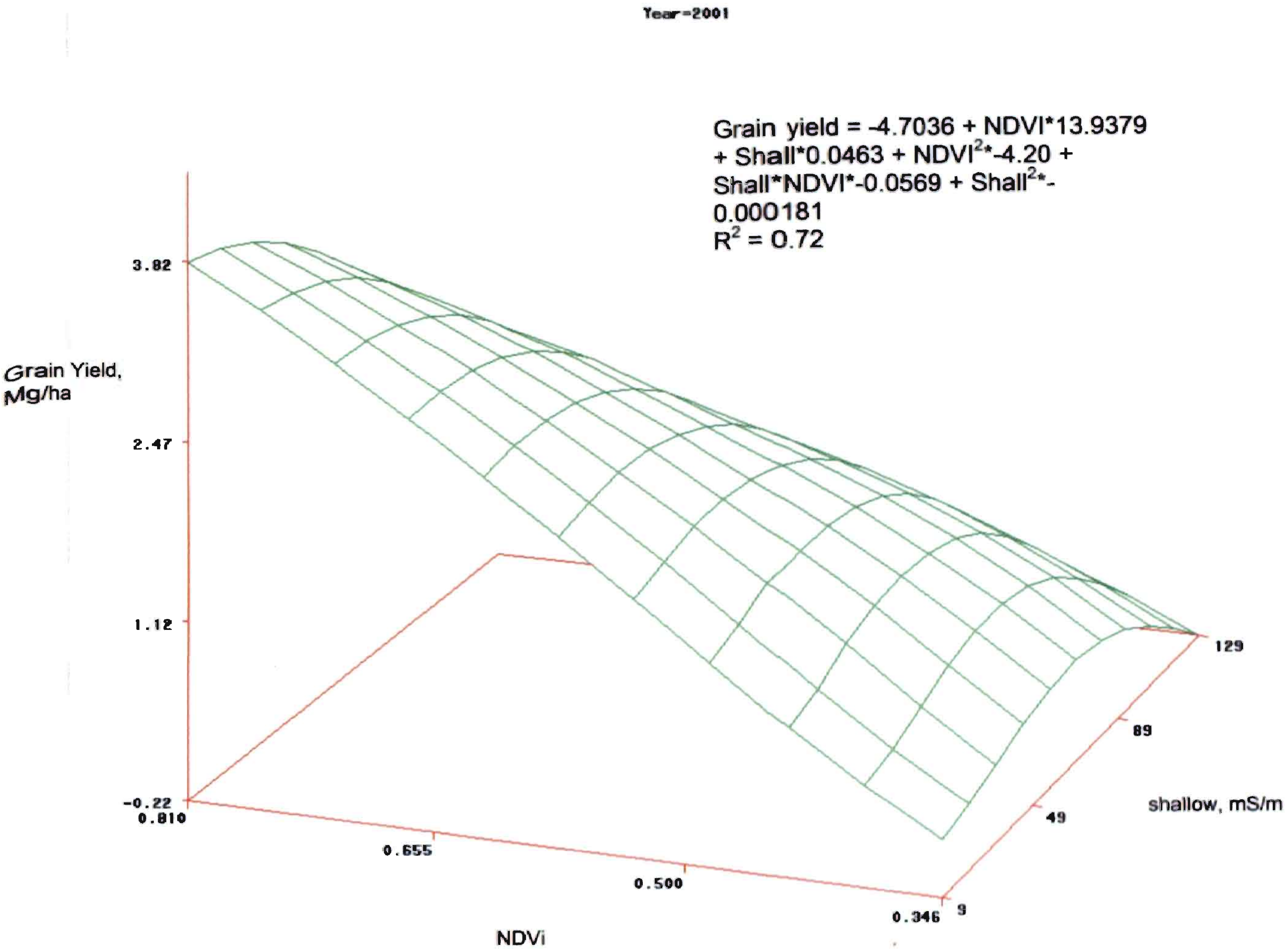


Figure 8. Surface response model for Veris EC shallow and NDVI versus grain yield in 2001 at Perkins N&P, Stillwater 222, Efaw 301, Efaw AANUE, and Haskell 801, Oklahoma.

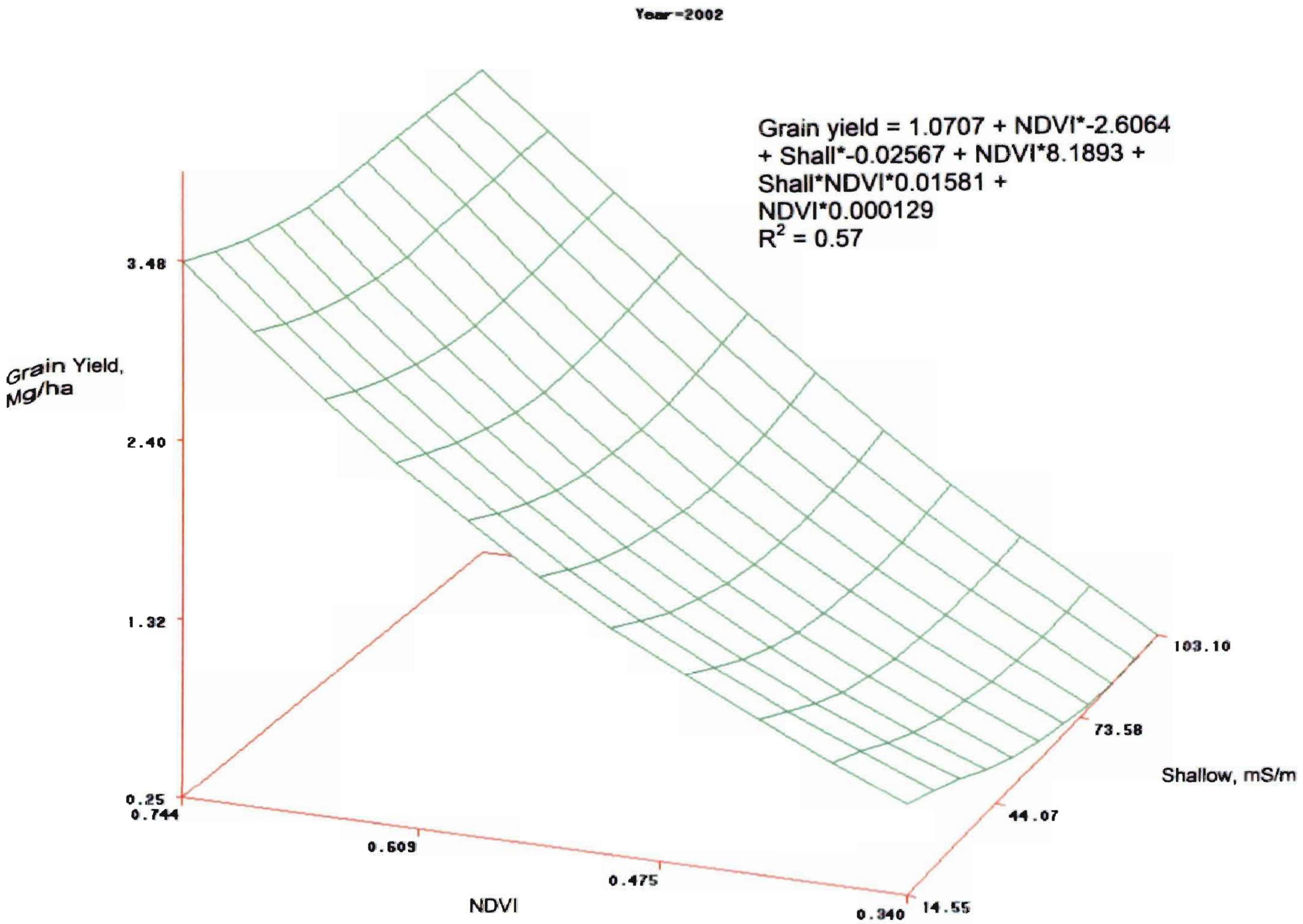


Figure 9. Surface response model for Veris shallow EC and NDVI versus grain yield in 2002 at Perkins N&P, Stillwater 222, Efaw 301 and Efaw AANUE, Oklahoma.

Table 1. Initial surface (0-15) soil test results for the Efaw, Haskell, Perkins, and Stillwater sites, 2001.

Location	N-P-K	PH	NH_4-N	NO_3-N	P	K	Total N	Organic C
			----------------mg kg^{-1}----------------				-----------g kg^{-1}---------	
Efaw AA	Check	6.0	2.5	11.3	19.9	197	0.94	10.4
Classification: Easpur loam (fine-loamy, mixed, superactive, thermic Fluventic Haplustoll								
Efaw SS	Check	5.8	6.9	5.0	30.2	16.8	1.06	11.9
Classification: Norge loam (fine mixed, thermic Udertic Paleustoll								
Perkins N&P	Check	5.4	2.6	9.1	16.5	132	0.79	7.0
Classification: Teller sandy loam (fine-loamy, mixed, thermic Udic Argiustoll)								
Stillwater 222	Check	5.9	12.0	8.6	31.8	462	0.86	7.9
Classification: Kirkland silt loam (fine-loamy, mixed, thermic Pachic Argiustoll)								
Haskell 801	Check	5.6	19.3	14.5	95.6	558	1.05	11.9
Classification: Shellabarger sandy loam (fine-loamy, mixed, thermic Udic Argiustoll)								

Table 2. Weather data for the week prior to taking Veris EC readings at all locations, 2002.

		Air Temperature (F)				Air Humidity %			Rain	4" Soil Temperatures			
Site	Period	Max	Min	Avg	Dewpt	Max	Min	Avg	(in)	Sod	Bare	Max	Min
Stillwater 222 unt	6/25/2002 - 7/5/2002	85.29	69.14	76.54	69.61	96.29	59.29	81.14	0.12	78.60	79.69	84.57	75.29
Perkins N&P unt	7/9/2002 - 7/15/2002	90.71	69.71	79.39	68.87	94.14	46.86	72.57	0.01	79.30	79.09	81.57	76.57
Efaw AANUE unt	7/10/2002 - 7/16/2002	89.43	67.71	78.26	68.34	96.14	47.43	73.71	0.00	80.19	83.66	89.00	78.57
Efaw 301 unt	7/10/2002 - 7/16/2002	89.43	67.71	78.26	68.34	96.14	47.43	73.71	0.00	80.19	83.66	89.00	78.57
Magruder till	7/20/2002 - 7/26/2002	97.57	72.86	84.77	69.71	87.57	39.57	63.29	0.00	83.24	88.19	94.71	82.14
Efaw AANUE till	9/19/2002 - 9/25/2002	78.43	51.14	64.69	53.94	97.86	41.14	73.00	0.05	71.31	70.67	78.00	64.14
Stillwater 222 till	9/19/2002 - 9/25/2002	78.43	51.14	64.69	53.94	97.86	41.14	73.00	0.05	71.31	70.67	78.00	64.14
Efaw 301 till	9/19/2002 - 9/25/2002	78.43	51.14	64.69	53.94	97.86	41.14	73.00	0.05	71.31	70.67	78.00	64.14

Table 3. Correlation Coefficients (r) of soil test data with grain yield and Veris shallow and deep EC readings.

	Grain Yield	Veris shallow EC	Veris deep EC	Lab EC
NH4-N	0.349 ***	-0.289 **	-0.359 ***	0.415 ***
NO3-N	NS	0.557 ***	NS	0.936 ***
P	NS	NS	NS	NS
K	-0.499 ***	NS	0.486 ***	NS
pH	0.279 **	NS	NS	0.414 ***
OC	NS	NS	NS	NS
TN	NS	NS	NS	NS
Lab EC	NS	0.479 ***	NS	--

*, **, *** significant at the 0.05, 0.01, 0.001 probability levels, respectively.
P - Mehlich III extractable phosphorus
K - Mehlich III extractable potassium
OC - soil organic carbon
TN - total soil nitrogen
Lab EC – saturated paste extract
n = 99

Table 4. Correlation coefficients and associated significance for grain yield vs. the following: NDVI, INSEY, Veris readings, and Veris transformations evaluated in simple Linear regression, by location over years 2001-2002.

Loc	NDVI	INSEY	Shall	Deep	Shall/	Deep/	RShaMx/RDeMx	RShaMn/RDeMn	Shall*Deep	NDVI/(Sha/De)	(NDVI+Sha)/Deep	NDVI+Deep
AANUE	(.544)***	(.38)**	n	n	(.332)**	(-.35)**	(.318)**	(.33)**	n	n	(.336)**	n
301	(.652)***	(.634)***	n	n	n	n	n	n	n	(.333)*	n	n
222	(.844)***	(.72)***	(.352)**	n	n	(-.30)*	n	n	n	(.69)***	n	n
N&P	(.486)**	(.571)**	n	n	n	n	n	(-.529)	n	n	n	n
801	(.645)***	(.645)***	(-.67)***	(-.545)***	(-.578)***	(.453)**	(-.578)***	(-.578)***	(-.61)***	(.507)***	(-.564)***	(-.542)***

*, **, *** Significant at the .1, .05, .01 levels respectively.

RShaMx = All shallow readings divided by the maximum shallow reading, by site, by year

RDeMx = All deep readings divided by the maximum deep reading, by site, by year

RShaMn = All shallow readings divided by the minimum shallow reading, by site, by year

RDeMn = All deep readings divided by the minimum deep reading, by site, by year

APPENDIX

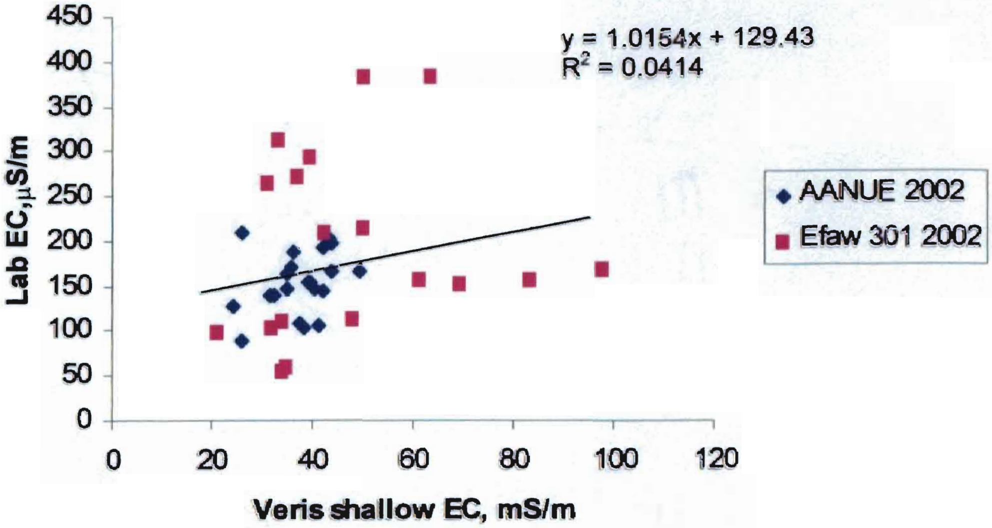


Figure 1. Relationship between saturated paste extract (Lab EC) and Veris shallow EC at Efaw AANUE and Efaw 301, Stillwater, Oklahoma, 2002.

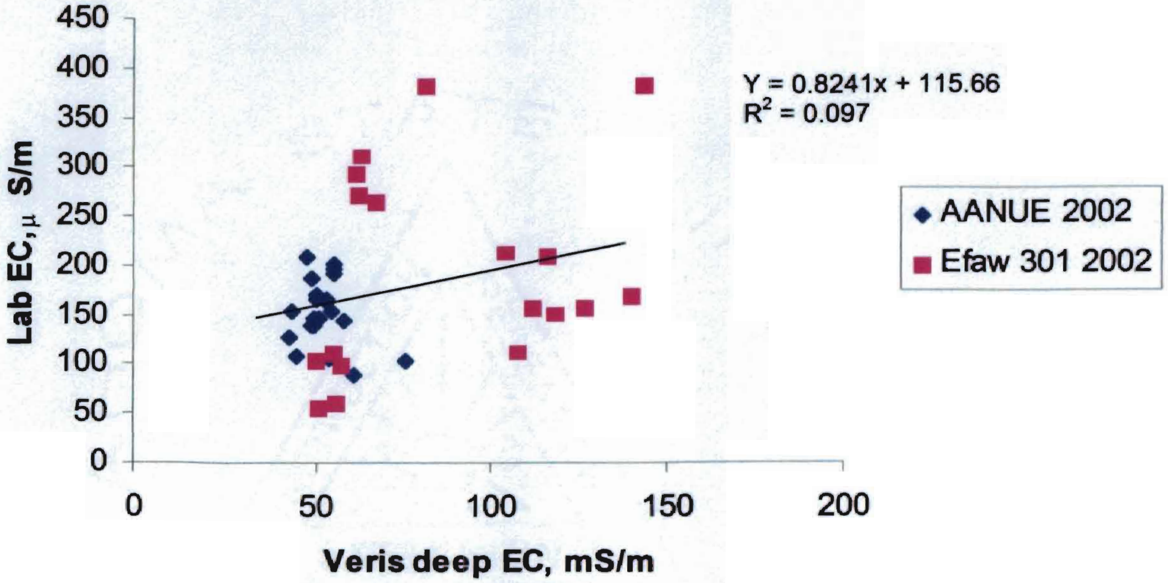


Figure 2. Relationship between saturated paste extract (Lab EC) and Veris deep EC at Efaw AANUE and Efaw 301, Stillwater, Oklahoma, 2002.

2.

VITA

Micah Todd Humphreys

Candidate for the Degree of

Master of Science

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