AN EVALUATION OF ELECTRICAL CONDUCTIVITY METERS FOR MAKING IN-FIELD SOIL SALINITY MEASUREMENTS

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Lee Galen Briese

In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Soil Science

April 2010

Fargo, North Dakota

North Dakota State University
Graduate School

Title

An Evaluation of Electrical Conductivity Meters for Making In-Field

Soil Salinity Measurements

By

Lee Galen Briese

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

ABSTRACT

Briese, Lee Galen, M.S., Department of Soil Science, College of Agriculture, Food Systems, and Natural Resources, North Dakota State University, May 2010. An Evaluation of Electrical Conductivity Meters for Making In-Field Soil Salinity Measurements. Major Professor: Dr. Thomas M. DeSutter.

Soil electrical conductivity (EC) can be used as a parameter to assist agricultural producers in making economically important management decisions. Since particular crops and crop varieties respond dynamically to soluble salt levels in relation to crop growth stage and soil moisture content, many management decisions regarding crop type and variety must be made prior to planting. Some crop stress factors could be removed or mitigated if a handheld EC meter could be implemented during the growing season. The objectives of this research were to 1) determine the accuracy of four handheld EC meters for measuring soil EC across a range of environmental temperatures of 15, 20 and 25^0 C, soil clay concentrations of 10.2, 17.8, 19.3, 32.3 and 50.4 %, and salt solutions containing Na-Mg-SO_4 or Na-Mg-Cl at concentrations of approximately 0, 1, 2, 4 and 8 dS m^{-1} under controlled laboratory conditions; 2) identify functional differences of the meters that might pose problems for in-field use; and 3) determine if meter price is related to accuracy. The EC values provided by three of the handheld EC meters were significantly different than the standard meter at all treatment levels. Measurements at different temperatures of the standard KCl calibration solution (known EC 1.413 dS m^{-1}) varied by ±0.15, -0.01 to +0.16, -0.14 to -0.03, and ±0.03 dS m^{-1}, for the Hanna Black (HI993310), Hanna Blue (HI98331), Field Scout, and SensION 5 meters, respectively. When salinity was 3 dS m^{-1} or greater the difference between the test meters and standard meter (EC

Response) was larger. Test meter measurements for the salinity by clay interaction were different than the standard meter by ±0.5, ±1, and -2.5 to +1.5 dS m^{-1}, for EC levels of less than 3, 3 to 4, and greater than 4 dS m^{-1}, respectively. The SensION 5 handheld was the only meter tested that was not significantly different than the standard meter ($p \leq 0.48$). Test meter accuracy was highly dependent on temperature. Therefore, the most important criteria for selecting a portable meter for in-field EC measurements is the accuracy of the specific meter's temperature measurement and temperature compensation model.

ACKNOWLEDGEMENTS

I would like to extend my thanks and gratitude to the following

Dr. Thomas M. DeSutter for his encouragement guidance and assistance with this project and throughout my graduate studies

Dr. R. Jay Goos, Dr. David W. Franzen, and Dr. James J. Hammond for their participation and guidance as committee members

Dr. Chris Vahl for his assistance with the design and statictical analysis of this project

Dr. Edward Deckard for his encouragement and assistance during my undergraduate and graduate studies

My wife Penny Briese for her love, support, encouragement and companionship in my life and all the goals I pursue.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

LIST OF APPENDIX TABLES

LIST OF APPENDIX FIGURES

GENERAL INTRODUCTION

The salinization of soil is an on-going land degradation process that reduces the abundance, diversity, and biomass productivity of the soil resource (Rhoades et al., 1999). Soil salinity is characterized by the accumulation of soluble salts at or near the soil surface. The salt accumulation results in an increase in soil in osmotic water potential and may adversely affect plant nutrient availability (USDA, 1993). As the osmotic pressure potential of the soil water increases plants have greater difficulty in acquiring moisture from the soil matrix. The reduced moisture availability initially causes drought-like symptoms, reduced biomass productivity, and can ultimately result in plant death (Blaylock, 2002). High levels of ions such as Na^+ and Cl^- in the saline soil solution compete with and reduce the uptake of essential plant nutrients and can also cause leaf burn and senescence (Abrol et al., 1988).

No single method has been identified to correct or mitigate soluble salt accumulation in soils. However, management techniques and alternatives that address ground water levels as well as recharge and discharge areas can be employed by the land manager to reduce the rate and severity of the spread of soil salinity (Franzen, 2007). Salinity is primarily caused by soluble salts that are transported by the movement of soil water to the surface. Water evaporates from the system and leaves the salts behind. Strategies that reduce or eliminate the net upward flow of ground water and evaporation at the surface will slow the process of soil salinization, and may enable the land manager to reverse it. Such strategies include the use of saline tolerant crops, cover crops, and subsurface drainage systems (USDA, 1993; Abrol et al., 1988; Franzen, 2007). The selection of appropriate management techniques depends upon the extent and severity of the soil salinity in a particular location as well as the source of the water carrying the salts to the surface. Soil electrical conductivity (EC) is a measurement of soil salinity used to quantify the severity of the accumulated soluble salts (SSGTC, 2008). A portable EC meter is one tool that can be used to quantify the soluble salt concentration in soil. The purpose of this thesis is to evaluate the accuracy of four commercially available portable EC meters for in-field use under a variety of conditions.

LITERATURE REVIEW

Electrical Conductivity

The general definition of electrical conductivity (EC) is the reciprocal of the electrical resistance measurement of a material across a specified volume (Rhoades et al., 1999). The units of electrical conductivity, as recognized by the Soil Science Society of America since 1971, are deci Siemens per meter (dS m^{-1}). Seimens was approved as the replacement for mhos as the SI unit of measure for electrical conductance at the 14th General Conference on Weights and Measures in 1971 (BIPM, 1971). The EC units of dS m^{-1} refer to specific conductance, or the amount of electrical conductance through a given volume (Rhoades et al., 1999). The standard laboratory method for determining the electrical conductivity of a soil is to measure EC on a saturation extract (EC_e) (SSSA, 2008). Soil EC_e measurements are used to classify soils as saline or nonsaline. By definition, a saline soil is nonsodic and contains enough soluble salts to adversely affect the growth of most crop plants. The lower EC_e limit of saline soils is conventionally set a 4 dS m^{-1} (SSSA, 2008; NRCS, 2008; US Salinity lab, 1954). Other specific conductance units that are present in soil science literature prior to 1971 and are currently in use in other science disciplines include μS cm^{-1}, mmhos cm^{-1}, μmohs cm^{-1}.

Total dissolved solids (TDS) expressed as mg L^{-1} and milliequivalents per liter expressed as meq L^{-1} are measurements that are also used to quantify salinity. Total dissolved solids represent the weight of the dissolved solids that remains after the complete evaporation of a specific volume of water from a sample (Suarez, 2005). Since, EC is linearly related to the concentration of dissolved solids in a solution and TDS requires more labor to measure directly, TDS is commonly estimated from EC measurements (Suarez, 2005). Conversion factors for units commonly used to assess salinity are listed in Table 1 (Scianna, 2007; Rhoades, et al., 1999).

Table 1. Conversion factors for electrical conductivity units. (Multiply reported unit value by conversion factor to calculate equivalent in SI standard units)

Reported unit	Conversion factor	SI standard unit
mmhos cm^{-1}	1	dS m^{-1}
μmhos cm^{-1}	0.001	dS m^{-1}
μS cm^{-1}	0.001	dS m^{-1}
mg L^{-1} (TDS)	640†	dS m^{-1}
mg L^{-1} (TDS)	800‡	dS m^{-1}
meq L^{-1}	§Dependent upon atomic weight and charge of specfic element	dS m^{-1}
$mmol_c$ L^{-1}	10¶	dS m^{-1}

†Approximate conversion factor for samples measuring < 5 dS m^{-1}
‡Approximate conversion factor for samples measuring > 5 dS m^{-1}
§meq L^{-1} equals mg L^{-1} divided by equivalent weight; equivalent weight equals atomic weigth divided by atomic charge
¶Approximate conversion factor

In relation to soil salinity, meq L^{-1} represents the equivalent concentration of a specific ion or compound in solution (Seelig, 2000). The use of equivalents simplifies calculations that would otherwise require the use of Avogadro's number to calculate the exact number of atoms. Salinity can also be characterized for specific ions as $mmol_c$ L^{-1}. The charges of the ions in aqueous solution provide one pathway through which electricity can be conducted (Rhoades et al., 1989a) therefore, the total amount of electricity that can be conducted through an aqueous solution is related to the type and concentration of ions dissolved in the solution (Reluy et al., 2004). However, since saline soil commonly contains multiple soluble salts, these ion specific measurements are uncommon because they do not represent the sum effect of the soluble salts in the soil solution and can be difficult to obtain.

Design of EC Meters

The specific conductance of a soil is the conductance of electricity through a 1 cm cube of sample (Rhoades et al., 1999). Since, the instrument electrodes that produce the electrical current and conductivity cells that contain the sample do not typically have dimensions of 1 cm^3, the electrical conductivity measured by an EC meter is corrected to reflect the actual geometry or cell constant of the specific EC meter using the relationship that, "the resistance of a conducting material is inversely proportional to its cross-sectional area (A) and directly proportional to its length (L)" (Rhoades et al., 1999). The EC of aqueous solutions increases as temperature increases at a rate of approximately 1.9% per ^{0}C, necessitating the need for maintaining a constant known temperature or measuring and compensating for temperature changes (Rhoades et al., 1999).

Portable commercially available EC meters have either 2-pole or 4-pole electrodes configurations. The 2-pole configuration is the simplest electrode configuration (Thermo, 2008) and is a common design feature of many of the portable EC meters considered for this study. The 2-pole electrode configuration functions by applying an alternating voltage (electrical potential) to two plates placed in the sample solution. The electrical current (flowing electric charge) produced by the alternating voltage is then measured (Thermo, 2008). This electrical current measurement is corrected for the cell constant of the meter and the temperature measured. The corrected measurement of the EC value of the sample is then displayed.

The 4-pole configuration differs from the 2-pole configuration in that it utilizes an alternating voltage applied to two drive electrodes to produce an electric current, and two sense electrodes to sense the voltage applied to the sample (Themo, 2008). The voltage measured by the sense electrodes controls the amplitude of the voltage applied to the drive electrodes (Themo, 2008). The design of the sense electrode circuit and its location in the cell allow for high accuracy measurements of the voltage applied to the sample (Thermo, 2008). The meter uses the sensed voltage signal to maintain the applied voltage at a constant strength (Thermo, 2008). The advantages of the 4-pole system are that it reduces the errors due to cable resistance, and contamination and polarization of the electrodes (Thermo, 2008).

Field Methods of Soil EC Analysis

One of the first methods for the field investigation of soluble salts in soils was described by Whitney and Means in 1897. Whitney and Means used a portable wheatstone bridge circuit and measured the resistance of saturated soil paste (Reitemeier and Wilcox, 1946). This method is different than the standard laboratory EC_e method in that EC is measured directly in the soil paste (EC_p) and the soil has not been dried or ground prior to the measurement. The "Bureau of Soils" cup method (US Salinity lab, 1954) is the same or is closely related to the Whitney and Means method. The bureau of soils cup method involves the preparation of a saturated soil paste, which is then measured for electrical resistance using a wheatstone bridge apparatus (EC_p). Then the temperature is measured with a thermometer, and the soil texture is estimated by hand (feel). These measurements and estimates are used with accompanying tables to convert the resistance reading to a percent salt (US Salinity lab, 1954).

An alternative to the saturated paste methods that can also be used in the field is the soil water slurry method ($EC_{1:n}$, where 1:n= the ratio of soil to water, commonly 1:1, 1:2 or 1:5). One soil water slurry method for in-field EC measurements recommends the use of a graduated bottle (baby bottle) or jar and a portable EC meter. The method instructions are to add enough soil to fill the bottle or jar to the 100 ml mark, add rainwater to the 600 ml mark ($EC_{1:5}$), shake for one minute, allow the mixture to settle for one minute, and then obtain the EC reading with a portable EC meter (Henschke and Herrmann, 2007). A second soil water slurry method suggests similar equipment and the same 1:5 soil:water ratio, but increases the equilibration time before the reading to greater than 30 minutes. This second soil slurry method recommends two cycles of shaking the prepared sample 50 times and allowing the sample to settle for 15 minutes prior to taking the reading (Walker, 2008). Specific instructions are not included in other literature recommending in-field measurements.

Methods for large scale in-field measurements of the apparent bulk soil EC (EC_a) were developed in the 1970's (de Jong et al., 1979). Apparent EC is determined with sensors that use soil contact electrodes or electromagnetic induction to measure EC_a. These EC_a methods, combined with data logging and global satellite positioning (GPS) technologies, have been used to evaluate large tracts of land (Sudduth et al., 2005). The current EC_a methods use a sensor attached to a cart or placed in a sled allowing for EC measurements to be taken while the sensor is in motion. Various models of mobile EC_a

sensors are commercially available (Veris, 2010; Geonics, 2010)[1]. Data logging and automation allows the sensor to take hundreds to thousands of measurements per hectare (Clay, 2001). The linkage of GPS information to the readings allows the user to create high resolution EC_a maps that reflect the spatial variability in the field (Veris, 2010, Geonic, 2010)[1]. The values recorded by EC_a sensors are an indirect measurement of soil EC (Sudduth et al., 2005) and as such are not the same as in-field EC values obtained from saturated soil paste or soil water slurry methods. EC_a measurements are highly correlated to salinity in saline soils (Sudduth et al., 2005) but must be calibrated with saturated paste extract (EC_e) measurements in order to make the data useful for salinity management decisions (Corwin, 2009). Soil characteristics such as bulk density, particle density, and volumetric water content can also influence EC_a measurements (Sudduth et al., 2005). In nonsaline soils, one or more of these may be the dominate soil property being measured by EC_a surveys (Sudduth et al, 2005). The calibration and correlation of EC_a data to the dominant soil property being measured can be accomplished by obtaining numerous traditional samples and/or estimates of soil saturation and clay content percentages from the field and entering them into formulas developed for the soils being examined (Rhoades et al., 1989a). The correlation requirements using laboratory analysis can greatly increase the time needed to make EC_a maps useful for field management decisions.

EC_e is the standard laboratory method for soil salinity and plant tolerance classification. The laboratory EC_e method differs from the in-field EC_p method in that the

[1] Reference to a trade or company name is for specific information only and does not imply approval or recommendation of the company or product by NDSU.

soil samples are air-dried and ground to pass a 2mm screen before the saturated paste is made. EC is then measured on the extract of the saturated soil paste whereas the in-field EC_p method uses in-situ field moist soil and the measurement is taken directly in the soil paste. In theory, EC_e is the most practical method that allows the soil water content to be standardized while closely representing the actual soil environment that plant roots experience (Rhoades et al., 1999). However, many soil testing laboratories conduct EC measurements on soil water slurries ($EC_{1:n}$) or the extract of soil to water slurries, because the $EC_{1:n}$ method is less expensive and requires less time to perform (Lee, 2010). Formulas that relate EC_a to EC of the soil solution have been developed. For example Eq. [1] was shown to effectively represent laboratory data for a range of soil water contents and salinity levels (Rhoades et al., 1989b).

$$EC_a = EC_s + T\theta_w\, EC_w \qquad [1]$$

For Eq. [1] EC_a is the apparent bulk soil conductivity, EC_s is the apparent conductivity of the solid phase of soil, T is a transmission coefficient used to correct for the tortuosity of current flow through the soil matrix, θ_w is volumetric water content, and EC_w is the electrical conductivity of the soil solution (Rhoades et al., 1989a). The utilization of Eq. [1] requires calibration data and linear regression analysis of EC_a and EC_w for different soil types (Rhoades et al., 1989a). The slope ($T\theta_w$) of the linear regression was related to the saturation percentage and the intercept (EC_s) was related to percent clay content (Rhoades et al., 1989a). Relationships between field capacity water content and percent clay content were used to create calibration estimates to reduce the need for field calibration (Rhoades et al., 1989b). Soil EC_e can be substituted for EC_w and calculated in a similar manner but soil specific calibration and linear regression analysis is still required to use Eq. [1] to calculate EC_e from EC_a. Simpler formulas can be used to provide less accurate, yet useful estimates of EC_e from $EC_{1:1}$ measurements (Franzen, 2007). The following equations can be used to estimate EC_e from $EC_{1:1}$ for coarse, medium, and fine textured soils, Eq. [2], [3], and [4], respectively (Franzen, 2007).

$$EC_e = 3.01\ EC_{1:1} - 0.06 \qquad [2]$$

$$EC_e = 3.01\ EC_{1:1} - 0.77 \qquad [3]$$

$$EC_e = 2.96\ EC_{1:1} - 0.95 \qquad [4]$$

All four equations require the measurement or estimation of soil texture or clay percentage and Eq. [1] also requires the measurement of the soil water saturation percentage.

Effects of Soil Salinity on Higher Plants

Salinity affects plants in two main ways 1) reduced water availability due to increased osmotic potential, and 2) causing toxicity from excessive quantities of by specific ionic species (Blaylock, 1994; Ogle et al., 2004). As the concentration of ions in the soil solution increases the amount of plant available water decreases. The symptoms associated with salinity induced water stress such as stunting, wilting, reduced growth, and death are similar to drought (Blaylock, 1994). Ionic toxicity in plants can be caused by the excessive accumulation of essential or non-essential nutrients in plant tissues. Ions such as Na^+ and Cl^- can reach toxic levels in plant tissues causing leaf tip burn, chlorosis, and the premature senescence of leaves or the entire plant (Ogle et al., 2004). In general, plants can be divided into two groups 1) halophytes, which are tolerant to salinity and 2) glycophytes which are not. Plant tolerance to soil salinity has been shown to be highly variable not only between species but also between different cultivars of the same species. The soybean (*Glycine max*) cultivar Manokin (glycophyte) was shown to have higher salinity tolerance than the soybean cultivar Lee (Wang and Shannon, 1999). The salinity tolerance of plant species can vary by growth stage as well as by cultivar (Wang and Shannon, 1999; Katerji et al., 2000). Research has been conducted to assess the salinity tolerance of many field crops, forages, and ornamental plant species (Katerji et al., 2000; Maas and Hoffman, 1977). Plant tolerance to salinity has been related to soil EC_e measurements. Plant growth responses to salinity are characterized by a linear plateau model. This model predicts that there will be no reduction in growth until the soil EC_e reaches the threshold level of the crop, and that growth reductions at soil EC_e levels exceeding the threshold level can be predicted by the linear portion of the model (Maas and Hoffman, 1977).

$$Y = 100 - B(EC_e - A) \qquad [5]$$

Equation [5] is a simplified form of the linear portion of the Maas and Hoffman model, where Y is the calculated crop yield in percent, B is the slope or percent yield decrease per 1 $dS\ m^{-1}$ increase in salinity, EC_e is the average root zone salinity (saturated extract), and A is the crop threshold in $dS\ m^{-1}$ (Tanji and Kielen, 2002) For instance, corn (*Zea mays*) has a threshold value of 1.7 $dS\ m^{-1}$ and a slope of 12.0 % (Tanji and Kielen, 2002), therefore at a soil EC_e of 4.0 $dS\ m^{-1}$,

$$Y = 100 – 12(4.0 – 1.7) = 72.4$$

Grain corn planted into a soil with an EC_e of 4.0 dS m^{-1} would have an expected yield potential of approximately 72% of the potential yield had the soil not been saline.

Soil Salinity Management

Soil salinity management is primarily accomplished through soil water management (Ogle et al., 2004; Franzen, 2007; USDA, 1993; Abrol et al., 1988). The amount of salts (EC_e), types of salt ions (Na^+, Ca^{2+}, SO_4^{2-}, and Cl^-), topography, and economics will influence the feasibility of salinity management and must be considered when developing a salinity management plan. The three main procedures recommended for salinity management are 1) leaching, 2) subsurface drainage, and 3) the use of tolerant plants (USDA, 1993; Barrett-Lennard, 2002; Abrol et al., 1988; Francois and Mass, 1994; Katerji et al., 2000; Ogle et al., 2004).

Leaching consists of applying water in excess of crop use demands. Leaching is primarily used in irrigated cropping systems where sufficient low salinity water and adequate drainage is available (USDA, 1993). The goal of leaching is to apply enough excess water to dissolve and leach the soluble salts below the crop root zone (Abrol et al., 1988). The quantity of water needed to accomplish leaching is known as the leaching requirement (LR) and can be calculated using Eq. [6].

$$LR = EC_w/5(EC_e) - EC_w \quad [6]$$

For Eq. [6], LR is the leaching requirement, ECw is the electrical conductivity of the leaching water (dS m^{-1}), and EC_e is the target soil electrical conductivity (dS m^{-1}) at which no yield loss occurs (Watson and Knowles, 1999).

The effectiveness of leaching will be influenced by the quality, quantity, and timing of water availability. For example, higher evaporation rates during summer months will increase the amount of water needed to leach the salts from the crop root zone (leaching requirement). Soil properties such as texture, permeability, and drainage can reduce the effectiveness of leaching as a salinity management tool. Some soils may require the installation of subsurface drainage to carry leached salts out of the area and prevent water table levels from rising. The depth to water table is an important consideration for salinity management. Saline water in shallow water tables can contribute to root zone salinity through capillary rise (Franzen, 2007). As water evaporates from the soil surface the soil matric potential can draw ground water to the surface. Soil texture influences the depth from which water can be drawn to the surface. Capillary rise in fine textured soils could potentially draw water from a depth of up to 4.5 meters (Knuteson et al., 1989).

Subsurface drainage systems (tile drains) are designed to remove excess (gravitational) water from soil (Sands, 2010). The removal of excess water using tile drainage allows for greater infiltration of fresh rainwater and the tiles provide a conduit through which leached salts can be removed from the field (Abrol et al., 1988). Tile drains may also be used to control the depth of ground water tables (Abrol et al., 1988). The specific design of the tile drainage system must consider the soils, landscape, and economics of each site (Sands and Wright, 2001). Land managers are encouraged to closely evaluate the potential benefits of tile drainage and perform a cost benefit analysis prior to installation (Sands, 2010). The potential environmental impacts of tile drainage effluent water in North Dakota are still being studied (Johnson, 2009).

The use of deep rooted perennial and saline tolerant plants is a commonly recommended strategy for the management of saline soils (Franzen, 2007; USDA, 1993; Maas and Hoffman, 1977; Barrett-Lennard, 2002). Changes in land vegetation due to modern production agriculture can result in ecosystem changes that cause the development of soil salinity. This type of soil salinity is called secondary salinity (Barrett-Lennard, 2002). Deep rooted and/or perennial plants have been used as a means of increasing water usage and reducing or preventing the rise in ground water levels (Barrett-Lennard, 2002). Plants can also be used to provide buffer areas that can help prevent the spread of salinity to adjacent areas (Franzen, 2007; USDA, 1993). For instance, planting of alfalfa (*Medicago sativa*) strips between saline wetlands and the field has been recommended as a method to prevent salinity from further encroaching into the field (Franzen, 2007). The use of winter cover crops in California has been shown to help reduce surface soil salinity (Mitchell et al., 1999). Cover crops were planted in the fall and irrigated with saline drainage water. Soil salinity in the fall when the cover crops were planted was 7.0 dS m^{-1} and was 5.3 dS m^{-1} in the spring when the cover crops were harvested (Mitchell et al., 1999). Planting saline tolerant crops can result in higher yields and greater economic returns on low to moderately saline soils (USDA, 1993; Maas and Hoffmann, 1977). In all cases, the land manager needs to know the soil salinity level (EC_e) in order to make good decisions about which management alternatives are best suited for their needs.

AN EVALUATION OF ELECTRICAL CONDUTIVITY METERS FOR MAKING IN-FIELD SOIL SALINITY MEASUREMENTS

Abstract

Soil electrical conductivity (EC) can be used as a parameter to assist agricultural producers in making economically important management decisions. Since particular crops and crop varieties respond dynamically to soil soluble salt levels in relation to crop growth stage and soil moisture content, many management decisions regarding crop type and variety must be made prior to planting. Some crop stress factors could be removed or mitigated if a handheld EC meter could be implemented during the growing season. The objectives of this research were to 1) determine the accuracy of four handheld EC meters for measuring soil EC across a range of environmental temperatures of 15, 20 and 25^0 C, soil clay concentrations of 10.2, 17.8, 19.3, 32.3 and 50.4 %, and salt solutions containing Na-Mg-SO_4 or Na-Mg-Cl at concentrations of approximately 0, 1, 2, 4 and 8 dS m^{-1} under controlled laboratory conditions; 2) identify functional differences of the meters that might pose problems for in-field use; and 3) determine if meter price is related to accuracy. The EC values provided by three of the handheld EC meters were significantly different than the standard meter at all treatment levels. Measurements at different temperatures of the standard KCl calibration solution (known EC 1.413 dS m^{-1}) varied by ±0.15, -0.01 to +0.16, -0.14 to -0.03, and ±0.03, for the Hanna Black (HI993310), Hanna Blue (HI98331), Field Scout, and SensION 5 meters, respectively. When salinity was 3 dS m^{-1} or greater the difference between the test meters and standard meter (EC Response) was larger. Test meter measurements for the salinity by clay interaction were

different than the standard meter by ±0.5, ±1, and -2.5 to +1.5 dS m^{-1}, for EC levels of less than 3, 3 to 4, and greater than 4 dS m^{-1}, respectively. The SensION 5 handheld was the only meter tested that was not significantly different than the standard meter ($p \leq 0.48$). Test meter accuracy was highly dependent on temperature. Therefore, the most important criteria for selecting a portable meter for in-field EC measurements, is the accuracy of the specific meter's temperature measurement and temperature compensation model.

Introduction

Electrical conductivity (EC) is the standard parameter used to measure soil salinity levels. Electrical conductivity estimates the quantity of ions in the soil that are in solution and thereby affect the osmotic potential of the soil. As the ionic concentration or EC of the soil increases, the plant available water decreases, which can cause reduced plant growth, crop yield loss and/or plant death (Maas and Hoffman, 1977). Competition for plant absorption between certain ionic species in the soil solution can also cause adverse affects in plants. High soil solution concentrations and consequently excessive absorption of ions such as Na^+ and Cl^- can cause toxic reactions and senescence (USDA, 1993). Tolerance to soil salinity levels varies greatly by crop, variety, and growth stage (Maas and Hoffman, 1977). For example, sugar beets (*Beta vulgaris L. ssp vulgaris*) can tolerate much higher levels of soil salinity when the plants are mature than when the seedlings are germinating (Olge et al., 2004). Soybean has shown significant variance in soil salinity tolerance in the range of 2.0 to 5.0 dS m^{-1} EC_e, which is attributed to differences in individual variety tolerance (Katerji et al., 2000; Maas and Hoffman, 1977).

Managing soil salinity can be difficult. Different management strategies include, but are not limited to, irrigation management (US Salinity Lab, 1954), drainage, lowering ground water levels (Pannell and Ewing, 2005), crop selection (Franzen, 2007), seed placement, and variety selection. A number of the salinity management changes that could be made are time dependant and could be improved if soil salinity measurements could be accurately acquired in the field at the time decisions need to be made. Differences in soil salinity of less than 1 dS m^{-1}, as determined by measuring the electrical conductivity of the extract of a saturated soil paste (EC_e), could be enough to justify the choice of one crop over another, one variety over another or classify a soil as saline versus non-saline (Abrol et al., 1988). Therefore, having the ability to determine soil salinity levels on a timely basis (less than 1 day) would be greatly advantageous to agricultural producers and soil scientists. In-field diagnosis could also be used to calibrate sensors that measure apparent bulk soil electrical conductivity (EC_a), or target environmentally sensitive areas that need intensive evaluation, monitoring, and management. Sensors that measure EC_a are widely used to conduct field surveys by agriculture and government personnel. However, the measurements generated by these sensors need to be calibrated with laboratory measurements of soil EC_e. Since variations in soil texture, water content and temperature can be present in the field at the time of measurement they could influence the values obtained during EC_a surveys (Corwin, 2009). In-field measurements of soil EC with portable handheld meters could be used to help make crop and variety selections at planting time and help calibrate EC_a sensors.

Hand-held EC meters are commonly available through many vendors. Most meters can determine EC between 0 and 20 dS m^{-1} with resolutions that vary from 0.001 to 0.1 dS m^{-1} and a claimed accuracy of ±2% (Table 2). The cost of hand-held meters varies from less than $100 to over $1000 dollars (US) depending on the number of functions desired. Suggestions and comments about the different types of meters have been published (Walker, 2008), but research evaluating the accuracy of commercially available hand-held EC meters over a range of temperatures, soil types and salt concentrations has not been found in the literature.

Table 2. Specifications and features of standard and evaluated hand-held electrical conductivity meters. Probe voltage not available from vendors. Photographs of meters used are included in Appendix B.

Manufacturer	Hach Company	Hach Company	Hanna Instruments	Hanna Instruments	Spectrum Technologies
Model	SensION 378†	SensION 5†	Hanna HI 993310	Hanna HI 98331‡	Field Scout
Exp Name	Standard	SensION 5	Hanna Black	Hanna Blue	Field Scout
Temp. correction	non-linear NaCl	non-linear NaCl	2% per °C	2% per °C	2% per °C
Power source	110 VAC	4-AA	1-9V	4-LR44	4-LR44
Range (dS m^{-1})	0-199.9	0-199.9	0-19.99	0-19.99	0-19.99
Resolution	0.01	0.01	0.01	0.01	0.01
Accuracy	±0.5% Full Scale	±0.5% Full Scale	±2% Full Scale	±2.5-7.5%	±2% Full Scale
Calibration	1 point	1 point	1 point	1 point	1 point
Temp. display	Yes	Yes	No	Yes	Yes
Value Storage	199	99	None	None	Current
Solution use	Yes	Yes	Yes	Yes	Yes
Direct soil use	No	No	Yes	Yes	Yes
Probe type	Single 4 pole	Single 4 pole	Single 2 pole	Single 2 pole	Double 2 pole
Probe material	Platinized stainless steel	Platinized stainless steel	Stainless steel	Proprietary	Stainless steel
Price	$1,359	$583.00	$460.80	$95.40	$365.00

†Multiple ranges with varying resolution
‡Manufacturer states that this meter "gives indicitive readings with lower accuracy between 4 and 10 dS m^{-1}" (Hanna, 2008).

Variations in sample temperature (Gartley, 1995), soil texture (Franzen, 2007), specific ion concentration and composition could all contribute to the error of in-field EC measurements. Specific temperature correction formulas chosen by the manufacturer could potentially cause significant errors at temperatures other than the standard temperature of 25°C (Hayashi, 2003). The temperature correction of commercially available hand-held conductivity meters can vary from 1-3% (Thermo, 2008; Coleparmer, 2008). Most hand-held meters claim a fixed 2% per degree C temperature compensation. Some of the meters allow the user to adjust the temperature coefficient used based on the ionic composition of the solution (Coleparmer, 2008). Temperature coefficients have been determined for some solutions that contain specific homogenous substances, but when the solution is composed of multiple substances the user needs to determine a calibration curve based on additional measurements taken over a range of temperatures (Coleparmer, 2008).

Experts who recommend in-field soil EC measurements caution the user that the results can vary greatly and should only be used as a rough estimate (Franzen, 2007; Walker, 2008). While errors caused by sampling and measurement technique can be reduced by careful attention of the user, error inherent in the instrument cannot. Therefore, if handheld EC meters differ significantly in accuracy over a range of field conditions, the user would be well advised to select the instrument that provides the highest accuracy. Therefore, the objectives of this research were to 1) evaluate four commercially available handheld EC meters for accuracy under a range of temperatures, soil clay concentrations, and salinity levels; 2) identify functional differences of the meters that might pose problems for in-field use; and 3) determine if meter price is related to accuracy.

Materials and Methods

Portable Meters

The four commercially available handheld EC meters selected for comparison were 1) SensION model 5 (Hach Company, Loveland, CO), 2) Hanna model HI993310 referred to here as Hanna Black (Hanna Instruments Inc, Woonsocket, RI), 3) Field Scout direct soil EC meter (Spectrum Technologies, Plainfield, IL) and 4) Hanna model HI 98331 direct soil conductivity and temperature tester referred to here as Hanna Blue (Hanna Insturments Inc, Woonsocket, RI)[2]. All experimental readings were compared to the SensION model 378 (Hach Company, Loveland, CO). The SensION 378 is a laboratory grade bench top meter that was used as a standard during the experiments. The SensION 5 meter uses a non-linear NaCl based temperature compensation curve, has a range of 0-199.9 dS m^{-1} with full scale claimed accuracy of ± 0.5%, continuously displays measured temperature, and is powered by 4 AA batteries. The Hanna Black uses a fixed 2% per ^{0}C temperature compensation, has a range of 0-19.99 dS m^{-1} with a full scale claimed accuracy of ±2%, does not display measured temperature, and is powered by one 9 volt battery. The Field Scout uses a fixed 2% per ^{0}C temperature compensation curve, has a range of 0-19.99 dS m^{-1} with a full scale claimed accuracy of ±2%, continuously displays measured temperature, and is powered by 4 LR-44 batteries. The Hanna Blue uses a fixed 2% per ^{0}C temperature compensation, has a range of 0-19.99 dS m^{-1} with claimed accuracy of ±2.5%

[2] Reference to a trade or company name is for specific information only and does not imply approval or recommendation of the company or product by NDSU to the exclusion of others that may be suitable.

for 0-4 dS m^{-1} and ±7.5% for readings greater than 4 dS m^{-1}, measured temperature can be displayed by pushing the "temp" button, and this meter is powered by 4 LR-44 batteries. The SensION 378, referred to as the standard meter uses a non-linear NaCl based temperature compensation curve, has a range of 0-199.99 dS m^{-1} with a full scale claimed accuracy of ±0.5%, continuously displays measured temperature and is powered by 110 volt AC. Additional meter specifications are listed in Table 2. All meters were calibrated at the beginning of each replication according to manufacturer instructions.

Soils

The five different soils used throughout this study were collected from crop production fields in south central North Dakota. These soils were sent to the North Dakota State University (NDSU) soil testing laboratory and analyzed for particle size, water extractable cations and anions, organic carbon, and saturated paste extract electrical conductivity (EC_e) (Table 3).

Table 3. Soil physical and chemical analysis performed by North Dakota State University soil testing laboratory.

Exp. Label	Series	Texture	Sand	Silt	Clay	NDSU EC_e	Std EC_e†	Std $EC_{1:2}$	pH	TC‡	IC§	OC¶
			------------g kg^{-1}----------			--------------dS m^{-1}-------------				---------g kg^{-1}-------		
10%	Embden fine sandy loam	Sandy loam	883	15	102	0.704	0.715	0.095	7.6	13.0	0	13.0
17%	Svea-Barnes loam	Loam	415	407	178	0.479	0.486	0.113	6.8	23.4	0	23.4
20%	Tonka Silt loam	Silt loam	279	528	193	0.671	0.690	0.206	7.8	35.1	0	35.1
30%	Aberdeen silty clay loam	Silty clay loam	222	455	323	0.388	0.416	0.166	7.0	27.7	0.6	27.1
50%	Sinai silty clay	Silty clay	51	445	504	0.462	0.467	0.237	7.8	25.3	5.9	19.4

†SensION 378 (standard meter) measurement of soil saturation extract prepared by NDSU soil testing laboratory
‡Total Carbon
§Inorganic carbon
¶Organic carbon

The soils were a Tonka silt loam (fine, smectitic, frigid Argiaquic Argialboll), Svea-Barnes loam (fine-loam, mixed, superactive, frigid Pachic Hapludoll), Embden fine sandy loam (Coarse-loamy, mixed, superactive, frigid Pachic Hapudoll), Aderdeen silty clay loam (fine, smectitic, frigid Glossic Natrudoll), and a Sinai silty clay (fine, smectitic, figid Typic Hapludert). Soil used in this experiment was air-dry and less than 2 mm in diameter.

Salinity

The two types of salt solutions used in this study were Na-Mg-SO_4 and Na-Mg-Cl. These are the predominant water extractable cations and anions in some of the highly saline soils in the South Central region of North Dakota. From laboratory grade chemicals, 0.5 M stock solutions of $MgSO_4$-Na_2SO_4 and $MgCl_2$-NaCl were made. The salts used were not dehydrated. The SO_4 solution was made by adding 123.14 g (0.5 M) $MgSO_4$ and 71.01 g (0.5 M) Na_2SO_4 to one liter of ultra pure water. The Cl solution was made by adding 101.58 g (0.5 M) $MgCl_2$ and 29.22 g (0.5 M) NaCl to one liter of ultra pure water. One batch of 4 liters of each salt solution (Mg-Na-SO_4 and Mg-Na-Cl) was made at the beginning and was sufficient to complete all experiments. The EC of the 0.5 M stock solutions was 48.0 dS m^{-1} for the Mg-Na-SO_4 solution and 61.7 dS m^{-1} for the Mg-Na-Cl solution. The target soil EC levels of 0, 1, 2, 4, and 8 dS m^{-1} were prepared from the 0.5 M stock solutions by adding 0, 0.5, 1.25, 2.5, and 5 ml of either Mg-Na-SO_4 or Mg-Na-Cl stock solution to plastic cups containing 25 g of soil. After which, each cup was brought up to 50 mL total volume using ultra pure water dispensed from 4-L bottles equipped with calibrated repipettes. The resulting soil:solution ratio was 1:2.

Laboratory Procedure

The soils, salt solutions and meters were placed in a temperature controlled laboratory and allowed to equilibrate for 12 hours to the treatment temperatures of 15, 20, and 25°C prior to measurements being taken. The sample cups of the different soils were randomly assigned to five rows within a tray (one row for each soil). Next, one row at a time, the ten created salt solutions and one soil-less KCl standard solution (EC=1.413 dS m^{-1}, Hanna HI 7031) were randomly added to one sample cup within each row. Each sample was stirred for 30 seconds and allowed to stand for 15 minutes, which preliminary research showed was enough time for equilibration to occur. Finally, by row, each meter was used to measure the EC of every sample. The meter order was randomized for each sample and only one sample was analyzed at a time. The meter probes were operated independently and cleaned with ultra pure water between each sample. A wooden box was constructed to hold the meters, probes, and sample cups. Plastic polyvinyl chloride (PVC) pipe was used within the box to hold the electrode of each meter's probe at the same depth in each sample. The 1:2 (soil:solution) ratio was required to allow the electrodes to be positioned so that they did not contact the soil but were completely submerged in the solution supernatant. After each run, the temperature controlled laboratory was reset to the next random temperature until nine temperature runs were completed. In addition to the soil experiment, the same procedure as described above was conducted with only the salt solutions in the cups (no-soil) to test if the effect of soluble salts in the resident soil was impacting the target soil EC levels and to mimic irrigation water.

Statistical Analysis

The soil experiment was set up as a split-strip plot design and was replicated three times at each temperature. The whole plot temperature was the split-plot, the strip-plot effect was soil clay concentration, and the sub-plot effect was salt concentration (Table 4). The treatments consisted of the four test EC meters and the standard meter as the control.

Table 4. Experimental design of the soil experiment with effect variables and levels.

Split Plot	Strip plot		Sub plot			Treatment	
Temperature	Clay concentration		Salinity			Meter	
		Salt type	Exp. label	Target EC	Exp. mean†	Model	Exp. Label
°C	%			--------dS m^{-1}----------			
15	10.2	None	S0,0 S1,0	0.00	0.14	SensION 5	A
20	17.8	SO_4	S0,1	1.00	1.04	Hanna Black	B
25	19.3	SO_4	S0,2	2.00	2.10	Field Scout	C
	32.3	SO_4	S0,4	4.00	3.61	Hanna Blue	D
	50.4	SO_4	S0,8	8.00	6.13	Standard	E
		Cl	S1,1	1.00	0.98		
		Cl	S1,2	2.00	2.12		
		Cl	S1,4	4.00	3.82		
		Cl	S1,8	8.00	6.98		
		‡KCl	Std	1.41	1.42		

†Soil experiment EC mean of the salinity main effect across all other levels
‡KCl standard calibration solution (EC= 1.413 dS m^{-1} at 25°C)

The no-soil experiment was set up as a split-plot design and was also replicated three times at each temperature (Table 5). Where the whole plot was temperature, the sub-plot effect was salt concentration, and the treatments were the four test EC meters and the standard meter as the control. For normalization, the difference between each test meter and the standard meter was used in all statistical analyses, and was termed the EC Response. The data for each experiment were analyzed in SAS using Proc Mixed (ver. 9.1, SAS Institute Inc, Cary, NC). Values where $p \leq 0.05$ were considered significantly different. The soil and no-soil experiment means for the salt main effect and temperature by salt interaction were analyzed for differences using student's t-test. The t-test showed no significant differences between the soil and no-soil experiment means, which indicated that the resident soluble salts in the soil samples did not affect target soil EC levels and therefore comparisons between these two experiments are considered valid. In order to clarify the salinity by meter effect, all sample EC values obtained from each test meter were plotted against the sample EC values of the standard meter and analyzed using linear regression.

Table 5. Experimental design of the no-soil experiment with effect variables and levels.

Split Plot			Sub plot		Treatment	
Temperature			Salinity		Meter	
	Salt type	Exp. Label	Target EC	Exp. mean†	Model	Exp. Label
°C			------------dS m^{-1}------------			
15	None	S0,0 S1,0	0.00	0.35	SensION 5	A
20	SO_4	S0,1	1.00	0.99	Hanna Black	B
25	SO_4	S0,2	2.00	2.29	Field Scout	C
	SO_4	S0,4	4.00	4.13	Hanna Blue	D
	SO_4	S0,8	8.00	7.34	Standard	E
	Cl	S1,1	1.00	0.86		
	Cl	S1,2	2.00	2.11		
	Cl	S1,4	4.00	4.04		
	Cl	S1,8	8.00	7.57		
	‡KCl	Std	1.41	1.42		

†No-soil experiment EC mean of the salinity main effect across all other levels
‡KCl standard calibration solution (EC= 1.413 dS m^{-1} at 25°C)

Results and Discussion

Temperature Effects

The response of all meters to temperature was significantly different than the standard meter ($p \leq 0.0001$). When compared to the standard meter, the grouping of individual observations reveals that the Hanna Blue meter was precise but not accurate, the Hanna Black and Field Scout were neither precise nor accurate and the SensION 5 meter was both precise and accurate. When summarized across all temperatures, the individual meter readings for the known EC of the KCl standard conductivity solution (1.413 dS m^{-1}) ranged from 1.40 to 1.57, 1.27 to 1.56, 1.27 to 1.38, 1.38 to 1.43, and 1.39 to 1.44 dS m^{-1} for the Hanna Blue, Hanna Black, Field Scout, SensION 5, and standard meter, respectively (Figure 1).

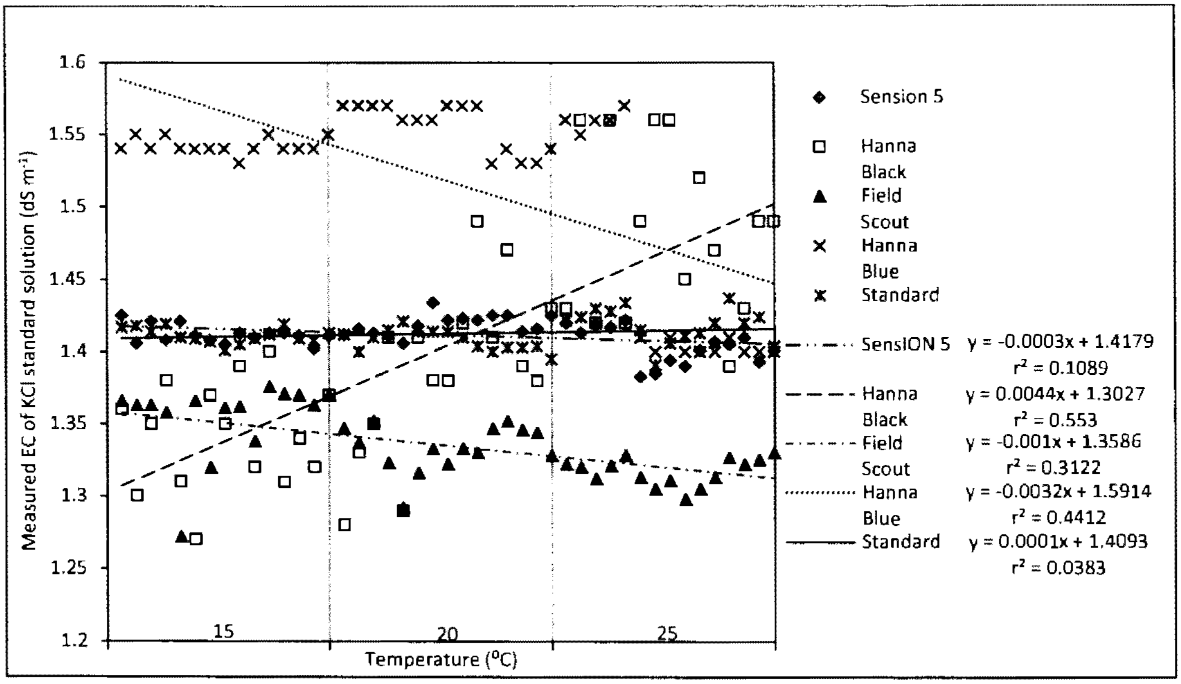

Fig. 1. Soil experiment meter EC readings of standard KCl calibration solution (1.413 dS m^{-1}) by temperature. Data are presented grouped by temperature and do not represent continuous observations.

For comparison to the manufacturer claimed accuracy of each meter (Table 2), these values represent differences of up to 11.1, 10.4, 10.0, 2.1, and 1.7%, with average differences of 7.7, 4.5, 5.5, 0.6, and 0.5%, for the Hanna Blue, Hanna Black, Field Scout, SensION 5 and standard meter, respectively. In the case of the Hanna Blue, Hanna Black and Field Scout the average variability is more than double the claimed accuracy.

Increasing temperature caused the Hanna Blue and Field Scout trends to decrease and the Hanna Black trend to increase (Figure 1). The SensION 5 trend line was nearly flat (slope= -0.0003) and closely followed the standard meter trend line (Figure 1). Similar trends were observed for the KCl standard conductivity solution measurements taken in the no-soil experiment (Figure 2).

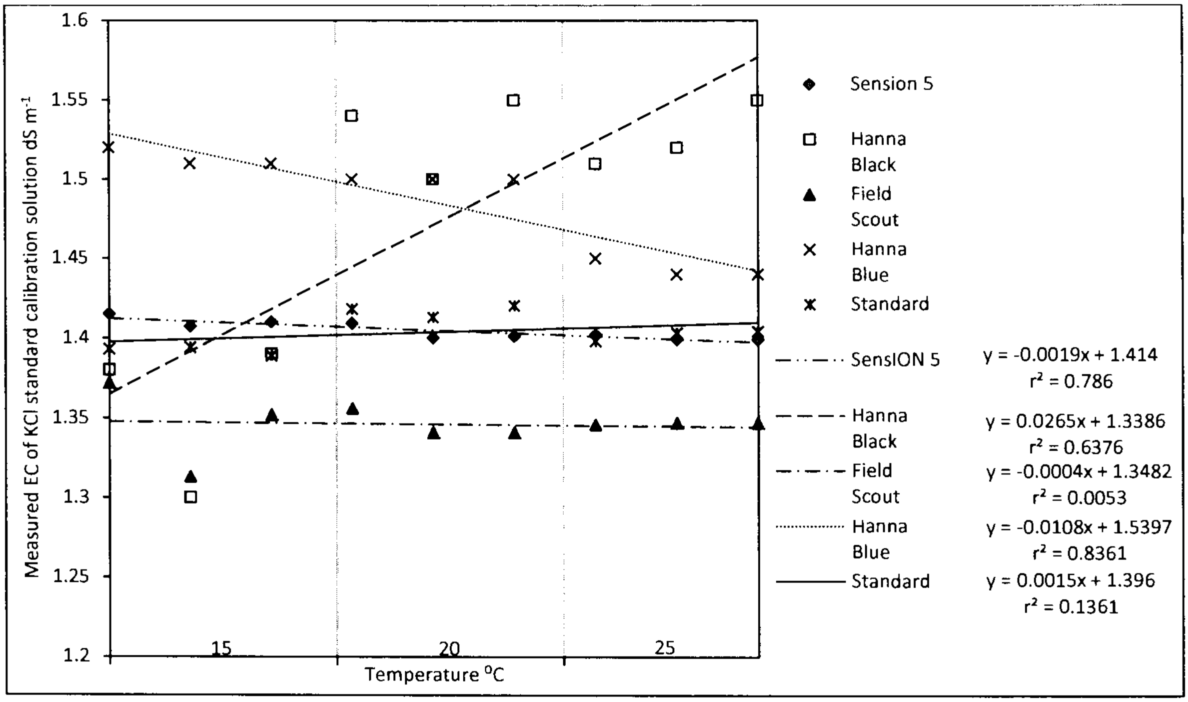

Fig. 2. No-soil experiment meter EC readings of standard KCl calibration solution (1.413 dS m^{-1}) by temperature. Data are presented grouped by temperature and do not represent continuous observations.

In the soil experiment, there were 3 temperature levels and 10 salinity levels (Table 4) resulting in 30 two-way temperature by salinity interactions across all soil clay concentrations and meters. Nine of these interactions were significant ($p \leq 0.05$). Where one was significant ($p \leq 0.0001$) at a salinity of less than 3 dS m^{-1}, (sulfate salt at 2 dS m^{-1} at 15°C). The other eight occurred when the salinity was greater than 3 dS m^{-1}, (four at

15°C, two at 20°C, and two at 25°C). The no-soil experiment also had 30 two-way temperature by salinity interactions (Table 5), 7 of which were significant ($p \leq 0.05$) across all meters and five of these significant interactions occurred with EC greater than 3 dS m^{-1}. The test meters overestimated sample EC for 8 of 9 temperature by salinity interactions in the soil experiment versus 4 of 7 in the no-soil experiment indicating that the temperature by salinity interaction for the soil experiment was also influenced by clay percentage. The temperature by salinity interaction illustrates that as temperature increased and salinity decreased, the EC Response of the test meters decreased. Hence, the magnitude of difference between the EC reported by the test meters and the standard meter was greatest at the low temperature (15°C) and high EC. Despite automatic temperature compensation and frequent calibration, the accuracy of the test meters decreased when used to measure EC on soil slurry samples at temperatures below the standard reference temperature of 25°C.

The two-way interaction of temperature by soil clay concentration across all meters and salinity levels was significant for eleven of the fifteen interactions ($p \leq 0.05$), including all soil clay concentrations at 15°C. The non-significant interactions occurred at 20°C for soil clay concentrations of 20 and 50%, and 25°C for soil clay concentrations of 17 and 30%. The soil experiment EC mean across all temperatures, salinity levels, and meters sharply decreased as soil clay concentration increased from 10 to 20%, but increased slightly for soil clay concentrations of 30 and 50% (Figure 3). This suggests that the maximum amount of ion absorption from the solution had occurred at 20% soil clay concentration. The reason for this is not clear, but may be related to ion selectivity or solubility of the salts used in the experiment.

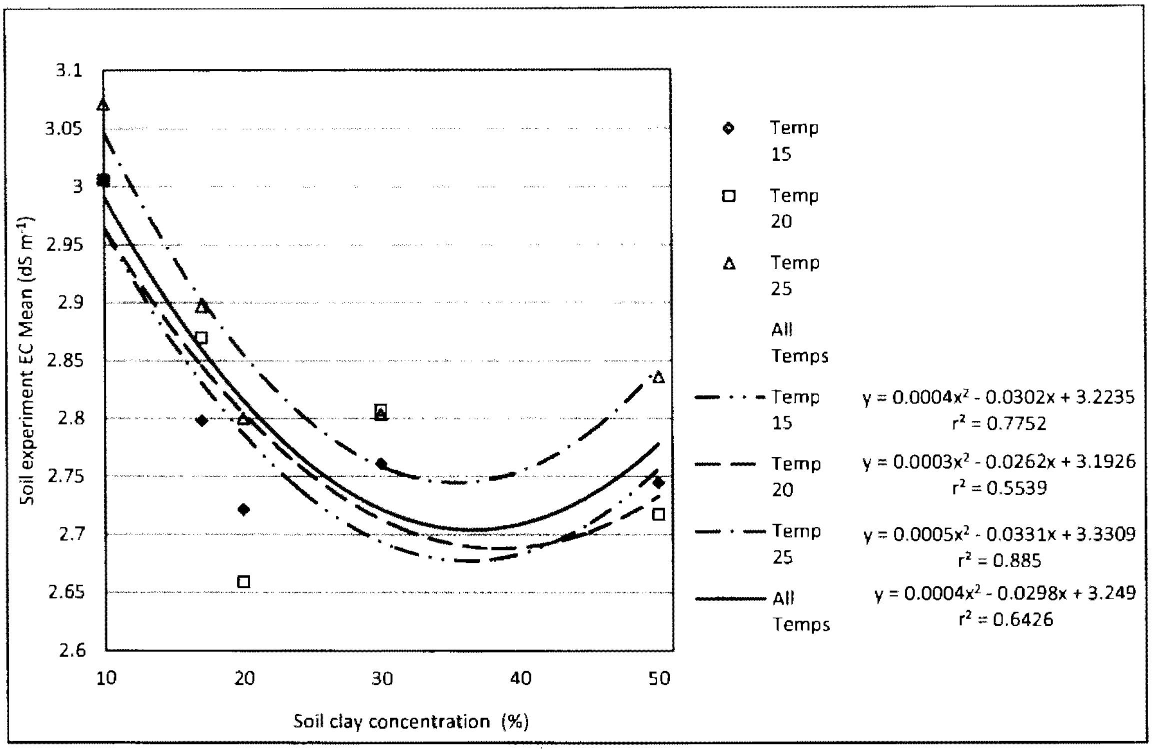

Fig. 3. Soil experiment EC mean by soil clay concentration across all temperatures, salinity levels and all meters; labeled by temperature.

The EC Response of the test meters increased as clay percentage increased and decreased as temperature increased (Figure 4). The test meters read ECs lower than the standard meter on the 10% clay soil at 15, 20 and 25^{0}C and the 17% soil at 20^{0}C, but higher at all other soil clay concentrations and temperatures. Once again, the difference between the test meters and the standard meter readings reached a maximum at 20% clay and appeared to decrease for the 30 and 50% clay levels.

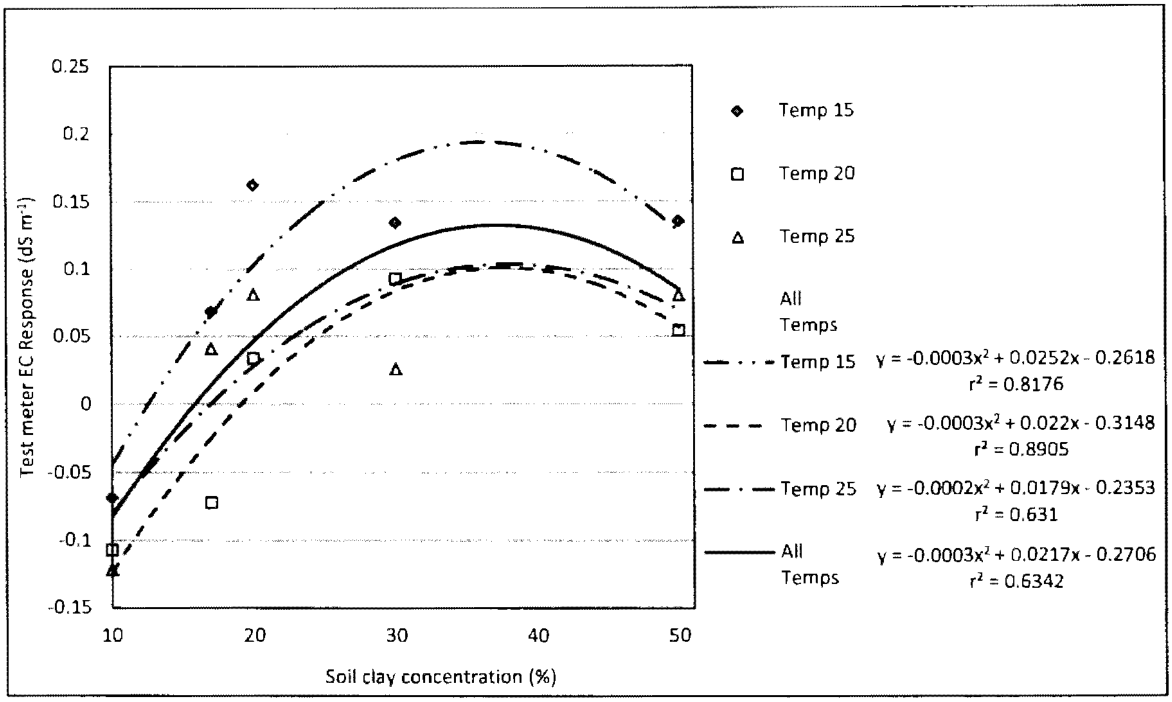

Fig. 4. Soil experiment test meter EC response by soil clay concentration for all salinity levels and all test meters; labeled by temperature.

Salinity Level and Salt Type Effects

The trend for the main effect of salinity in both experiments (soil and no-soil) showed that test meter variability (EC Response) increased as EC increased, resulting in lower accuracy of the test meters when salinity was greater than 3 dS m^{-1} (Figure 5). The non-significant point at approximately 7 dS m^{-1} represents the Cl salt at the high salinity level. The non-significance of this point may be related to the temperature correction curves employed by the meters in the experiment. The temperature correction curves of all of the meters in this study are based on NaCl, but the SensION 5 and the standard were the only meters in this study that use a non-linear curve, all the other meters use a fixed 2% per ^{0}C curve. Therefore it is possible that the high Cl salinity level used in this experiment falls on or very near the temperature correction curve of all the meters, which would explain why this salinity level is not significant. When the data is plotted without the high Cl salinity level, the response curve provides a more accurate prediction of the data (Figure 6).

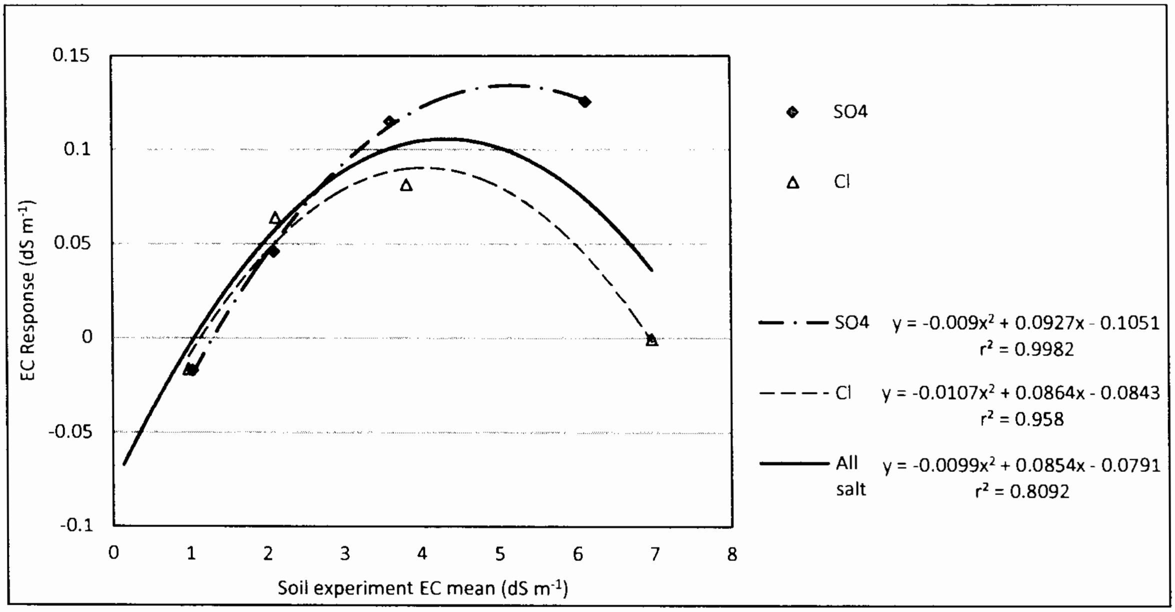

Fig. 5. Test meter EC Response versus the EC mean of the soil experiment for the main effect of salinity.

Average EC Response for all test meters for SO_4 salts was greater than that for Cl salts. The Cl and SO_4 salinity level of approximately 1 dS m^{-1} and the chloride salinity level of approximately 8 dS m^{-1}, were not significant but all other salinity levels were significantly different ($p=<0.05$)(Figure 5). As compared to the standard meter, the test meters overestimated the EC of all of the salinity levels that were significantly different in the soil experiment. In the no-soil experiment the SO_4 salts were also estimated higher than the Cl salts, but only four of eight salinity main effects were significant ($p\leq 0.05$); SO_4 salts at approximately 2, 4 and 8 dS m^{-1} and Cl salt at approximately 8 dS m^{-1}(Figure 7).

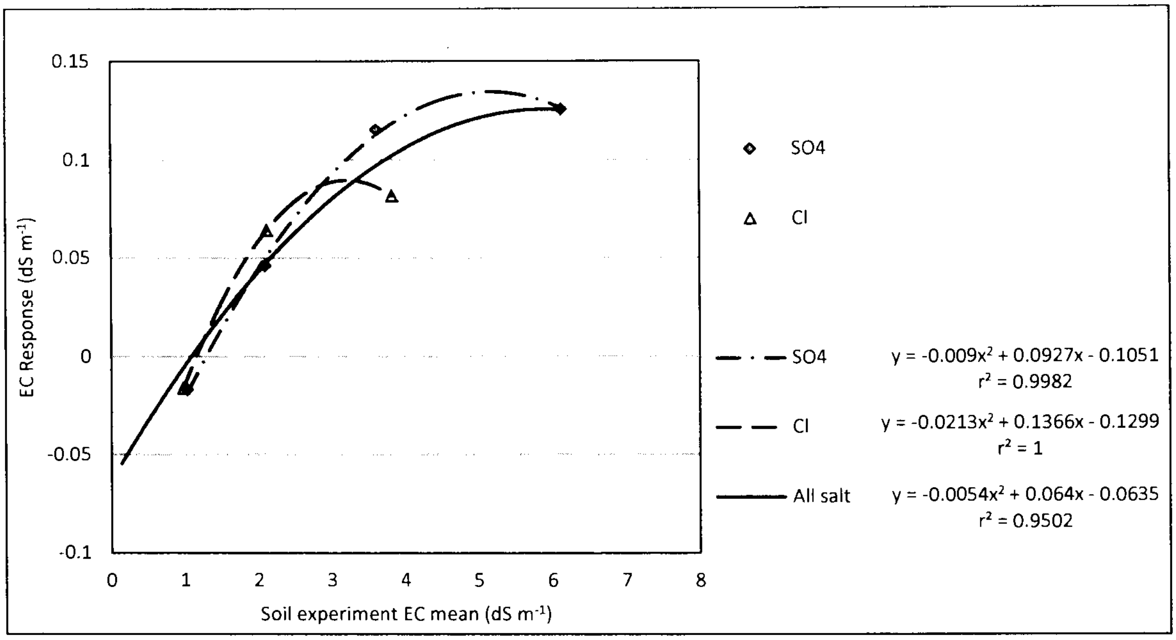

Fig. 6. Test meter EC Response versus EC mean of the soil experiment for the main effect of salinity; excluding the high Cl salinity level.

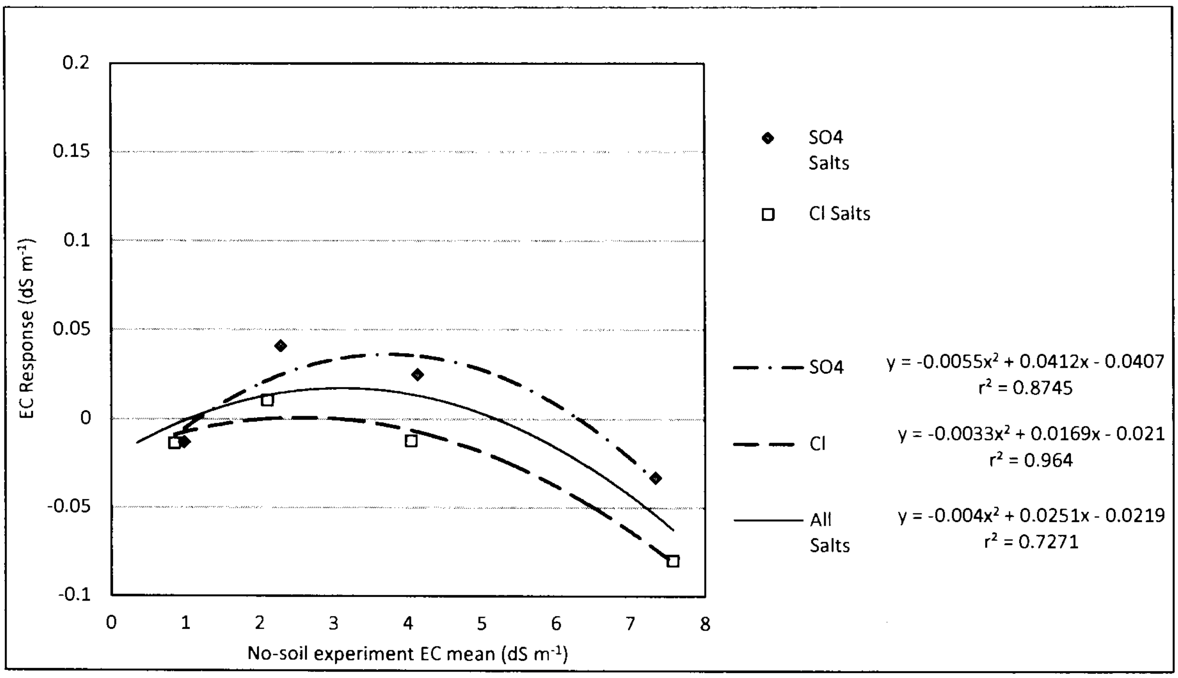

Fig. 7. Test meter EC Response versus EC mean of the no-soil experiment for the main effect of salinity.

Of these, the SO_4 salts at 2 and 4 dS m^{-1} were over estimated, while the SO_4 and Cl salts at 8 dS m^{-1} were underestimated as compared to the standard meter. Although, the student's t-test showed there was no significant difference between the soil and no-soil experiments for the salinity and temperature by salinity effects, the magnitude of the estimation error in the soil experiment was up to 3 times that of the no-soil experiment.

In the temperature by salinity level interactions of the soil experiment across all test meters, the EC response increased with increasing EC at 15°C (r^2=0.89)(Figure 8).

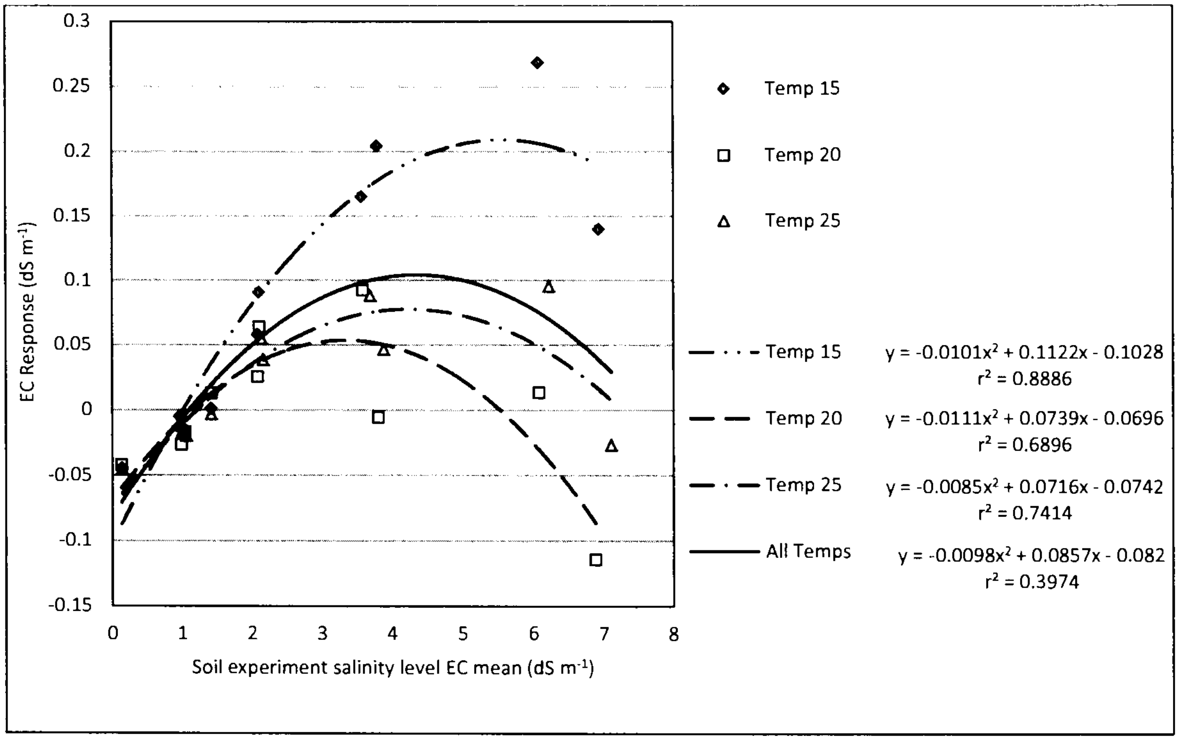

Fig. 8. Soil experiment test meter EC Response versus salinity level EC mean; plotted by temperature, across all soil clay concentrations and test meters.

The combined temperature (All temps) 20°C and the 25°C trend lines increase at lower EC levels and then decrease at the higher levels tested (r^2=0.40, 0.69 and 0.74, respectively). A visual examination of Figure 8 reveals a break point at a salinity level of approximately 3 dS m^{-1}, below which the data points are grouped but above 3 dS m^{-1} the variation in the data increases substantially. The temperature by salt interaction for the no-soil experiment showed less meter variance than the soil experiment (Figure 9).

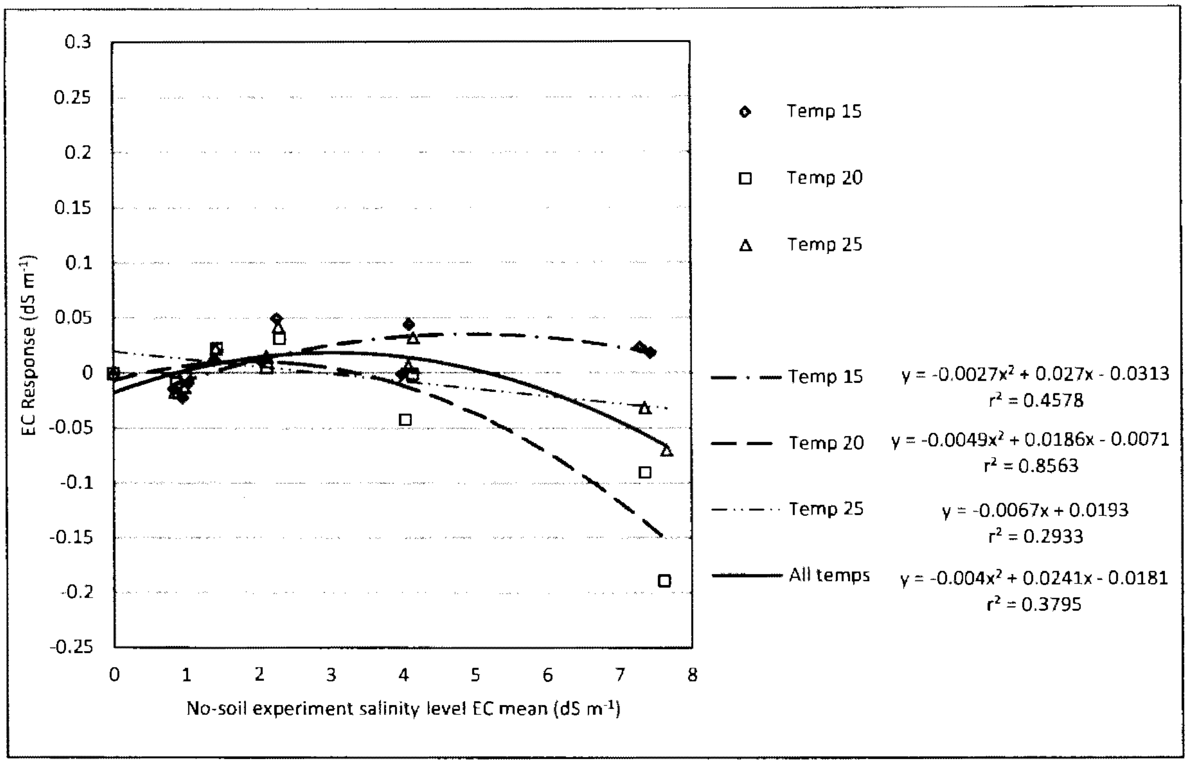

Fig. 9. No-soil experiment test meter EC Response versus salinity level EC mean; plotted by temperature, across all test meters.

The test meter variation in both experiments was similar for salinity levels of less than 3 dS m^{-1}. Despite the t-test showing there was no significant differences between the salinity and temperature by salinity means for the soil and no-soil experiments, during the soil experiment, the test meters measured higher EC than the standard meter whereas, in the no soil experiment the test meters tended to measure lower EC. All temperature by salt interaction trends for both experiments showed that test meter variability increased as EC increased, particularly when EC was greater than 3 dS m^{-1}.

Soil Clay Concentration Effects

The clay main effect was significant at all clay levels except 17% clay. The test meters read 0.1 dS m^{-1} lower than the standard meter on the 10% clay soil and slightly less than 0.1 dS m^{-1} higher on the 20, 30 and 50% soil. This ordering of the soils by clay percentage was consistent for most of the interactions involving the clay effect. The clay by salt interaction across all temperatures and meters produced variability of up to ±0.4 dS m^{-1}. Plotting the soil clay concentration by salinity level interaction as the test meter EC response over the EC measured for all salinity levels by soil clay concentration shows the differences in meter accuracies for the approximate salinity levels of less than 3, 3 to 4, and greater than 4 dS m^{-1} (Figure 10).

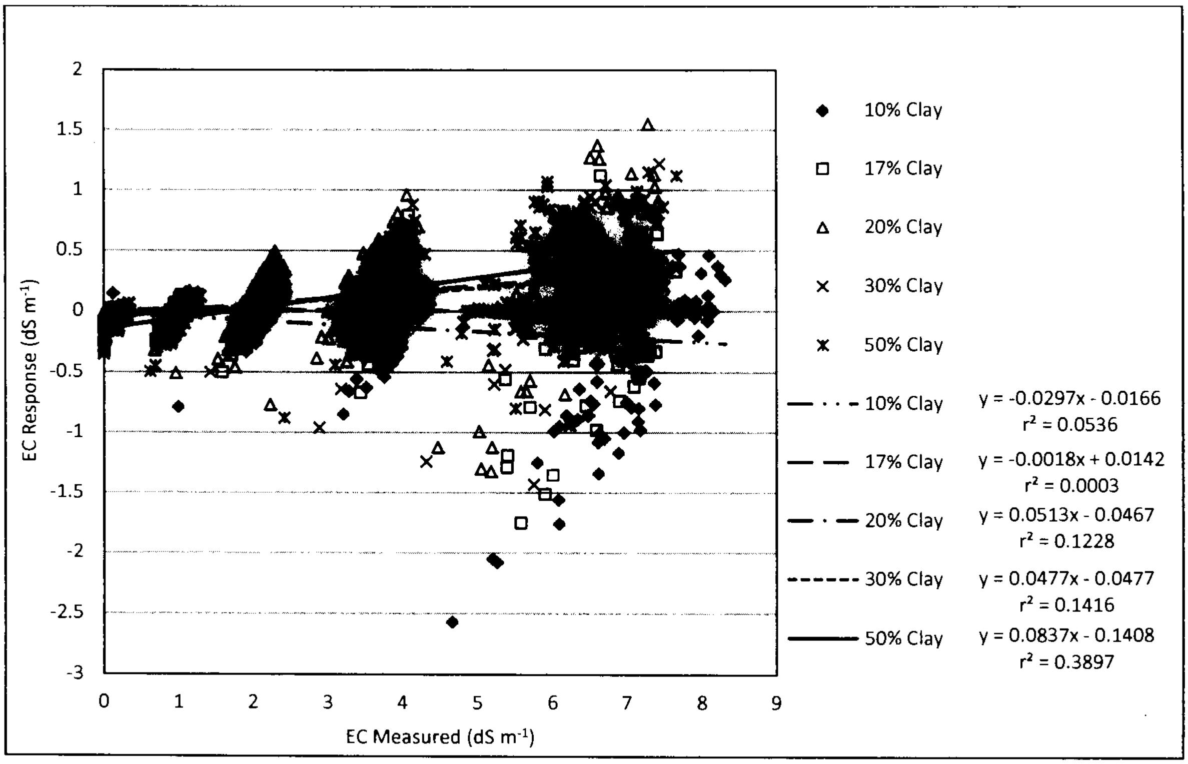

Fig. 10. Combined test meter EC Response versus EC measured across all temperatures, all meters, and all salinity levels by soil clay concentration.

As discussed earlier, the EC Response of all test meters increased at salinity levels of 3 dS m^{-1} and greater. However, the different levels of soil clay concentration affected whether or not the test meters over or under estimated the EC of the sample. Once again, salinity levels of 3 dS m^{-1} or greater seem to be the point at which the data begins to segregate (Figure 10). The test meters tended to under estimate sample EC at the 10% soil clay concentration level and over estimate sample EC at the 20, 30, and 50% soil clay concentration levels. Across all test meters the EC Response range for the soil clay concentration by salinity level interaction was approximately ±0.5, ±1, and -2.5 to +1.5 dS m^{-1}, for EC levels of less than 3, 3 to 4, and greater than 4 dS m^{-1}, respectively. This degree of variability resulted in a combined test meter accuracy of ±25-33%, which substantially exceeds the manufacturer's claims (Table 2).

The two-way interaction of soil clay concentration by meter revealed that the both the Field Scout and Hanna Blue meters were significantly different than the standard meter for all soil clay concentrations ($p \leq 0.001$, for all). The Hanna Black meter was significantly different than the standard meter at the soil clay concentration levels of 10, 17, and 30% ($p \leq 0.0001$, 0.0001, and 0.05, respectively). The SensION 5 meter was significantly different than the standard meter at the 20% soil clay concentration ($p \leq 0.05$). None of the soil clay concentration levels were significant across all test meters.

Meter Effects

The analysis results for the meter main effects from both experiments are shown in Table 6. Although all of the test meters were more accurate at salinity levels of less than 3 dS m^{-1}, the Hanna Black, Field Scout and Hanna Blue meter differences were highly significantly compared to the values from the standard meter for both the soil and no-soil experiments. The SensION 5 meter was the only meter that was not significantly different than the standard meter in the soil experiment. However, the SensION 5 meter was significantly different than the standard meter in the no-soil experiment. The linear analysis of the salinity by meter two way effect does not help to explain the significance of the difference between the test meters and the standard meter for the no-soil experiment (Table 7).

Table 6. Results of the analysis for meter main effect in the soil and no-soil experiments.

Meter	EC Response estimate	Standard error	Degrees of freedom	t value	p value
Soil experiment					
Hanna Black	-0.1105	0.01283	1425	-8.61	0.0001
Field Scout	0.103	0.01283	1425	8.03	0.0001
Hanna Blue	0.1958	0.01283	1425	15.26	0.0001
SensION 5	-0.009	0.01283	1425	-0.7	0.4831
No-soil experiment					
Hanna Black	-0.04056	0.007509	286	-5.4	0.0001
Field Scout	-0.1575	0.007509	286	-20.98	0.0001
Hanna Blue	0.1485	0.007509	286	19.77	0.0001
SensION 5	0.01892	0.007509	286	2.52	0.0123

p value ≤ 0.05 considered significant
p value ≤ 0.01 considered highly significant

Therefore, the temperature effect and probe material are the only explanations for the significant difference between the test meters and the standard meter for the no-soil experiment. However, this explanation does not address the significance of the SensION 5 meter when compared to the standard meter. Both the SensION 5 and the standard meter use the same temperature correction equation and sample probes. The linear analysis of the soil experiment salinity by meter effect does show the importance of salinity levels of greater than 3 dS m^{-1} (Table 7).

Table 7. Linear equations and r^2 values of the linear regression analysis of the salinity by meter effect for each meter.

	All salinity levels		Salinity ≥ 3 dS m^{-1}	
Meter	Linear equation	r^2	Linear equation	r^2
Soil experiment				
Hanna Black	y= 0.9629x - 0.022	0.9618	y= 0.8056x + 0.8448	0.8134
Field Scout	y= 1.028x + 0.0181	0.9779	y= 0.8891x + 0.7983	0.8945
Hanna Blue	y= 1.0502x + 0.0499	0.9923	y= 1.001x + 0.3213	0.9619
SensION 5	y= 0.9917x + 0.031	0.9950	y= 0.982x + 0.0668	0.9753
No-soil experiment				
Hanna Black	y= 0.9759x + 0.034	0.9950	y= 0.9459x + 0.2205	0.9764
Field Scout	y= 0.9289x + 0.0578	0.9979	y=0.8774x + 0.3705	0.9923
Hanna Blue	y= 1.0468x + 0.0007	0.9987	y= 1.057x - 0.0735	0.9930
SensION 5	y= 1.0089x - 0.0086	0.9998	y=1.0141x - 0.0418	0.9990

The increased variability of the Hanna Black, Hanna Blue and Field scout meters when the salinity exceeds 3 dS m^{-1} is troubling or a cause for concern. A soil is classified as saline when it has an EC_e of 4 dS m^{-1} or greater (US Salinity lab, 1954). The identification of saline soils is important for classification as well as crop management. Equally important is the identification of soils that have an EC_e of approximately 2 to 4 dS m^{-1}. These soils are considered slightly saline (Abrol, 1988). Slightly saline soils should be targeted for management practices to prevent or slow the further accumulation of soluble salts. Many agricultural techniques have been developed to mitigate the salinization of slightly saline soils (Abrol, 1988; Mass and Hoffman, 1977). Once soils have become strongly saline ($EC_e \geq 8$ dS m^{-1}) the management and remediation of these soils becomes more difficult because tolerant plant species and expensive water management strategies must be employed. Variations in temperature, soil clay concentration, and salinity levels greater than 3 dS m^{-1} significantly affected the accuracy of the Hanna Blue, Hanna Black, and Field Scout meters.

Hanna Black

The Hanna Black meter was significantly different than the standard meter ($p \leq 0.0001$). This meter did not effectively measure and compensate for temperature, which is a serious drawback for use in the field where the soil and ambient temperature can be expected to vary significantly within a few hours. This meter was the only one that consistently read 0.00 dS m^{-1} on samples where the standard meter measured 0.17 dS m^{-1} or less. The accuracy of the Hanna Black meter as compared to the standard meter was especially reduced when salinity levels were greater than 3 dS m^{-1} (r^2=0.81)(Table 7). The majority of the Hanna Black EC values at the higher salinity levels were ±0.5 dS m^{-1} different than the standard meter and varied by as much as ±2.5 dS m^{-1}. The 9 volt battery proved to be unreliable after about 12 hours of use. Difficulty calibrating the meter was the only sign that the battery needed to be replaced. If the user does not calibrate this meter prior to each use they will not know if the battery is becoming low and will run the risk of greater inaccuracy. The Hanna Black probe is designed with a stainless steel sensor recessed within the probe tip. This design prevents the sensors from contacting the sides and bottom of the sample container. However, if the Hanna Black meter is used to measure EC on saturated soil pastes the probe design will make it difficult to assure adequate sensor to sample contact and will make it difficult to clean between samples. The Hanna Black meter is one example that a more expensive instrument does not necessarily provide greater accuracy. For example, the Hanna Black was the second most expensive test meter in the experiments; however, it had the lowest accuracy of the meters tested when salinity levels were greater than 3 dS m^{-1} (Table 7).

Field Scout

The Field Scout's water proof compact design and carrying case make it desirable for field use, however, the user should be cautioned that this meter 1) needs a unique calibration standard, 2) was significantly different than the standard meter ($p=<0.0001$) and 3) had the second lowest accuracy of the meters tested for salinity levels of 3 dS m^{-1} or greater ($r^2=0.89$)(Table 7). On more than one occasion during the experiment the Field Scout incorrectly displayed an over-the-readable-limit error. This meter continuously displays the temperature reading and automatically adjusts the cell constant to provide greater resolution for different levels of salinity. Although the 4-LR44 batteries were regularly changed during the experiment, preliminary use of the Field Scout showed that they could provide enough power for more than 15 hours of use. While the automatic cell constant adjustment is a useful feature, the display of the units in use is very small, which makes it difficult for the user to accurately record the measurement in both artificial and sunlight conditions. The stainless steel probe of the Field Scout is designed for direct insertion into soil and therefore the sensors are exposed at the tip of the probe. This design allows for easy cleaning between samples and provides assurance that there is adequate contact of the sensor with a sample prepared in a container; however, it also requires the user to take precautions to prevent the sensor from contacting the sides or bottom of the sample container. The Field Scout instrument manual instructs the user to avoid touching the probe sensor with the hand or fingers to prevent skin oils from fouling the sensor. However, the remedy for a fouled sensor is to clean with alcohol and this could be accomplished in the field with an alcohol cleaning wipe.

Hanna Blue

The Hanna Blue was significantly different than the standard meter ($p=<0.0001$), but was the second most accurate test meter when salinity levels were greater than 3 dS m^{-1} ($r^2=0.96$)(Table 7). This meter is an example of an inexpensive EC meter that can provide accuracy equal to or greater than more expensive models. The Hanna Blue is compact, waterproof, and can display the sample temperature. The probe of the Hanna Blue meter is designed to be inserted directly into the soil, which makes it easy to clean between samples and assures adequate contact of the sensor with a sample prepared in a container. The user should use care to prevent the probe from contacting the sides and bottom of a sample container to prevent interference with measurement. The manufacturer refused to disclose the materials used to construct the Hanna Blue probe. Since the probe is designed for direct insertion into soil and other media it is possible that the probe is constructed from stainless steel, however the Hanna Blue meter performed better than the Hanna Black and Field Scout meters which have stainless steel probes. Another cautionary point is that the probe tip of the Hanna Blue meter is very sharp and could easily puncture skin or plastic sample containers. One major drawback of the Hanna Blue meter is that it does not automatically power down. If the user forgets to turn this meter off or accidently presses the power button when placing it in storage, the battery charge will be depleted. The LR-44 batteries are not uncommon, but are expensive compared to AA or 9 volt batteries and could be difficult to find in rural areas.

If the Hanna Blue meter is intended to be routinely used in the field the user would be wise to purchase a carrying case in which to keep the meter, probe, calibration solution (not included with the meter), and adjustment screwdriver because all of these pieces are separate and necessary for normal use.

SensION 5

The SensION 5 meter was not significantly different than the standard meter ($p=0.48$) and was the most accurate at all temperatures, salinity levels, and soil clay concentrations tested ($r^2=0.98$)(Table 7). This is most likely due to the fact that the SensION 5 is the only test meter that has a platinized 4-pole electrode and uses a non-linear NaCl based temperature correction coefficient. The 4-pole electrode uses a reference voltage to protect against errors due to probe deterioration. The non-linear temperature coefficient of the SensION 5 and standard meter more accurately reflected the change in conductivity with temperature (Figure 1). The sensor in the probe of the SensION 5 meter is recessed and protected on the bottom. This meter required a deeper sample than the other test meters to provide good sample to sensor contact. If used to measure EC on saturated soil pastes, the placement of the sensor could make it difficult clean and assure good contact of the sensor with the sample. The SensION 5 meter tells the user how long to wait for the sensors to adjust to the sample temperature before recording the measurement. The display shows the message "stabilizing...". When this message is no longer displayed the measurement is ready to be recorded. Although this meter is waterproof, the user is again encouraged to purchase some type of carrying case because the size and weight of the meter could make it cumbersome to carry.

Conclusions

The differences in the test meter responses for temperature, salinity and clay percentage were caused by differences in meter temperature measurement, temperature correction, and reduced meter accuracy at salinity levels greater than 3 dS m^{-1}. For the purposes of measuring irrigation or other water samples at a temperature of 20 ^{0}C and salinity levels that are less than 3 dS m^{-1}, all the meters tested can be expected to provide accurate estimates. However, if temperature cannot be controlled, EC exceeds 3 dS m^{-1}, or test samples contain soils with varying amounts of clay, the SensION 5 is the only meter tested that provided highly accurate results. Despite the manufacturer's claim that the Hanna Blue meter "gives indicative readings with lower accuracy between 4 and 10 dS m^{-1}", this meter proved to be the second most accurate meter tested. Based on the results of this experiment, the Hanna Blue meter can be expected to perform better in the field than the Hanna Black or the Field Scout meters. However, this experiment showed that the Hanna Blue as well as the Hanna Black and Field Scout meters provided EC values that were significantly different than standard meter EC values. The SensION 5 meter was the only meter tested that provided EC estimates that were highly correlated to the standard meter ($p \leq 0.48$)(Table 6) for all temperatures, soil clay concentrations, and salinity levels tested.

The method of soil sample preparation for in-field measurements is an important consideration. The probe designs of all the meters tested will easily accommodate field prepared soil slurries (1:1, 1:2, or 1:x soil:water slurry). However, if the user intends to use a saturated soil paste preparation method, the recessed sensor design of the probes of the SensION 5 and Hanna Black meters will make it difficult for the user to assure adequate contact with the soil paste and will also make them difficult to clean in between samples. The Field Scout and Hanna Blue meter probes are designed for direct insertion into the soil and will allow ease of use for soil:water slurry or saturated paste methods in a field setting. Further research is needed to evaluate the accuracy of other portable EC meters that are designed for in-field use and the different in-field methods of soil sample preparation. Specifically, research is needed to evaluate the effect of in-situ soil water content of samples, which is a potential source of error for in-field EC measurement methods.

References

Abrol, I.P., J.S.P. Yadav, and F.I. Massoud. 1988. Salt-affected soils and their management. FAO soils bulletin 39.

Cole-Parmer Technical Library. 2008. Conductivity Theory. [online]. Available at http://www.coleparmer.com/techinfo/techinfo.asp?htmlfile=Conductivity.htm&ID=78. (verified April 7, 2010).

Corwin, D. L. 2009. Dryland saline and sodic soils training. Bismarck, ND. September 28 2009.

Francois LE, Maas EV. 1994. Crop response and management on salt-affected soils. *In*: Pessarakli M, ed. Handbook of plant and crop stress. New York: Marcel Dekker, 149–181.

Franzen, David F. 2007. Managing saline soils in North Dakota. NDSU Extension Service. SF-1087 (revised).

Gartley, K.L. 1995. Recommended soluble salts tests. *In*: Recommended soil testing procedures for the northeastern United States. 2nd ed. [online]. Available at http://ag.udel.edu/extension/agnr/pdf/soiltesting/INTRO.pdf. (verified April 7, 2010).

Hayashi, Masaki. 2004. Temperature-electrical conductivity relation of water for environmental monitoring and geophysical data inversion. Environ. Monit. Assess. 96: 119-128.

Katerji, N., van Hoorn, J.W., Hamdy, A. and Mastrorilli, M., 2000. Salt tolerance classification of crops to soil salinity and to water stress day index. Agric. Water Manage. 43: 99–109.

Maas E.V., and Hoffman G.J. 1977. Crop salt tolerance—current assessment. J. Irrig. Drain. Div. Am. Soc. Civ. Eng., 103, 115–134.

Ogle, D., M. Majerus, and L. St. John. 2004. Plants for saline to sodic soil conditions. USDA-NRCS. Technical Note No. 9 (revised).

Pannell, David J., and Michael A. Ewing. 2006. Managing secondary dryland salinity: options and challenges. Agric. Water Manag. 80:41-56.

USDA. 1993. National Engineering Handbook. Part 623.0205 Leaching requirements for salinity control.

U.S. Salinity Laboratory Staff, 1954. Diagnosis and improvement of saline and alkali soils, USDA Handbook 60. U.S. Government Printing Office, Washington, DC, USA, pp. 1-160.

Walker, I. (2008). Using conductivity meters in agriculture. Queensland Government Department of Primary Industries and Fisheries. [online]. Avaliable at http://www2.dpi.qld.gov.au/horticulture/3096.html. (verified April 27, 2008).

GENERAL CONCLUSIONS

The soil salinity level (EC_e) is an important piece of information needed in order to make good salinity management decisions. The EC_e of soil is important for the purposes of soil classification and management. The severity of soil salinity is an important factor used in making crop and variety choices, calculating leaching requirement, and other decisions involving the management of saline soils. Portable EC meters can be used to accurately measure soil EC over a range of conditions that may exist during in-field EC measurements. Portable EC meters that accurately sense temperature and correct for temperature and use a 4-pole electrode can be expected to provide values equally accurate to laboratory grade EC meters. Portable EC meters could be used as an important tool in the diagnosis, quantification, and management of saline soils. Additional research is needed to identify in-field soil preparation methods that will provide the greatest accuracy and repeatability of in-field EC measurements.

REFERENCES

Abrol, I.P., J.S.P. Yadav, and F.I. Massoud. 1988. Salt-affected soils and their management. FAO soils bulletin 39.

Barrett-Lennard, E.G. 2002. Restoration of saline land through revegetation. Agric. Water Manage. 53: 213-226.

Blaylock, A.D. 1994. Soil salinity, salt tolerance, and growth potential of horticultural and landscape plants. University of Wyoming Cooperative extension service B-988.

BIPM. 1971. Bureau of International des Poids and Mesures. 14th General Conference on Weigths and Measures (CGPM). [online]. Available at http://www.bipm.org/en/convention/cgpm/14/pascal-siemens.html. (verified April 7, 2010).

Clay, R. B. 2001. Working with the EM-38 earth conductivity meter: geophysical survey at the Hopeton Earthwork, Chilicothe, Ohio. [online]. Available at http://www.crai-ky.com/education/reports/em38.pdf. (verified April 7, 2010).

Cole-Parmer Technical Library. 2008. Conductivity Theory. [online]. Available at http://www.coleparmer.com/techinfo/techinfo.asp?htmlfile=Conductivity.htm&ID=78. (verified April 7, 2010).

Corwin, D. L. 2009. Dryland saline and sodic soils training. Bismarck, ND. September 28 2009.

de Jong, E., A.K. Ballantyne, D.R. Cameron, and D.W.L. Read. 1979. Measurement of apparent electrical conductivity of soils by electromagnetic induction probe to aid salinity surveys. Soil Sci. Soc. Am. J. 43:810-812.

Francois L.E., and E.V. Maas. 1994. Crop response and management on salt-affected soils. *In*: Pessarakli M, ed. Handbook of plant and crop stress. New York: Marcel Dekker, 149–181.

Franzen, D.F. 2007. Managing saline soils in North Dakota. NDSU Extension Service. SF-1087 (revised).

Gartley, K.L. 1995. Recommended soluble salts tests. *In*: Recommended soil testing procedures for the northeastern United States. 2nd ed. [online]. Available at http://ag.udel.edu/extension/agnr/pdf/soiltesting/INTRO.pdf. (verified April 7, 2010).

Geonics Limited. 2010. [online]. Available at http://geonics.com/. (verified April 2, 2010).

Hayashi, Masaki. 2004. Temperature-electrical conductivity relation of water for environmental monitoring and geophysical data inversion. Environ. Monit. Assess. 96: 119-128.

Helms, D. 2001. The early soil survey. Engine for soil conservation movement. *In*: D. E. Stott, R.H. Mohtar, and G.C. Steinhardt (eds.) 2001. Sustaining the global farm. selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29 1999. Purdue University. [online]. Available at http://www.tucson.ars.ag.gov/isco/isco10/SustainingTheGlobalFarm/P273-Helms.pdf. (verified April 7, 2010).

Henschke, Chris, and Tim Herrmann. 2007. Testing for soil and water salinity: Why test for salt? Govt. of South Australia. Fact Sheet No: 66/00. [online]. Available at http://www.pir.sa.gov.au/__data/assets/pdf_file/0005/37841/soilwatr.pdf. (verified April 7, 2010).

Johnson, R. 2009. Water quality monitoring of subsurface drains in Cass county. NDSU Extension Service. [online]. Available at http://www.ag.ndsu.edu/ext-emp/evaluation/reports/impactreports/08state-r.johnson2.pdf. (verified April 5, 2010).

Katerji, N., van Hoorn, J.W., Hamdy, A. and Mastrorilli, M., 2000. Salt tolerance classification of crops to soil salinity and to water stress day index. Agric. Water Manage. 43: 99–109.

Knuteson, J.A., J.L. Richardson, D.D. Patterson, and L. Prunty. 1989. Pedogenic carbonates in a calciaquoll associated with a recharge wetland. Soil Sci. Soc. Am. J. 53:495-499.

Lee, J. 2010. Personal communication. Soil scientist. marketing manager of Agvise Laboratories. Northwood, ND.

Maas E.V., and Hoffmann G.J. 1977. Crop salt tolerance—current assessment. J. Irrig. Drain. Div. Am. Soc. Civ. Eng., 103, 115–134.

Mitchell, J.P., C.D. Thomsen, W.L. Graves, C. Shennan. 1999. Cover crops for saline soils. J. Agron. Crop Sci. 183: 167-178.

Natural Resources Conservation Service. NRCS conservation practice standard. Salinity and sodic soil management. Code 610. [online]. Available at http://efotg.nrcs.usda.gov/references/public/NE/NE610.pdf. (verified April 2, 2010).

Ogle, D., M. Majerus, and L. St. John. 2004. Plants for saline to sodic soil conditions. USDA-NRCS. Technical Note No. 9 (revised).

Pannell, David J., and Michael A. Ewing. 2006. Managing secondary dryland salinity: Options and challenges. Agric. Water Manag. 80:41-56.

Reluy, F.V., J.M. des Paz Bescartes, R.D. Zapata-Hernandez, and J.D. Sanchez. 2004. Development of an equation to relate electrical conductivity to soil and water salinity in a Mediterranean agricultural environment. Aust. J. Soil Res. 42, 381-388.

Reitemeier, R. F. and L. V. Wilcox. 1946. A critique of soil solution concentration from the electrical conductivity of saturated soils. Soil Sci. Vol. 61 Iss. 4. 281-294.

Rhoades, J. D., N.A. Manteghi, P.J. Shouse, and W.J. Alves. 1989a. Estimating soil salinity from saturated soil-paste conductivity. Soil Sci. Soc. Am. J. 53:428-433.

Rhoades, J. D., N.A. Manteghi, P.J. Shouse, and W.J. Alves. 1989b. Soil electrical conductivity and soil salinity: New formulas and calibrations. Soil Sci. Soc. Am. J. 53:433-439.

Rhoades, J. D., F. Chanduvi, and S. Lesch. 1999. Soil salinity assessment, methods and interpretation of electrical conductivity measurement. FAO Irrigation and Drainage Paper 57.

Scianna, J. et al. NRCS Plant materials technical note No. MT-60. 2007. [online]. Available at http://www.plant-materials.nrcs.usda.gov/pubs/mtpmctn7579.pdf. (verified April 2, 2010).

Scianna, J. et al. NRCS Plant materials technical note No. MT-62. 2007. [online]. Available at ftp://ftp-fc.sc.egov.usda.gov/MT/www/technical/plants/technotes/PM_Tech_Note_MT62.pdf. (verified April 7, 2010).

Sands, G.R. 2010. Tile drainage for profitable crop production. University of Minn extension service. [online]. Available at http://www.smallgrains.org/drainage/home.html. (verified April 5, 2010).

Sands, G.R. and J. Wright. 2001. Planning an agricultural subsurface drainage system. University of Minn. extension service. BU-07685-S.

Seelig, B. D. 2000. Salinity and Sodicity in North Dakota soils. NDSU extension bulletin EB-57.

Soil Science Glossary Terms Committee. 2008. Glossary of soil science terms 2008. SSSA 2008. [online]. Available at https://www.soils.org/publications/soils-glossary/. (verified April 7, 2010).

Suarez, D. L., 2005. Chapter 15. Chemistry of Salt affected soils. *In*: M.A. Tabatabai and D.L. Sparks (eds.) Chemical processes in soils. SSSA Madison, WI.

Sudduth, K.A., N.R. Kitchen, W.J. Wiebold, W.D. Batchelor, G.A. Bollero, D.G. Bullock, D.E. Clay, H.L. Palm, F.J. Pierce, R.T. Schuler, and K.D. Thelen. 2005. Relating apparent electrical conductivity to soil properties across the north-central USA. Comput. Elect. Agric. 46, 263-283.

Tanji, K.K. and N.C. Kielen. 2002. Agricultural drainage water management in arid and semi-arid areas. FAO Irrigation and drainage paper 61. Rome. [online]. Available at http://www.fao.org/docrep/005/Y4263E/y4263e00.htm#Contents. (verified April 5, 2010).

Thermo Corp. 2008. Orion Conductivity Theory. [online]. Available at http://www.thermo.com/eThermo/CMA/PDFs/Articles/articlesFile_11377.pdf. (verified April, 2, 2010).

USDA. 1993. National Engineering Handbook. Part 623.0205 Leaching requirements for salinity control.

U.S. Salinity Laboratory Staff, 1954. Diagnosis and improvement of saline and alkali soils, USDA Handbook 60. U.S. Government Printing Office, Washington, DC, USA, pp. 1-160.

Veris Technologies. 2010. [online]. Available at http://www.veristech.com/. (verified April 7, 2010).

Walker, I. (2008). Using conductivity meters in agriculture. Queensland Government Department of Primary Industries and Fisheries. [online]. Available at http://www2.dpi.qld.gov.au/horticulture/3096.html. (verified April 7, 2010).

Wang, D. and M.C. Shannon. 1999. Emergence and seedling growth of soybean cultivars and maturity groups under salinity. Plant and Soil 214: 117-124.

Watson, J., and T. Knowles. 1999. Leaching for maintenance: Factors to consider for determining the leaching requirement for crops. [online]. Available at http://cals.arizona.edu/pubs/water/az1107.pdf. (Verified April 5, 2010).

Whitney M. and T. Means. 1897. USDA Division of soils bulletin 7.

APPENDIX A. SOIL EXPERIMENT SUPPLIMENTAL DATA

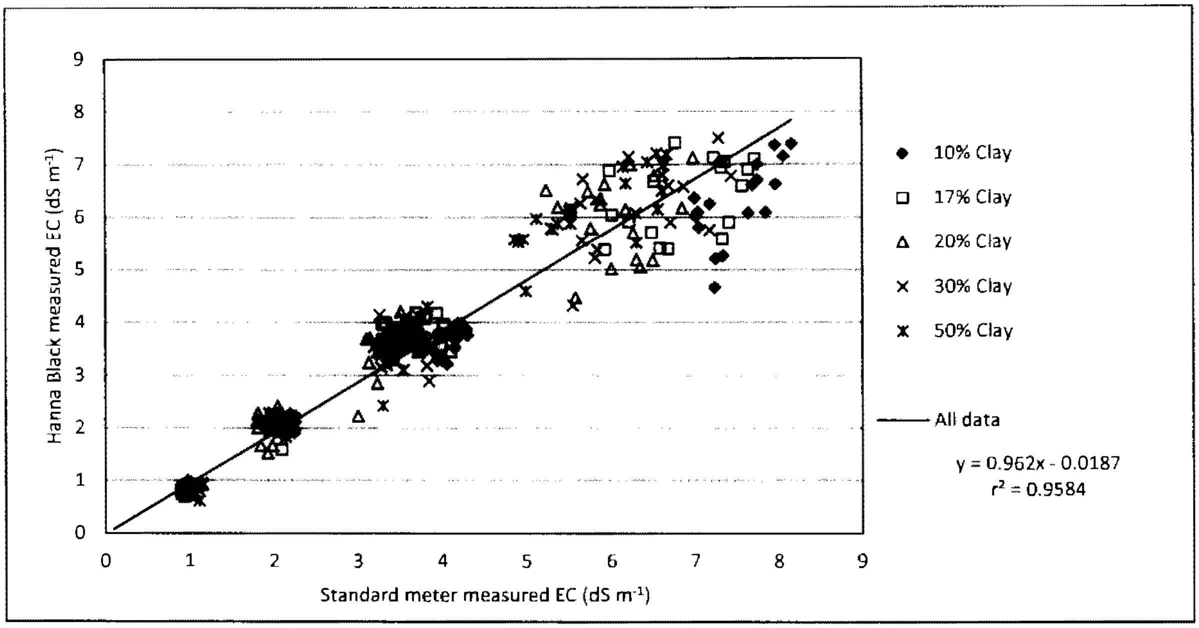

Fig. 11. Soil experiment Hanna Black measured EC versus standard meter measured EC across all temperatures and salinity levels; plotted by soil clay concentration.

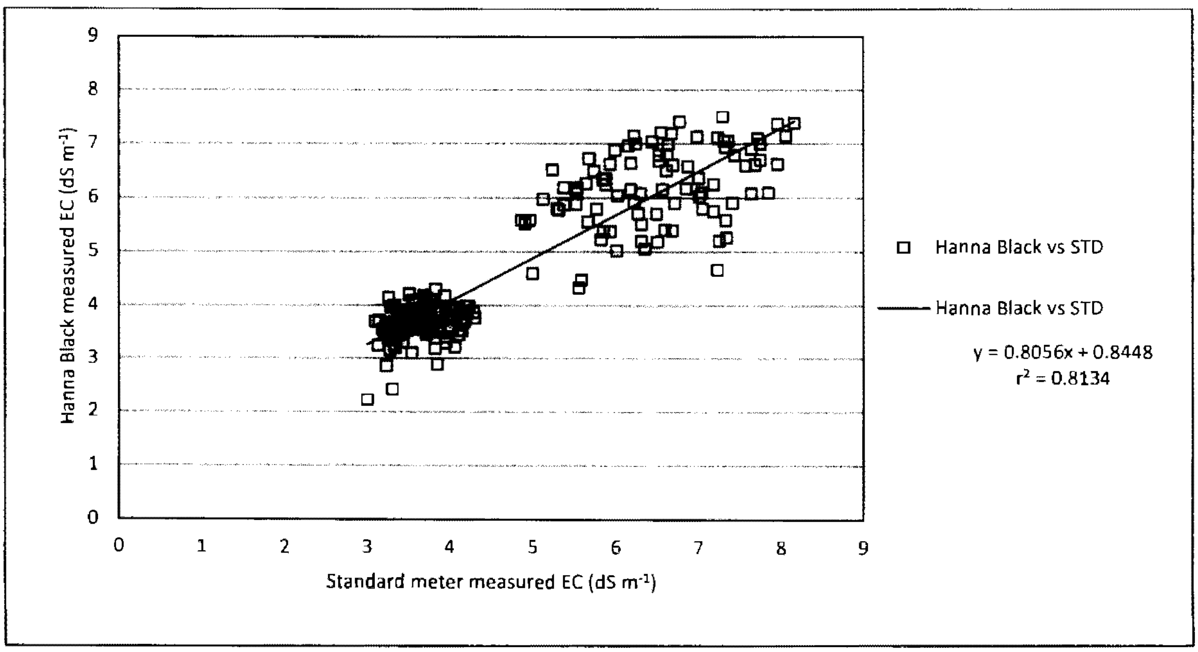

Fig. 12. Soil experiment Hanna Black measured EC versus standard meter measured EC across all temperatures and soil clay concentrations for salinity levels greater than 3 dS m^{-1}.

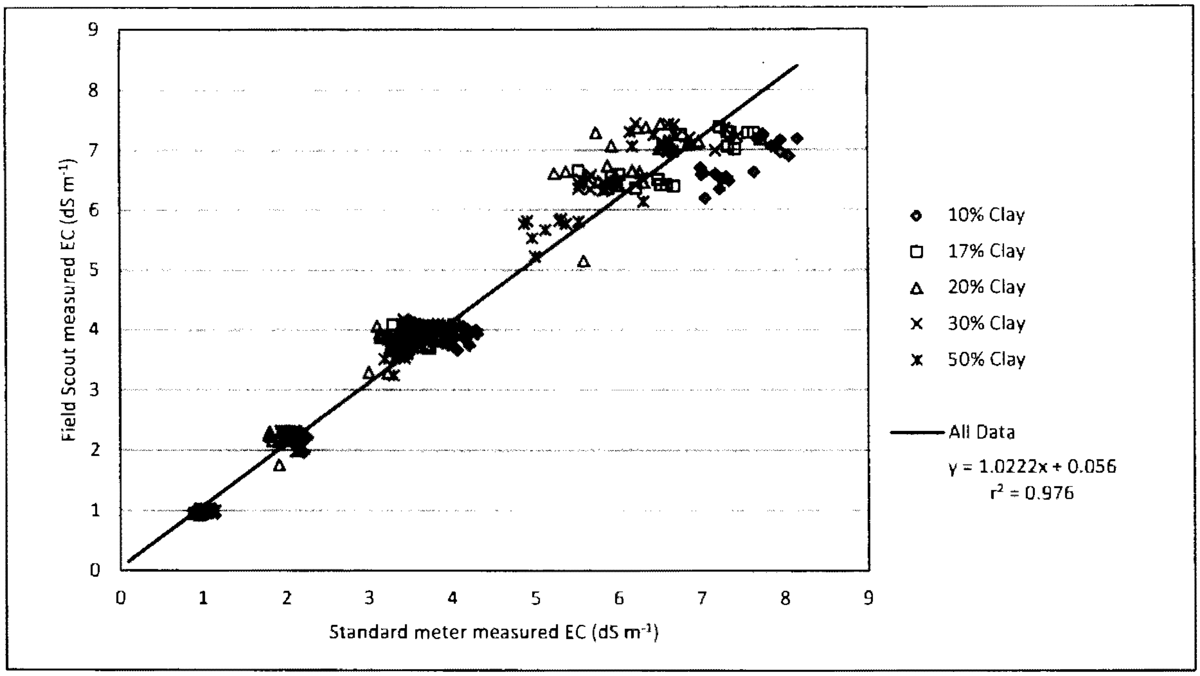

Fig. 13. Soil experiment Field Scout measured EC versus standard meter measured EC across all temperatures and salinity levels; plotted by soil clay concentration.

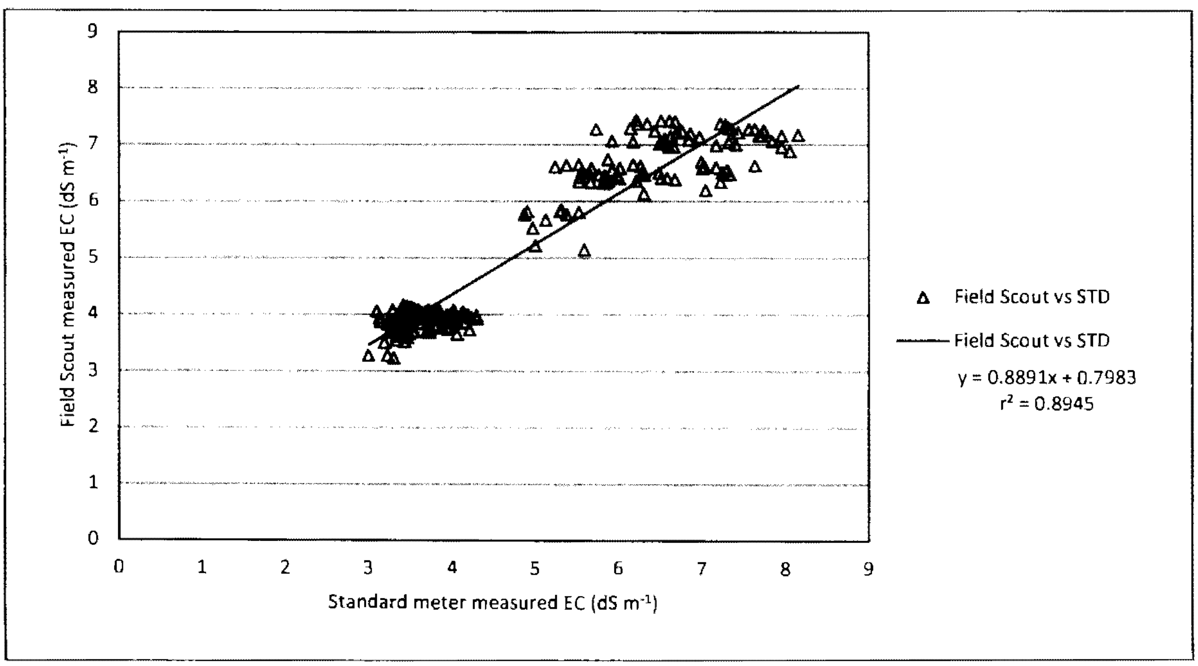

Fig. 14. Soil experiment Field Scout measured EC versus standard meter measured EC across all temperatures and soil clay concentrations for salinity levels greater than 3 dS m^{-1}.

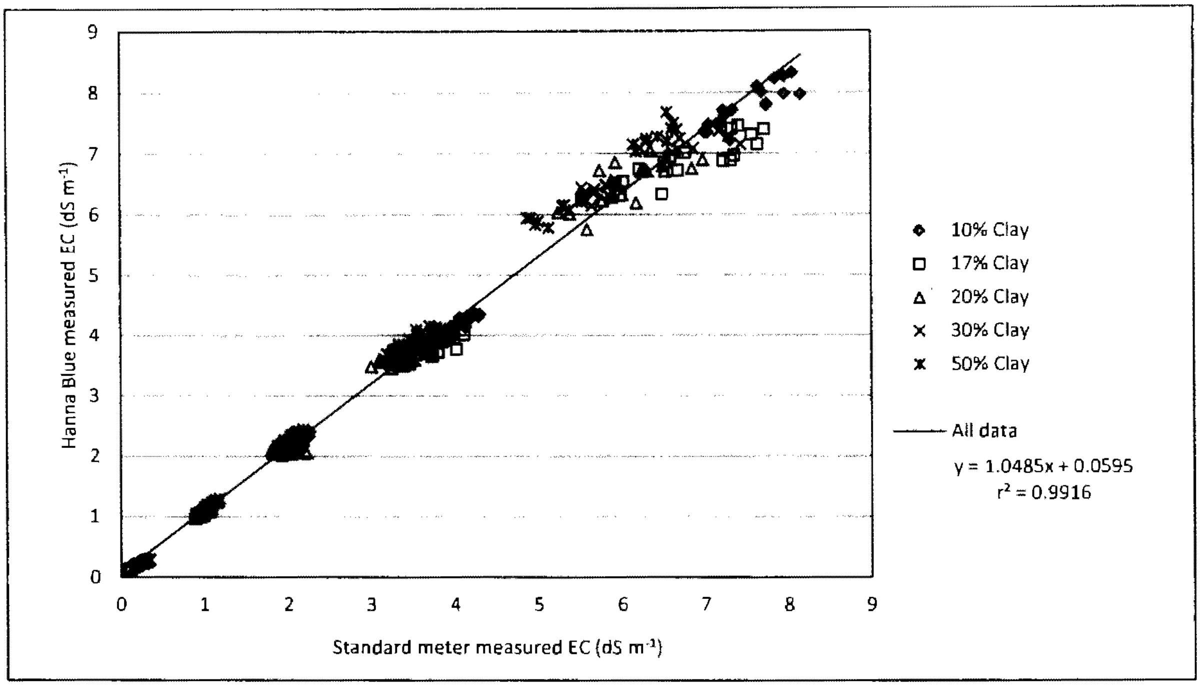

Fig. 15. Soil experiment Hanna Blue measured EC versus standard meter EC measured across all temperatures and salinity levels; plotted by soil clay concentration.

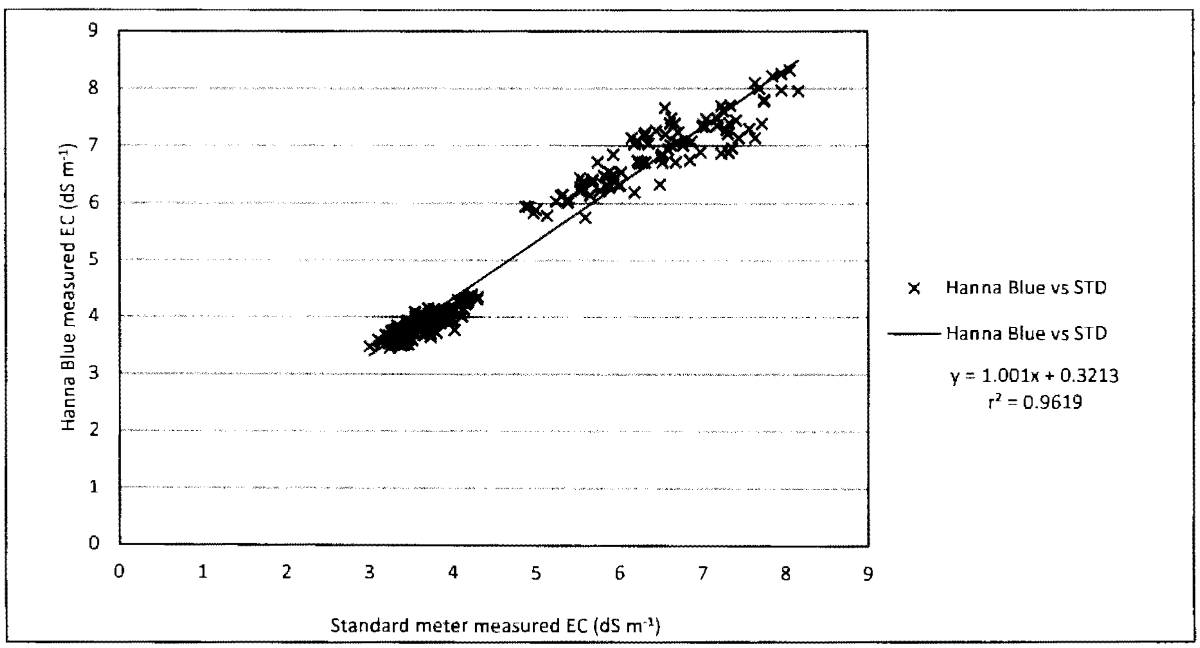

Fig. 16. Soil experiment Hanna Blue measured EC versus standard meter measured EC across all temperatures and soil clay concentrations for salinity levels greater than 3 dS m^{-1}.

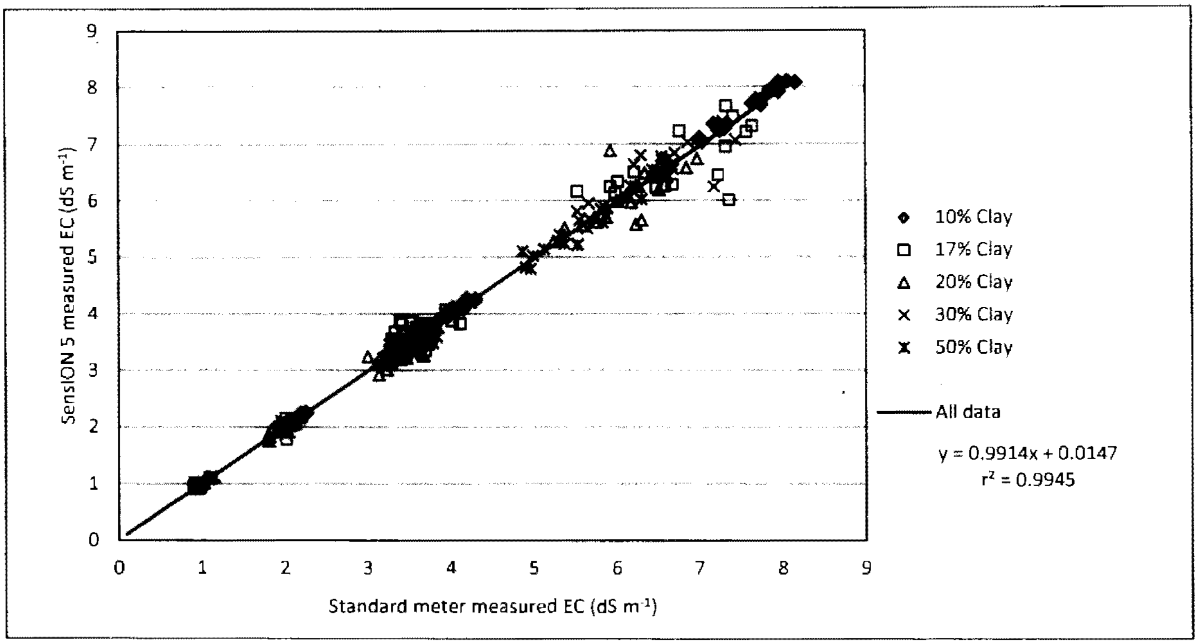

Fig. 17. Soil experiment SensION 5 measured EC versus standard meter EC measured across all temperatures and salinity levels; plotted by soil clay concentration.

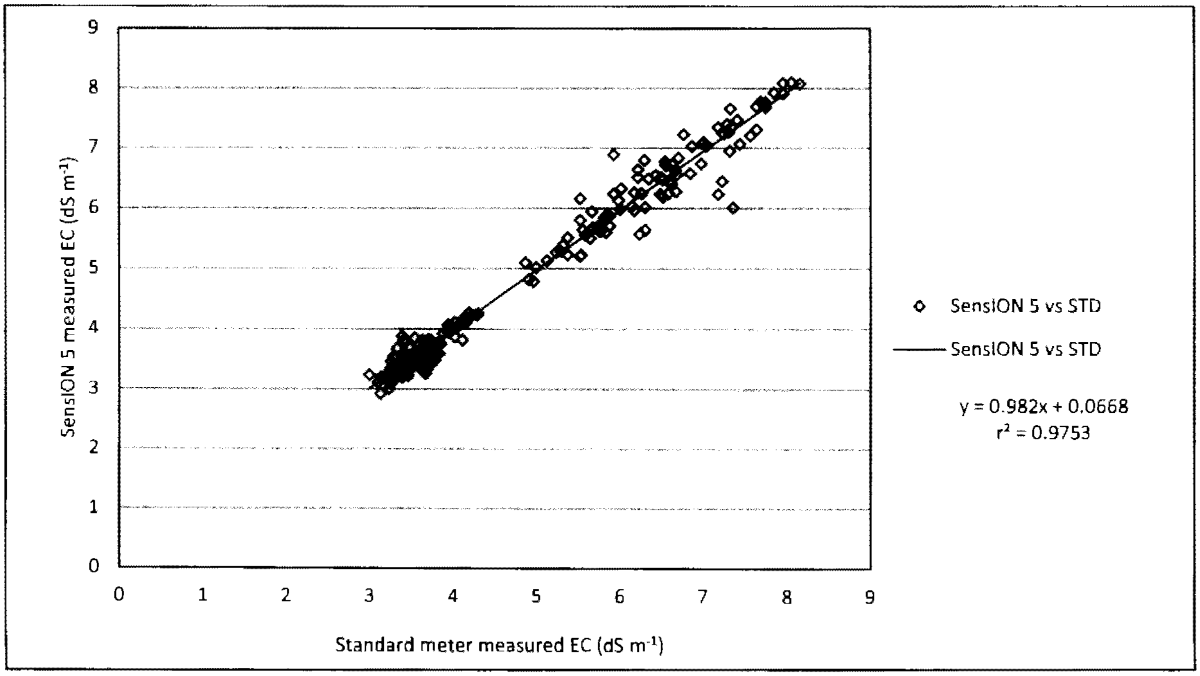

Fig. 18. Soil experiment SensION 5 measured EC versus standard meter measured EC across all temperatures and soil clay concentrations for salinity levels greater than 3 dS m^{-1}.

Table 8. SAS analysis output for soil experiment; main effects and two-way interactions.

Effect	Temp	Clay	Salt	Meter	DF	t Value	Pr > |t|
Temp	15				6	101.49	0.0001
Temp	20				6	101.7	0.0001
Temp	25				6	104.21	0.0001
Clay		10			24	143.27	0.0001
Clay		17			24	135.11	0.0001
Clay		20			24	129.05	0.0001
Clay		30			24	132.08	0.0001
Clay		50			24	130.9	0.0001
Salt			S0,0; S1,0		54	6.55	0.0001
Salt			S0,1		54	46.44	0.0001
Salt			S0,2		54	93.93	0.0001
Salt			S0,4		54	161.71	0.0001
Salt			S0,8		54	274.43	0.0001
Salt			S1,1		54	44.03	0.0001
Salt			S1,2		54	94.98	0.0001
Salt			S1,4		54	171.14	0.0001
Salt			S1,8		54	312.46	0.0001
Salt			Std		54	63.42	0.0001
Meter				SensION 5	1425	163.88	0.0001
Meter				Hanna Black	1425	157.91	0.0001
Meter				Field Scout	1425	170.46	0.0001
Meter				Hanna Blue	1425	175.91	0.0001
Temp*Clay	15	10			24	82.12	0.0001
Temp*Clay	20	10			24	82.13	0.0001
Temp*Clay	25	10			24	83.9	0.0001
Temp*Clay	15	17			24	76.45	0.0001
Temp*Clay	20	17			24	78.42	0.0001
Temp*Clay	25	17			24	79.15	0.0001
Temp*Clay	15	20			24	74.36	0.0001
Temp*Clay	20	20			24	72.66	0.0001
Temp*Clay	25	20			24	76.51	0.0001
Temp*Clay	15	30			24	75.45	0.0001
Temp*Clay	20	30			24	76.71	0.0001
Temp*Clay	25	30			24	76.61	0.0001
Temp*Clay	15	50			24	74.99	0.0001
Temp*Clay	20	50			24	74.25	0.0001
Temp*Clay	25	50			24	77.49	0.0001
Temp*Clay	15	10			24	82.12	0.0001
Temp*Clay	15	17			24	76.45	0.0001
Temp*Clay	15	20			24	74.36	0.0001

Table 8 (continued)

Temp*Clay	15	30		24	75.45	0.0001
Temp*Clay	15	50		24	74.99	0.0001
Temp*Clay	20	10		24	82.13	0.0001
Temp*Clay	20	17		24	78.42	0.0001
Temp*Clay	20	20		24	72.66	0.0001
Temp*Clay	20	30		24	76.71	0.0001
Temp*Clay	20	50		24	74.25	0.0001
Temp*Clay	25	10		24	83.9	0.0001
Temp*Clay	25	17		24	79.15	0.0001
Temp*Clay	25	20		24	76.51	0.0001
Temp*Clay	25	30		24	76.61	0.0001
Temp*Clay	25	50		24	77.49	0.0001
Temp*Salt	15		S0,0; S1,0	54	3.79	0.0004
Temp*Salt	15		S0,1	54	26.18	0.0001
Temp*Salt	15		S0,2	54	53.81	0.0001
Temp*Salt	15		S0,4	54	92.19	0.0001
Temp*Salt	15		S0,8	54	157.04	0.0001
Temp*Salt	15		S1,1	54	24.87	0.0001
Temp*Salt	15		S1,2	54	54.22	0.0001
Temp*Salt	15		S1,4	54	97.85	0.0001
Temp*Salt	15		S1,8	54	179.25	0.0001
Temp*Salt	15		Std	54	36.52	0.0001
Temp*Salt	20		S0,0; S1,0	54	3.62	0.0006
Temp*Salt	20		S0,1	54	26.84	0.0001
Temp*Salt	20		S0,2	54	53.79	0.0001
Temp*Salt	20		S0,4	54	92.6	0.0001
Temp*Salt	20		S0,8	54	157.33	0.0001
Temp*Salt	20		S1,1	54	25.54	0.0001
Temp*Salt	20		S1,2	54	54.44	0.0001
Temp*Salt	20		S1,4	54	98.28	0.0001
Temp*Salt	20		S1,8	54	178.03	0.0001
Temp*Salt	20		Std	54	36.73	0.0001
Temp*Salt	25		S0,0; S1,0	54	3.92	0.0003
Temp*Salt	25		S0,1	54	27.41	0.0001
Temp*Salt	25		S0,2	54	55.09	0.0001
Temp*Salt	25		S0,4	54	95.3	0.0001
Temp*Salt	25		S0,8	54	160.97	0.0001
Temp*Salt	25		S1,1	54	25.86	0.0001
Temp*Salt	25		S1,2	54	55.85	0.0001
Temp*Salt	25		S1,4	54	100.29	0.0001
Temp*Salt	25		S1,8	54	183.91	0.0001

Table 8 (continued)

Temp*Salt	25		Std		54	36.6	0.0001
Temp*Meter	15			SensION 5	1425	91.8	0.0001
Temp*Meter	20			SensION 5	1425	95.5	0.0001
Temp*Meter	25			SensION 5	1425	96.53	0.0001
Temp*Meter	15			Hanna Black	1425	92.18	0.0001
Temp*Meter	20			Hanna Black	1425	87.29	0.0001
Temp*Meter	25			Hanna Black	1425	94.03	0.0001
Temp*Meter	15			Field Scout	1425	100.19	0.0001
Temp*Meter	20			Field Scout	1425	96.64	0.0001
Temp*Meter	25			Field Scout	1425	98.41	0.0001
Temp*Meter	15			Hanna Blue	1425	99.62	0.0001
Temp*Meter	20			Hanna Blue	1425	102.23	0.0001
Temp*Meter	25			Hanna Blue	1425	102.84	0.0001
Clay*Salt		10	S0,0; S1,0		216	2.79	0.0058
Clay*Salt		10	S0,1		216	30.31	0.0001
Clay*Salt		10	S0,2		216	64.99	0.0001
Clay*Salt		10	S0,4		216	115.63	0.0001
Clay*Salt		10	S0,8		216	201.17	0.0001
Clay*Salt		10	S1,1		216	28.35	0.0001
Clay*Salt		10	S1,2		216	64.82	0.0001
Clay*Salt		10	S1,4		216	119.87	0.0001
Clay*Salt		10	S1,8		216	221.55	0.0001
Clay*Salt		10	Std		216	41.64	0.0001
Clay*Salt		17	S0,0; S1,0		216	2.97	0.0033
Clay*Salt		17	S0,1		216	29.43	0.0001
Clay*Salt		17	S0,2		216	61.29	0.0001
Clay*Salt		17	S0,4		216	107.72	0.0001
Clay*Salt		17	S0,8		216	185.42	0.0001
Clay*Salt		17	S1,1		216	27.65	0.0001
Clay*Salt		17	S1,2		216	61.51	0.0001
Clay*Salt		17	S1,4		216	113.13	0.0001
Clay*Salt		17	S1,8		216	209.48	0.0001
Clay*Salt		17	Std		216	41.76	0.0001
Clay*Salt		20	S0,0; S1,0		216	5.74	0.0001
Clay*Salt		20	S0,1		216	30.35	0.0001
Clay*Salt		20	S0,2		216	60.51	0.0001
Clay*Salt		20	S0,4		216	101.43	0.0001
Clay*Salt		20	S0,8		216	176.61	0.0001
Clay*Salt		20	S1,1		216	28.53	0.0001
Clay*Salt		20	S1,2		216	59.57	0.0001
Clay*Salt		20	S1,4		216	105.83	0.0001

Table 8 (continued)

Clay*Salt	20	S1,8		216	192.75	0.0001
Clay*Salt	20	Std		216	41.7	0.0001
Clay*Salt	30	S0,0; S1,0		216	4.53	0.0001
Clay*Salt	30	S0,1		216	30.41	0.0001
Clay*Salt	30	S0,2		216	60.41	0.0001
Clay*Salt	30	S0,4		216	103.72	0.0001
Clay*Salt	30	S0,8		216	176.16	0.0001
Clay*Salt	30	S1,1		216	28.89	0.0001
Clay*Salt	30	S1,2		216	62.13	0.0001
Clay*Salt	30	S1,4		216	110.63	0.0001
Clay*Salt	30	S1,8		216	203.15	0.0001
Clay*Salt	30	Std		216	41.65	0.0001
Clay*Salt	50	S0,0; S1,0		216	6.86	0.0001
Clay*Salt	50	S0,1		216	32.07	0.0001
Clay*Salt	50	S0,2		216	61.4	0.0001
Clay*Salt	50	S0,4		216	102.75	0.0001
Clay*Salt	50	50,8		216	162.25	0.0001
Clay*Salt	50	S1,1		216	31.26	0.0001
Clay*Salt	50	S1,2		216	64.02	0.0001
Clay*Salt	50	S1,4		216	112.79	0.0001
Clay*Salt	50	S1,8		216	199.61	0.0001
Clay*Salt	50	Std		216	41.6	0.0001
Clay*Meter	10		SensION 5	1425	0.42	0.6729
Clay*Meter	17		SensION 5	1425	0.12	0.9056
Clay*Meter	20		SensION 5	1425	-2.03	0.0422
Clay*Meter	30		SensION 5	1425	-0.1	0.9202
Clay*Meter	50		SensION 5	1425	-0.54	0.5884
Clay*Meter	10		Hanna Black	1425	-19.19	0.0001
Clay*Meter	17		Hanna Black	1425	-4.71	0.0001
Clay*Meter	20		Hanna Black	1425	0.11	0.9142
Clay*Meter	30		Hanna Black	1425	-2.52	0.012
Clay*Meter	50		Hanna Black	1425	0.11	0.9144
Clay*Meter	10		Field Scout	1425	-10.59	0.0001
Clay*Meter	17		Field Scout	1425	4.12	0.0001
Clay*Meter	20		Field Scout	1425	14.11	0.0001
Clay*Meter	30		Field Scout	1425	10.97	0.0001
Clay*Meter	50		Field Scout	1425	5.82	0.0001
Clay*Meter	10		Hanna Blue	1425	5.84	0.0001
Clay*Meter	17		Hanna Blue	1425	3.38	0.0008
Clay*Meter	20		Hanna Blue	1425	9.7	0.0001
Clay*Meter	30		Hanna Blue	1425	11.59	0.0001

Table 8 (continued)

Clay*Meter	50		Hanna Blue	1425	15.92	0.0001
Salt*Meter		S0,0; S1,0	SensION 5	1425	7.27	0.0001
Salt*Meter		S0,1	SensION 5	1425	36.09	0.0001
Salt*Meter		S0,2	SensION 5	1425	69.66	0.0001
Salt*Meter		S0,4	SensION 5	1425	119.72	0.0001
Salt*Meter		S0,8	SensION 5	1425	204.42	0.0001
Salt*Meter		S1,1	SensION 5	1425	34.15	0.0001
Salt*Meter		S1,2	SensION 5	1425	70.05	0.0001
Salt*Meter		S1,4	SensION 5	1425	125.72	0.0001
Salt*Meter		S1,8	SensION 5	1425	234.86	0.0001
Salt*Meter		Std	SensION 5	1425	48.04	0.0001
Salt*Meter		S0,0; S1,0	Hanna Black	1425	0.06	0.9508
Salt*Meter		S0,1	Hanna Black	1425	30.3	0.0001
Salt*Meter		S0,2	Hanna Black	1425	68.26	0.0001
Salt*Meter		S0,4	Hanna Black	1425	119.98	0.0001
Salt*Meter		S0,8	Hanna Black	1425	197.54	0.0001
Salt*Meter		S1,1	Hanna Black	1425	28.77	0.0001
Salt*Meter		S1,2	Hanna Black	1425	69.97	0.0001
Salt*Meter		S1,4	Hanna Black	1425	127.49	0.0001
Salt*Meter		S1,8	Hanna Black	1425	224.25	0.0001
Salt*Meter		Std	Hanna Black	1425	47.79	0.0001
Salt*Meter		S0,0; S1,0	Field Scout	1425	5.6	0.0001
Salt*Meter		S0,1	Field Scout	1425	34.95	0.0001
Salt*Meter		S0,2	Field Scout	1425	73.41	0.0001
Salt*Meter		S0,4	Field Scout	1425	127.64	0.0001
Salt*Meter		S0,8	Field Scout	1425	214.49	0.0001
Salt*Meter		S1,1	Field Scout	1425	33.21	0.0001
Salt*Meter		S1,2	Field Scout	1425	74.86	0.0001
Salt*Meter		S1,4	Field Scout	1425	135.81	0.0001
Salt*Meter		S1,8	Field Scout	1425	242.46	0.0001
Salt*Meter		Std	Field Scout	1425	45.43	0.0001
Salt*Meter		S0,0; S1,0	Hanna Blue	1425	7.42	0.0001
Salt*Meter		S0,1	Hanna Blue	1425	39.24	0.0001
Salt*Meter		S0,2	Hanna Blue	1425	75.77	0.0001
Salt*Meter		S0,4	Hanna Blue	1425	128.14	0.0001
Salt*Meter		S0,8	Hanna Blue	1425	222.05	0.0001
Salt*Meter		S1,1	Hanna Blue	1425	37.18	0.0001
Salt*Meter		S1,2	Hanna Blue	1425	76.02	0.0001
Salt*Meter		S1,4	Hanna Blue	1425	133.98	0.0001
Salt*Meter		S1,8	Hanna Blue	1425	248.23	0.0001
Salt*Meter		Std	Hanna Blue	1425	51.65	0.0001

APPENDIX B. ILLUSTRATIONS OF TEST METERS, EXPERIMENT APPARATUS, AND PROCEDURES

Fig. 19. Photograph of Hanna Black meter used in experiments.

Fig. 20. Photograph of Field Scout meter used in experiments.

Fig. 21. Photograph of Hanna Blue meter used in experiments.

Fig. 22. Photograph of SensION 5 meter used in experiments.

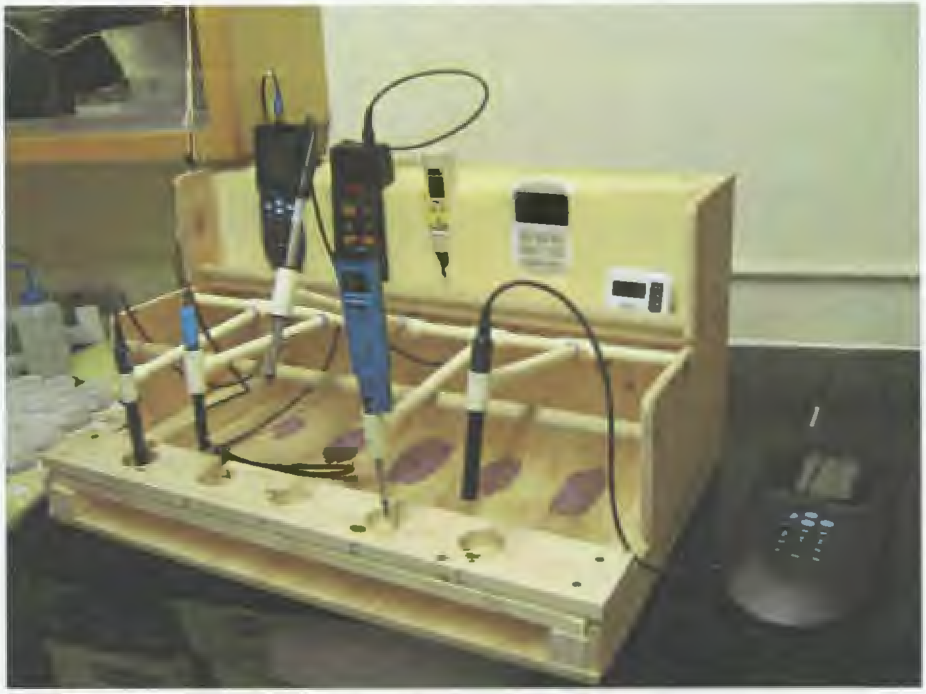

Fig. 23. Photograph of wooden box used to ensure consistent probe placement in all samples.

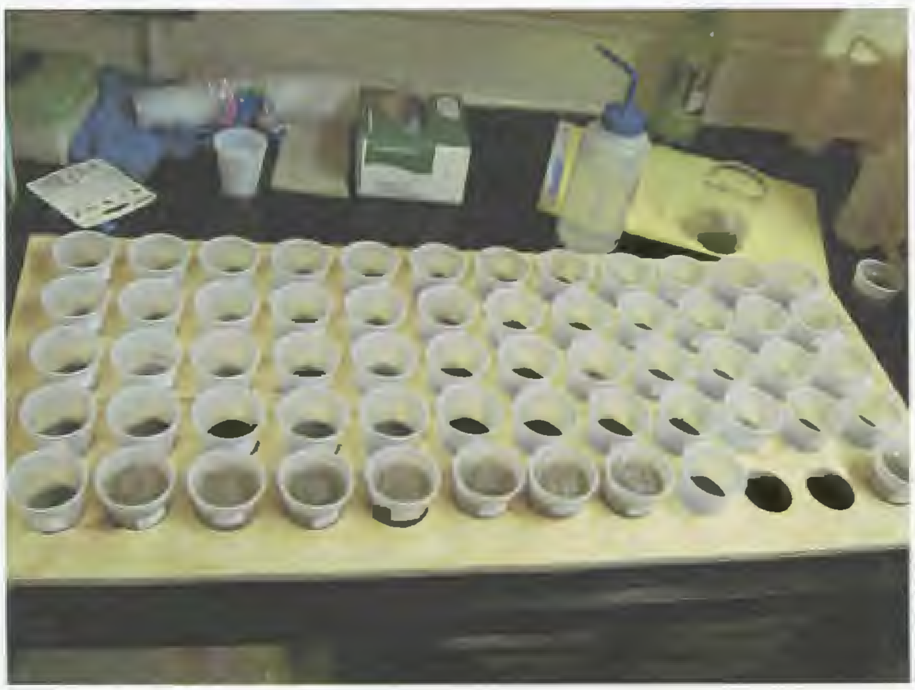

Fig. 24. Photograph of tray used to hold and organize samples during experiments.

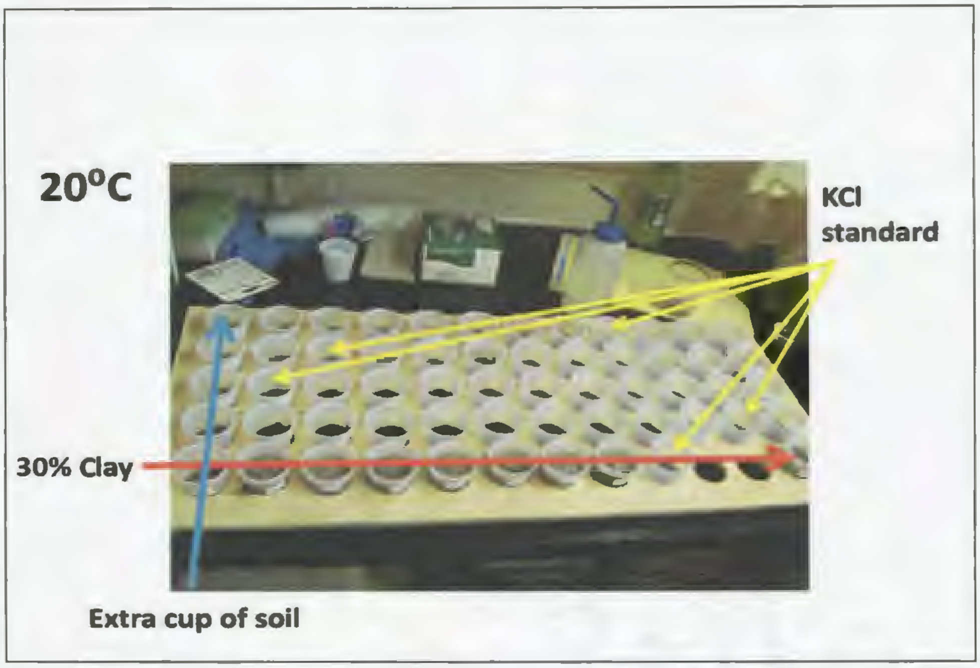

Fig. 25. Photograph illustrating the random order of samples; soils by row and salinity levels by column.

Fig. 26. Photograph of stock salt solutions (right) and ultra pure water containers fitted with repipette dispensers (middle). The pipettes in front of the water bottles were used to add the salt solution to the samples (left).

Table 9. Example of data sheets used to record measurements for the soil experiment and randomization of temperature, soil clay concentration, salinity, and meter levels.

Run 1 Date

Room Temperature 20

Salt

Clay	S1,8	S0,0	S1,1	Std	S1,2	S0,8	S0,1	S0,2	S1,0	S0,4	S1,4
50	A	E	C	E	E	E	B	E	A	B	A
	C	D	B	B	A	D	E	D	B	C	E
	E	A	D	A	C	C	A	A	D	A	D
	D	B	E	C	D	A	C	C	C	E	C
	B	C	A	D	B	B	D	B	E	D	B

Salt

	S0,8	S1,2	Std	S0,4	S0,0	S1,4	S1,0	S1,8	S1,1	S0,2	S0,1
20	D	D	E	B	D	A	B	A	D	B	D
	C	A	D	E	A	E	C	B	C	A	C
	B	B	C	D	E	D	A	C	A	E	A
	A	C	B	A	C	B	D	E	B	C	E
	E	E	A	C	B	C	E	D	E	D	B

Salt

	S1,4	S0,0	S0,8	S0,4	S1,2	S1,0	S1,8	S0,1	S1,1	S0,2	Std
10	B	C	A	C	A	C	B	A	E	B	E
	A	D	E	D	E	D	D	D	D	D	B
	E	A	B	A	C	E	C	C	B	E	D
	D	B	D	E	D	B	E	B	C	C	A
	C	E	C	B	B	A	A	E	A	A	C

Salt

	S0,2	S0,4	S0,0	S0,1	S1,1	S1,0	S1,4	S1,2	S0,8	Std	S1,8
30	C	C	E	E	E	B	D	E	D	E	E
	D	E	C	C	D	C	B	C	E	A	C
	B	A	B	B	B	D	A	D	C	D	A
	E	B	D	A	C	E	E	A	B	B	B
	A	D	A	D	A	A	C	B	A	C	D

Salt

	S0,4	S1,1	Std	S1,2	S0,8	S1,0	S0,0	S0,2	S1,8	S0,1	S1,4
40	D	A	C	B	A	C	C	C	B	E	A
	C	D	E	C	C	E	A	B	C	A	D
	E	E	B	E	B	D	E	A	E	B	B
	A	B	D	A	E	A	D	E	D	C	C
	B	C	A	D	D	B	B	D	A	D	E

Meters are represented by letters. SensION 5 (A), Hanna Black (B), Field Scout (C), Hanna Blue (D), and Standard (E).