Comparison and sensitivity of measurement techniques for spatial distribution of soil salinity

A. Akramkhanov[1*], R. Sommer[2], C. Martius[1#], J. M. H. Hendrickx[3], P. L. G. Vlek[1]

[1] Center for Development Research (ZEF), University of Bonn, Walter-Flex-Str. 3, 53113 Bonn, Germany

[2] ICARDA, PO Box 5466, Aleppo, Syria

[3] New Mexico Tech, LeRoy Place 801, Socorro NM 87801, USA

[#]Present address: ICARDA-PFU, P.O. Box 4564, Tashkent 100000, Uzbekistan

[1*] Corresponding author. Fax: +998 62 2243347. E-mail address: akmal@zef.uzpak.uz

Keywords: electrical conductivity, regression tree, salinity assessment

Abstract

In Khorezm, a district of Uzbekistan situated in the Aral Sea Basin, soil salinization is an important driver of soil degradation in irrigated agriculture. The main objective of this study was to identify techniques that enable rapid estimation of soil salinity. Therefore, bulk electrical conductivity of the soil ($EC_{a\text{-}meas}$) was measured with three different devices (2P, 4P, and CM-138) and electrical conductivity of the saturated paste ($EC_{p\text{-}meas}$) was measured with the so-called 2XP device. These measurements were compared with independent estimates of $EC_{a\text{-}calc}$ and $EC_{p\text{-}calc}$ based on laboratory measurements of electrical conductivity of the saturated extract, EC_e, of soil samples from the same sites.

Soil salinity could be assessed satisfactorily with all four devices. $EC_{p\text{-}meas}$ could be well reproduced by the 2XP device (R^2=0.76), whereas $EC_{a\text{-}meas}$ estimates using 2P, 4P, and CM-138 in the field were less accurate (R^2<0.50). The sensitivity of all devices to the main ions Cl^- and Ca^{2+} suggests that the measuring principles are similar for all instruments. The devices can therefore be used interchangeably. Field assessment of soil salinity was considerably enhanced by the use of CM-138, because large areas can be quickly assessed, which may be desirable in spite of the lower accuracy.

1 INTRODUCTION

Inefficient irrigation and an excessive use of water on agricultural lands in the Aral Sea Basin over several decades have led to shallow groundwater tables. Secondary soil salinization thus is a constant threat to agriculture. Most of the soils in Khorezm, located in the Aral Sea Basin of Uzbekistan, are classified as medium to highly saline (Abdullaev, 2003). Pre-season salt leaching by application of significant amounts of water has become an essential part of agriculture in the Aral Sea region. To assess pre-season leaching requirement and to avoid waste of water, there is a basic need for repeated monitoring of soil salinity on a scale beyond field level. Salinity appraisal, however, is still dependent upon traditional, labor- and time-intensive soil surveys with subsequent laboratory analyses for determining conductivity of the saturation extract (EC_e), total dissolved solids (TDS) and/or solute concentration.

Although TDS and EC_e provide good estimates of salinity, there are variations within the devices used and methods of analyses. Besides, salt/solute concentrations in the soil can be derived by *in-situ* measurement of the apparent soil electrical conductivity (EC_a). EC_a estimates rely either on measuring soil electrical resistivity (Rhoades and van Schilfgaarde, 1976), or time domain reflectometry (TDR; Wraith, 2002), or on electromagnetic induction (EM; Hendrickx et al., 2002). The latter is currently becoming one of the most frequently used techniques for characterizing the spatial variability of soil salinity.

Derivation of solute concentration from EC_a is a two-step process (Hendrickx et al., 2002). First, the electrical conductivity of the soil water (EC_w) is derived from EC_a using an empirical regression equation or a physically based model. Next, EC_w is converted into the solute concentration, which depends on its ionic composition. There are several models (Mualem and Friedman, 1991; Rhoades et al., 1989), which are based on the general principle that EC_a depends on soil porosity and permeability (Archie, 1942), clay content and degree of pore saturation (Rhoades et al., 1989). A detailed review of various models and developments is given by Hendrickx et al. (2002).

Studies on the comparison of soil salinity approximated by the various devices with estimates based on conventional laboratory methods are scarce, particularly in countries of the Commonwealth of Independent States (CIS). Additionally, disparity between the definition of soil textural fractions by the Kachinsky classification (Kachinsky, 1958) adopted in CIS countries, and the definition used by the Food and Agriculture Organization (FAO) might hinder the use of models where clay content is an important factor. Moreover, knowledge of the particular solute concentration is needed for determination of salinity type, toxicity or soil sodicity; an information that is also widely lacking.

The main objective of this paper is to identify and compare quick and practical determination techniques for soil salinity appraisal. Additionally, the study explores the sensitivity of each device to the individual salt constituent using regression trees, an advanced data analysis techniques.

2 MATERIALS AND METHODS

2.1 Electrical conductivity

Electrical conductivity of the soil can be assessed in different ways (Figure 1). The most referenced is the electrical conductivity of the saturation extract, EC_e and the electrical conductivity of the soil paste, EC_p. Rhoades et al. (1989) point out that determining EC_p

as an estimate of EC_e has been in use in the USA since early 1900. The apparent electrical conductivity of the soil, which is a measure of the bulk electrical conductivity of the soil and includes the effects of the actual water content, is termed EC_a.

Bulk electrical conductivity of the soil ($EC_{a\text{-}meas}$) was measured with three different devices (2P, 4P, and CM-138) and electrical conductivity of the saturated paste ($EC_{p\text{-}meas}$) was measured with the so-called 2XP device. 2P and 2XP are locally made two-electrode conductometers (Agromeliotaraqqiyot, Tashkent, Uzbekistan; assembled by A. Chernishev, *personal communication*, 2002). The reason for including them in this study was that locally made devices are much easier to come by for local researchers in CIS countries and that they are generally much cheaper than imported equipment. The commercially available four-electrode conductivity probe 4P (EC-Probe, Eijkelkamp, The Netherlands) was developed by Rhoades and van Schilfgaarde (1976;). The CM-138 apparent conductivity meter (GF-Instruments, Czech Republic) is similar to the widely used EM-38 of Geonics Ltd. (Canada). CM-138 has a dipole center distance of 1 m, with a maximum effective penetration depth of 1.5 m in vertical (CMv) and 0.75 m in horizontal (CMh) position.

2.2 Site description

The experiments were conducted on the research farm (41°36’N, 60°31’E) of the Urgench State University (UrSU), south-west of the city of Khiva, in Khorezm, Uzbekistan. The area is located in a transition zone where alluvial soils in the north merge with desert sand of the south. FAO (2003) attributes these meadow soils on alluvium and sands to gleyic and calcaric Arenosols.

The climate in Khorezm is arid with an annual precipitation of about 100 mm (ranging from 35 mm to 170 mm during dry and wet years, respectively), about 70 % of it occurring in the winter and spring. The sampling area (3 km x 4 km) includes soils varying from loamy to sandy. Most of the area is cultivated land. However, bare or abandoned land was also included in the study to possibly increase the variability of soil salinity. The main crops grown in the area are cotton (*Gossypium hirsutum* L.), wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.).

2.3 Field survey

Field measurements were conducted from June to August 2002 in an area of approximately 1200 ha. Core sampling and EC measurements were done over a systematic 150 m by 200 m square grid. Some fields were sampled at a finer 40 m by 40 m grid to identify short range variation. At each grid-node, soil core samples from 0-30 cm depth were taken, in duplicate, with a split tube sampler with an inner diameter of 53 mm. One sample was used for the analysis of the water content and bulk density in the laboratory at UrSU. The second sample was air dried and analyzed by the Soil Research Institute (SRI) in Tashkent for EC_e, total dissolved solids (TDS), soluble salts (Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+), and soil texture. Additionally, electrical conductivity ($EC_{p\text{-}meas}$) of the air-dried soil sample was measured with the 2XP conductivity meter.

Electrical conductivity of the bulk soil ($EC_{a\text{-}meas}$) in the field was measured using the three above-described devices: (i) CM-138, (ii) 4P and (iii) 2P. In order to check the basic congruity of measurements carried out with the 2P and 4P instruments, a bucket experiment with two solution types was carried out. Soil paste of low, medium, and high salinity was compared with distilled water with different amounts of salt diluted in it. Readings at each salinity level and in the each bucket were taken in 5 replications.

Soil samples and measurements were, where appropriate, taken from the top of the ridge. To minimize interference from other devices, the CM-138 readings were taken first, followed by soil core sampling. $EC_{a\text{-}meas}$ measurements were made immediately next to the core sampling spot.

Volumetric soil moisture content of the 0-30 cm depth was measured with a frequency domain sensor (ThetaProbe type ML2x; Delta-T Devices Ltd., UK). It was inserted vertically to obtain topsoil moisture content and horizontally along a 30 cm deep trench to obtain average readings for the soil moisture of the layer. In total, six or seven readings were made per location and their average value was used for the analyses.

2.4 Data analysis

First, the validity of $EC_{p\text{-}meas}$ measured with the 2XP probe was calculated by comparing the values with calculated $EC_{p\text{-}calc}$ based on the soil parameters as outlined by Rhoades et al. (1989).. The model calculates $EC_{p\text{-}calc}$ as:

$$EC_p = \left[\frac{(V_s + \theta_{ws})^2 EC_e EC_s}{V_s EC_e + \theta_{ws} EC_s} \right] + (\theta_w - \theta_{ws}) EC_e \quad [1]$$

where θ_w is the (total) soil water content ($cm^3\ cm^{-3}$), V_s is the volumetric content of soil particles ($cm^3\ cm^{-3}$), θ_{ws} *is* the soil water ($cm^3\ cm^{-3}$) in the series-coupled pathways and EC_s ($dS\ m^{-1}$) is the average electrical conductivity of the soil particles.

Sensitivity analyses and practical use of these models was demonstrated by Rhoades et al. (1989; 1990) together with indication of which parameters can be estimated accurately and which should be measured. Given the approximation of most of the parameters in equation 1, only θ_w, clay content, and TDS remained to be determined independently, and was done as outlined earlier.

Similarly, to check the validity of $EC_{a\text{-}meas}$ measured by the 2P, 4P, and CMv and CMh, an equation provided by Rhoades et al. (1989) was used to calculate $EC_{a\text{-}calc}$.The model calculates $EC_{a\text{-}calc}$ as

$$EC_a = \left[\frac{(\theta_s + \theta_{ws})^2 EC_{ws} EC_s}{(\theta_s) EC_{ws} + (\theta_{ws}) EC_s} \right] + (\theta - \theta_{ws}) EC_{wc} \qquad [2]$$

where EC_w is the total, EC_{ws} the immobile and EC_{wc} the mobile soil water electrical conductivity.

For the regression analysis, to obtain normally-distributed data sets, all data were log-transformed except the CM-138 data, which were normalized by reciprocal transformation.

Sensitivity of the equipment to individual ions was analyzed by regression tree analysis using CART 5.0 (Salford Systems, USA).The software CART 5.0 generates a summary report that lists the variable importance used as a splitting variable when constructing the tree. The most important variable has a ranking of 100, and the remaining variables are ranked in decreasing order of importance. Assuming that the variation range of the contribution of individual ions to total EC is not substantial, the contribution of ions to $EC_{a\text{-}meas}$ and $EC_{p\text{-}meas}$ can be ranked.

3 RESULTS

3.1 Descriptive statistics

The readings for the $EC_{p\text{-}meas}$ of the soil paste ranged from 0.3 to 16.8 dS m^{-1}, with a mean of 2.2 dS m^{-1}. A soil with $EC_e > 4$ dS m^{-1} is generally considered to be saline (Richards, 1954), while at 6-7 dS m^{-1} yields of cotton and wheat, the major crops in the area, are already reduced by 20% (Maas and Hoffman, 1977). TDS ranged from 0.07 to 3.28 g $100g^{-1}$, with a mean of 0.35 g $100g^{-1}$ (Table 1).

The 4P instrument could not always be inserted successfully into the soil when the topsoil was dry. Hanson and Grattan (1990) experienced similar problems with their 28 mm diameter 4P, noting that it was extremely difficult to insert it into the soil, even with a pilot hole, and equally difficult to extract. Thus, to avoid bias due to the soil conditions (wetness, compaction, etc.), the number of observations for all devices was equalized (Table 2). Nevertheless, the remaining samples were well distributed within the sampling area and reflected different textures and, to lesser extent, crop types.

Measured values varied widely for all sensors. Average electromagnetic signal readings (measured by CM-138) showed low coefficients of variation (CV) while probe CVs (measured by 2P and 4P) were three times higher. Low CV for electromagnetic conductivity was also observed by Hassan et al. (1983) and Hanson and Grattan (1990), who pointed out the dependence of such variation on sampling volume. The sampling volume of CM-138 is about 1 m^3 of soil compared to a volume of 80 cm^3 measured by the 4P device; thus, CM-138 readings provide more of a site average, whereas probe estimations are inevitably point estimates.

3.2 Comparison of instruments

3.2.1 Similarity of 2P and 4P instruments

The bucket experiment allowed the comparison of $EC_{a\text{-}meas}$ readings made by the 2P and 4P instruments in two types of soil with different solute salt concentrations. A strong linear relationship ($R^2 = 0.89$) and a slope of the regression equation equal 1 proved that both instruments provide similar readings of $EC_{a\text{-}meas}$, and identical measurements in water solution with varying levels of salinity confirmed this assumption (Figure 2).

Results demonstrate that under ideal conditions, the 2P instrument is as sensitive to salinity as the commercially available 4P instrument. Given the strong relationship, the 2P readings in the field could even be equated to the second replicate of the 4P instrument measurement. In this sense, the two EC probe readings per sampling location could serve as an indication of soil salinity variability at this fine scale.

The 2P and 4P readings in aquatic solution at low salinity levels seem to deviate from each other more than at higher salinity levels. However, the measurements in the soil paste are quite close also at relatively low salinity levels, which is most important because of crop sensitivity and sharp yield decreases at these levels. The good match between 2P and 4P readings in the soil paste indicates that their performance is almost identical (?).

3.2.2 EC_e and $EC_{p\text{-}meas}$ measured with 2XP

Equation 1 was used to calculate $EC_{p\text{-}calc}$ from known EC_e and other measured values, particularly by using different ways of defining the percentage clay content. Results of the correlation of measured $EC_{p\text{-}meas}$ and calculated $EC_{p\text{-}calc}$ using clay content defined as particles with a size smaller than 0.001 and 0.002 mm, yielded a correlation coefficient (R) of 0.875 and 0.872, respectively. No discernible difference between clay content expressions could thus be detected. Although their skewness was low, the histograms of the clay content in different definitions showed that clay content distribution is bimodal. Thus, the definition of the clay fraction did not substantially change the classification of the soil and did not have any notable effect on the correlation between $EC_{a\text{-}meas}$ and $EC_{a\text{-}calc}$ and $EC_{p\text{-}meas}$ and $EC_{p\text{-}calc}$. For further analysis, the Kachinsky classification (clay particles <0.001 mm) was used, which is Uzbek standard. The regression equation between $EC_{p\text{-}meas}$ and $EC_{p\text{-}calc}$ using the local definition for clay (<0.001) thus yielded:

$$EC_{p\text{-}meas} = 1.152\ (EC_{p\text{-}calc}) + 0.152 \qquad [3]$$

with a reasonably good R^2 of 0.77; only slightly lower than that reported by (Rhoades et al., 1989).

Since local authorities work with TDS or recently more frequently with EC_e, $EC_{p\text{-}meas}$ measured with the 2XP probe was also correlated with EC_e, which yielded:

$$EC_e \text{ (calculated from TDS)} = 2.47\ (EC_{p\text{-}meas}) \quad [4]$$

The estimate of the EC_e from $EC_{p\text{-}meas}$ also had a reasonably high R^2 (0.76) and low intercept. The slope of 2.47 is close to the 2.2 reported in Landon (1984), but lower than the 3.5 established for some soils in Uzbekistan (Shirokova et al., 2000). This means that the coefficient of conversion reflects site-specific features and should be established independently for each location. On the other hand, large amounts of soil (600-900 g) were collected from the 30 cm soil depth, and only a small subsample was taken for the analyses of TDS, probably not accurately reflecting measured EC_e. Larger subsample sizes are reported to have less variability (Hassan et al., 1983). Rhoades et al. (1990) also stress that sample variability could be due to differences in volumes and locations of soil used to measure salinity. They judged the error involved to be appreciable and to result in low R^2 values in the instrumental/model comparison. Further errors may have been introduced during analyses for TDS and $EC_{p\text{-}meas}$, which were conducted separately in different laboratories. Furthermore, considering that TDS itself is highly variable, and that $EC_{p\text{-}meas}$ was able to explain 76 % of the variance in measured TDS, it can be concluded that $EC_{p\text{-}meas}$ can be used to estimate salt concentration in soils.

3.2.3 EC_e and $EC_{a\text{-}meas}$ measured with 2P, 4P, and CM-138

Calculation of $EC_{a\text{-}calc}$ using three distinct approaches and different clay representations show varying correlation coefficients (Table 3). All correlations were significant at the 0.01 level (2-tailed). For all devices, the best results are obtained with a clay content represented as locally termed ‘physical’ clay, which aggregates all particles smaller than 0.01 mm. The low correlation coefficient for the 2P in the topsoil was probably the result of poor electrode-soil contact due to dry and loose topsoil. The correlation improved in lower layers and was similar to R obtained for 4P.

For the highest correlation coefficients for each device and 'physical clay' the following regression equations were calculated. The remaining measurements were not used to build regression equations, because they were highly auto-correlated and would have resulted in similar equations. The dependent variable was $EC_{a\text{-}meas}$ measured by different devices and the independent variable $EC_{a\text{-}calc}$ calculated using Eq.2.

$\ln EC_{a\text{-}meas}$ measured by 2P (10-30 cm) $= 0.8\ (\ln EC_{a\text{-}calc}) - 0.96$ [5]

$\ln EC_{a\text{-}meas}$ measured by 4P (0-20 cm) $= 0.91\ (\ln EC_{a\text{-}calc}) - 1.4$ [6]

$\ln EC_{a\text{-}meas}$ measured by CM-138 (CMh) $= 1.63 - 0.41\ (1/EC_{a\text{-}calc})$ [7]

The accuracy of the devices was somewhat lower (R^2 0.44, 0.48, and 0.47 for the 2P, 4P, and CMh, respectively) compared to previous studies (Rhoades et al., 1990). This result should be treated as indicative, since the 2P and 4P readings of the 20 cm layer were compared with $EC_{a\text{-}calc}$ of bulk topsoil (30 cm). Therefore, 2 or 3 incremental readings by these probes should improve the accuracy. The same applied to the CM-138 readings, i.e., the device showed reasonable accuracy with only one horizontal reading and good potential for determining the depth-weighted salinity of the layers of interest. There are already established techniques for calibrating the instrument (Corwin and Rhoades, 1982, but because they are usually site specific and cannot be readily implemented for other areas or for upscaling, they will not be covered in this paper. Correlation of $EC_{a\text{-}meas}$ to TDS, which is related to EC_e yielded very low accuracy and is not discussed further.

3.3 Sensitivity of devices to individual salt ions

Different salt ions contribute to the electrical conductivity in the soil. In this study, chloride-sulphate salts predominated. The relation between the electrical conductivity and the salt content of various solutions was reported by Richards (1954). He observed that the EC curves for the chloride salts and Na_2SO_4 almost coincide, but $MgSO_4$, $CaSO_4$, and $NaHCO_3$ had lower conductivities than the other salts at equivalent concentrations.

Considering that certain ions contribute more to the EC of certain devices, sensitivity was assessed by classification and regression tree (CART) analyses. The response variable in this regression tree was $EC_{a\text{-}meas}$ measured by 2P, 4P, and CM-138, $EC_{p\text{-}meas}$ measured by 2XP, and the explanatory variables used were individual ions (HCO_3^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+). A regression tree was built for each depth (for 2P and 4P) and height (for CM-138) increment. Variable importance data were obtained from the summary reports. The results for the variable importance for the 2P and 4P devices at different depths were averaged (Figure 3). Only one horizontal CM-138 reading is presented in the graph, because its response curve was closer to the topsoil for which the analysis of ions was obtained, while the other CM-138 measurements were similar to the CMh measurements.

Clearly, chloride and calcium were the most sensitive ions for all the devices. The relative ranking of the other ions varied between devices but, in general, ions ranked similarly for 2P and CM-138, whereas for 4P the rankings were different. However, the overall sensitivity of all devices to Cl suggested that the measuring principles were similar for all three instruments. The devices might therefore be used interchangeably. The likely reasons for the dissimilarities in sensitivity to ions between devices will be presented in the discussion.

4 DISCUSSION

Depending on salinity type, Kaurichev (1989) reported that soils become saline at TDS > 0.15 g $100g^{-1}$. Richards (1954) reported that some plants are adversely affected at

0.1 g 100g^{-1}. There are no easy or straightforward analyses for measuring soil salinity, because of in-situ temporal and spatial variability. The electrical conductivity instruments used in the study to measure soil salinity performed reasonably well given the number of influencing factors as for instance the soil texture which ranged from sandy to loamy. Approximations such as representation of clay content in different systems or as EC_e calculated from TDS could have introduced some errors. Nevertheless, as a first step, the use of $EC_{p\text{-}meas}$ measured by 2XP to replace laborious and time consuming EC_e analyses proved to be successful.

Of the three EC_a devices, the 2P showed the lowest accuracy, probably because the 2-electrode conductivity instrument, as opposed to the 4-electrode probe (4P), was prone to polarization, contamination and cable resistance errors (Thermo, 2004). Polarization errors might occur at the boundary layers between the measuring electrode and the ion-conducting measuring medium. Contamination due to deposits on the electrode surface has a similar effect, i.e., the conductivity reading is lower than the actual value. Cable resistance adds to the measured sample conductance.

Despite these obvious disadvantages of the 2P device, slope and intercept values of 2P and 4P (Eq. 5 and 6) were close, which was not the case for the CM-138. Again, there was a technical reason for this. In the horizontal mode, the CM-138 measured the bulk of 75 cm, whereas the laboratory analyses were not based upon a similar depth of measurement. Similar depth-related differences and degrees of soil profile layering between sites were observed by Sudduth et al. (2003).

A single reading by CM-138 offers additional information about the salt in the soil profile than probe (spot) measurements which generally rely on topsoil samples only. Generally, high CM-138 readings mean high salt storage within the profile and, depending on management of the field and climate, salt can move towards the surface very rapidly as observed by many researchers (Hendrickx et al., 1992; Forkutsa, 2005). Thus, a salinization risk from deeper salt storage can be detected with the CM-138 even when topsoil salinity is low. The authors verified the well-known fact that salinization in arid areas can be relatively fast, and that irrigation and soil management in flat irrigated lands determines the spatial variability of salinity to much larger extent than prevalent soil characteristics.

Apart from these physical hindrances in EC measurements, there are theoretical problems that are hard to account for. Although EC of individual ions is known, their conductance varies with the kind of the soil (Li, 1997). As Li (1997) explains, the EC of ions in a colloidal system is determined by the distribution of these ions between the electric double layer and the free solution and their distribution within the double layer. These distributions are dependent mainly on the surface charge density of the soil colloid. Another effect of the electric conductance of the soils mentioned by Li (1997) is the frequency of the applied current, especially in the presence of electrolytes. He also noted that the effect of anions on conductivity dispersion was greater than that of cations. Although Li (1997) mainly discusses the effect on variable charge soils, the principles equally apply for constant charge soils, which can be seen from the sensitivity analyses, where all Cl anions ranked the first for all devices.

5 CONCLUSIONS

Soil salinity assessment using electrical conductivity provides a quick and inexpensive alternative to laboratory-based analyses. The locally assembled 2XP for measurement of electrical conductivity in the soil paste ($EC_{p\text{-meas}}$) was checked against the calculated $EC_{p\text{-calc}}$ using the Rhoades model and explained 77 % variance The 2XP also estimated

TDS (which is related to EC_e) with 76 % accuracy. Based on this analysis, it can be concluded that the 2XP can replace laboratory measurements of TDS or EC_e with high confidence.

The $EC_{a\text{-}meas}$ values measured by the 2P, 4P, and CM-138 devices were generally less accurate than $EC_{a\text{-}calc}$ using the Rhoades model. However, the equal sensitivity of all devices to Cl and Ca proves the devices' validity.

The direct estimation of TDS from $EC_{a\text{-}meas}$ (measured by 2P, 4P, or CM-138) however, was not satisfactory. Differences in the measured volume of TDS and $EC_{a\text{-}meas}$ and the use of TDS conversion instead of real EC_e measurement were perhaps the main factors complicating the direct conversion from $EC_{a\text{-}meas}$ to TDS.

Acknowledgements

This study was funded by the German Ministry for Education and Research (BMBF; project number 0339970A).

6 REFERENCES

Abdullaev U (2003) Republic of Uzbekistan. Land degradation assessment in drylands (LADA). Uzgip (State Design and Research Uzgipromeliovodkhoz Institute), Tashkent, pp. 43

Archie GE (1942) The electrical resistivity log as an aid to determining some reservoir characteristics. Transactions of the AIME 146:54-63

Breiman L, Friedman JH, Olshen RA, and Stone CJ (1984) Classification and regression trees. Wadsworth, Belmont, California

Corwin DL, Rhoades JD (1982) An improved technique for determining soil electrical conductivity-depth relations from above-ground electromagnetic measurements. SSSAJ 46:517-520

FAO (2003) Fertilizer use by crop in Uzbekistan. Land and Water Development Division, Rome

Hanson BR, Grattan SR (1990) Field sampling of soil, water, and plants. In: Tanji KK (ed) Agricultural salinity assessment and management, vol 71. ASCE, New York, pp186-200

Hassan HM, Warrick AW, Amoozegar-Fard A (1983) Sampling volume effects on determining salt in a soil profile. SSSAJ 47:1265-1267

Hendrickx JMH, Baerends B, Raza ZI, Sadig M, Chaudhry AM (1992) Soil salinity assessment by electromagnetic induction of irrigated land. SSSAJ 56:1933-1941

Hendrickx JMH, Das B, Corwin DL, Wraith JM, Kachanoski RG (2002) Relationship between soil water solute concentration and apparent soil electrical conductivity. In: Dane JH and Topp GC (eds) Methods of soil analysis, vol 4. SSSA Book Series 5, Madison, WI, pp1275-1282

Kachinsky NA (1958) Mehanicheskiy i microagregatniy sostav pochvi. Metodi ego izucheniya (Texture and microagregate composition of the soil. Methods of study). AN SSSR, Moscow

Kaurichev IS (ed) (1989) Pochvovedenie (Soil science). Agropromizdat, Moscow

Landon JR (ed) (1984) Booker tropical soil manual. Booker Agriculture International Limited, Bath

Li CB (1997) Electric conductance. In: Yu TR (ed) Chemistry of variable charge soils. Oxford University Press, New York

Maas EV, Hoffman GJ (1977) Crop salt tolerance - current assessment. Irrigation and Drainage Division, ASCE 103:115-134

Mualem Y, Friedman SP (1991) Theoretical prediction of electrical conductivity in saturated and unsaturated soil. Water Resources Research 27:2771-2777

Rhoades JD, van Schilfgaarde J (1976) An electrical conductivity probe for determining soil salinity. SSSAJ 40:647-651

Rhoades JD, Waggoner BL, Shouse PJ, Alves WJ (1989) Determining soil salinity from soil and soil-paste electrical conductivities: Sensitivity analysis of models. SSSAJ 53:1368-1374

Rhoades JD, Shouse PJ, Alves WJ, Manteghi NA, Lesch SM (1990) Determining soil salinity from soil electrical conductivity using different models and estimates. SSSAJ 54:46-54

Richards LA (ed) (1954) Diagnosis and improvement of saline and alkali soils, vol 60. USDA, Washington

Robbins CW, Wiegand CL (1990) Field and laboratory measurements. In: Tanji KK (ed) Agricultural salinity assessment and management, vol 71. ASCE, New York, pp201-219

Shirokova Y, Forkutsa I, Sharafutdinova N (2000) Use of electrical conductivity instead of soluble salts for soil salinity monitoring in Central Asia. Irrigation and Drainage Systems 14:199-205

Sudduth KA, Kitchen NR, Bollero GA, Bullock DG, WieboldWJ (2003) Comparison of electromagnetic induction and direct sensing of soil electrical conductivity. Agron J 95:472-482

Thermo (2004) Orion conductivity theory. Available via Thermo Electron Corporation http://www.thermo.com/eThermo/CMA/PDFs/Articles/articlesFile_11377.pdf. Cited 10 Sep 2004

Wraith JM (2002) Time domain reflectometry. In: Dane JH and Topp GC (eds) Methods of soil analysis, vol 4. SSSA Book Series 5, Madison, WI, pp1289-1296

Figures

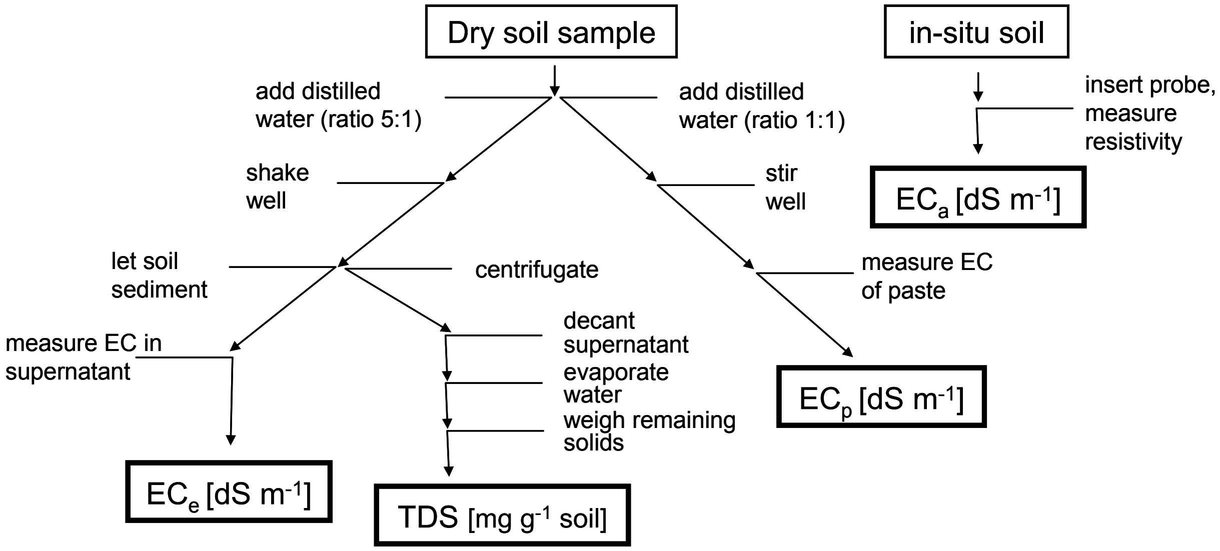

Figure 1 Different measurements for soil salinity assessment used in this study

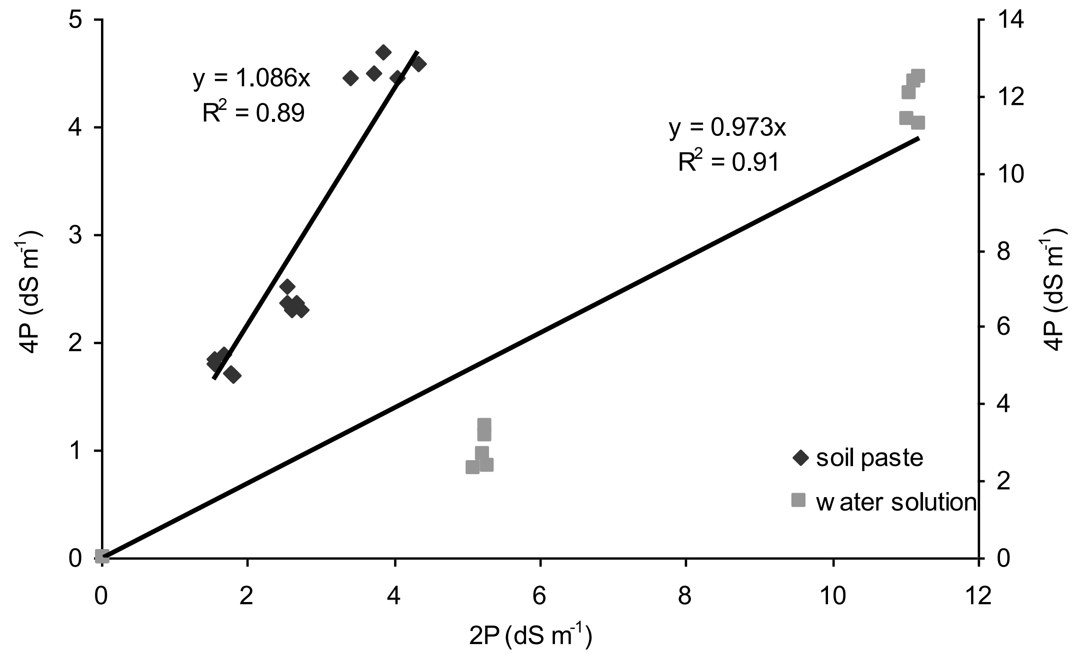

Figure 2 Relationship between $EC_{a\text{-}meas}$ measured with the 2P and 4P instrument as measured in soil paste and water solution with different concentrations of salt

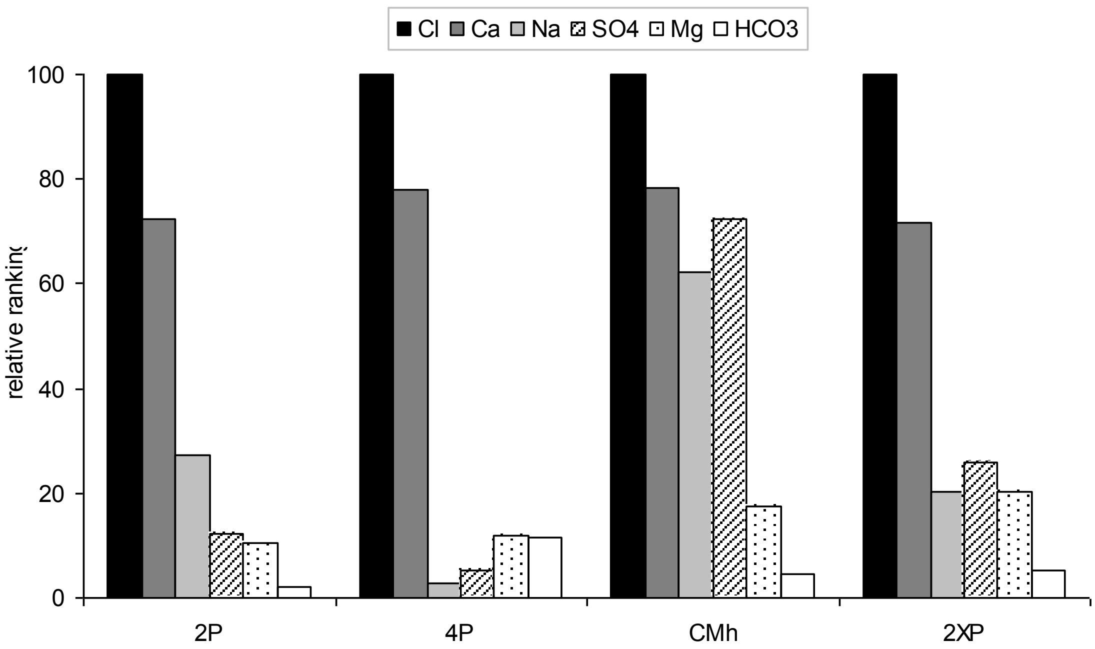

Figure 3 Ranked contribution of salt ions (cmol(c) kg-1) to $EC_{a\text{-}meas}$ and $EC_{p\text{-}meas}$ measured by the different devices as determined by regression tree analysis

Tables

Table 1 Descriptive statistics of selected variables for 2XP analysis (all variables n=264)

Variable	Median	Mean	Std. Dev	Min	Max	CV	Skewness
$EC_{p\text{-}meas}$ (dS m^{-1})	1.75	2.2	1.77	0.31	16.83	80.45	3.24
TDS (g $100g^{-1}$)	0.27	0.35	0.33	0.07	3.28	94.29	4.75
(calc) EC_e (TDS640) (dS m^{-1})	4.14	5.41	5.09	1.02	51.25	94.09	4.75
CLAY (<0.001) (%)	11.55	11.61	3.08	4.6	21.3	26.53	-0.05
CLAY (<0.002) (%)	15.4	15.32	4.84	4.59	31.48	31.59	0.15

Table 2 Descriptive statistics for $EC_{a\text{-}meas}$ measured with the three devices (all variables n=71)

$EC_{a\text{-}meas}$ measured by*	Median	Mean	Std. Dev.	Min	Max	CV	Skewness
	-----------------dS m^{-1}------------------------					%	
2P (0-20 cm)	0.34	0.52	0.46	0.08	2.37	88.33	1.55
2P (10-30 cm)	0.43	0.68	0.56	0.07	2.94	81.37	1.68
2P (20-40 cm)	0.53	0.80	0.77	0.11	5.41	96.06	3.43
4P (0-20 cm)	0.26	0.50	0.46	0.09	1.83	92.83	1.35
4P (10-30 cm)	0.33	0.61	0.65	0.10	4.07	106.93	2.86
4P (20-40 cm)	0.41	0.69	0.71	0.13	4.50	101.71	2.86
CMv	0.71	0.76	0.25	0.47	1.85	33.18	1.44
CMh	0.65	0.73	0.24	0.44	1.66	33.21	1.60

**2P (0-20 cm)=$EC_{a\text{-}meas}$ of 20 cm soil layer; 4P (0-20 cm)=$EC_{a\text{-}meas}$ of 20 cm soil layer*

CMv and CMh=$EC_{a\text{-}meas}$ in vertical and horizontal positions

Table 3 Correlation table of calculated $EC_{a\text{-}calc}$ versus measured $EC_{a\text{-}meas}$ using different devices in relation to particle fractions for clay

$EC_{a\text{-}meas}$ measured by*	EC_e derived by TDS/640		
	Clay particle sizes		
	<0.001 mm	<0.002 mm	<0.01 mm
2P (0-20 cm)	0.41	0.47	0.55
2P (10-30 cm)	0.55	0.61	0.69
2P (20-40 cm)	0.51	0.57	0.65
4P (0-20 cm)	0.61	0.66	0.72
4P (10-30 cm)	0.54	0.60	0.67
4P (20-40 cm)	0.53	0.59	0.67
CMv	0.54	0.61	0.69
CMh	0.53	0.61	0.70

**2P (0-20 cm)=$EC_{a\text{-}meas}$ of 20 cm soil layer; 4P (0-20 cm)=$EC_{a\text{-}meas}$ of 20 cm soil layer; CMv and CMh=$EC_{a\text{-}meas}$ in vertical and horizontal positions*