Soil Salinity Using Saturated Paste and 1:1 Soil to Water Extracts

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ABSTRACT

Saturated paste (SP) and 1:1 soil/water extractions (1:1) are commonly used to assess soil salinity for field remediation. Correlation of electrical conductivity (EC) and other analytes between the SP and 1:1 extraction methods have been documented, except the relationships were based on limited soil types and require further examination to be adequately evaluated. This study examined these relationships using 170 soils from petroleum and agriculture production sites. Saturated pastes and 1:1 extracts were prepared and analyzed for EC, major cations (Na^+, K^+, Mg^{2+}, Ca^{2+}), and major anions (Cl^-, SO_4^{2-}). Relationships of all analytes were established between the two methods using linear regression. Saturated paste extract EC (EC_{SP}) was highly correlated with that of 1:1 extract EC ($EC_{1:1}$) ($r^2 = 0.85$, $P < 0.001$). Significant relationships also existed ($r^2 > 0.73$, $P < 0.001$) between different ions in SP and 1:1 extracts. An independent validation set of 22 soils showed that the slopes of the regressions between predicted EC, Na^+, and Cl^- of SP equivalents from 1:1 extract measurements and direct SP extract measurements were very close to 1.0 suggesting that the regressions developed can accurately assess soil salinity in salt affected soils using 1:1 extract analysis instead of using the more expensive and time-consuming SP extraction.

Petroleum and natural gas production are important economic sectors of the USA contributing over \$110 billion to the gross domestic product (GDP) in 2001 (United States Department of Energy, 2003). Petroleum production often yields contaminants such as brine or heavy metals within the accompanying produced waters (American Petroleum Institute; 1997; Oklahoma Mid-Continent Oil and Gas Association, 1998). Before environmental regulations were established in the 1970's, produced salt waters were commonly released onto the ground near well sites or into nearby streams. Current regulations prohibit the release of untreated waters into the environment, so produced waters are often injected back into wells to assist in maintaining the pressure of the oil reserve or deposited into large evaporation ponds where the salts and contaminants can be contained and concentrated. When released into the environment, produced waters often cause "salt-scars" or areas of high salinity leading to the degradation of soil structure and alteration of the osmotic gradient between plant roots and the soil (Olsen and Peech, 1960; Franklin, 1969; Barzegar et al., 1997; Holliday and Deuel, 1997). As a result, sites affected by produced waters exhibit loss of vegetation and increased soil erosion (Barzegar et al., 1997).

The remediation of produced water contaminated sites has been a priority of the oil and gas industry in recent years due to increased government regulations and public pressure. As a result, in Oklahoma the state's oil and natural gas producers and royalty owners formed the Oklahoma Energy Resources Board, an organization that deals specifically with restoring abandoned or orphaned petroleum extraction sites. Since 1995, the organization has remediated or improved over 4000 sites within the state that had been degraded by petroleum production.

Because soil remediation recommendations are based on soil salt contents, soil salinity testing methods must be capable of delivering accurate and precise results in a timely manner. Currently, two widely used extraction methods for soil salinity analysis are a 1:1 extraction and SP extraction (USDA, 1954; Rhoades, 1996). Saturated paste extractions attempt to simulate the environment of naturally occurring moisture-saturated soil. Of the extraction methods available, results from SP extractions are thought to be the best predictor of plant and soil response to salinity (USDA, 1954; Longenecker and Lylerly, 1964; Vaughn et al., 1995).

Unlike the SP method, the 1:1 extraction method does not attempt to simulate natural soil conditions. Due to the consistency in the amount of water used and objective nature of the method, the 1:1 extraction method can reduce the difficulties in sample preparation and reproducibility often encountered with SP extractions (USDA, 1954; Longenecker and Lylerly, 1963; Sonneveld and Van Den Ende, 1971; Fowler and Hamm, 1980). Ion concentrations and $EC_{1:1}$ extracts are typically lower than those of SP extracts due to increased dilution. Despite the differences in results between the two methods, many soil salinity samples are analyzed using a 1:1 extract because of reduced monetary and time investments.

Many salinity samples analyzed by the Oklahoma State University Soil, Water and Forage Laboratory (SWAFL) originate from produced water contaminated environments associated with oil and gas exploration and production. Current regulations in Oklahoma mandate the remediation of salt contaminated areas based on total soluble salts (TSS) from a soil analysis (Oklahoma Mid-Continent Oil and Gas Association, 1998). Presently in Oklahoma, TSS is often calculated using a SP or adjusted 1:1 analysis of soil EC (USDA, 1954). Remediation rec-

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Abbreviations: $Ca^{2+}_{1:1}$, calcium in 1:1 soil/water extracts; Ca^{2+}_{SP}, calcium in saturated paste extracts; $Cl^-_{1:1}$, chloride in 1:1 soil/water extracts; Cl^-_{SP}, chloride in saturated paste extracts; EC, electrical conductivity; $EC_{1:1}$, 1:1 soil/water extract electrical conductivity; EC_{SP}, saturated paste electrical conductivity; $K^+_{1:1}$, potassium in 1:1 soil/water extracts; K^+_{SP}, potassium in saturated paste extracts; $Mg^{2+}_{1:1}$, magnesium in 1:1 soil/water extracts; Mg^{2+}_{SP}, magnesium in saturated paste extracts; $Na^+_{1:1}$, sodium in 1:1 soil/water extracts; Na^+_{SP}, sodium in saturated paste extracts; OSU, Oklahoma State University study (this study); $SO^{2-}_{41:1}$; sulfate in 1:1 soil/water extracts; SO^{2-}_{4SP}; sulfate in saturated paste extracts; SP, saturated paste extraction; TSS, total soluble salts.

Table 1. Correlation equations established by different studies to convert 1:1 soil/water (1:1) measurements to saturated paste (SP) equivalents.

Parameter	USDA, 1954	Hogg & Henry, 1984	Franzen, 2003	OSU (this study)
EC, ds m^{-1}	SP = 3.00 (1:1)	SP = 1.56 (1:1) − 0.06	SP = 3.0 (1:1) − 0.77	SP = 1.85 (1:1)
Cl^-, mg kg^{-1}	SP = 2.78 (1:1)	SP = 0.95 (1:1) + 5.31		SP = 2.04 (1:1)
SO_4^{2-}, mg kg^{-1}	SP = 1.67 (1:1)			SP = 1.35 (1:1)
K^+, mg kg^{-1}	SP = 2.78 (1:1)			SP = 2.48 (1:1)
Na^+, mg kg^{-1}	SP = 2.78 (1:1)	SP = 0.95 (1:1) − 30.5		SP = 1.91 (1:1)
Ca^{2+}, mg kg^{-1}	SP = 1.67 (1:1)	SP = 0.7 (1:1) − 9.39		SP = 2.10 (1:1)
Mg^{2+}, mg kg^{-1}	SP = 1.67 (1:1)	SP = 0.7 (1:1) − 9.39		SP = 2.08 (1:1)

ommendations for salt-affected areas are often made without differentiating between which analytical method was used or considering whether an adjustment of results was incorporated.

Because of the relative ease of the 1:1 method, theoretical relationships have been developed to convert 1:1 extraction results to a SP extraction equivalent (USDA, 1954; Freidman, 1998). Despite the reports of highly correlated relationships between the two methods, adjustment of 1:1 results to SP approximations are often imprecise and inaccurate (Wagenet and Jurinak, 1978; Franzen, 2003). Therefore, further study of the relationship between the results generated by 1:1 and SP extractions is needed to improve soil remediation strategies based on adjusted 1:1 analysis of soil salinity.

Currently, the EC and major ion concentrations acquired using the 1:1 method are adjusted with conversion factors from Table 2 of USDA Handbook 60 (USDA, 1954) (Table 1). These conversion factors were based on soil moisture holding capacities and the theoretical and actual chemical solubility of ions in aqueous systems (USDA, 1954) but not the impact of soil texture, salt concentrations, and organic matter content on ion concentrations and EC. The exclusion of these soil properties in the conversion factors, coupled with the lack of extensive examination of relationships between the two methods and minimal experimental verification, could contribute to imprecise adjustment of 1:1 analyses when applied to a variety of soils (Franzen, 2003). To improve on the original factors, researchers have developed new conversion techniques using experimental data to generate empirical relationships.

Franzen (2003) divided EC conversion factors into three textural divisions and arrived at conversion factors for coarse, medium, and fine soils (Table 1). Hogg and Henry (1984) reported factors for EC and individual ionic species (Table 1). Variation in conversion factors generated by previous studies necessitates further examination and comparison of the two extraction methods to generate a more refined adjustment of 1:1 analyses over a wide range of soils. By exploring and identifying factors contributing to differences in 1:1 and SP extract analyses in various soils, adjustments to the 1:1 characterization of soil salinity could be improved. The objectives of this study were to (i) determine the relationship between the EC of SP and 1:1 extracts and (ii) determine the relationship between major cations and major anions of SP and 1:1 extracts.

MATERIALS AND METHODS

Soils

Approximately 170 samples from various locations in Oklahoma and Texas were characterized using both 1:1 and SP extraction methods. These samples were from both brine contaminated and agricultural production areas with a broad range of soil conditions and analyte concentrations (Table 2).

Validation of Empirical Relationships Between 1:1 and Saturated Paste

Most remediation techniques for salt contaminated areas are based on TSS from a soil analysis (American Petroleum Institute, 1997; Oklahoma Mid-Continent Oil and Gas Association, 1998). Total soluble salts are often calculated using a SP or adjusted 1:1 analysis of soil EC (USDA, 1954). Twenty-two Oklahoma soil samples independent of those used to generate the regressions for this study were used to validate the relationships between SP and 1:1. To allow for direct comparisons of the predictive capabilities of the regression equations generated by this study (hereafter referred to as OSU) and USDA regressions, regressions that forced zero and omitted the *y* intercept were utilized for the validation study. The OSU and USDA equations were used to predict SP equivalents of EC and ions from 1:1 measurements; the results were then compared with actual SP measurements of EC and ions.

Table 2. Summary statistics for major ions and electrical conductivity (EC) of 170 soils used to establish relationships between 1:1 soil/water (1:1) and saturated paste (SP) extracts.

Statistic	EC	Cl^-	SO_4^{2-}	K^+	Na^+	Ca^{2+}	Mg^{2+}
	ds m^{-1}	mg kg^{-1}					
				SP extract			
Mean	13.4	4 930	771	43.0	2 650	539	135
Median	3.81	760	151	18.0	426	119	41.0
Minimum	0.165	5.00	15.0	0.00	5.00	5.00	1.00
Maximum	108	80 500	10 700	1270	43 200	8490	1450
				1:1 extract			
Mean	6.69	2 340	509	23.0	1 390	255	56.3
Median	1.81	322	78.0	13.0	272	55.0	18.5
Minimum	0.06	4.00	7.00	0.00	2.00	2.00	0.00
Maximum	49.0	33 900	7 360	273	17 900	3340	866

Saturated Paste Extraction

Saturated pastes were prepared by adding deionized water to approximately 500 g of soil sample as received until it reached a condition of complete saturation, as described by guidelines in USDA Handbook 60 (USDA, 1954). Saturated pastes were allowed to equilibrate for 18 h. An extract from the SP was acquired using a low-pressure filter press (Fann Equipment, Low Pressure Filter Press, Houston, TX). The extracts were analyzed for Na^+, K^+, S, Mg^{2+}, and Ca^{2+} using an inductively coupled argon plasma emission spectrometer (Spectro CirOs, ICAP, Fitchburg, MA), for Cl^- using the Lachat Quickchem 8000 flow injection analyzer (Zellweger Analytics, Milwaukee, WI); and for EC using a flow-through cell (Orion, 162A Conductivity Probe, Beverly, MA). Sulfur was expressed as SO_4^{2-} as commonly done by analytical labs, although total dissolved S was measured by ICAP (Gavlak et al., 2003).

1:1 Soil to Water Extraction

One hundred milliliters of deionized water was added to 100 g of ground (2-mm sieve), oven-dried sample to create a suspension with equal parts of soil and water. The suspensions were allowed to equilibrate for 4 h and extracts were obtained using the low-pressure filter press previously mentioned. Analytes in the 1:1 extracts were analyzed using the same methods as with the SP extracts.

Statistical Analysis

Analysis of variance (ANOVA) was performed using PROC GLM (SAS Institute, 2001). When significance at a 0.05 level was indicated, means were separated by a Fisher's Least Significant Difference Procedure. To assess the possible linear relationship of SP to 1:1, simple linear regression models were fit with the response of 1:1 as the *x* variable and the response of SP as the *y* variable. PROC REG of SAS was used for these analyses, and the analysis performed for each ion and EC.

RESULTS AND DISCUSSION

Electrical Conductivity and Ion Concentrations of Saturated Paste and 1:1 Soil/Water Extracts

Electrical conductivities for the soil samples studied ranged from 0.165 to 108 ds m^{-1} for the SP extracts with the EC for the 1:1 extracts ranging from 0.06 to 49.0 ds m^{-1} (Table 2). Therefore, a wide range in salinity levels was obtained for comparing the SP with the 1:1 extraction methods. Mean EC of SP (EC_{SP}) of 13.4 ds m^{-1} was significantly greater ($P < 0.001$) than that of 6.69 ds m^{-1} in 1:1 (Table 2). Our results are similar to those of other researchers who reported that the EC_{SP} extracts was greater than the EC of 1:1 ($EC_{1:1}$) soil/water extracts (USDA, 1954; Hogg and Henry, 1984; Franzen, 2003). The significant difference between the $EC_{1:1}$ and EC_{SP} extracts is most likely due to a dilution effect that has been suggested by other researchers (Reitemeier, 1946; Schofeild, 1947; USDA, 1954; Sonneveld and Van Den Ende, 1971). Approximately 63% of the soils had an $EC_{SP} < 10.0$ ds m^{-1} while approximately 80% of the soils had an $EC_{1:1} < 10.0$ ds m^{-1} (Table 3).

Mean ion concentrations (Cl^-, SO_4^{2-}, K^+, Na^+, Ca^{2+}, and Mg^{2+}) for the SP extracts were approximately twofold greater ($P < 0.001$) than those in the 1:1 soil/water extracts (Table 2). Our results for ion concentrations contrast with those of Hogg and Henry (1984) who found that concentrations of Cl^- and Na^+ were approximately equal in SP extracts and 1:1 soil/water extracts.

Table 3. Saturated paste (SP) and 1:1 soil/water (1:1) EC distributions for 170 study soils used to establish relationships between 1:1 and SP extracts.

	SP extracts		1:1 extracts	
Range of EC	Number of soils	Soils	Number of soils	Soils
		%		%
0–5 ds m^{-1}	91	54.5	110	65.9
5–10	14	8.38	24	14.4
10–20	25	15.0	14	8.38
20–50	24	14.4	19	11.4
50–100	13	7.78	0	0.00

Relationship Between Electrical Conductivity of Saturated Paste and 1:1 Extract

Electrical conductivity of SPs was highly correlated with $EC_{1:1}$ for all the study soils ($r^2 = 0.85$, $P < 0.001$) (Fig. 1). The results of our study are similar to those reported by other researchers who found that highly significant relationships existed between the EC_{SP} and $EC_{1:1}$ (Hogg and Henry, 1984; Shirokova et al., 2000). The slope of our relationship of 1.79 is very similar to the slope of 1.56 (Table 1) reported by Hogg and Henry (1984) for a combination of coarse, medium, and fine-textured soils. However, our results differ drastically from those reported by Franzen (2003) who found a slope of 3.01 (Table 1) for the same relationship. Our results also differ drastically from the theoretically derived relationship published by the USDA (1954), which used a slope of 3.0 (Table 1) for the relationship. The theoretically derived relationships published by the USDA (USDA, 1954) forced the regression through zero and omitted the *y* intercept. Therefore for a more direct comparison, a second regression was performed that forced the regression through zero and omitted the *y* intercept. Forcing the regression line through zero slightly increased the slope from 1.79 to 1.85 for the study soils (Table 1).

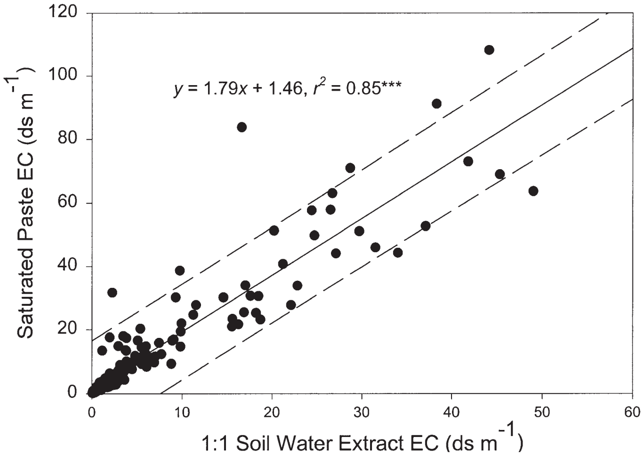

Fig. 1. Relationship between electrical conductivity (EC) of saturated paste and 1:1 soil/water extracts for 170 study soils. ***$P < 0.001$. The dashed lines represent the 95% confidence interval for the regression.

Table 4. Coefficients of determination (r^2) and regression equations describing the relationship between 1:1 and saturated paste extracts for 170 study soils.

	With y intercept		Without y intercept	
Parameter	Regression equation†	r^2	Regression equation	r^2
EC	$SP = 1.79x + 1.46$	0.85‡	$SP = 1.85x$	0.85
Cl^-	$SP = 2.03x + 174$	0.86	$SP = 2.04x$	0.86
SO_4^{2-}	$SP = 1.32x + 101$	0.82	$SP = 1.35x$	0.81
K^+	$SP = 2.80x - 21.3$	0.73	$SP = 2.48x$	0.70
Na^+	$SP = 1.92x - 27.8$	0.89	$SP = 1.91x$	0.89
Ca^{2+}	$SP = 2.10x + 3.37$	0.87	$SP = 2.10x$	0.87
Mg^{2+}	$SP = 2.00x + 22.8$	0.82	$SP = 2.08x$	0.82

† x = electrical conductivity of 1:1 extract.
‡ All regression equations were significant at $P < 0.001$.

The slope reported by USDA (1954) was approximately 68% greater than the one found in our study.

Relationships Between Ions Extracted Using Saturated Paste and 1:1 Soil/Water Ratio

Highly significant relationships existed ($P < 0.001$) between ions extracted by SP and 1:1 extracts with regression coefficients (r^2) ranging from 0.73 to 0.89 (Table 4). Similarly, Hogg and Henry (1984) found strong relationships existed between Cl^-, and Na^+ in SP and 1:1 extracts. While Hogg and Henry (1984) did not report the relationship between K^+ and SO_4^{2-} in SP and 1:1 extracts, they noted a significant relationship existed between the sum of Ca and Mg extracted by SP and by 1:1 soil/water but did not report the individual relationships for Ca^{2+} or Mg^{2+} in their study.

The slopes of the relationships derived in our study for ions are different from those reported by the USDA (1954) with the exception of K^+. The slope of 2.48 found in our study for K^+ is close to the slope reported by USDA (1954) (Table 4). Overall, the slopes of relationships for ions extracted by SP and 1:1 soil/water in our study are approximately 25 to 30% less than those found by USDA (1954) for Cl^-, SO_4^{2-}, and Na^+ while the slopes of the Ca^{2+} and Mg^{2+} relationships for our study are approximately 20 to 30% greater than the relationships reported by USDA (1954).

Validation of Empirical Relationships Between 1:1 and Saturated Paste

Mean EC_{SP} predicted by the OSU regression equation of 9.20 ds m^{-1} was not significantly different ($P > 0.05$) than mean actual measured EC_{SP} of 9.12 ds m^{-1} in the validation soils (Table 5). However, mean EC_{SP} of 14.9 predicted by the USDA regression equation was significantly greater ($P < 0.05$) than the mean actual measured EC_{SP} of 9.12 ds m^{-1}. Mean measured concentrations of 1490 mg Na^+ kg^{-1} in SP of the validation soils were not significantly different than Na^+ of 1400 mg kg^{-1} predicted by the OSU regression equation but was significantly less than Na^+ of 2040 mg kg^{-1} predicted by the USDA regression equation. Concentrations of Cl^- actually measured (2720 mg kg^{-1}) and predicted by the OSU regression equation (2400 mg kg^{-1}) were statistically equivalent while Cl^- concentrations predicted by the USDA regression equation were greater than measured concentrations. Actual measured concentrations of Ca^{2+} were significantly greater than concentrations predicted by either the OSU or the USDA regression equation (Table 4). Concentrations of SO_4^{2-} predicted by the OSU regression equation were significantly less than actual measured concentrations of SO_4^{2-} while concentrations of SO_4^{2-} predicted by the USDA regression equation were statistically equivalent to those actually measured (Table 5).

Table 5. Summary of mean comparisons for actual measurements of EC and ion concentrations in saturated paste (SP) and those predicted by the Oklahoma State University study (OSU) and USDA regression equations.

Parameter	Actual measurement	Predicted by USDA	Predicted by OSU
EC, ds m^{-1}	9.12	14.9†	9.20‡
Na^+, mg kg^{-1}	1490	2040†	1400‡
Cl^-, mg kg^{-1}	2720	3270†	2400‡
Ca^{2+}, mg kg^{-1}	447	251†	315†
SO_4^{2-}, mg kg^{-1}	592	574‡	464†

† Significantly different from SP measurement at $\alpha = 0.05$.
‡ Not significantly different from SP measurement at $\alpha = 0.05$.

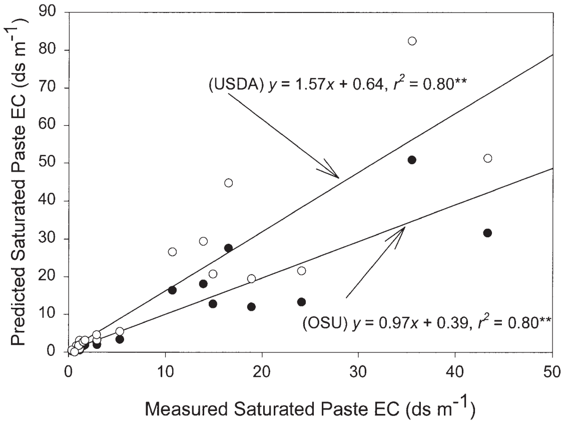

Fig. 2. Relationship between electrical conductivity (EC) of saturated paste predicted with measured 1:1 soil/water extract and USDA regression equation or OSU regression equation and actual measured EC of saturated paste for 22 random soils. **$P < 0.01$.

Values of EC_{SP} and SP ion concentrations predicted by both the OSU regression equation and the USDA regression equations using 1:1 extractions were also compared with actual measurements via regression analysis. A significant relationship ($r^2 = 0.80$, $P < 0.01$) was found between actual measured EC_{SP} and EC_{SP} equivalent predicted by the OSU regression equation (Fig. 2). Additionally, a significant relationship ($r^2 = 0.80$, $P < 0.01$) existed between actual measured EC_{SP} and EC_{SP} predicted by the USDA regression equation (Fig. 2). Slopes for the OSU and USDA relationships were 0.97 and 1.57, respectively. Ideally, if the predicted EC_{SP} were exactly the same as the measured EC, the slope would equal 1.0, the y intercept would equal zero, and r^2 would equal 1.0. The slope for the relationship between predicted and measured SP EC was much closer to 1.0 for the OSU regression than that of the USDA regression indicating the OSU regression equation was more accurate than the USDA conversion factor in predicting EC_{SP} from 1:1 measurement.

Sodium predicted by both the OSU and USDA regres-

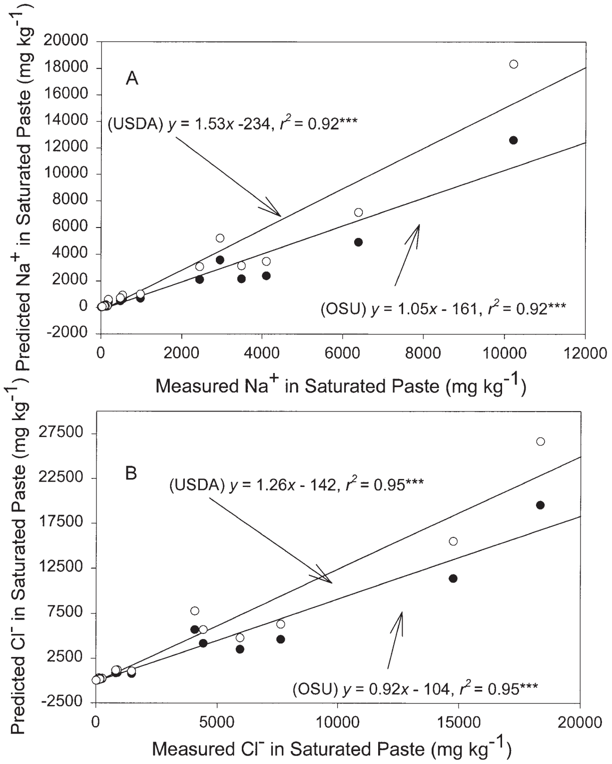

Fig. 3. Relationship between (A) Na$^+$ predicted by OSU and USDA regression equations and measured Na$^+$ in saturated paste extracts for 22 random soils and (B) Cl$^-$ predicted by Oklahoma State University study and USDA regression equations and measured Cl$^-$ in saturated paste extracts for 22 random soils. **$P < 0.01$.

sion equations was highly related ($r^2 = 0.92$, $P < 0.01$) with actual measured $\text{Na}^{+}_{\text{SP}}$ extracts with slopes of 1.05 and 1.53 for the OSU and USDA relationships, respectively (Fig. 3A). The slope for the relationship between predicted and measured $\text{Na}^{+}_{\text{SP}}$ was much closer to 1.0 for the OSU regression than the USDA regression indicating the OSU regression equation was more accurate than the USDA regression equation in predicting $\text{Na}^{+}_{\text{SP}}$.

Significant relationships ($r^2 = 0.95$, $P < 0.01$) were found between actual measured $\text{Cl}^{-}_{\text{SP}}$ and $\text{Cl}^{-}_{\text{SP}}$ predicted by the OSU and USDA regression equations (Fig. 3B). Slopes for the OSU and USDA relationships were 0.92 and 1.26, respectively. The closeness to 1.0 for the slope of the OSU relationship shows that it was a better predictor of $\text{Cl}^{-}_{\text{SP}}$ than the USDA regression equation.

Highly significant relationships ($r^2 = 0.91$, $P < 0.01$) existed between actual measured Ca^{2+} in SP extracts and Ca^{2+} predicted by the OSU and USDA regression equations (Fig. 4A). However, extremely low slopes were observed for the OSU relationship (slope = 0.66) and the USDA relationship (slope = 0.53) indicating that neither of the regression equations was an adequate predictor of Ca^{2+} from 1:1 to its SP equivalent.

Measured concentrations of $\text{SO}^{2-}_{4\text{SP}}$ were highly correlated ($r^2 = 0.92$, $P < 0.01$) with $\text{SO}^{2-}_{4\text{SP}}$ predicted by the OSU and USDA regression equations (Fig. 4B). Slopes for the OSU and USDA relationships were 0.78 and 0.96, respectively, indicating the USDA regression equation was better at predicting $\text{SO}^{2-}_{4\text{SP}}$ than the OSU regression equation.

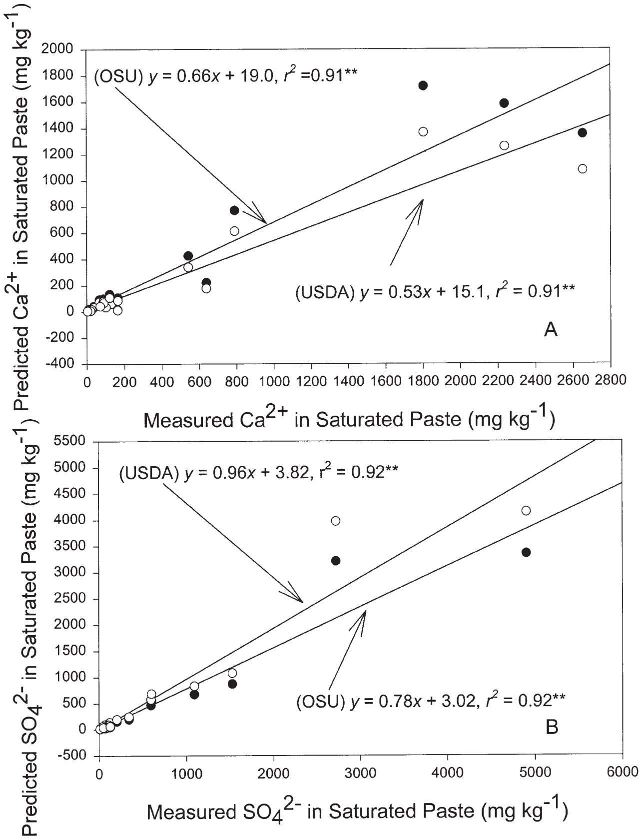

Fig. 4. Relationship between (A) Ca^{2+} predicted by Oklahoma State University study (OSU) and USDA regression equations and measured Ca^{2+} in saturated paste extracts for 22 random soils and (B) SO$_4^{2-}$ predicted by OSU and USDA regression equations and measured SO$_4^{2-}$ in saturated paste extracts for 22 random soils. **$P < 0.01$.

CONCLUSIONS

It is possible to achieve a higher degree of precision and accuracy in predicting EC and Na$^+$, and Cl$^-$, which are the major ions in salt-affected soils, from 1:1 extracts to their SP equivalents using the conversions generated by this study. Because of the wide range of EC and ion concentrations evaluated by this research, the derived equations have the potential to be used in a variety of soil conditions although the appropriateness of these equations for use in other regions also needs to be evaluated.

Overall, the benefits of converting 1:1 to SP extraction equivalents are potentially large, as laboratories can minimize the cost and time associated with soil salinity analysis by using the less costly 1:1 method while maintaining a high level of accuracy and precision. Although using adjusted 1:1 analyses can be accurate in approximation of SP measurements, adjusted 1:1 measurements are not as precise as SP at characterizing soil salinity, and should not be viewed as a sound substitution for SP measurements. Further investigation of adjusting 1:1 soil extracts using soils from a variety of regions across the country could allow for a more accurate characterization of soil salinity using 1:1 analysis by region.

REFERENCES

American Petroleum Institute. 1997. Remediation of salt-affected soils at oil and gas production facilities. API Publication No. 2663. API, Washington, DC.

Barzegar, A.R., P.N. Nelson, J.M. Oades, and P. Rengasamy. 1997. Organic matter, sodicity, and clay type: Influence on soil aggregation. Soil Sci. Soc. Am. J. 61:1131–1137.

Gavlak, R., D. Horneck, R.O. Miller, and J. Kotuby-Amacher. 2003. Plant, Soil, and Water Reference Methods for the Western Region, WREP 125. 2nd ed. Oregon State University Corvallis, OR.

Fowler, D.B., and J.W. Hamm. 1980. Crop response to saline soil conditions in the parkland area of Saskatchewan. Can. J. Soil Sci. 60: 439–449.

Franklin, R.E. 1969. The suspension effect and its relationship to ion uptake by excised roots. Soil Sci. Soc. Am. J. 33:330–331.

Franzen, D. 2003. Managing saline soils in North Dakota. Available online at http://www.ext.nodak.edu/extpubs/plantsci/soilfert/sf1087-1.htm. (verified 29 Mar. 2005). North Dakota State University Extension Service, Fargo.

Freidman, S.P. 1998. Simulation of a potential error in determining soil salinity from measured apparent electrical conductivity. Soil Sci. Soc. Am. J. 62:593–599.

Hogg, T.J., and J.L. Henry. 1984. Comparison of 1:1 and 1:2 suspensions and extracts with the saturation extract in estimating salinity in Saskatchewan soils. Can. J. Soil Sci. 64:669–704.

Holliday, G., and L.E. Deuel, Jr. 1997. Soil Remediation for the Petroleum Extraction Industry. 2nd ed., PennWell Publishing Co., Tulsa, OK.

Longenecker, D.E., and P.J. Lylerly. 1964. Making soil pastes for salinity analysis: A reproducible capillary procedure. Soil Sci. 97: 268–275.

Oklahoma Mid-Continent Oil and Gas Association. 1998. Oklahoma Corporation Commission environmental handbook. Oklahoma City, OK.

Olsen, R.A., and M. Peech. 1960. The significance of the suspension effect in the uptake of cations by plant from soil-water systems. Soil Sci. Soc. Am. J. 24:257–261.

Reitemeier, R.F. 1946. Effect of moisture content on the dissolved and exchangeable ions of soils of arid regions. Soil Sci. 61:195–214.

Rhoades, J.D. 1996. Salinity: Electrical conductivity and total dissolved salts. p. 417–436. *In* D.L. Sparks et al. (ed.) Methods of soil analysis. Part 3. SSSA Book series No. 5. ASA and SSSA, Madison, WI.

Schofeild, R.K. 1947. A ratio law governing the equilibrium of cations in the soil solution. Int. Congr. Pure Appl. Chem. 3:257–261.

Shirokova, Y., I. Forkutsa, and N. Sharafutdinova. 2000. Use of electrical conductivity instead of soluble salts for soil salinity monitoring in Central Asia. Irrig. Drain. Syst. 14:199–205.

Sonneveld, C., and J. Van Den Ende. 1971. Soil analysis by means of 1:2 a volume extract. Plant Soil 35:505–516.

SAS Institute. 2001. SAS user's guide: Statistics. Ver 8.2. SAS Institute, Cary, NC.

USDA. 1954. Diagnosis and improvement of saline and alkali soils. Agric. Handb. no. 60. United States Salinity Laboratory, Riverside, CA.

United States Department of Energy. 2003. Historic petroleum production. Available online at http://www.eia.doe.gov/neic/historic/hpetroleum2.htm (verified 29 Mar. 2005).

Vaughn, P.J., S.M. Lesch, D.L. Corwin, and D.G. Cone. 1995. Water content effect on soil salinity prediction: A geostatistical study using cokriging. Soil Sci. Soc. Am. J. 59:1146–1156.

Wagenet, R.J., and J.J. Jurinak. 1978. Spatial variability of soluble salt content in a mancos shale watershed. Soil Sci. 126:342–349.