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FINAL REPORT

SALINITY AND SODICITY INTERACTIONS OF WEATHERED MINESOILS IN NORTHWESTERN NEW MEXICO AND NORTH EASTERN ARIZONA

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ABSTRACT

Weathering characteristics of minesoils and rooting patterns of key shrub and grass species were evaluated at sites reclaimed for 6 to 14 years from three surface coal mine operations in northwestern New Mexico and northeastern Arizona. Non-weathered minesoils were grouped into 11 classifications based on electrical conductivity (EC) and sodium adsorption ratio (SAR). Comparisons of saturated paste extracts, from non-weathered and weathered minesoils show significant ($p < 0.05$) reductions in SAR levels and increased EC. Weathering increased the apparent stability of saline and sodic minesoils thereby reducing concerns of aggregate slaking and clay particle dispersion. Root density of fourwing saltbush (*Atriplex canascens*), alkali sacaton (*Sporobolus airoides*), and Russian wildrye (*Psathyrostachys junceus)* were nominally affected by increasing EC and SAR levels in minesoil.

Results suggest that saline and sodic minesoils can be successfully reclaimed when covered with topsoil and seeded with salt tolerant plant species.

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EXECUTIVE SUMMARY

Relationships between electrical conductivity (EC) and sodium adsorption ratio (SAR) in reconstructed soils at surface coal mining operations are insufficiently documented in the literature. Chemical and physical properties of minesoils are unique and quite different from natural soils formed through pedogenic processes. These differences largely occur because relatively non-weathered overburden is exposed during mining processes and subsequently used as a lower root-zone medium (minesoil) during soil reconstruction. Some of these materials are classified as saline, sodic, or saline-sodic and are considered unsuitable rooting media for establishment of native vegetation. Weatherable minerals (i.e., pyrite, $CaCO_3$, gypsum, and other geologic substrates) present in minesoils can remediate or mitigate elevated SAR levels by maintaining or increasing electrolytes in the soil and providing sources of exchangeable calcium and magnesium. Coversoil (e.g., topsoil) enhances remediation through physical and chemical buffering between minesoils and the reconstructed soil surface.

This investigation advances our understanding of weathered minesoil chemistry and the influence of soil chemistry on rooting of reclamation plant species. Specifically, weathered minesoils experience little reduction in permeability whereas non-weathered minesoils can experience substantially decreased permeability when exposed to low-conductivity water, such as precipitation. Increased soil salinity adversely affects plant production but its affect on root density remains unclear.

INTRODUCTION

The chemistry of minesoil materials (e.g., backfill or spoil) used for soil reconstruction at coal mining operations in arid regions of the southwestern U.S. has received little attention from the scientific community. In addition, limited data are available on changes in minesoil chemistry from geochemical weathering under reclaimed conditions. The purpose of this research was to evaluate chemical changes in minesoils at three surface coal mining operations 6 to 14 y after reclamation. A secondary objective is to determine effects of salinity and sodicity on key plant species used for reclamation at these same operations.

Fine-textured, sodium (Na) enriched strata are found in overburden of Cretaceous and Tertiary age coal deposits in the western U.S. (Sandoval et al., 1973; Rai et al., 1974; Farmer and Richardson, 1976). Overburden is removed during coal extraction and placed in temporary stockpiles. Upon removal, and for the purposes of this paper, these earthen materials are referred to as minesoils. During reclamation, minesoils are graded to a specified final topography, covered with coversoil (i.e., unconsolidated soils salvaged prior to coal extraction), and re-vegetated.

The destructive influence of Na on soil physiochemical properties has been extensively documented (Shainberg and Letey, 1984; Sumner et al., 1998; Condom et al., 1999; Mace and Amrhein, 2001; Qadir and Schubert, 2002). The two common indices used to measure soil Na concentrations are (1) exchangeable sodium percentage (ESP), which is the proportion of the exchange complex that is occupied by Na, and (2) SAR, which reflects the relative balance of Na to calcium (Ca) and magnesium (Mg) in the soil solution (Sumner et al., 1998). Sodicity of the soil is a property of the exchange complex composition; however, the fundamental soil property that is currently used to establish sodicity of a soil material is SAR because of its relative ease of determination (Essington, 2004). In USDA Handbook 60 (United States Salinity Laboratory Staff, 1954) SAR is defined by the equation:

$$SAR = \frac{[Na]}{([Ca] + [Mg]/2)^{0.5}}$$

Where, Na, Ca, and Mg represent concentrations of a saturated paste extract in milliequivalents per liter (meq L^{-1}).

The most common definition of a sodic soil is from the United States Salinity Laboratory Staff (1954) where soils with ESP >15 or SAR >13 are sodic (Sumner, 1993). However, this definition is severely flawed because total electrolyte concentration (TEC) of the soil solution and clay mineralogy is not considered in the evaluation of sodic materials (Shainberg and Letey, 1984; Sumner et al., 1998; Quirk, 2001). It is impossible to estimate the impacts of SAR on the physical state of a soil material without knowing the TEC of the system (Quirk and Schofield, 1955; Shanmuganathan and Oades, 1983; Sumner et al., 1998). Sumner (1993, p. 687) states

"In view of the continuous effect of Na, from low to high levels, on soil behavior, the establishment of a critical level for ESP is very arbitrary and has caused considerable confusion. As will be shown later, what is of real importance is the interrelationship between ESP of a soil and its equilibrium TEC in solution in determining its field behavior." The following relationship describes the association between EC and TEC of a solution:

$$10 * EC\ (dS\ m^{-1}) \approx TEC\ (mmol_c\ L^{-1})$$

Critical SAR levels used to evaluate the suitability of minesoils have largely been developed without consideration for TEC. Consequently, the coal mining industry is expending considerable resources to mitigate, often by burial, materials that are inappropriately evaluated as unsuitable with regard to SAR. Unnecessary mitigation increases reclamation costs, which are passed to coal consumers.

Quirk and Schofield (1955) proposed the concept of 'threshold concentration' which is the concentration of electrolytes in the percolate that causes a 25% reduction in permeability (K) at a given ESP or SAR level. This concept has been applied to other soils (McNeal and Coleman, 1966; Cass and Sumner, 1982). Soil K can be maintained at elevated ESP provided that the TEC of the soil solution is maintained above the threshold concentration. The two primary mechanisms responsible for a decrease in K are (1) swelling of clay particles which increase with sodicity and (2) clay particle deflocculation or dispersion which occurs when TEC is below the flocculation value (FV) or critical coagulation concentration (CCC). Flocculation value is defined as the minimum electrolyte concentration that causes flocculation (Shainberg and Letey, 1984). Clay particle dispersion can only occur when TEC is below FV. Flocculation values are dependent on mineralogy, counter ion valency, and pH of the solution. At ESP values of 5, 10, and 20, the FV for Na/Ca-montmorillonite is 3.0, 4.0, and 7.0 $mmol_c\ L^{-1}$, respectively, and the FV for Na/Ca-illite is 6.0, 10, and 18 $mmol_c\ L^{-1}$, respectively (Shainberg and Letey, 1984).

Development of poor physical condition including reduced infiltration rate (IR), K, and aeration is the fundamental problem associated with sodic soils. Research has shown that SAR well above the arbitrary value of 13 does not cause physical degradation of soil if the system also contains high levels of salts (Quirk and Schofield, 1955; McNeal et al., 1968; Frenkel et al., 1978; Shainberg et al., 1981; Abu-Sharar et al., 1987; Chiang et al., 1987; Lima et al., 1990; Malik et al., 1992; Curtin et al., 1994; Mace and Amrhein, 2001; Quirk, 2001). The potential for aggregate slaking, soil swelling, and clay dispersion is amplified as ESP increases or EC decreases.

The chemical and physical properties of minesoils are unique and quite different from natural soils formed through pedogenic processes. Minesoils are typically derived from strata deep in the geologic column where there has been limited exposure to oxidation and weathering reactions (Haering et al., 1993). Although these materials are often classified as sodic (SAR

$>$13), they often contain sufficient EC levels to maintain clay flocculation and hence permeability (Quirk and Schofield, 1955; McNeal and Coleman, 1966; Rengasamy et al., 1984; Quirk, 2001). Weatherable minerals (i.e., pyrite (FeS), $CaCO_3$, and gypsum ($CaSO_4$)) are present that can remediate or mitigate an elevated SAR condition by increasing soil solution EC and availability of polyvalent exchangeable cations (i.e., Ca^{2+} and Mg^{2+}). Coversoil is placed over minesoil materials during soil reconstruction to enhance revegetation efforts and to provide a physical and chemical buffer between sodic minesoils and the reconstructed soil surface. Coversoils derived from Aridisols and Alfisols of northwestern New Mexico and northeastern Arizona often contain $CaCO_3$, gypsum, and other weatherable minerals that provide electrolytes including Ca to the soil solution (Musslewhite et al., 2005). Coversoils reduce the interaction between low EC precipitation and minesoils. The degrading effect of low EC water on surfaces of sodic materials is one of the most commonly reported limitations in sodic soil management (Shainberg and Letey, 1984; Sumner 1993; Levey et al., 1998; Qadir and Schubert, 2002; Ganjegunte et al., 2005). Tejedor et al. (2003) showed that saline/sodic soils covered by 10 to 15 cm of tephra mulch (basaltic volcanic material), resulted in significant remediation of underlying soils with respect to EC and ESP. Reducing energy from raindrop impacts or supplying sufficient soluble electrolyte at the surface of sodium affected materials, as is done with coversoils, can alleviate surface crusting (Sumner, 1993).

Dollhopf et al. (1980), Jurinak and Wagenet (1982), Richardson and Farmer (1982), and Hall and Berg (1983), investigated natural geochemical weathering effects on sodic overburden and minesoil samples collected from mines in Montana, North Dakota, Colorado, and New Mexico. These laboratory and field studies showed Ca^{2+} levels increased during weathering, while significant decreases were recorded for ESP and SAR. The importance of mineral weathering can be significant in reducing the sodicity of overburden and minesoil when dealing with slightly weathered calcareous overburden or those that contain small amounts of gypsum and pyrite. In two different field studies at the West Decker mine in Montana, SAR levels decreased 8 to 9 units in the upper 30 cm of minesoil over a 2 to 7 y period due to apparent increases in Ca^{2+} and Mg^{2+} and leaching of Na (Dollhopf et al., 1980; Richardson and Farmer, 1982). Similarly, Weber et al. (1979) found SAR in northwestern New Mexico minesoils was reduced from 37.7 to 3.7 and 8.0 $mmol^{1/2}$ $L^{-1/2}$ at the 0 to 6.4 cm and 6.4 to 12.7 cm depths, respectively, following eight irrigations of low salinity (EC = 1.0 dS m^{-1}) tap water. Carlstrom et al. (1987) reported high EC levels and occasional heavy rain or winter snowmelt promoted downward salt leaching and decreased EC and SAR with time in reclaimed coversoil-minesoil pedons at the San Juan Mine in New Mexico.

Plant species used for reclamation of reconstructed soils in arid and semi-arid regions of the southwest must be widely adapted to salinity and drought while meeting the overall vegetative production, cover, and diversity goals of the post-mining land use. The predominant shrub species used for mineland reclamation in northwestern New Mexico and northeastern Arizona is fourwing saltbush and the predominant grass species are alkali sacaton and Russian wild rye. Fourwing saltbush, alkali sacaton, and Russian wild rye are highly tolerant to drought and soil salinity (USDA, 2005). These plant species have fair to excellent ratings for livestock grazing and wildlife use. Miyamoto (1978) found no reduction in vegetative yield of fourwing saltbush and alkali sacaton irrigated with salt solutions of 200 $mmol_c\ L^{-1}\ Na_2SO_4$ (EC ≈ 20 $dS\ m^{-1}$). Growth of fourwing saltbush and alkali sacaton was slightly inhibited with NaCl solutions above 150 and 100 $mmol_c\ L^{-1}$. The apparent effect of Cl^- on these species has limited value since SO_4^{2-} is typically the dominant anion in solutions from southwestern minesoils (Musslewhite et al., 2005). Research conducted by Richardson and McKell (1980) found good establishment and growth of fourwing saltbush in oil shale with EC values ranging from 4 to 18 $dS\ m^{-1}$. Ries et al. (1976) evaluated survival and growth of eight perennial forage species used for revegetation work on minesoils from Montana. Above ground and below ground biomass of all species except fourwing saltbush and alkali sacaton were significantly reduced as EC was increased from 1.0 to 10 $dS\ m^{-1}$. Moreover, no effect between $NaSO_4$, $MgSO_4$, and mixed salt solutions on vegetative growth of these species was observed. Russian wild rye might have growth responses similar to fourwing saltbush and alkali sacaton given its high drought and salinity tolerance status (USDA, 2005) and its successful establishment on arid mined lands in northeastern Arizona. However, limited research has been completed on this species to confirm this supposition.

OBJECTIVES

The purpose of this research project was to increase our understanding of weathered minesoil chemistry and the influence of soil chemistry on rooting of reclamation species 6 to 14 years after reclamation at mine sites located in northwestern New Mexico and northeastern Arizona.

METHODS

Non-weathered Minesoils

Reclamation plots from surface coal mines in northwestern New Mexico and northeastern Arizona were selected for this study. Non-weathered minesoil quality was determined at regularly spaced grid locations prior to coversoil placement and revegetation. Minesoil samples were collected at each grid location from 30 cm increments to a depth of 90 cm. Samples were disaggregated to <2mm and pH, EC, soluble Na, Ca, and Mg were determined from soil saturated paste extracts. Approximately 15 to 45 cm of coversoil was spread over minesoils and seeded with reclamation species common to the arid southwest.

Non-weathered mine soils were grouped by EC-SAR class based on average profile EC and SAR (Table 1). A total of four locations within each EC-SAR class (40 sites) were randomly selected for post-reclamation characterization. Selected sites were located in reclamation plots based on original grid coordinates.

Root Density

A target indicator shrub, fourwing saltbush, and a target grass, alkali sacaton (New Mexico) or Russian wild rye (Arizona), were selected for evaluation based on commonality among reclamation areas in northwestern New Mexico and northeastern Arizona. Test pits, excavated with a backhoe to a depth of 150 cm, were oriented to expose root structures of target shrub and grass species.

Root intercept measurements were collected separately below each plant species using a method similar to the root counting procedure described by Schoeneberger et al. (2002). A 5×3 array of 100-cm^2 metal squares was placed directly under the plant root crown. Measurements were collected within each square in 10-cm depth increments beginning at 10 cm above the interface between coversoil and minesoil to 90 cm below the interface between coversoil and minesoil. The number of root intercepts within each square was recorded by fine (<2 mm), medium (2-5 mm), and coarse (>5 mm) root diameter (size) classes. Medium and coarse root intercepts were counted within each square. Fine root intercepts were counted within a 1-cm^2 frame superimposed at 5 cm depth along the left edge of each square. Mean root intercepts by size class were calculated from the three horizontal measurements at each depth (i.e., from each of the 5 rows in the 5×3 array).

Weathered Minesoils

Weathered coversoil and minesoil samples were collected subsequent to root measurements. Samples were collected from the top and bottom halves of coversoil and within the 0 to 5 cm, 5 to 15 cm, 15 to 30 cm, 30 to 60 cm, and 60 to 90 cm depth ranges of weathered minesoil. Separate samples were collected under each plant species. Samples were passed through a 6.3-mm sieve and equal sample volumes from each plant species location and depth were combined and homogenized.

Samples were air dried and processed to <2 mm (sieved <2 mm for coversoil and disaggregated for minesoil). Soil texture was determined using the hydrometer method (Gee and Bauder, 1986) and paste extracts were prepared using the Rhoades (2001) method for saturated paste extracts. Extract from each sample was analyzed for pH, EC, alkalinity, soluble Na, Ca, Mg, SO_4^{-2}, Cl^{-1}, and NO_3^{-1}.

Statistical Analysis

Statistical analyses for weathered soil data were conducted using the GLM procedure of the Statistical Analysis System (SAS; Statistical Analysis System, 1998). Assessments for normality of residuals were conducted using the UNIVARIATE procedure in SAS. Paired t-tests (Snedecor and Cochran, 1967) were used to compare various levels of weathered soils with appropriate levels of baseline soils using the MEANS procedure of SAS.

Root intercept analyses of variances were conducted separately for each depth by root class combination. These tests were conducted using a one-way analysis of variance set in a completely randomized design (Snedecor and Cochran, 1967). Means were separated using Fisher's protected least significant difference (Snedecor and Cochran, 1967).

The CORR procedure in SAS was used to generate Pearson correlation coefficients (Snedecor and Cochran, 1967), and the REG procedure in SAS was used to conduct regression analysis using both simple linear and multiple linear models; both types of regressions were conducted using standard ordinary least squares techniques (Weisberg, 1980). Normality of residuals was assessed using the UNIVARIATE procedure in SAS and equality of variances, as well as 'correctness' of the linear models, were qualitatively assessed using the PLOT procedure in SAS.

RESULTS

The mine soils evaluated in this study represent a broad range of salinity and sodicity levels with mean EC_e of non-weathered minesoils ranging from 2.2 to 12.1 dS m^{-1} and SAR values ranging from 3.1 to 54.9 $mmol^{1/2}$ $L^{-1/2}$ (Table 2). Saline and sodic minesoils are reclaimed with a surface mantle of coversoil ranging in thickness from 15 to 45 cm. The following results are presented where the 0-cm depth is the interface between coversoil and minesoil. The primary purpose of EC-SAR classes was to evaluate interactions between EC and SAR level on weathering characteristics. Development of EC-SAR classes was loosely based on EC and SAR suitability standards for root-zone (minesoils) materials in the southwestern U.S. and USDA soil salinity classes (Soil Survey Division Staff, 1993).

Comparisons between 42 non-weathered and weathered minesoils, without consideration for EC-SAR class, show significant ($P < 0.05$) reduction of SAR at all depths and significant EC increases in the 5- to 90-cm zone (Table 2). The EC in the 0- to 5-cm increment increased slightly by 0.6 dS m^{-1} and SAR was reduced by 7.40 $mmol^{1/2}$ $L^{-1/2}$. Electrical conductivity increased from 2.8 to 1.9 dS m^{-1} and SAR, was reduced by 2.1 to 5.2 $mmol^{1/2}$ $L^{-1/2}$ below the 5-cm depth. The increasing EC trend and decreasing SAR show an apparent improvement in minesoil stability with weathering. Numerous studies have shown that an increase in electrolyte concentration at a given SAR reduces physical degradation of a soil material (Quirk and Schofield, 1955; McNeal and Coleman, 1966; Shainberg et al., 1981; Rengasamy et al., 1984; Yousaf et al., 1987; Shainberg et al., 1991; Aringhieri and Giachetti, 2001; Quirk, 2001).

Sample sizes within each class were limited to between 2 to 5 replications; thus statistically significant conclusions among individual classes were not apparent in some cases but observed trends in weathering warrant further discussion. Weathering of EC 0 to 4 classed minesoils (1, 2, 3, and 4) was apparently enhanced by SAR level (Table 2). The EC of class 1 (SAR <15) minesoils decreased 2.3 dS m^{-1} at the 0- to 5-cm depth. Conversely, EC of class 2 (SAR 15-25), 3 (SAR 25-40), and 4 (SAR > 40) minesoils increased by 3.7, 2.1, and 4.1 dS m^{-1}, respectively. Reduction in SAR at this same depth was 0.1, 8.9, 10.1, and 19.8 $mmol^{1/2}\ L^{-1/2}$ for class 1, 2, 3, and 4 minesoils, respectively. Weathering of class 1, 2, 3, and 4 minesoils below 5 cm followed similar relationships with the magnitude of EC increase and SAR reduction decreasing with depth.

The EC 4 to 8 classed minesoils (5, 6, 7, and 8) follow a similar weathering trajectory with respect to salinity where EC increase is apparently related to Na level. The EC of class 5 (SAR<15) decreased nearly 1.0 dS m^{-1} at the 0 to 5 cm depth while EC of class 6 (SAR 15-25), 7 (SAR 25-40), and 8 (SAR >40) minesoils increased by 0.4, 3.2, and 7.0 dS m^{-1}, respectively. The SAR level of weathered materials in all but the > 40 class materials was not significantly ($P < 0.05$) altered with weathering. SAR in the >40 class was reduced between 19.4 and 13.5 $mmol^{1/2}\ L^{-1/2}$ at all depths.

Weathering patterns of minesoils within the high (8-16) EC class were slightly different than the less saline materials with apparent reductions of both EC and SAR at 0 to 30 cm of class 9 (SAR 15-25) and class 10 (SAR 25-40) minesoils. Both EC and SAR of weathered class 9 and 10 minesoils were essentially unchanged below 30 cm. The EC of weathered class 11 (SAR > 40) minesoils increased between 0.4 and 4.0 dS m^{-1} at all depths and SAR was lower at all depths with significant ($P < 0.05$) reduction of 10.0 $mmol^{1/2}\ L^{-1/2}$ at the 0- to 5-cm depth and 5.40 $mmol^{1/2}\ L^{-1/2}$ at the 30- to 60-cm depth.

DISCUSSION

Increases in minesoil salinity apparently result from several weathering processes. Exchangeable and crystalline cations are released from soil minerals as a result of hydrolysis and chemical weathering. Rhoades et al. (1968) demonstrated a significant contribution of soluble ions to the soil solution from primary mineral weathering and that exchangeable Na increased the total amounts of Ca^{2+} and Mg^{2+} released by weathering. Oster and Shainberg (1979), Shainberg et al. (1981), Suarez and Frenkel (1981), Frenkel et al. (1983), and Aringhieri and Giachetti (2001) also concluded that the total amount of electrolytes from weathering processes increases as the amount of exchangeable Na increases. Increases in EC and SAR reductions observed in this study correspond with their conclusions.

The areas of investigation for this study are characterized as arid with 10 to 28 cm of annual precipitation. Level of precipitation in these areas controls salt migration and soil development as illustrated by shallow saline soils developing from Fruitland Formation shales in northwestern New Mexico (Sandoval and Gould, 1978). A laboratory study conducted by Musslewhite et al. (2005) found coversoil materials from northwestern New Mexico and northeastern Arizona contributed Ca^{2+} and Mg^{2+} to leachates from simulated weathering. Under field conditions the products from coversoil weathering are apparently translocated below the coversoil-minesoil interface to the 15- to 30-cm minesoil depth where the highest levels of salts were observed.

Reduction in mine soil SAR from weathering largely results from increased levels of soluble Ca and Mg relative to Na increases in the soil solution. Increased Ca and Mg result from apparent dissolution of $CaCO_3$, gypsum, and primary minerals (i.e., Ca and Mg silicates). Hall and Berg (1983) showed a significant (22%) reduction in SAR of sodic minesoils after 224 days of simulated weathering. The reduction largely resulted from increased soluble Ca that the authors attributed to dissolution of $CaCO_3$ which was possibly enhanced by sulfide oxidation, delamination of Ca-tactoids, and dissolution of gypsum. Weber et al. (1979) conducted a column study to evaluate the effects of irrigation water quality, amendment type, and timing of amendment application on infiltration rates of saline-sodic minesoils from the San Juan Basin, New Mexico. The SAR values of 0- to 6.4-cm and 6.4- to 12.7-cm depths were reduced from, 37.7 $mmol^{1/2}$ $L^{-1/2}$ to 3.7 and 8.0 $mmol^{1/2}$ $L^{-1/2}$, respectively, after irrigation with low salinity tap water. Musslewhite et al. (2005) found similar levels of SAR reduction in a simulated weathering study of sodic minesoils.

Soil permeability is dependent on the ESP or SAR of the soil and on the electrolyte concentration of the percolating or soil solution (Quirk and Schofield, 1955; McNeal and Coleman, 1966; Oster and Schroer, 1979). The TEC concept originally proposed by Quirk and Schofield (1955) along with relationships developed by McNeal and Coleman (1966) for the Waukena and Oasis soil types, and the classification system proposed by Rengansamy et al. (1984) involving SAR and total cation concentration of 1:5 soil water extracts are shown on Figure 1. Mean EC and SAR of all depths for 11 classes of non-weathered minesoils are also plotted on Figure 1. Using established threshold relationships from the work previously discussed, class 3, 4, and 8 non-weathered minesoils have the greatest susceptibility to reduced K with class 4 minesoils representing the greatest sodium hazard. Comparison of weathered minesoils with established threshold relationships shows that all of the materials are within the stable or minor reduction in permeability region of the chart (Figure 2). The overall weathering trajectory is a downward shift to the right which imparts greater physical stability of the materials, however, increased salinity can adversely affect vegetation productivity particularly if salt-sensitive plants are used for reclamation.

CONCLUSIONS

This study demonstrates that all weathered minesoils are expected to have little or no reduction in permeability based on established threshold EC and SAR relationships. Also, based on these thresholds, class 3, 4, and 8 non-weathered minesoils are likely to show substantial reduction in permeability if exposed to low EC percolating solutions (i.e., precipitation). Good quality coversoils overlying minesoils function as a chemical buffer by providing electrolytes to the percolating solution and as a physical buffer by eliminating dispersive effects of raindrop impacts and overland flow. Increased salinity can adversely affect vegetative production; however, our data indicate limited relationships between root density of salt-tolerant species and EC or SAR of weathered minesoils. Regional minesoil suitability guidelines classify materials with EC > 12 or 16 dS m^{-1}, depending on the guideline, as unsuitable. Weathered minesoils with initial SAR >40 and EC > 4 have EC >12, but none of the weathered EC levels exceeded the 16-dS m^{-1} guideline. The SAR guidelines for minesoils should be re-evaluated based on buffering characteristics of coversoil along with EC, texture, and mineralogy of the minesoil rather than enforcement of arbitrary values similar to those developed by the U.S. Salinity Laboratory (1954).

REFERENCES

Abu-Sharar, T.M., F.T. Bingham, and J.D. Rhoades. 1987. Stability of soil aggregates as affected by electrolyte concentration and composition. Soil Sci. Soc. Am. J. 51:309-314.

Aringhieri, R. and M. Giachetti. 2001. Effect of sodium adsorption ratio and electrolyte concentrations on the saturated hydraulic conductivity of clay-sand mixtures. European J. Soil Sci. 52:449-458.

Cass, A. and M.E. Sumner. 1982. Soil pore structural stability and irrigation water quality: 1. Empirical sodium stability model (1). Soil Sci. Soc. Am. J. 46:503-507.

Carlstrom, M.G, F.A. Amendola, D.A. Shay, and D.J. Dollhopf. 1987. Sodium, p. 75-108. *In* R.D. Williams and G.E. Schuman (eds.) Reclaiming Minesoils and Overburden in the Western United States – Analytic Parameters and Procedures. Soil Conserv. Soc. Am. Ankeny, Iowa.

Chiang, S.C., D.E. Radcliffe, W.P. Miller, and K.D. Newman. 1987. Hydraulic conductivity of three southeastern soils as affected sodium, electrolyte concentration, and pH. Soil Sci. Soc. Am. J. 51:1293-1299.

Curtin, D., H. Steppuhn, and F. Selles. 1994. Clay dispersion in relation to sodicity, electrolyte concentration and mechanical effects. Soil Sci. Soc. Am. J. 58:955-962.

Condom, N., M. Kuper, S. Marlet, V. Valles, and J. Kijne. 1999. Salinization, alkalinization and sodification in Punjab (Pakistan): Characterization of the geochemical and physical processes of degradation. Land Degrad. Develop. 10:123-140.

Dollhopf. D.J., E.J. DePuit, and M.G. Klages. 1980. Chemical Amendment and Irrigation Effects on Sodium Migration and Vegetation Characteristics in Sodic Minesoils in Montana. Bull. 736. Montana Agric. Exp. Stn. Montana State Univ., Bozeman.

Essington, M.E. (ed.) 2004. Soil Salinity and Sodicity. p. 499-521. *In* Soil and Water Chemistry An Integrative Approach. CRC Press, Boca Raton, FL.

Farmer, E.F. and B.Z. Richardson. 1976. Hydrologic and soil properties of coal mine overburden piles in southeastern Montana. p. 120-130. *In*: Fourth Symposium on Surface Mining and Reclamation. National Coal Assn., Washington, DC.

Frenkel, H., J.O. Goertzen, and J.D. Rhoades. 1978. Effects of clay type and content, exchangeable sodium percentage, and electrolyte concentration of clay dispersion and soil hydraulic conductivity. Soil Sci. Soc. Am. J. 42:32-39.

Frenkel, H., C. Amrhein, and J.J. Jurinak. 1983. The effect of cations on soil mineral weathering. Soil Sci. Soc. Am. J. 47:649-53.

Ganjegunte, G.K., G.F. Vance, and L.A. King. 2005. Soil chemical changes resulting from irrigation with water co-produced with coalbed natural gas. J. Environ. Qual. 64:2217-2227.

Gee, G.W. and J.W. Bauder, 1986. Particle size analysis. p. 383-409. *In* Soil Science Society of America Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods 2nd ed. ASA and SSSA, Madison, WI.

Haering, K.C., W.L. Daniels, and J.A. Roberts. 1993. Changes in mine soil properties resulting from overburden weathering. J. Environ. Qual. 22:194-200.

Hall, A. and W.A. Berg. 1983. Prediction of Sodium Hazard in Coal Mine Overburden. Reclam. Reveg. Res. 2:191-204.

Jurinak, J.J. and R.J. Wagenet. 1982. Spring Creek Coal: Factors Affecting the Sodicity and Reclamation of Overburden Materials. Annual Report 2. Utah Agric. Exp. Stn, Utah State Univ., Logan.

Levey, G.J., I. Shainberg, and W.P. Miller. 1998. Physical properties of sodic soils. p. 77-94. *In* M.E. Sumner and R. Naidu (eds.), Sodic Soils: Distribution, Properties, Management, and Environmental Consequences. Oxford University Press, New York.

Lima, L.A., M.E. Grismer, and D.R. Nielsen. 1990. Salinity effects of Yolo loam hydraulic properties. Soil Sci. 150(1):451-458.

Mace, J.E. and C. Amrhein. 2001. Leaching and reclamation of soil irrigated with moderate SAR waters. Soil Sci. Soc. Am. J. 65:199-204.

Malik, M., M.A. Mustafa, and J. Letey. 1992. Effect of mixed Na/Ca solutions on swelling, dispersion and transient water flow in unsaturated montmorillonitic soils. Geoderma. 52:17-28.

McNeal, B.L. and N.T. Coleman. 1966. Effect of solution composition on soil hydraulic conductivity. Soil Sci. Soc. Am. Proc. 30:308-312.

McNeal, B.L., D.A. Layfield, W.A. Norvell, and J.D. Rhoades. 1968. Factors influencing hydraulic conductivity of soils in the presence of mixed-salt solutions. Soil Sci. Soc. Am. Proc. 32:187-190.

Musslewhite, B.D., T.H. Brown, G.W. Wendt, and C. Johnston. 2005. Weathering characteristics of saline and sodic minesoils in the southwestern United States. p. 765-768. *In* Proc. 2005 National Meeting of American. Soc. Mining and Reclamation. Breckinridge, CO. 19-24 June 2005. ASMR, Lexington, KY.

Miyamoto, S. 1978. Tolerance of some southwestern range plants to sodium chloride and sulfate. PR-3480. Texas Agric. Exp. Stn., Texas A&M Univ., College Station.

Qadir, M. and S. Schubert. 2002. Degradation processes and nutrient constraints in sodic soils. Land Degrad. Develop. 13:275:294.

Oster, J.D. and I. Shainberg. 1979. Exchangeable cation hydrolysis and soil weathering as affected by exchangeable sodium. Soil Sci. Soc. Am. J. 43:70-75.

Quirk, J.P. 2001. The significance of the threshold and turbidity concentrations in relation to sodicity and microstructure. Australian J. of Soil Res. 39:1185-1217.

Quirk, J.P. and R.K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. J. Soil Sci. 6:163-178.

Rai, D., P.J. Wierenga, and W.L. Gould. 1974. Chemical and physical properties of core samples from a coal-bearing formation in San Juan County, New Mexico. NMSU Agr. Exp. Station Res. Rept. 287, p 13.

Rengasamy, P., R.S.B. Greene, G.W. Ford, and A.H. Mehanni. 1984. Identification of dispersive behavior and the management of red-brown earths. Aust. J. Soil Res. 22:413-31.

Richardson, B.Z. and E.E. Farmer. 1982. Changes in Sodium Adsorption Ratios Following Revegetation of Coal Mine Spoils in Southeastern Montana. INT-87. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Ogden, Utah.

Richardson, S.G. and C.M. McKell. 1980. Salt tolerance of two saltbush species grown in processed oil shale. J. Range Mange. 33(6):460-462.

Ries, R.E., F.M. Sandoval, J.F. Power, and W.O. Willis. 1976. Perennial forage species response to sodium and magnesium sulfate in mine spoil. *In* Surface Mining and Reclamation. Symposium. 4:173-183.

Rhoades, J.D., D.B. Krueger, and M.J. Reed. 1968. The effect of mineral weathering on the sodium hazard of irrigation waters. *In* Soil Sci. Soc. Am. Proc. 32:643-47.

Rhoades, J.D. 2001. Salinity: Electrical Conductivity and Total dissolved Solids. p. 417-435. *In* D.L. Sparks (ed.) Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Series no. 5. SSSA, Madison WI.

Sandoval, F.M., J.J. Bond, J.F. Power, and W.O. Willis. 1973. Lignite mine spoils in the northern Great Plains-characteristics and potential for reclamation. p. 1-24. *In* M.K. Wali (ed.), Some Environmental Aspects of Strip Mining in North Dakota. North Dakota Geol. Survey. Educational Series 5, Grand Forks, ND.

Sandoval, F.M. and W.L. Gould. 1978. Improvement o saline- and sodium-affected disturbed lands. p. 485-504. *In* F.W. Schaller and P. Sutton (eds.) Reclamation of Drastically Disturbed Lands. ASA, CSSA, SSSA, Madison, WI.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., and Broderson, W.D. (eds), 2002. Field book for describing and sampling soils, Version 2.0. NRCS, National Soil Survey. Center, Lincoln, NE.

Shainberg, I., J.D. Rhodes, and R.J. Prather. 1981. Effect of low electrolyte concentration on clay dispersion and hydraulic conductivity of a sodic soil. Soil Sci. Soc. Am. J. 45:273-277.

Shainberg, I. and G. J. Letey. 1984. Response of soils to sodic and saline conditions. Hilgardia 52:1-57.

Shanmuganathan, R. T. and J. M. Oades. 1983. Modification of soil physical properties by addition of calcium compounds. Aust. J. Soil Res. 21:285-300.

Snedecor, G. W. and W.G. Cochran. 1967. Statistical methods. 6th ed. Iowa State University Press, Ames.

Soil Survey Division Staff. 1993. Soil Survey Manual. USDA Agric. Handbook. 18. U.S. Gov. Print. Office, Washington, DC.

Statistical Analysis System (SAS), version 8.1; Cary, North Carolina.

Statistical Analysis System. 1998. SAS Software version 7.0. SAS Institute Inc., Cary, North Carolina.

Suarez, D.L. and H. Frenkel. 1981. Cation release from sodium- and calcium-saturated clay-sized soil fractions. Soil Sci. Soc. Am. J. 45:716-721.

Sumner, M. E. 1993. Sodic Soils: new perspectives. Aust. J. Soil Res. 31:683-750.

Sumner, M.E., P. Rengasamy and R. Naidu. 1998. Sodic Soils: A Reappraisal. p. 3-17. *In* M.E. Sumner and R. Naidu (eds.), Sodic Soils: Distribution, Properties, Management, and Environmental Consequences. Oxford University Press, New York.

Tejedor, M., C.C. Jimenez, and F. Diaz. 2003. Use of volcanic mulch to rehabilitate saline-sodic soils. Soil Sci. Soc. Am. J. 67:1856-1861.

USDA, NRCS. 2005. The *PLANTS* Database, Version 3.5 (http://plants.usda.gov). Data complied from various sources by M.W. Skinner. National Plant Data Center, Baton Rouge, LA.

United States Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkai soils. USDA Handbook. 60. U.S. Gov. Print. Office, Washington, D.C.

Weber, S.J., M.E. Essington, G.A. O'Connor, and W.L. Gould. 1979. Infiltration studies with sodic mine spoil material. Soil Sci. 128(5):312-318.

Weisberg, S. 1980. Applied linear regression. Wiley, New York.

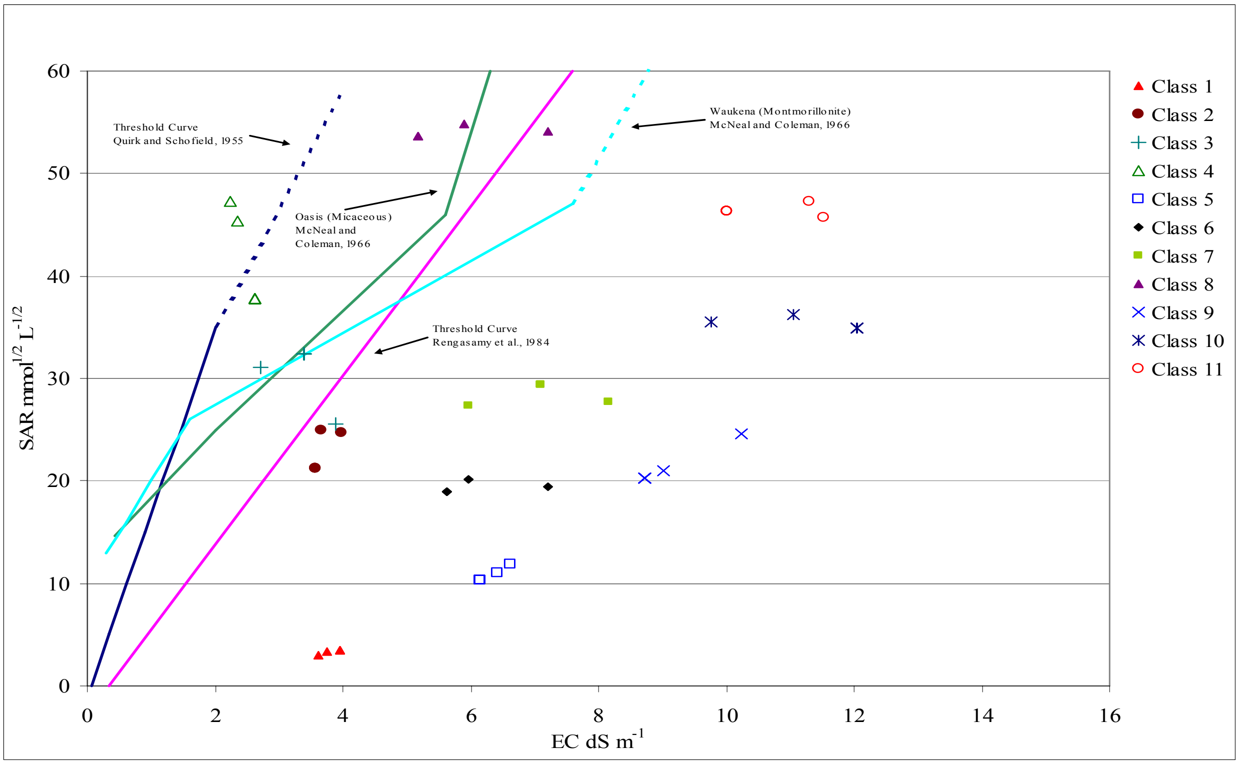

Figure 1. Mean electrical conductivity (EC) and sodium adsorption ratio (SAR) of different classes of non-weathered minesoils and threshold relationships from Quirk and Schofield (1955), McNeal and Coleman (1966), and Rengasamy et al. (1984).

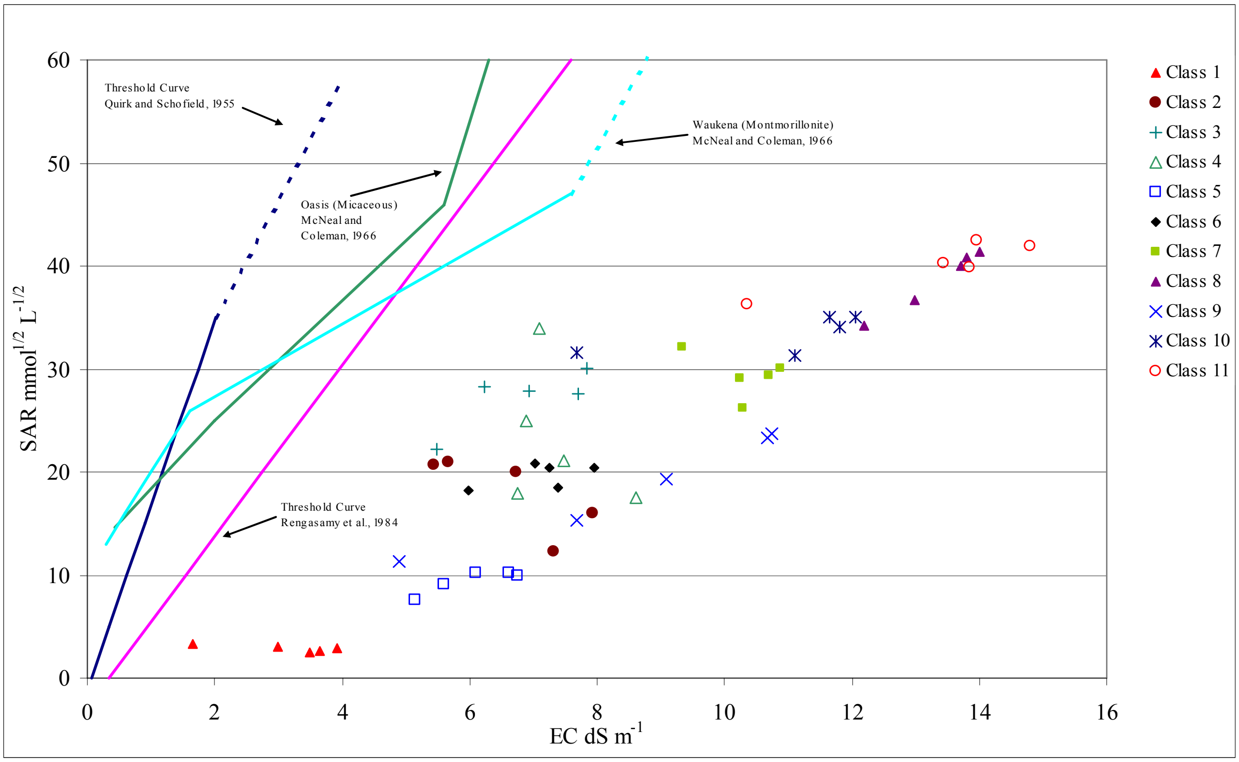

Figure 2. Mean electrical conductivity (EC) and sodium adsorption ratio (SAR) of different classes of weathered minesoils and threshold relationships from Quirk and Schofield (1955), McNeal and Coleman (1966), and Rengasamy et al. (1984).

Table 1. EC and SAR class combinations for non-weathered mine soils.

EC (dS/m)	SAR			
0-4	-	15-25	25-40	40+
4-8	<15	15-25	25-40	40+
8-16	-	15-25	25-40	40+

Table 2. Mean EC and SAR of mine soils before and after weathering separated by EC-SAR class and depth.

			Non-Weathered Mine soils					Weathered Mine soils				
			Depth (cm)									
Variable	Class	N	0-5	5-15	15-30	30-60	60-90	0-5	5-15	15-30	30-60	60-90
EC	1	4	3.95	3.95	3.95	3.75	3.62	1.67*	3.00	3.91	3.65	3.50
dS m^{-1}	2	3	3.57	3.57	3.57	3.97	3.66	7.31	7.93*	6.72*	5.66	5.43
	3	4	3.39	3.39	3.39	2.71	3.88	5.49	7.71	7.83†	6.94	6.23
	4	2	2.63	2.63	2.63	2.35	2.23	6.76	8.62*	7.48†	6.90	7.10†
	5	4	6.14	6.14	6.14	6.62	6.42	5.15	5.59	6.62	6.76	6.09
	6	4	5.63	5.63	5.63	5.97	7.21	5.99	7.38†	7.95*	7.26	7.03
	7	4	7.09	7.09	7.09	5.97	8.16	10.3*	10.7†	10.9†	10.2*	9.34
	8	4	5.18	5.18	5.18	7.21	5.89	12.2*	13.0*	13.8*	13.7†	14.0*
	9	4	8.73	8.73	8.73	10.2	9.01	4.89*	7.69†	9.09	10.7	10.7
	10	4	12.1	12.1	12.1	9.76	11.1	7.69†	11.1	11.8	11.6	12.1
	11	5	10.0	10.0	10.0	11.3	11.5	10.4	13.8*	14.0*	14.8*	13.4
	All	42	6.54	6.54	6.54	6.71	7.00	7.16	8.92*	9.35*	9.25*	8.89*
SAR	1	4	3.47	3.47	3.47	3.35	3.05	3.33	3.08	2.85*	2.68†	2.50†
$mmol^{1/2}$ $L^{-1/2}$	2	3	21.2	21.2	21.2	24.8	25.0	12.3*	16.0*	20.1	20.9	20.7
	3	4	32.4	32.4	32.4	31.1	25.5	22.3*	27.6	30.1	27.9	28.3
	4	2	37.8	37.8	37.8	45.4	47.3	18.0	17.5	21.1	25.0	33.9
	5	4	10.3	10.3	10.3	11.9	11.0	7.65	9.15	10.2	10.0	10.2
	6	4	19.0	19.0	19.0	20.1	19.4	18.2	18.5	20.4	20.5	20.8
	7	4	29.4	29.4	29.4	27.3	27.7	26.2	29.4	30.1	29.1	32.1
	8	4	53.7	53.7	53.7	54.1	54.9	34.3*	36.8*	40.9*	40.0*	41.4*
	9	4	20.3	20.3	20.3	24.6	21.0	11.3*	15.3†	19.3	23.7	23.3
	10	4	35.0	35.0	35.0	35.5	36.3	31.6	31.4	34.1	35.0	35.1
	11	5	46.3	46.3	46.3	47.3	45.7	36.3*	39.9	42.5	41.9*	40.3
	All	42	28.2	28.2	28.2	29.4	28.4	20.8*	23.0*	25.4*	25.6*	26.3†

* Significant differences between means of non weathered and weathered minesoils at the 0.05 probability level.
† Significant differences between means of non weathered and weathered minesoils at the 0.10 probability level.