SALINITY AND SODICITY INTERACTIONS OF WEATHERED MINESOILS IN THE FOUR CORNERS REGION[1]

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Abstract. Relationships between electrical conductivity (EC) and sodium adsorption ratio (SAR) changes over time in reconstructed soils at surface coal mining operations are insufficiently documented in the literature. Some minesoils (i.e., rootzone material) are classified as saline, sodic, or saline-sodic and have been considered unsuitable rooting media for establishment of native vegetation. Weatherable minerals (e.g., pyrite, calcite, gypsum, and other geologic substrates) commonly present in minesoils can mitigate the effects of elevated SAR levels by maintaining or increasing electrolytes in the soil and provide sources of exchangeable calcium and magnesium. Coversoil (i.e., topsoil) enhances this mitigation through physical and chemical buffering of minesoils. Weathering characteristics of minesoils and rooting patterns of key reclamation species were evaluated at sites from three surface coal mines in northwestern New Mexico and northeastern Arizona. Unweathered minesoils were grouped into 11 classifications based on EC and SAR. Comparison of saturated paste extracts from unweathered and weathered (6 to 14 years after reclamation) 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 risks of aggregate slaking and clay particle dispersion. Root density of fourwing saltbush (*Atriplex canescens*), alkali sacaton (*Sporobolus airoides*), and Russian wildrye (*Psathyrostachys junceus)* were generally unaffected by increasing minesoil EC and SAR levels. Saline and sodic minesoils can be successfully reclaimed when covered with topsoil and seeded with salt tolerant plant species.

Additional Key Words: Sodium adsorption ratio, coversoil, rootzone material, root density

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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. Specifically, data available on changes in minesoil chemistry from geochemical weathering are limited. Critical sodium adsorption ratio (SAR) levels used to evaluate minesoil suitability have largely been developed without consideration of total electrolyte concentration (TEC) in the soil solution. Consequently, the coal mining industry is expending considerable resources to mitigate, commonly by burial, materials that are inappropriately evaluated as unsuitable with regard to SAR. Unnecessary mitigation increases reclamation costs, which are passed to coal consumers.

Fine-textured, sodium (Na^+) enriched strata are frequently 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 removed during coal extraction and placed in temporary stockpiles, for the purposes of this paper, are referred to as minesoils. Reclamation, in the areas considered in this study, consists of grading minesoils to a specified final topography, covering the area with 15 to 45 cm of coversoil (i.e., unconsolidated soils salvaged prior to coal extraction), and revegetating the area with select plant species.

The chemical and physical properties of minesoils are quite different from natural soils formed through pedogenic processes. Minesoils are typically derived from strata deep in the geologic column with limited exposure to oxidation and weathering reactions (Haering et al., 1993). Although these materials are often classified as sodic (SAR >13 $mmol^{1/2}\ L^{-1/2}$), they frequently contain sufficient soluble salts to maintain clay flocculation and saturated permeability (*K)* (Quirk and Schofield, 1955; McNeal and Coleman, 1966; Rengasamy et al., 1984; Quirk, 2001). Weatherable minerals (such as pyrite (FeS), calcite ($CaCO_3$), and gypsum ($CaSO_4 \bullet 2H_2O$)) can be present in sufficient quantity to remediate or mitigate an elevated SAR condition by increasing soil solution electrical conductivity (EC) and providing polyvalent exchangeable cations (i.e., calcium (Ca^{+2}) and magnesium (Mg^{+2})) (Musslewhite et al., 2005).

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 coal mines in Montana, North Dakota, Colorado, and New Mexico, respectively. Their laboratory and field studies showed that Ca^{+2} levels increased during weathering, while significant decreases were recorded for exchangeable sodium percentage (ESP) and SAR. Mineral weathering can substantially reduce the sodicity of minesoils when dealing with slightly weathered calcareous materials or those containing small amounts of $CaSO_4 \bullet 2H_2O$ and FeS. In two different field studies at the West Decker mine in Montana, SAR levels decreased 8.0 to 9.0 $mmol^{1/2}\ L^{-1/2}$ in the upper 30 cm of minesoil over a 2 to 7 yr 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 that SAR in northwestern New Mexico minesoils was reduced from 37.7 to 3.70 and 8.00 $mmol^{1/2}\ L^{-1/2}$ at the 0 to 6.4 cm and 6.4 to 12.7 cm depths, respectively, following eight irrigations (32 cm) of low salinity (EC = 1.00 dS m^{-1}) tap water. Carlstrom et al. (1987) reported that occasional heavy rain or winter snowmelt promoted downward salt leaching and decreased EC and SAR with time in reclaimed minesoils with coversoils at the San Juan Mine in New Mexico.

Coversoil is typically 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 reduce the interaction between low-EC precipitation and minesoils. The degrading effect of low-EC water on the surfaces of sodic materials is one of the most commonly reported limitations in sodic soil management (Shainberg and Letey, 1984; Sumner 1993; Letey et al., 1998; Qadir and Schubert, 2002; Ganjegunte et al., 2005). Tejedor et al. (2003) showed that saline/sodic soils covered with 10 to 15 cm of tephra mulch (basaltic volcanic material) resulted in significant remediation of underlying soils with respect to EC and ESP. Coversoils reduce energy from raindrop impacts and provide a source of soluble electrolytes to Na^+ affected minesoils.

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). There are two common indices used to measure the degree of Na^+ prominence in soil: 1) ESP, namely the proportion of the exchange complex occupied by Na^+, and 2) SAR, which reflects the relative balance of Na^+ and Ca^{2+} plus Mg^{2+} in the soil solution as measured in saturated paste extracts (Sumner et al., 1998). Soil sodicity 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 No.60 (U.S. Salinity Laboratory Staff, 1954), SAR is defined by the equation (milliequivalents were used in the original equation):

$$SAR = \frac{[Na^+]}{([Ca^{+2}] + [Mg^{+2}])^{0.5}} \qquad (1)$$

where Na^+, Ca^{2+}, and Mg^{2+} represent concentrations of a saturated paste extract in millimoles per liter (mmol L^{-1}).

The most common definition of a sodic soil is from the U.S. Salinity Laboratory Staff (1954) where soils with ESP >15% or SAR >13 $mmol^{1/2}$ $L^{-1/2}$ are classified as sodic (Sumner, 1993). However, this definition is limited because TEC of the soil solution and clay mineralogy are not considered in the evaluation of sodic materials (Shainberg and Letey, 1984; Sumner et al., 1998; Quirk, 2001). The effect of SAR on the physical state of soil material is dependent upon TEC (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 approximates the association between EC and TEC of a solution:

$$10*EC\ (dS\ m^{-1}) \approx TEC\ (mmol_c\ L^{-1}) \qquad (2)$$

Quirk and Schofield (1955) proposed the concept of 'threshold concentration' which is the concentration of electrolytes in the soil or percolating solution that causes a 25% reduction in saturated permeability (*K*) at a given ESP or SAR level, a concept applied by other researchers (McNeal and Coleman, 1966; Cass and Sumner, 1982; Rengasamy et al., 1984). Soil *K* can be maintained at elevated ESP provided that soil solution TEC is maintained above the threshold concentration. There are two primary mechanisms responsible for decrease in *K*: 1) swelling of clay particles which increases with sodicity and 2) clay particle deflocculation or dispersion which occurs when TEC is below the flocculation value (FV). Flocculation values are dependent on mineralogy, counter-ion valency, and soil solution pH. The FV for Na/Ca-montmorillonite are 3.0, 4.0, and 7.0 $mmol_c\ L^{-1}$ and for Na/Ca-illite are 6.0, 10, and 18 $mmol_c\ L^{-1}$ for ESP values of 5.0, 10, and 20, respectively (Shainberg and Letey, 1984).

Development of undesirable soil conditions including reductions in infiltration rate, *K*, aeration, and aggregate stability are the fundamental problems associated with sodic soils. Elevated SAR values (>13.0 $mmol^{1/2}\ L^{-1/2}$) do not cause physical degradation of soil if the system also contains high levels of soluble 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). Conversely, physical degradation has been observed in soils with SAR levels below 13.0 $mmol^{1/2}\ L^{-1/2}$ when combined with low EC (Sumner, 1993). The potential for aggregate slaking, soil swelling, and clay dispersion is enhanced as ESP increases and/or EC decreases.

Plant species used for coal-mine reclamation in arid and semi-arid regions of southwestern U.S. must be widely adapted to salinity and drought while meeting overall vegetative production, cover, and diversity goals for the post-mining land use. The predominant shrub species used for mineland reclamation in the northwestern New Mexico and northeastern Arizona is fourwing saltbush (*Atriplex canescens*) and two of the most common grass species are Alkali sacaton (*Sporobolus airoides*) and Russian wildrye (*Psathyrostachys junceus*). Fourwing saltbush, alkali sacaton, and Russian wildrye share a high tolerance to drought and soil salinity and have fair to excellent ratings for livestock grazing and wildlife use (USDA-NRCS, 2005). Miyamoto (1978) found no reduction in vegetative yield of fourwing saltbush and alkali sacaton when irrigated with salt solutions of 200 $mmol_c\ L^{-1}$ Na_2SO_4 (EC $\approx$ 20 $dS\ m^{-1}$). Richardson and McKell (1980) found good establishment and growth of fourwing saltbush in oil shale with EC values ranging from 4.0 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. Biomass of all species except fourwing saltbush and alkali sacaton was significantly reduced as EC was increased from 1.0 to 10 $dS\ m^{-1}$. Moreover, neither $NaSO_4$, $MgSO_4$, nor mixed salt solutions affected vegetative growth of these species. We surmise that Russian wildrye would have similar growth responses based on its drought resistance, salinity tolerance (USDA-NRCS, 2005), and successful establishment on arid mined lands in northeastern Arizona, though limited research has been completed on this species.

The purpose of this research was to increase our understanding of weathered minesoil chemistry and the influence of soil chemistry on the rooting of revegetation species 6 to 14 years after reclamation at coal mines in northwestern New Mexico and northeastern Arizona. The SAR and EC of minesoils should be of limited importance when they are maintained within levels that have minor effects on soil physical properties and vegetation establishment.

Materials and Methods

Reclamation sites from surface coal mines in northwestern New Mexico and northeastern Arizona were selected for this study based upon test results of unweathered minesoil sampled before coversoil was applied. These initial minesoil samples were collected at regularly spaced grid locations in 30 cm increments to a total depth of 90 cm. Samples were disaggregated to <2 mm and pH, EC, and soluble Na^+, Ca^{2+}, and Mg^{2+} were determined from saturated paste extracts.

From this initial characterization, unweathered minesoils were grouped into 11 EC-SAR classes based on average profile EC and SAR (Table 1). A total of four locations (replications) within each EC-SAR class were randomly selected for a second round of post weathering characterization 6 to 14 years after reclamation. These sites were relocated based on original grid coordinates.

Root Density

A target shrub, fourwing saltbush, and a target grass, alkali sacaton (New Mexico) or Russian wildrye (Arizona), were selected for evaluation based on local commonality among reclamation areas. 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 metal frame comprised of three, 100 cm^2 squares horizontally and five, 100 cm^2 squares vertically was placed against the sampling pit wall, centered under the plant root crown. Measurements were recorded as the number of root intercepts within each 100 cm^2 frame, 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. Root intercepts were recorded separately by root diameter (size) class. Medium (2 to 5 mm) and coarse (>5 mm) root intercepts were counted within the entire area of each 100 cm^2 frame. Fine (<2 mm) root intercepts were counted within a 1 cm^2 sub-frame superimposed 5 cm beneath the top-left corner of each 100 cm^2 frame. Mean root intercepts by size class were calculated from the three horizontal measurements at each depth.

Table 1. EC and SAR class combinations for unweathered minesoils†

Minesoil Class	EC ($dS\ m^{-1}$)	SAR ($mmol^{1/2}\ L^{-1/2}$)
1	0-4	0-15
2	0-4	15-25
3	0-4	25-40
4	0-4	>40
5	4-8	0-15
6	4-8	15-25
7	4-8	25-40
8	4-8	>40
9	8-16	15-25
10	8-16	25-40
11	8-16	>40

† No sites were found with EC 8-16 $dS\ m^{-1}$ and SAR < 15 $mmol^{1/2}\ L^{-1/2}$

Weathered Minesoils

Subsequent to root measurements, coversoil and weathered minesoil samples were collected from the top and bottom halves of coversoil and the 0 to 5, 5 to 15, 15 to 30, 30 to 60, and 60 to 90 cm depth intervals of minesoil. Separate coversoil and minesoil samples were collected under each plant species where root density measurements were recorded. All 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 Or, 2002) and saturated paste extracts were prepared using the method proposed by Rhoades (1996). Extracts were analyzed for pH, EC, alkalinity, soluble Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, and NO_3^-. Since the sampling intervals of unweathered and weathered minesoils differed to the 30 cm depth, the results for 0 to 30 cm of unweathered minesoil were used singularly to compare to individual 0 to 5, 5 to 15, and 15 to 30 cm depth intervals in the weathered minesoils.

Statistical Analysis

Statistical comparisons of baseline and 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 (Statistical Analysis System, 1998). Comparison of various levels of weathered soils with corresponding baseline soils were performed with paired t-tests (Snedecor and Cochran, 1967). The MEANS procedure of SAS was used for those calculations (Statistical Analysis System, 1998).

Root intercept analyses of variances were conducted separately for each depth by root size-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).

Correlations were conducted using the Pearson correlation coefficient (Snedecor and Cochran, 1967). Regressions were conducted using both simple linear models and multiple linear models; both types of regressions were conducted using standard ordinary least squares techniques (Weisberg, 1980). The CORR and REG procedures of SAS were used for these computations (Statistical Analysis System, 1998). Normality of residuals was assessed using the UNIVARIATE procedure (Statistical Analysis System, 1998). Equality of variances, as well as 'correctness' of the linear models, were qualitatively assessed using the PLOT procedure (Statistical Analysis System, 1998).

Results and Discussion

Minesoil Weathering

The minesoils in this study represent 11 EC-SAR classes based on unweathered minesoil chemistry (Table 1). The primary purpose of EC-SAR classes was to evaluate interactions between EC and SAR level on weathering chemistry. Development of EC-SAR classes was loosely based on common EC and SAR suitability standards for root-zone (minesoil) materials in southwestern coal mines and USDA soil salinity classes (Soil Survey Division Staff, 1993). Minesoils were reclaimed (i.e., coversoil placement and revegetated) for 6 to 14 yr prior to resampling. Using EC-SAR classes simplified the evaluation of weathering characteristics by placing defined bounds on the continuous variables, EC and SAR, to allow statistical replication. Class 2 and 4 minesoils were limited to 3 and 2 replications, respectively due to limited site availability. An additional replication was substituted in Class 11.

Unweathered minesoils represented a broad range of salinity and sodicity levels with mean EC ranging from 2.23 to 12.1 dS m^{-1} and SAR ranging from 3.05 to 54.9 $mmol^{1/2}$ $L^{-1/2}$ (Table 2). Minesoils used in this study were reclaimed with 15 to 45 cm of coversoil. The following results reference the zero (0) cm depth of minesoil as the interface between coversoil and minesoil materials.

Comparisons between 42 unweathered and weathered minesoils, without regard to EC-SAR Class, show significant reduction of SAR at all depths and significant EC increases in the 5 to 90 cm zone over the 6 to 14 year weathering period (Table 2). In the 0 to 5 cm increment, EC increased slightly by 0.62 dS m^{-1} and SAR was reduced by 7.40 $mmol^{1/2}$ $L^{-1/2}$. Below 5 cm, EC increased by 1.89 to 2.81 dS m^{-1} and SAR was decreased by 2.10 to 5.20 $mmol^{1/2}$ $L^{-1/2}$. These trends indicate an apparent improvement in minesoil stability with weathering, though at the expense of increased salinity. Numerous studies have shown that an increase in EC at a given SAR can reduce the risk of 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; Aringhieri and Giachetti, 2001; Quirk, 2001).

Sample sizes among classes were uneven and limited to between 2 and 5 replications; thus, while statistical differentiation was not provided in some cases, the observed trends in weathering warrant further discussion. Salinity changes of minesoils with the lowest initial EC (0 to 4 dS m^{-1}) (Classes 1, 2, 3, and 4) were related to initial SAR level (Table 2). The EC of Class 1 (SAR <15 $mmol^{1/2}$ $L^{-1/2}$) minesoils decreased 2.28 dS m^{-1} at the 0 to 5 cm depth. Conversely, EC of Class 2 (SAR 15 to 25 $mmol^{1/2}$ $L^{-1/2}$), 3 (SAR 25 to 40 $mmol^{1/2}$ $L^{-1/2}$), and 4 (SAR >40 $mmol^{1/2}$ $L^{-1/2}$) minesoils increased by 3.74, 2.10, and 4.13 dS m^{-1}, respectively. Corresponding reductions in SAR at the 0 to 5 cm depth were 0.14, 8.90, 10.1, and 19.8 $mmol^{1/2}$ $L^{-1/2}$ for Class 1, 2, 3, and 4 minesoils, respectively. In most cases the weathering trend for Class 1, 2, 3, and 4 minesoils below 5 cm followed similar relationships as 0 to 5 cm; albeit the magnitude of changes were dampened with depth. For the first three depth intervals of weathered minesoils, this analysis assumed that baseline EC and SAR values were uniform from 0 to 30 cm depth.

The EC 4 to 8 dS m^{-1} Classed minesoils (i.e., 5, 6, 7, and 8) followed a similar weathering trajectory with respect to salinity where EC increases were apparently related to SAR level. The EC of Class 5 (SAR <15 $mmol^{1/2}$ $L^{-1/2}$) minesoils decreased nearly 0.99 dS m^{-1} at the 0 to 5 cm depth while EC of Class 6 (SAR 15 to 25 $mmol^{1/2}$ $L^{-1/2}$), 7 (SAR 25 to 40 $mmol^{1/2}$ $L^{-1/2}$), and 8 (SAR >40 $mmol^{1/2}$ $L^{-1/2}$) minesoils increased by 0.36, 3.21, and 7.02 dS m^{-1}, respectively. The SAR level of weathered materials was not significantly altered in all but Class 8 minesoils where SAR was reduced between 12.8 and 19.4 $mmol^{1/2}$ $L^{-1/2}$ across all depths.

Table 2. Mean EC and SAR of minesoils before and after weathering (6 to 14 yr) separated by EC-SAR class and depth.

			Non Weathered Minesoils					Weathered Minesoils				
			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†

‡ EC and SAR ranges for each class defined in Table 1.
* 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.

Weathering patterns of minesoils within the high (8 to 16 dS m^{-1}) EC classes were slightly different than the less saline materials, with apparent reductions of both EC and SAR within the 0 to 30 cm zone of Class 9 (SAR 15 to 25 $mmol^{1/2} L^{-1/2}$) and Class 10 (SAR 25 to 40 $mmol^{1/2} L^{-1/2}$) minesoils. Both EC and SAR of weathered Class 9 and 10 minesoils were essentially unchanged from initial unweathered levels below the 30 cm depth. The EC of Class 11 (SAR >40 $mmol^{1/2} L^{-1/2}$) minesoils increased across all depths and SAR was lower at all depths. Again, while overall weathering trends were clear they are not always statistically significant for class-to-class comparisons. Complicating variables among classes included irregular coversoil depths, number of replications, and variable weathering periods.

Increased EC apparently resulted from hydrolysis of exchangeable cations, dissolution of silicate minerals, and limited leaching of soluble ions. Rhoades et al. (1968) demonstrated a significant contribution of soluble ions (e.g., Ca^{2+} and Mg^{2+}) to the soil solution from primary mineral weathering and/or $CaCO_3$ dissolution; and divalent ion release increased with increasing

SAR. Oster and Shainberg (1979), Shainberg et al. (1981), Suarez and Frenkel (1981), Frenkel et al. (1983), and Aringhieri and Giachetti (2001) also concluded that total amount of electrolytes from weathering processes increased as the amount of exchangeable Na^+ increased. We found similar results with respect to the difference in Ca^{2+} + Mg^{2+} concentrations between weathered and unweathered minesoils (Fig. 1). Changes in Ca^{+2} + Mg^{+2} were associated with higher SAR and lower EC levels in unweathered minesoils. The apparent suppression of Ca^{2+} and Mg^{2+} release in the concentrated minesoil solutions (i.e., higher EC) was likely due to a reduction in hydrolysis of exchangeable cations and/or mineral solubility. Cation increases may have also resulted from translocation through coversoils.

In arid areas, with 20 to 25 cm of annual precipitation, salt migration and soil development are expected to be limited, as demonstrated by the shallow saline soils developing from Fruitland Formation shales in the study area (Sandoval and Gould, 1978). A laboratory study conducted by Musslewhite et al. (2005) revealed that coversoil materials from the study area contributed Ca^{2+} and Mg^{2+} to leachates during simulated weathering. Under field conditions, products from coversoil weathering can be translocated into minesoils; increasing salinity and physical stability.

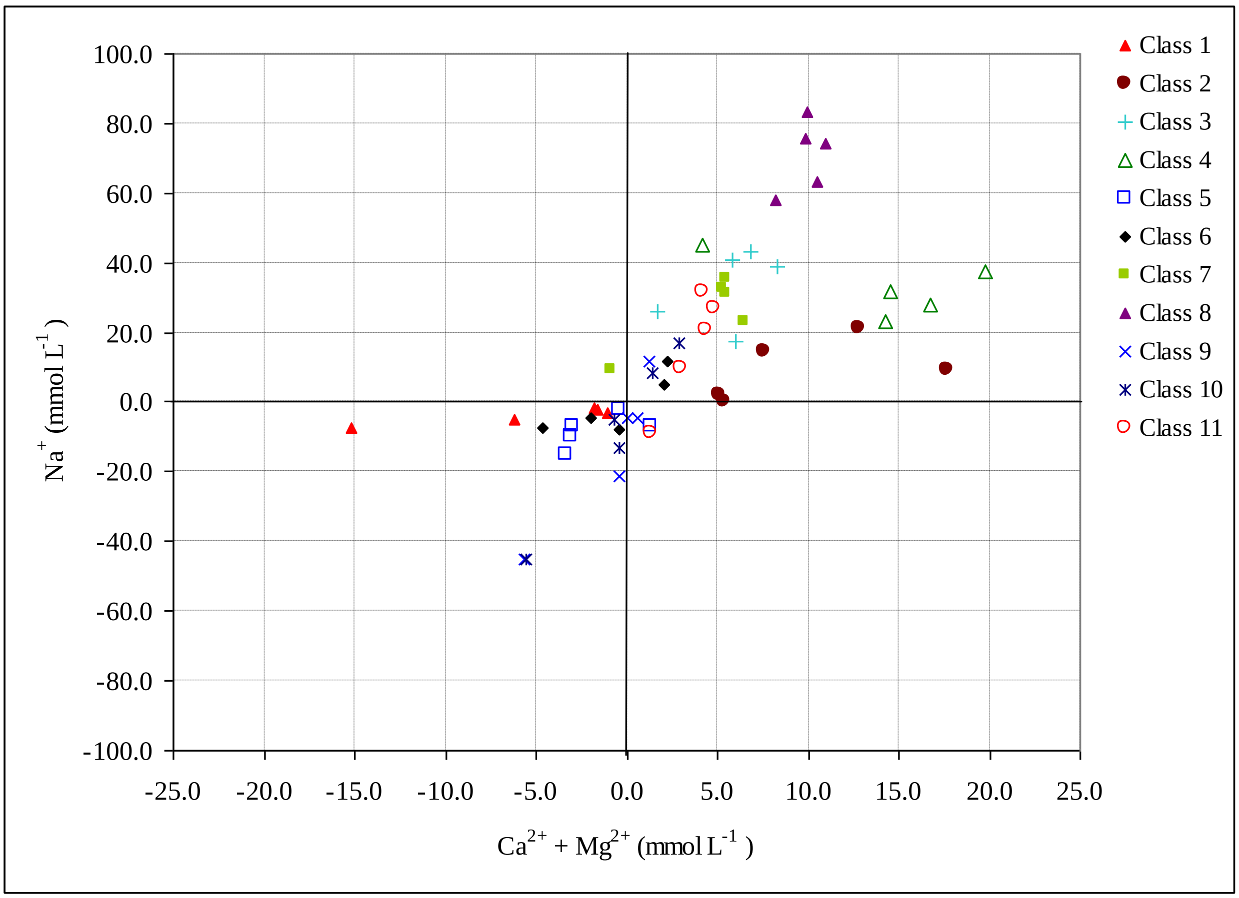

Figure 1. Changes in Na^+ and Ca^{2+} + Mg^{2+} with weathering in minesoils. See Table 1 for a description of the different minesoil classes.

Reduction of SAR in minesoils with initial SAR <25 mmol$^{1/2}$ L$^{-1/2}$, except for Class 2, resulted from Na^+ depletion (Fig. 1). Conversely, reduction of SAR in minesoils with initial SAR >25 mmol$^{1/2}$ L$^{-1/2}$ largely occurred from increased Ca^{2+} and Mg^{2+} relative to Na^+ in the soil solution. The increased Ca^{2+} and Mg^{2+} can result from dissolution of $CaCO_3$, $CaSO_4 \bullet 2H_2O$, Ca- and Mg-silicates, and from hydrolysis of exchangeable cations. Hall and Berg (1983) showed significant (22%) reduction in SAR of sodic minesoils after 224 days of simulated weathering. This reduction was largely due to increased soluble Ca^{2+} that was attributed to the dissolution of $CaCO_3$, delamination of Ca-tactoids, and, for two samples, dissolution of $CaSO_4 \bullet 2H_2O$. 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 at the 0 to 6.4 and 6.4 to 12.7 cm minesoil depths were reduced from 38 $mmol^{1/2}$ $L^{-1/2}$ 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 saline and sodic minesoils.

The threshold electrolyte concentration concept originally proposed by Quirk and Schofield (1955), the relationships developed by McNeal and Coleman (1966) for the Waukena and Oasis soil types, and the classification system proposed by Rengasamy et al. (1984) involving SAR and total cation concentration of 1:5 soil:water extracts are illustrated on Fig. 2 along with mean EC and SAR for the 11 Classes of unweathered minesoils (across all depths) from this study. Using these established threshold relationships, Class 3, 4, and 8 unweathered minesoils had the greatest susceptibility to reduced *K* with Class 4 minesoils representing the greatest Na^+ hazard.

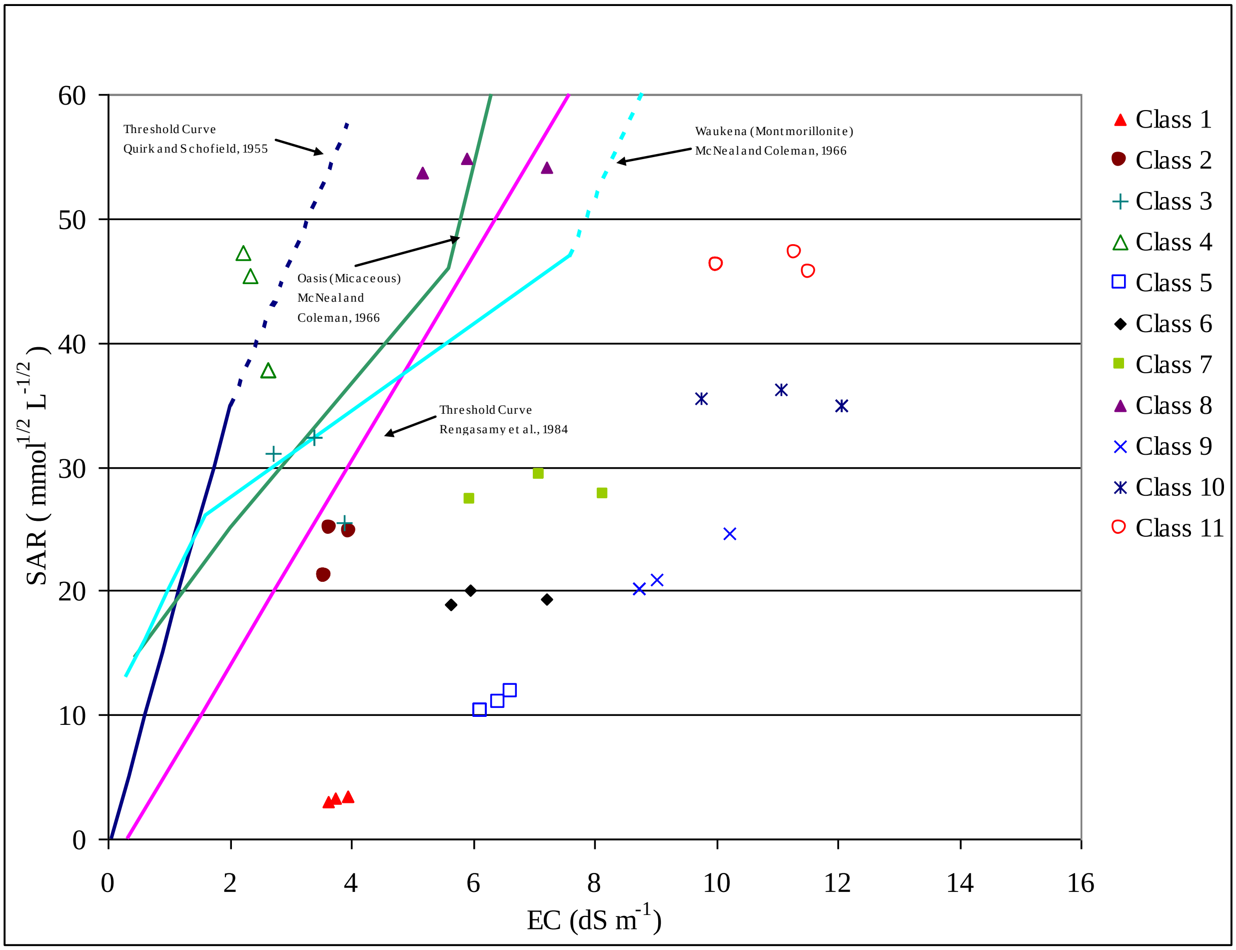

Figure 2. Mean EC and SAR of unweathered minesoils and threshold relationships from Quirk and Schofield (1955), McNeal and Coleman (1966), and Rengasamy et al. (1984). See Table 1 for a description of the different minesoil classes.

In Figure 3, all EC and SAR combinations of weathered minesoils are located to the right of threshold relationships (i.e., in the stable or minor reduction in permeability region of the chart). The Class 4 unweathered minesoils had the greatest initial risk of physical degradation; however, 6 to 14 yr of weathering resulted in a 13 to 20 mmol$^{1/2}$ L$^{-1/2}$ SAR reduction and 4.0 to 6.0 dS m^{-1} salinity increase. Minesoils that had greatest initial risk of physical degradation also had the greatest changes in EC and SAR with 6 to 14 yr of weathering. Overall, weathering proceeded to a state of improved physical stability for all minesoils. However, increased salinity can adversely affect vegetation productivity, particularly if salt sensitive plants are used for reclamation of saline minesoils.

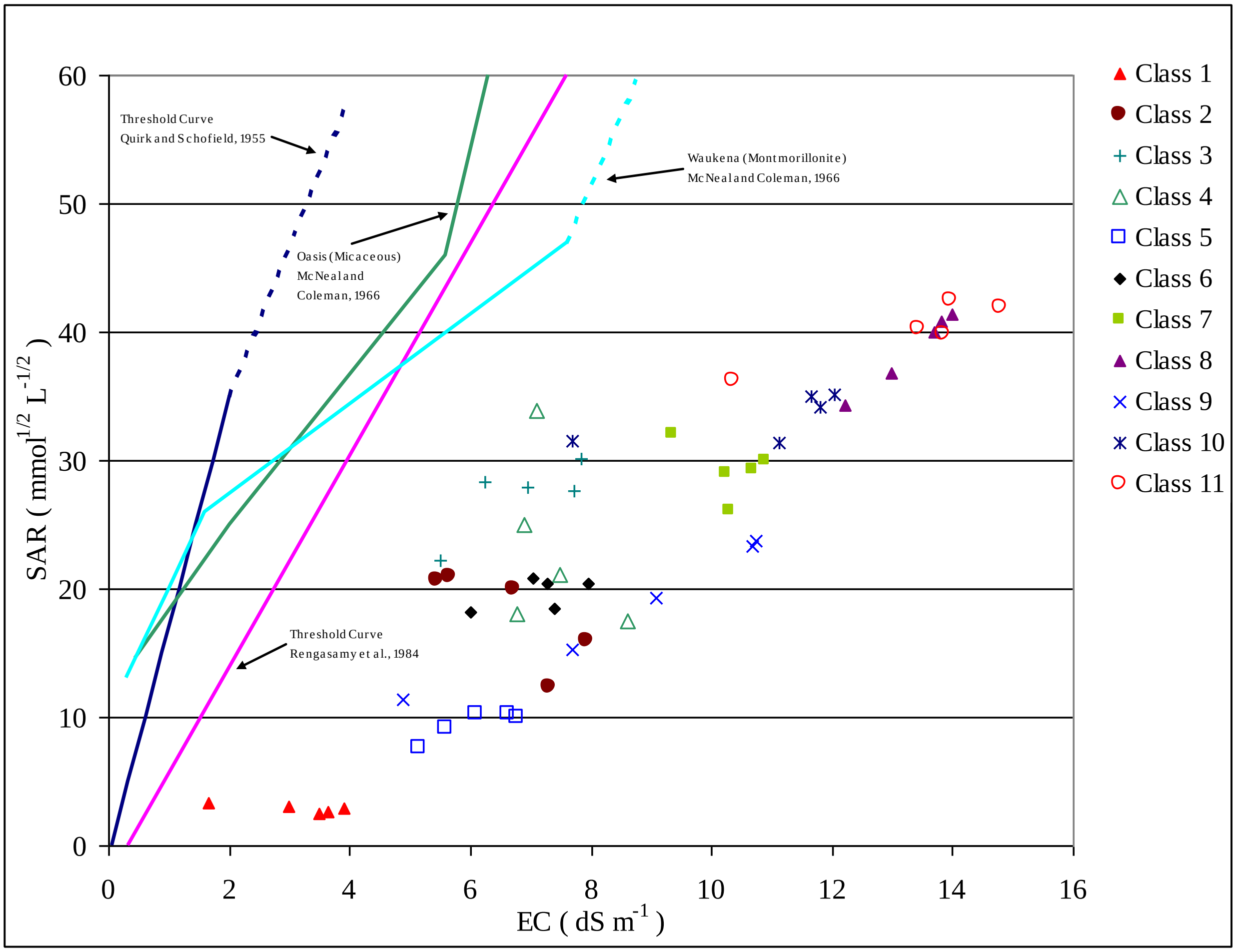

Figure 3. Mean EC and SAR of weathered minesoils and threshold relationships from Quirk and Schofield (1955), McNeal and Coleman (1966), and Rengasamy et al. (1984). See Table 1 for a description of the different minesoil classes.

<u>Rooting Characteristics of Reclaimed Plants</u>

Analysis of rooting characteristics showed very few statistically significant differences between EC-SAR Classes, irrespective of plant growth form (shrub or grass) or root size-class. Of the 60 combinations of root-size class/plant growth form/rooting depth that were tested, only 4 comparisons showed an effect of EC-SAR Class in means comparisons. These relationships were sometimes counter-intuitive, where rooting at a particular depth was more dense with higher salinity and/or SAR values. Linear models were significant in 17 cases, but these were associated with weak predictive quality (maximum r^2 of 0.16). Adding coversoil depth as a second independent variable (with SAR or EC) provided modest improvement to 12 of the models (maximum r^2 of 0.30). Although the overall predictive value of these models was low, the results followed our hypothesis that root density would be inversely related to coversoil depth and EC or SAR.

Generally, the variability of observed rooting density was not adequately captured by the parameters measured in this study. For example, we occasionally observed that rooting at depth was limited by abrupt textural changes, where a sandy textured coversoil was in contact with a (dense) clayey minesoil. The variability of minesoil texture in the fine-earth (moderately fine to clayey) and coarse fractions (gravelly to extremely stony), and associated properties of moisture availability and soil strength, varied widely within and among EC-SAR Classes. Where coversoil was relatively deep, the top-most measurement of rooting, from 0 to 10 cm above the coversoil-minesoil contact, was often well removed from the highest concentration of fine-sized shrub or grass roots. In addition, the sample size for fine roots, 1 cm^2 per 100 cm^2 area of a counting square, although recommended by Schoeneberger et al. (2002), was probably inadequate to capture representative rooting for this size class of roots. Finally, the age or size class of measured plants and the influence of nearby, non-target plants could not be controlled with the restrictions of pit placement and the availability of both plant forms in close proximity. We can not conclude from the ANOVA that either salinity or sodicity, by themselves or in combination, are significant factors for root-density of fourwing saltbush, atriplex canescens, or Russian wildrye. Multiple linear regressions show significant relationships between root density and coversoil depth and EC or SAR. However, these relationships do not provide adequate information due to small variations in the overall responses, thus suggesting that these models lack the power to be used for predictive purposes.

Conclusions

The SARs of minesoils studied were reduced after weathering under field conditions. The mechanism for SAR reduction can largely be separated between minesoils with initial SAR <25 $mmol^{1/2}\ L^{-1/2}$ and SAR >25 $mmol^{1/2}\ L^{-1/2}$. The minesoils with low SARs (<25 $mmol^{1/2}\ L^{-1/2}$) were reduced primarily from leaching of Na^+. This process is similar to minesoils subjected to accelerated weathering (Musslewhite et al., 2005). It is unclear if lower initial SAR levels allow for deeper percolation of water and hence leaching of Na^+ or if possible differences in mineralogy affect Na^+ movement. The process of SAR reduction in minesoils with elevated SAR levels (>25 $mmol^{1/2}\ L^{-1/2}$) is an increase in soluble Ca^{+2} and Mg^{+2} from apparent dissolution of $CaSO_4 \bullet 2H_2O$, $CaCO_3$, and silicate minerals; hydrolysis of exchangeable cations; and/or translocation from coversoils. Release of Ca^{+2} and Mg^{+2} is related to unweathered EC and SAR level. Minesoils that are conceptualized to be the most unsuitable because of elevated SAR and low EC have the greatest release of soluble cations from weathering and hence the largest reductions in SAR and increases in EC. The cation release mechanism is moderated by low SAR or high EC in unweathered minesoils. Thus, both initial EC and SAR are required to project minesoil chemistry after extended weathering.

Translocation of salts is limited by the 20 to 25 cm of annual precipitation on the reclamation areas evaluated in this study. The apparent Na^+ induced weathering and limited leaching of soluble ions increases minesoil salinity. These salinity increases have both positive and detrimental effects on the overall suitability. Increased salinity imparts greater physical stability at a given level of SAR, which is apparent from the relationships presented in Figures 2 and 3. However, salinity can negatively affect vegetative production and associated root density due to osmotic induced stress. We can not conclude from the ANOVA that either salinity or sodicity, by themselves or in combination, are significant factors for root-density of fourwing saltbush, atriplex canescens, or Russian wildrye. Multiple linear regressions show significant relationships between root density and coversoil depth and EC or SAR. However, the slopes of these relationships are relatively flat indicating that other variables may be equally important in determining root densities. These models are considered to be descriptive and lack the power to be used for predictive purposes. We believe that the power of the descriptive models could be improved by including other important variables such as minesoil bulk density, age of plants, and control on proximity of target to non-target plants.

Regional minesoil suitability guidelines classify materials with EC >12 or >16 dS m^{-1}, depending on the guideline, as unsuitable. In this study, weathered minesoils, with the exception of Class 8, 11, and the 60 to 90 cm depth of Class 10 (EC = 12.1 dS m^{-1}) have EC <12 dS m^{-1}, and none of the weathered EC levels exceed the higher 16 dS m^{-1} limit. The results from this study show that minesoil chemistry changes overtime and that salinity is an important factor in determining the physical stability of sodic minesoils. Minesoils that are initially conceptualized as being unsuitable with respect to SAR will often have weathered SAR values below suitability guidelines at the time of bond release (i.e., after10 yr of weathering).

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