SPOIL QUALITY EFFECTS ON VEGETATION ESTABLISHMENT AND SPECIES COMPOSITION FOLLOWING RECLAMATION OF MINED LANDS IN ARID NEW MEXICO[1]

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Abstract: In 1992 at the Navajo Mine in New Mexico, reclamation was completed in an area that had been topsoiled and where there was a wide range in measured EC and SAR values of the underlying spoil at the time of seed planting. The objective of this study was to examine the influence of spoil EC and SAR on subsequent vegetation establishment and species composition. In September 2008, vegetation cover and production were measured at 40 locations with spoil EC and SAR values that met current (2008) root-zone suitability criteria at the time of planting (suitable spoil) and 40 locations that did not meet the current criteria (unsuitable spoil). Results indicate that most vegetation parameters were not significantly different between suitable and unsuitable spoil. Galleta grass cover was higher in suitable (4.2±0.8%) than unsuitable (2.2±0.6%) spoil. Conversely, fourwing saltbush cover was higher in unsuitable (3.3±0.9%) than in suitable (1.0±0.3%) spoil. Shrub cover was higher in unsuitable than suitable spoil (3.7±1.0% and 1.0±0.3%, respectively) while annual forb cover (excluding weedy species) was higher in suitable than unsuitable spoil (1.7±0.2% and 1.0±0.2%, respectively). There were no significant differences between suitable and unsuitable suitable spoil in cover of 5 of the 7 most common species, total vegetation cover, vegetation production, or shrub density. Regression models were developed to correlate vegetation properties with spoil characteristics. None of the spoil characteristics included in the models consistently influenced vegetation cover or production. Results of the study indicate that EC and SAR values in suitable and unsuitable spoil had little influence on overall revegetation success, although spoil properties may have had a limited effect on species composition by affecting the relative proportion of shrub and herbaceous species.

Additional Key Words: coal mine reclamation, electrical conductivity, sodium adsorption ratio, revegetation, *Atriplex canescens*, *Pleuraphis jamesii*.

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Introduction

Since 1963, BHP Navajo Coal Company (BNCC) has conducted surface coal mining operations at Navajo Mine in San Juan County, approximately 40 miles southwest of Farmington, NM. Coal extraction was initiated in the northern portion of the mine lease, designated as the Watson and Bitsui areas, and moved progressively south. An active reclamation program has been an important component of overall coal mining operations to enhance environmental conditions following mining activities and restore disturbed areas to pre-mine land use, particularly grazing.

With enactment of the Surface Mining Control and Reclamation Act of 1977 (SMCRA), standards were established to enhance reclamation success on mined lands that included criteria for suitable root zone material in reclaimed areas. At Navajo Mine, root zone suitability criteria were developed that specify soil/spoil within four feet of the surface cannot have electrical conductivity (EC) values exceeding 16 deciSiemens per meter (dS m^{-1}) or sodium adsorption ratios (SAR, comparative measure of Na^{+}, Ca^{2+}, and Mg^{2+} ions in soil solution) above 18 unless EC is greater than 4 dS m^{-1}, in which case SAR can be up to 40 (BHP Navajo Coal Company, 2004). However, past research indicates that plant species native to the Navajo Mine area that were used in revegetation seeding mixes at the site can tolerate EC and SAR values outside the established thresholds (Hodgkinson, 1987; Lair, 2006; McFarland et al., 1987). Consequently, it is uncertain whether mitigation of spoil material that does not meet current EC and SAR standards is necessary to achieve revegetation success at Navajo Mine.

Since coal extraction in the Watson and Bitsui areas of Navajo Mine was completed in the 1960s, reclamation was not subject to SMCRA standards. Initial revegetation was attempted in the 1970s by planting directly into the spoil. This initial effort was less effective than desired, and in 1992 the spoil was covered with stockpiled topsoil and replanted with a species mix that included alkali sacaton (*Sporobolus airoides*), blue grama (*Bouteloua gracilis*), James' galleta grass (*Pleuraphis jamesii*), giant dropseed (*Sporobolus giganteus*), Indian ricegrass (*Achnatherum hymenoides*), sand dropseed (*Sporobolus cryptandrus*), western wheatgrass (*Pascopyrum smithii*), fourwing saltbush (*Atriplex canescens*), Mormon tea (*Ephedra viridis*), rabbitbrush (*Chrysothamnus* spp.), shadscale (*Atriplex confertifolia*), winterfat (*Krascheninnikovia lanata*), prairie aster (*Aster tancetifolius*), blue flax (*Linum lewisii*), globemallow (*Sphaeralcea* spp.), and Rocky Mountain penstemon (*Penstemon strictus*). At the same time, 330 spoil samples were collected in a grid pattern (100 m distance between samples) throughout approximately 850 acres of Watson and Bitsui areas to characterize spoil characteristics. These samples exhibited a wide range in spoil properties, and many samples did not meet the root zone suitability criteria that are currently applied to spoil parameters at Navajo Mine, particularly EC and SAR.

The primary objective of this study was to investigate the influence of spoil EC and SAR on vegetation properties. This would enable an evaluation of root zone suitability criteria for EC and SAR to determine whether current thresholds at Navajo Mine are appropriate or should be modified. Due to the influence of EC and SAR on plant establishment (Hodgkinson, 1987; Moore et al., 1991; Ogle et al., 2004), developing appropriate EC and SAR guidelines is critical to ensure reclamation efforts are effective and maximize the probability of revegetation success.

Methods

Site

The study site is located in the northern portion of Navajo Mine, which is in San Juan County, NM approximately 40 miles southwest of Farmington, NM. According to records from the National Climatic Data Center from 1938 to 1996 (World Climate, 2009), average annual precipitation in the area is 20cm. The average maximum daily temperature ranges from 33.5ºC in July to 5.2ºC in January, and the average minimum daily temperature ranges from 13.4ºC in July to -9.0ºC in January.

Sampling

Spoil samples were collected at four depths (0–30cm, 30–60cm, 60–90cm, and 90–120cm) from 330 points in 1992, which was the year the area was seeded. Spoil samples were analyzed for several physical and chemical properties, including SAR (Rhoades, 1982), EC (Rhoades, 1982), acid-base potential (Sobek et al. 1978), texture (Day, 1965), pH (McLean, 1982), saturation percent (Richards, 1954), and volumetric percent coarse fragments. Sample sites were classified as suitable or unsuitable based upon these analyses. Suitable spoil had EC values less than 16 dS m^{-1} and SAR values less than 18 (BHP Navajo Coal Company, 2004). However, interactive effects between EC and SAR influence soil/spoil physical stability (Musslewhite, 2006). Therefore, spoil was also considered suitable if EC was greater than 4 dS m^{-1} and SAR was less than 40 (BHP Navajo Coal Company, 2004). Additionally, suitable spoil had pH between 5 and 9, acid-base potential greater than -5 Mg $CaCO_3$ per 1000 Mg spoil, less than 50% clay content, and saturation percent less than 85 unless EC was greater than 4 dS m^{-1}, in which case saturation percent was less than 100. In order for a site to be classified as suitable, the spoil had to meet these criteria at all four sampling depths in the top 1.2m of spoil. Since we expected spoil quality effects on vegetation establishment to diminish with depth, unsuitable spoil was classified based on characteristics of only the top 0.6m of spoil. Of the 330 spoil sampling locations, 53 sites met root zone suitability criteria throughout the top 1.2m of spoil and were designated suitable sites, while 70 sites were designated unsuitable based on EC and SAR values in the top 0.6m of spoil.

Vegetation data collection was conducted at the end of the growing season during September 2008 to ensure all annual growth was included in production measurements. Sampling methodology for vegetation parameters followed protocol formerly established for the site (Buchanan Consultants, Ltd., 1993). Forty vegetation sampling sites were randomly selected from both the 53 suitable and 70 unsuitable sites. Geospatial coordinates of the spoil sample points were initially recorded in a 1992 survey of the area, and in 2008 a GPS was used to locate selected points for vegetation sampling. At each of these sampling points, data were collected from five 10m transects radiating from a central spoil sampling point with a 1m gap between the spoil sampling point and the start of each transect (Buchanan Consultants, Ltd., 1993). A magnetic compass was used to orient transects at 0° (magnetic north), 72°, 144°, 216°, and 288°. Plant, rock, and litter cover were measured along each 10m transect using the line-intercept method (Elzinga et al., 1998). Density of shrubs was measured by counting shrub bases within 1 m of both sides of each transect. At each sampling point, a random number generator was used in the field to select one transect to measure current year production. Annual grasses, perennial grasses, perennial forbs, and shrubs were clipped within an area 10 cm wide and 10 m long adjacent to the selected transect. Clipping was consistently conducted on the same side of the transects. Due to logistical constraints, annual forbs were not clipped, and production of perennial forbs was too low to enable statistical analyses. Vegetation clippings were oven-dried so that production values could be compared on a dry-weight basis. At each sampling point topsoil depth was estimated by randomly selecting two transects, measuring depth to spoil at the mid-point of both transects, and averaging the two depths.

Statistical Analysis

Data were analyzed with Minitab (Minitab Inc., 2007) statistical analysis software. Probability plots were used to determine normality of cover and production data, and most data did not exhibit a normal distribution. Consequently, a non-parametric method was required and data were analyzed using Kruskal-Wallis methodology. Stepwise regression analyses were conducted to correlate vegetation properties with spoil parameters. An alpha level of 0.10 was used to determine forward inclusion and backward removal of spoil parameters in the regression model. In this text, data averages are presented ± 1 standard error and statistical significance refers to a p-value less than 0.05.

Results

Physicochemical properties of suitable and unsuitable spoil are summarized in Table 1. In the top 30 cm, pH was significantly higher in unsuitable than suitable spoil, but from 30 to 120 cm there were no significant differences in pH. Electrical conductivity, saturation percent, and SAR were significantly higher in unsuitable spoil, while total sulfur acid-base potential was higher in suitable spoil for all four-depth increments. Spoil texture (sand, silt, and clay), coarse fragments, and topsoil depth were not significantly different between suitable and unsuitable spoil for any of the depth increments.

There were no statistically significant differences between suitable and unsuitable spoil for total vegetation cover, bare ground, or rock cover. Combining data from suitable and unsuitable spoil, total vegetation cover was 13.6±0.9%, bare ground was 64.8±1.4%, and rock cover was 2.8±0.6%. Litter was significantly greater on suitable (20.5±1.1%) than unsuitable spoil (17.2±1.2%).

The sample size of 7 plant species was sufficiently large to enable comparisons between suitable and unsuitable spoil (Table 2): James' galleta grass, alkali sacaton, cheatgrass (*Bromus tectorum*), flatspine stickseed (*Lappula occidentalis*), Russian thistle (*Salsola tragus*), woolly plantain (*Plantago patagonica*), and fourwing saltbush. Cover of fourwing saltbush was significantly greater on unsuitable than suitable spoil, and cover of James' galleta grass was greater on suitable than unsuitable spoil (Table 2). The cover of other species was not significantly affected by spoil suitability.

Table 1. Physicochemical properties of suitable and unsuitable spoil from 1992 spoil sampling.

Spoil Property	Depth (cm)	Suitable Spoil	Unsuitable Spoil
pH	0-30	7.4±0.1 a[†]	7.7±0.1 b
	30-60	7.3±0.1 a	7.4±0.2 a
	60-90	7.2±0.1 a	7.4±0.2 a
	90-120	7.3±0.1 a	7.3±0.2 a
EC (dS m^{-1})	0-30	7.3±0.6 a	10.3±0.8 b
	30-60	8.2±0.5 a	12.3±1.1 b
	60-90	8.5±0.5 a	11.4±1.1 b
	90-120	8.3±0.5 a	14.3±2.3 b
Saturation Percent	0-30	54.7±2.1 a	84.7±4.6 b
	30-60	55.0±2.3 a	86.5±5.4 b
	60-90	52.7±2.3 a	86.0±5.5 b
	90-120	52.2±2.5 a	81.5±5.2 b
SAR	0-30	17.3±1.9 a	39.4±1.8 b
	30-60	19.1±1.8 a	43.4±1.7 b
	60-90	18.6±1.7 a	38.2±1.8 b
	90-120	18.1±1.7 a	45.4±6.8 b
Coarse Fragments (%)	0-30	38.1±3.3 a	43.0±11.4 a
	30-60	46.3±4.2 a	56.3±7.2 a
	60-90	40.1±5.0 a	49.8±7.0 a
	90-120	40.4±6.5 a	57.7±2.1 a
Sand (%)	0-30	40.0±1.9 a	38.8±1.97 a
	30-60	42.0±2.4 a	38.9±1.9 a
	60-90	44.8±2.4 a	39.6±2.0 a
	90-120	44.3±2.7 a	40.5±2.1 a
Silt (%)	0-30	31.5±1.1 a	32.5±1.2 a
	30-60	30.1±1.4 a	31.9±1.3 a
	60-90	28.9±1.4 a	31.1±1.1 a
	90-120	29.4±1.5 a	30.9±1.2 a
Clay (%)	0-30	28.6±1.0 a	28.7±1.1 a
	30-60	27.9±1.4 a	29.2±1.1 a
	60-90	26.3±1.4 a	29.3±1.2 a
	90-120	26.3±1.5 a	28.6±1.2 a
Acid-Base Potential (Mg $CaCO_3$ per 1000 Mg)	0-30	51.7±6.1 a	29.6±10.2 b
	30-60	49.4±9.4 a	6.0±13.7 b
	60-90	44.5±8.6 a	7.5±12.5 b
	90-120	48.6±9.9 a	4.6±17.1 b
Topsoil Depth	N/A	10.0±1.2 a	8.2±0.7 a

[†] Within a row, values followed by the same letter are not significantly different at *p* = 0.05 level.

Table 2. Comparison of plant species cover on suitable and unsuitable spoil.

Species	Suitable Spoil	Unsuitable Spoil
James' galleta grass	4.2±0.8% a†	2.2±0.6% b
Alkali sacaton	3.8±0.8% a	3.8±0.6% a
Cheatgrass	0.8±0.3% a	0.8±0.2% a
Flatspine stickseed	0.4±0.1% a	0.2±0.1% a
Woolly plantain	0.4±0.1% a	0.4±0.1% a
Russian thistle	1.2±0.2% a	1.2±0.3% a
Fourwing Saltbush	1.0±0.3% a	3.3±0.9% b

† Within a species row, values followed by the same letter are not significantly different at $p = 0.05$ level.

Since many species were present at levels too low for direct comparisons between suitable and unsuitable spoil, all species were separated into five functional groups to enable statistical analyses incorporating all species. Functional groups included annual grasses, annual forbs, perennial grasses, perennial forbs, and shrubs. The annual grasses, annual forbs, and shrubs functional groups included several species that are commonly considered weeds (Whitson et al., 2002), including cheatgrass, Russian thistle, halogeton (*Halogeton glomeratus*), broom snakeweed (*Gutierrezia sarothrae*), and saltcedar (*Tamarix ramosissima*). Therefore, these functional groups were analyzed with and without weedy species so inferences could be made regarding establishment of desirable plant species (Table 3).

Table 3. Comparison of plant cover by functional group on suitable and unsuitable spoil.

Functional Group	Suitable Spoil	Unsuitable Spoil
Annual Grasses	1.2±0.3% a†	1.5±0.4% a
Annual Grasses excluding Weedy Species	0.5±0.2% a	0.2±0.3% a
Perennial Grasses	8.1±1.0% a	6.2±0.8% a
Annual Forbs	3.0±0.3% a	2.7±0.4% a
Annual Forbs excluding Weedy Species	1.7±0.2% a	1.0±0.2% b
Perennial Forbs	0.03±0.03% a	0%
Shrubs	1.0±0.3% a	3.7±1.0% b
Shrubs excluding Weedy Species	1.0±0.3% a	3.3±0.9% b

† Within a functional group row, values followed by the same letter are not significantly different at $p = 0.05$ level.

When weedy species were included in the analysis, shrub cover was significantly greater on unsuitable spoil, but other functional groups were not significantly affected by spoil suitability (Table 3). When weedy species were excluded from the analysis, cover of annual forbs was significantly higher on suitable spoil and shrub cover was greater on unsuitable spoil (Table 3).

There were no significant differences in production of annual grasses, perennial grasses, or shrubs on suitable and unsuitable spoil. Similarly, shrub density was not significantly influenced by spoil suitability. Combined production on suitable and unsuitable spoil was 1.0±0.1 kg ha^{-1} for annual grasses, 109±18 kg ha^{-1} for perennial grasses, and 92±30 kg ha^{-1} for shrubs. Combined shrub density on suitable and unsuitable spoil was 99±24 individuals per acre.

Stepwise regression models were developed to correlate spoil characteristics with vegetation properties and identify spoil parameters that may have influenced vegetation cover and production. Parameters included in the analyses were topsoil depth and spoil pH, EC, SAR, clay content, saturation percent, and coarse fragments. These spoil properties were measured at each vegetation sampling point at the time of seeding (1992) at 4 depths (0–30cm, 30–60cm, 60–90cm, and 90–120cm).

Regression models were developed for the 7 most common species recorded at the study site (Table 4). Fourwing saltbush and woolly plantain were not significantly correlated with any of the spoil parameters included in the analysis. There were no spoil parameters that were consistently correlated with species cover, indicating a differential response of each species to spoil conditions. EC at 30-60cm was negatively correlated with cover of alkali sacaton and cheatgrass, and SAR at 30-60cm was positively correlated with cover of alkali sacaton and flatspine stickweed. Other than these 2 spoil parameters, no spoil property was correlated with more than one species. The only spoil depths correlated with species cover were 30–60cm and 60–90cm.

Regression models were developed for each functional group (Table 5). Spoil properties influencing plant establishment varied among functional groups. Acid-base potential was negatively correlated with both annual grasses and annual grasses excluding weeds functional groups, although at different depths (30–60cm and 0–30cm, respectively). Acid-base potential at 60–90cm was negatively correlated with perennial forb cover. Spoil pH was negatively correlated with annual grasses excluding weeds at 0–30cm and perennial forbs at 60–90cm, but was positively correlated with perennial grasses and total vegetation at 0–30cm and 60–90cm, respectively. Clay content was negatively correlated with annual grasses at 30–60cm and negatively correlated with annual forbs and perennial grasses at 90–120cm (Table 5). Shrubs and shrubs excluding weeds were not significantly correlated with any of the spoil parameters included in regression analysis.

Table 4. Regression equations for species cover as influenced by spoil characteristics. Variables are listed in the order in which they entered the model.

Species	Spoil Property And Depth	Value	Adjusted R^2
James' galleta grass	Constant	12.14	0.25
	Saturation Percent 60–90cm	-0.141*	
Alkali sacaton	Constant	-12.76	0.74
	pH 60–90cm	1.9†	
	SAR 30–60cm	0.268**	
	EC 30–60cm	-0.62**	
Cheatgrass	Constant	5.631	0.68
	Clay 30–60cm	-0.099*	
	Acid-Base Potential 30-60cm	-0.023*	
	EC 30–60cm	-0.125†	
Flatspine stickseed	Constant	-0.622	0.46
	SAR 30–60cm	0.0339**	
Woolly plantain	-	-	-
Russian thistle	Constant	-0.2452	0.52
	Saturation Percent 60–90cm	0.081**	
	Coarse Fragments 60–90cm	-0.052†	
Fourwing Saltbush	-	-	-

†, *, **, Statistically significant at the 0.10, 0.05, and 0.01 levels of probability, respectively

Table 5. Regression equations for functional group cover as influenced by spoil characteristics. Variables are listed in the order in which they entered the model.

Functional Group	Spoil Property And Depth	Value	Adjusted R^2
Annual Grasses	Constant	6.415	0.48
	Clay 30–60cm	-0.134*	
	Acid-Base Potential 30–60cm	-0.038*	
Annual Grasses Excluding Weeds	Constant	8.806	0.44
	Acid Base Potential 0–30cm	-0.026†	
	pH 0–30cm	-1.00†	
Perennial Grasses	Constant	-27.06	0.27
	pH 0–30cm	5.4*	
	Clay 90–120cm	-0.22†	
Annual Forbs	Constant	-0.4610	0.69
	Saturation % 60–90cm	0.204**	
	Clay 90–120cm	-0.098*	
	Saturation % 30–60cm	-0.092†	
Annual Forbs Excluding Weeds	Constant	-0.01152	0.34
	SAR 0–30cm	0.40*	
Perennial Forbs	Constant	1.797	0.57
	pH 60–90cm	-0.250*	
	Acid-Base Potential 60-90cm	-0.0444**	
	EC 60-90cm	0.048*	
Shrubs	-	-	-
Shrubs Excluding Weeds	-	-	-
Total Vegetation Cover	Constant	-38.92	0.30
	pH 60–90cm	7.2*	

†, *, **, Statistically significant at the 0.10, 0.05, and 0.01 levels of probability, respectively

Regression analyses were also conducted to investigate the influence of spoil properties on production of annual grasses, perennial grasses, and shrubs. Annual grasses were positively correlated with EC (0–30cm) and negatively correlated with coarse fragments (90–120cm) and clay (90–120cm) (Table 6). Perennial grasses were negatively correlated with saturation percent

(0–30cm) and positively correlated with pH (0–30cm) (Table 6). Shrubs were not significantly correlated with any spoil properties.

Table 6. Regression equations for vegetation production as influenced by spoil characteristics. Variables are listed in the order in which they entered the model.

Functional Group	Spoil Property And Depth	Value	Adjusted R^2
Annual Grasses	Constant	1.372	0.72
	Coarse Fragments 90–120cm	-0.0322**	
	EC 0-30cm	0.096*	
	Clay 90–120cm	-0.026†	
Perennial Grasses	Constant	-75.65	0.51
	Saturation % 0-30cm	-0.44**	
	pH 0-30cm	14.9**	
Shrubs	-	-	-

†, *, **, Statistically significant at the 0.10, 0.05, and 0.01 levels of probability, respectively

Summary

There were significant differences between spoil classified as suitable and unsuitable, including higher EC, SAR, and saturation percent in the unsuitable spoil and higher acid-base potential in the suitable spoil. However, there were few significant differences in vegetation properties between areas with suitable and unsuitable spoil. When comparing cover of the seven most common species, only two were significantly different between suitable and unsuitable spoil. Cover of James' galleta grass was greater on suitable spoil while cover of fourwing saltbush was greater on unsuitable spoil. Vegetation cover was also analyzed by functional group, and cover of annual forbs excluding weedy species was higher on suitable spoil and shrub cover was higher on unsuitable spoil. There were no significant differences in total vegetation cover, bare ground, rock cover, annual grass production, perennial grass production, shrub production, or shrub density between suitable and unsuitable spoil. Litter was significantly greater on suitable spoil. The primary objective of this study was to ascertain whether spoil suitability based on EC and SAR criteria would influence revegetation success. Results indicate that comparable revegetation success can be achieved on spoil classified as suitable or unsuitable, although the relative proportion of shrub and herbaceous species may vary according to suitability.

Regression equations were developed to correlate spoil properties at four depths (0-30cm, 30-60cm, 60-90cm, and 90-120cm) with vegetation cover and production. Shrub, fourwing saltbush, and woolly plantain cover were not significantly correlated with any of the spoil properties included in regression analysis, but cover of other species and functional groups was correlated with one to three spoil properties. There was little consistency in either spoil properties or spoil depths that were significantly correlated with species cover and functional group cover and production, which precludes generalizations about the influence of spoil properties on vegetation properties. Results from regression analysis indicate that vegetation response to spoil quality at various depths is species specific and difficult to predict. Due to the differential response of plant species to spoil characteristics, variability in spoil properties throughout a reclamation area may promote greater diversity.

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