ASSESSMENT OF EFFECTS OF AMENDMENTS ON VEGETATION PERFORMANCE AT A BENTONITE MINESITE AFTER 25 YEARS[1]

D. R. Neuman, P. S. Blicker, J. D. Goering, and R. Pigors[2]

Abstract. In the 1980s a series of experimental plots, 15 treatments with 3 fertilizer rates nested within each treatment and replicated three times, were constructed on abandoned bentonite mine spoils near Belle Fourche, South Dakota, USA. Treatments varied from physical manipulations to additions of chemical and biological amendments. Plots were seeded with mixes of plant species. In 2005, a qualitative assessment of the vegetation status of the experimental reclamation plots was conducted and the following treatments were selected as supporting the "best vegetation": 1) manure at 112 Mg/ha + H_2SO_4 at 20 Mg/ha; 2) gypsum at 6.7 Mg/ha + $CaCl_2$ at 17.2 Mg/ha; and 3) 1.20 Mg/ha of $MgCl_2$ Brine. Quantitatively, mean vegetation cover values for each treatment were not significantly different among the three selected treatments. Mean canopy cover values were 21.1% for spoils treated with gypsum and $CaCl_2$, 24.4% for spoils treated with H_2SO_4 and manure, and 27.3% for spoils amended with a brine of $MgCl_2$. These cover values were markedly lower than those measured in previous years. Community composition did vary significantly ($P < 0.05$) among the treatments. Few of the seeded species were found growing on the experimental plots; other species have colonized the plots, but they contributed little to vegetation cover or biomass. Levels of soil pH across all treatment and depths were very similar (6.78 to 8.04), while electrical conductivity (EC) of spoils (top 20 cm) treated with H_2SO_4 and manure was markedly reduced compared to either the control samples or soils collected from other treated plots. The EC and SAR values for $MgCl_2$ brine-treated spoils have not changed since they were last measured in 1989. Incorporated manure was clearly visible in the soils profile. However, much of the manure had not decomposed since it was added to the spoils 25 years ago. Roots were abundant to a depth of 45 cm. Depth of the amended zone in the gypsum and $CaCl_2$ plot was clearly defined at 45 cm, and copious roots were found in the soil profile to this depth.

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Introduction

Mining of bentonitic clays from lands of the Northern Great Plains began in the 1940s and thousands of hectares of land were disturbed prior to reclamation requirements implemented in the 1970s. Chemical and physical attributes of bentonitic spoils coupled with the semi-arid climate of the region, make vegetation establishment difficult (Schuman et al., 2000). Topsoil salvage and replacement are now required for active mining operations to aid in reclamation, but large landscapes of abandoned spoils can be characterized as barren or very sparsely vegetated. These spoils cover many thousands of hectares in Montana, Wyoming, and South Dakota. Natural vegetation colonization of these areas has been very slow over the past 60 years, and attempts to reclaim spoils without coversoils or amendments have been relatively unsuccessful (Dollhopf and Bauman 1981, and Schuman et al. 1985). Several investigations using cover soil and spoil amendments to aid revegetation of abandoned bentonitic spoils are well described by Schuman and others (2000). The main limiting factors to revegetation are the saline and sodic properties of the remaining bentonitic clays, and the non-availability of coversoil. Modifications of spoil materials by the addition of chemical and/or physical amendments or placement of coversoil over the spoils are the generally accepted approaches to revegetation of these abandoned lands. Increasing infiltration of meteoric water into these high clay materials is an important factor in vegetation establishment and persistence. The use of wastes from lumber operations (sawdust, wood chips, and bark) has been shown to increase infiltration (Schuman and Sedbrook, 1984). Other studies were designed to find optimized rates of wood wastes and nitrogen requirements (Smith et al., 1986). These wood-based amendments increase infiltration and storage of water, and aid in leaching of salts, but also increase the sodicity of the amended zone. Additions of gypsum or calcium chloride together with infiltration enhancing wood wastes are thought to be necessary to ensure long-term revegetation success (Schuman et al. 2000). The primary Bureau of Land Management goal for the reclamation of these areas is to build soil and prevent sedimentation. A secondary goal is to provide grazing and wildlife use (Pigors, 2006).

This paper describes the persistence of vegetation seeded into abandoned bentonite spoils near Belle Fourche, South Dakota that were amended with several different amendments in the 1980s. Vegetation canopy cover, species composition, above ground biomass, and rooting depths were quantified for plants growing on selected treatment plots. In addition, spoil attributes including pH, soluble salts, sodium absorption ratios, and electrical conductivity values were determined. These data are compared to information last reported seventeen years ago (Dollhopf et al. 1990).

Initial Experiments and Results

In the 1980s, 135 experimental plots [15 treatments with 3 fertilizer rates nested within each treatment and replicated three times] were implemented on bentonite spoils near Belle Fourche, South Dakota. One hundred and seventeen of the plots were implemented in 1980, while the remaining 18 were installed in 1986. Treatments varied from physical manipulations to additions of chemical and biological amendments. The plots were seeded with mixes of plant species. Effects of these amendments and treatments on spoil chemistry and vegetation were documented in several early reports (Dollhopf et al. 1981, 1988, 1990). Twenty-five years later, in 2005, a reconnaissance team from the Reclamation Research Unit conducted a qualitative assessment of the vegetation status of the experimental reclamation plots to determine which of the treatments supported the "best" vegetation. These treatments were then targeted for quantitative evaluations of the vegetation and collection and analysis of the treated bentonite spoils. The objectives of this study were as follows:

1. Conduct a site reconnaissance and qualitatively determine which of the fifteen different treatments supported the “best” vegetation;
2. Conduct quantitative assessment of vegetation attributes – canopy cover, above ground biomass, species present and rooting patterns – of species growing on the selected treatments, and compare these data to those found in the 1980s;
3. Determine physical and chemical attributes – pH, electrical conductivity, concentrations of soluble calcium, magnesium, and sodium, and sodium absorption ratio (SAR) - of the treated bentonite spoils in each selected treatment, and compare these data to earlier results.

Methods

Initial Reconnaissance

In the spring of 2005, a reconnaissance team visited the experimental site and using earlier reports, the initial field design was verified. Many of the experimental plots were devoid of vegetation, others supported minimal plants, and some were judged to sustain good vegetation cover. Vegetation in each of the 135 experimental plots was qualitatively judged as poor, poor/fair, fair, fair/good, and good. A relative ranking of the treatments was determined by assigning a numerical value to each treatment plot: Good = 5 points; Fair/good = 4 points; Fair = 3 points; Poor/fair = 2 points; and Poor = 1 point.

The numerical scores were then summed for each of the treatments. Based on this relative system, the “best” vegetation was found growing on three of the treatments and these were then selected for quantitative vegetation and spoil evaluations. The fence enclosing the experimental plots was repaired to exclude livestock until quantitative assessments could be made.

Vegetation Attributes

In early July of 2005, canopy cover by life form within each of the selected plots was determined using the Daubenmire cover class method (Daubenmire, 1959). Ten 20 x 50 cm frames were place along two diagonal transects on each plot. Cover class for each life form (perennial grasses, annual grasses, and perennial forbs) within the frame was recorded. A 25 x 25 cm frame was placed in the same location as each of the cover frames and vegetation within each frame was clipped and segregated by life form and placed into separate labeled paper bags for transport to the RRU/MSU laboratories. The samples were oven dried (70º C) for 24 to 36 hours to achieve a constant weight. The vegetation mass in each bag was weighed to the nearest 0.01 gram. These data were used to calculate above ground biomass. Attempts were made to identify all plant species growing in each of the selected experimental plots so that comparisons to species in the original seed mixes could be made. While soil samples were being collected, the rooting patterns of the vegetation were described in terms of depth of rooting, density of roots as a function of depth, and evidence of the depth of treatment.

Treated Spoil Attributes

A small backhoe was employed to excavate soil pits in one experimental plot of each of the three treatments, and in an offsite non-treated location (experimental control). Samples were collected from the following depths: 0 to 5 cm, 5 to 10 cm, 10 to 20 cm, 20 to 38 cm, 38-76 cm, and 76 to 152 cm. These sampling depths are the same as those evaluated in previous studies.

The samples were placed in new polybags and transported to RRU/MSU laboratories where they were dried, disaggregated, and the following attributes were determined using standard laboratory methods: pH, electrical conductivity (EC), and soluble concentrations of calcium, magnesium, and sodium. The sodium absorption ratio was then calculated from the cation concentrations.

Results

Selection of Treatments for Quantitative Evaluation

The initial experimental design was implemented in 1980 (Dollhopf and Bauman, 1981) consisted of 12 treatments, replicated three times, and within each replication three levels of fertilizer were added (none, low and high). In 1986, two additional treatments were added to the initial design, and these were also replicated three times and fertilizer was added identically as the first plots (Table 1). During reconnaissance, the vegetation in each plot was rated as poor, fair/poor, fair, fair/good, or good. Numerical scores were assigned to each vegetation assessment [poor = 1, poor/fair = 2, fair = 3, fair/good = 4, and good = 5]. The numerical scores were then summed for each treatment as shown in Fig. 1.

The amendment, phosphogypsum (Treatment 15) is no longer available for treating of soils or mine spoils, and will not be discussed further in this paper. The effect of initial fertilization of the plots on the vegetation growing after either 25 years or 19 years was not apparent for any of the 15 treatments. Based on this relative system, the "best" vegetation was found growing on the following three treatments:

- Treatment #7 – Manure at 112 Mg/ha + H_2SO_4 at 20 Mg/ha
- Treatment #9 – Gypsum at 6.7 Mg/ha + $CaCl_2$ at 17.2 Mg/ha
- Treatment #14 - $MgCl_2$ brine – 1.2 Mg/ha

Table 1. Treatments implemented in either 1980 (1 through13) or 1986 (14 and 15).

Treatment Number	Treatment Description
1	Deep tillage without straw mulch
2	Deep tillage
3	Deep tillage plus irrigation
4	Surface gouging
5	Vertical mulch and manure
6	Manure applied at the rate of 224Kg/ha
7	Manure applied at rate of 112 Mg/ha + H_2SO_4 applied at rate of 20 Mg/ha
8	Wood chips applied at rate of 1660 m^3/ha
9	Gypsum applied at rate of 6.7 Mg/ha + $CaCl_2$ applied at rate of 17.2 Mg/ha
10	Gypsum applied at rate of 6.7 Mg/ha + H_2SO_4 applied at rate of 1112.3 Mg/ha
11	Gypsum applied at a rate of 6.7 Mg/ha + H_2SO_4 applied at rate of 1112.3 Mg/ha + irrigation
12	Topsoil applied to a depth of 10.2 cm
13	Topsoil applied to a depth of 10.2 cm + irrigation
14	$MgCl_2$ brine applied at a rate of 1.2Mg/ha
15	Phosphogypsum applied at a rate of 6.7 Mg/ha

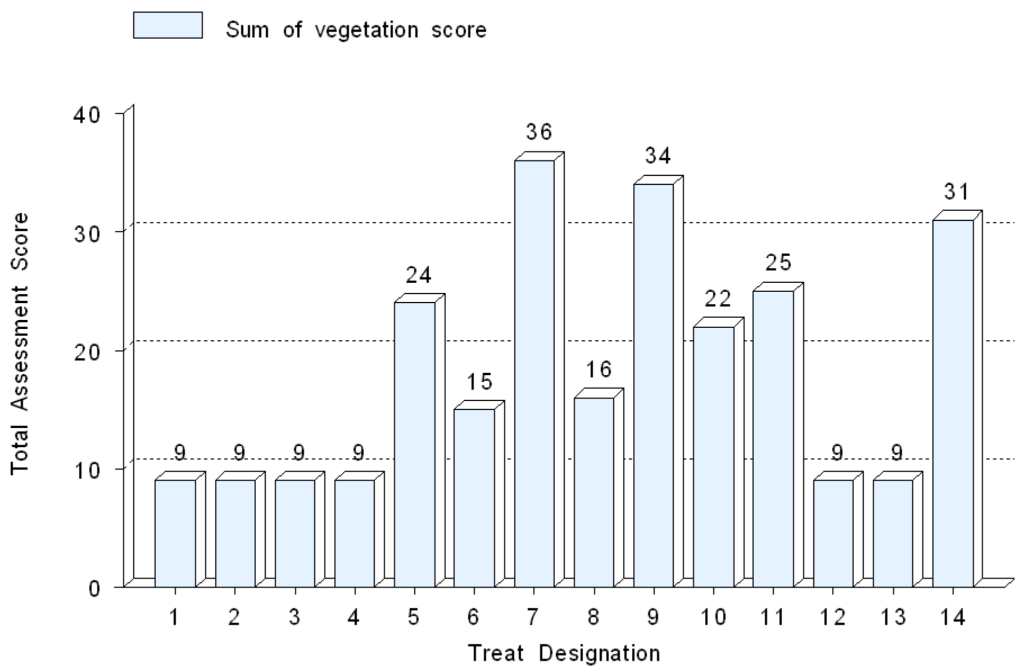

Figure 1. Qualitative scoring of vegetation growing on each treatment.

<u>Canopy Cover</u>

The vegetation growing on experimental plots representing three selected treatments of bentonite spoils was evaluated. Canopy cover by life form within each plot was determined using the Daubenmire cover class method (Daubenmire 1959). Ten 20 x 50 cm frames were placed along two diagonal transects (Fig. 2) on each plot. Cover class for each life form (perennial grasses, annual grasses, and perennial forbs) within the frame was recorded. The mean percent canopy cover of live vegetation, by life form – perennial grasses, annual grasses and perennial forbs - is displayed in Fig. 3.

The mean vegetation cover values for each treatment, across all replications, were not significantly different among the three chosen treatments. Mean canopy cover values were 21.1% for spoils treated with gypsum and $CaCl_2$, 24.4% for spoils treated with H_2SO_4 and manure, and 27.3% for spoils amended with a brine of $MgCl_2$. Community composition did vary significantly ($P < 0.05$) among the treatments (Fig. 3). Perennial grasses, specifically alkali sacaton (*Sporobolus airoides),* dominated the vegetation community growing on the spoils treated with Mg Cl_2 (Fig. 4). This species is a native bunch grass. Two other bunchgrasses, crested wheatgrass (*Agropyron cristatum)* and tall wheatgrass (*A. elongatum)*, contributed to vegetation cover on the spoils treated with the $MgCl_2$ Brine. In contrast it has been suggested (Smith et al 1985) that sod-forming grasses are generally better suited than bunchgrasses for revegetation of bentonite spoils. Perennial forbs, chiefly forage kochia *(Kochia prostrata)* accounted for the majority of the v

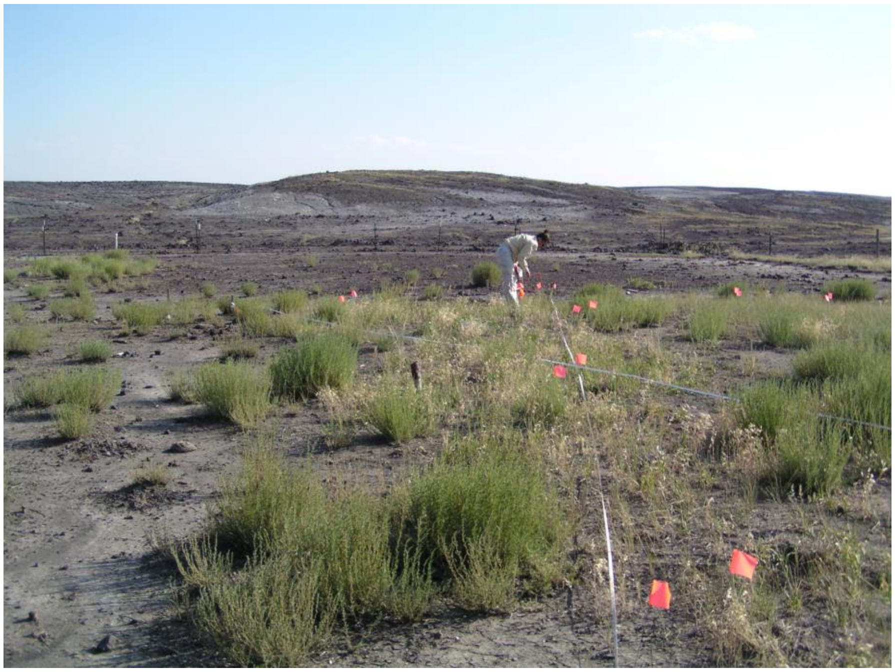

Figure 2. Randomly located sampling areas (flags) along the diagonal transects on an experimental plot of Treatment 9 (Gypsum at 6.7 Mg/ha + $CaCl_2$ at 17.2 Mg/ha).

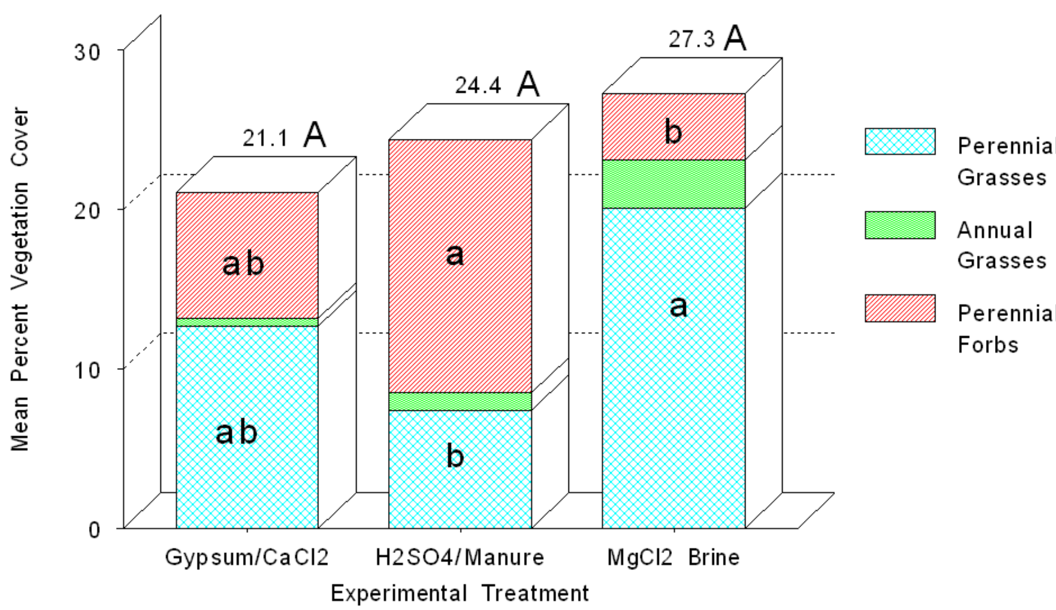

Figure 3. Mean percent cover of vegetation growing on treated bentonite spoils. Vegetation growing on the materials initially treated with H_2SO_4 and manure (Fig. 5).

In 1987 and 1989, the mean percent canopy cover of vegetation growing on the $MgCl_2$ brine treated plots was 39.3% and 46.0%, respectively (Dollhopf et al., 1990). These cover values are greater than the mean value of 27.3% found in 2005. Species contributing the most to the cover in 1989 were slender wheatgrass (*A. trachycaulum*), alkali sacaton (*S. airoides*), and forage kochia (note this species was identified in the 1990 report as *K. scoparia*, but was most likely *K. prostrata*). In 2005, alkali sacaton contributed most to the vegetation cover, with minor contributions from forage kochia. In 1986, mean vegetation cover values measured on the spoils treated with gypsum and $CaCl_2$ and those treated with H_2SO_4 and manure were 54.0 and 77.6%, respectively. In both treatments perennial grasses contributed most to the cover values. These mean cover percentages are much greater than those measured in 2005 (Fig 2).

Figure 4. Perennial grasses, specifically alkali sacaton (*Sporobolus airoides)*, dominated the vegetation community growing on the spoils treated with $MgCl_2$ Brine.

Figure 5. Forage kochia *(Kochia prostrata)*, accounted for the majority of the vegetation growing on the materials initially treated with H_2SO_4 and manure.

Species List

Attempts were made to identify all plant species growing in each of the nine experimental plots and then to compare those species to those in the original seed mixes. Treatment plots 7 and 9 were initially seeded in 1980 (Table 2), while the plots amended with the $MgCl_2$ brine were seeded in 1986 (Table 3). The seed mixes were slightly different.

Tables 2, 3 and 4 display a species list of all plants found within each of the nine experimental plots. Many of the species growing on these plots were not part of the initial seeded species. Of the 18 species seeded into the plots treated with gypsum and $CaCl_2$, only three were found growing in these plots after twenty-five years (Table 4). Many other species have volunteered into these plots, but few contributed very much to cover or above ground biomass (refer to the next section).

Table 5 shows the plant species found growing on the three experimental plots treated with sulfuric acid and manure in 1980. Of the 18 species seeded in 1980, seven were found growing on these plots in 2005. Five of these were wheatgrasses, and the other two were yellow sweetclover (*Melilotus officinalis)*, and forage kochia. Fifteen species including grasses, forbs, and shrubs have invaded these plots, but none of them contribute appreciably to the vegetative cover or biomass.

Table 2. Plant species seeded in 1980.*

Scientific Name	Common Name
Agropyron cristatum	Crested wheatgrass
Agropyron dasystachyum	Thickspike wheatgrass
Agropyron elongatum	Tall wheatgrass
Agropyron riparium	Streambank wheatgrass
Agropyron smithii	Western wheatgrass
Agropyron trachycaulum	Slender wheatgrass
Bouteloua curtipendula	Sideoats grama
Sporobolus airoides	Alkali sacaton
Achillea millefolium	Common yarrow
Helianthus spp.	Sunflower
Kochia prostrata	Forage kochia
Linum lewisii	Prairie flax
Ratibida columnifera	Prairie coneflower
Astragalus cicer	Cicer milkvetch
Melilotus officinalis	Yellow sweetclover
Atriplex canescens	Fourwing saltbush
Atriplex gardneri (nuttallii)	Gardner's saltbush
Sarcobatus vermiculatus	Greasewood

* These plant species were seeded into Treatments 7 and 9 plots.

Table 3. Plant species seeded in 1986.*

Scientific Name	Common Name
Agropyron cristatum	Crested wheatgrass
Agropyron dasystachyum	Thickspike wheatgrass
Agropyron elongatum	Tall wheatgrass
Agropyron riparium	Streambank wheatgrass
Agropyron smithii	Western wheatgrass
Agropyron trachycaulum	Slender wheatgrass
Bouteloua curtipendula	Sideoats grama
Sporobolus airoides	Alkali sacaton
Achillea millefolium	Common Yarrow
Dalea purpurea	Purple prairie clover
Ratibida columnaris	Prairie coneflower
Linum lewisii	Prairie flax
Astragalus cicer	Cicer milkvetch
Melilotus officinalis	Yellow sweetclover
Atriplex canescens	Fourwing saltbush
Atriplex gardneri (nuttallii)	Gardner's saltbush
Atriplex confertifolia	Shadscale saltbush
Artemisia cana	Silver sagebrush

* These were seeded into the plots treated with $MgCl_2$ brine.

Table 4. Plant species identified growing on plots treated with gypsum and $CaCl_2$ (Treatment 7).

Scientific Name	Common Name	Rep 1	Rep 2	Rep 3	Seeded
Tetradymia canescens	Spineless horsebrush			X	No
Agropyron spp.	Wheatgrass	X	X	X	Yes
Kochia prostrata	Forage kochia	X	X	X	Yes
Bromus inermis	Smooth brome		X	X	No
Bromus tectorum	Cheatgrass	X	X	X	No
Lepidium spp	Pepperweed	X		X	No
Achillea millefolium	Common yarrow	X	X	X	Yes
Distichlis spicata	Inland saltgrass		X		No
Chrysothamnus nauseosus	Rubber rabbitbrush			X	No
unknown forb/subshrub #1		X	X	X	No
unknown forb/subshrub #2		X	X	X	No
unknown forb #3			X	X	No
Sporobolus airoides	Alkali sacaton		X		No
Chenopodium album	Lambsquarters	X	X		No
Poa spp. (Secunda?)	Blue grass spp.	X			No
Artemisia tridentata	Big sagebrush	X			No
Unknown annual grass		X			No

Table 5. Plant species identified growing on plots treated with H_2SO_4 and manure (Treatment 9).

Scientific Name	Common Name	Rep 1	Rep 2	Rep 3	Seeded
Agropyron spp.	Wheatgrass	X	X		Yes
Agropyron cristatum	Crested wheatgrass			X	Yes
Agropyron elongatum	Tall wheatgrass		X		Yes
Artemisia tridentata	Big sagebrush			X	No
Bromus inermis	Smooth brome	X	X	X	No
Bromus tectorum	Cheatgrass		X	X	No
Agropyron dasystachyum	Thickspike wheatgrass	X	X		Yes
Taraxacum officinale	Common dandelion	X			No
Polygonum spp.	Knotweed spp.	X			No
Melilotus officinalis	Yellow sweetclover	X			Yes
Poa spp. (Secunda?)	Bluegrass spp.	X		X	No
Chrysothamnus nauseosus	Rubber rabbitbrush	X			No
Bromus tectorum	Smooth brome	X			No
Hordeum jubatum	Foxtail barley	X			No
Lepidium spp.	Pepperweed	X	X	X	No
Agropyron smithii	Western wheatgrass	X			Yes
Distichlis spicata	Inland saltgrass	X			No
Kochia prostrata	Forage kochia	X	X		Yes
unknown forb/subshrub #1		X	X	X	No
unknown forb/subshrub #2		X	X	X	No
Unknown forb #3			X		No
Unknown annual grass		X			No

A slightly different seed mix (Table 3) was used in 1986 when additional experimental plots, including those treated with $MgCl_2$ brine were implemented (Table 6). Six species, wheatgrasses, yarrow (*Achillea millefolium)*, alkali sacaton, and gardner's saltbush (*Atriplex gardneri (nuttallii)*, of the initial mix of eighteen species were found after 19 years. These plots were dominated by alkali sacaton. It is interesting to note that forage kochia was not seeded, but it has volunteered into these plots.

Above Ground Biomass

Above ground biomass was calculated from weights of collected vegetation (Fig. 6). As expected, the above ground biomass of vegetation growing on the gypsum and $CaCl_2$ was greatest owing to forage kochia, where as the $MgCl_2$ Brine treated plots supported mostly the grass, alkali sacaton.

Soil Chemistry

Initially, a truck-mounted Giddings Soil Core apparatus was to be used for the collection of multiple soil samples at various depths within the soil profile in each experimental plot. However, this machine was unable to penetrate the bentonite spoils to the depths required due to tight, dense, and dry spoils. A small backhoe (Fig. 7) was employed to excavate soil pits in replication 2 of each of the three treatments, and in an offsite non-treated location (experimental control).

Table 6. Plant species identified growing on plots treated with $MgCl_2$ brine.

Scientific Name	**Common Name**	**Rep 1**	**Rep 2**	**Rep 3**	**Seeded**
Agropyron cristatum	Crested wheatgrass		X	X	Yes
Agropyron elongatum	Tall wheatgrass		X		Yes
Agropyron spp.	Wheatgrass spp.		X		Yes
Achillea millefolium	Common yarrow	X			Yes
Artemisia tridentata	Big sagebrush	X			No
Bromus tectorum	Cheatgrass	X	X	X	No
Chrysothamnus nauseosus	Rubber rabbitbrush	X			No
Festuca spp.	Fescue spp.		X		No
Sporobolus airoides	Alkali sacaton	X	X	X	Yes
Kochia prostrata	Forage kochia	X	X	X	No
Atriplex gardneri (nuttallii)	Gardner's saltbush	X	X	X	Yes
Hordeum jubatum	Foxtail barley			X	No
Lepidium spp.	Pepperweed	X		X	No
unknown forb/subshrub #1		X	X	X	No
unknown forb/subshrub #2		X	X	X	No
unknown forb #3		X	X	X	No
unknown annual grass		X	X	X	No
unknown lichen	Ground lichens	X			No

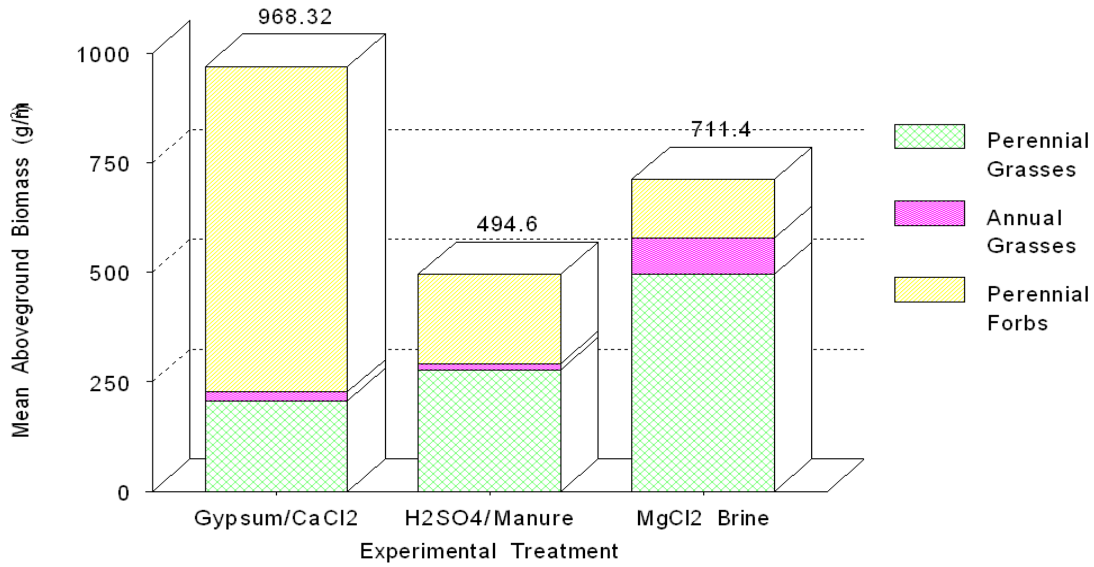

Figure 6. Mean (g/m^2) above round biomass of vegetation growing on treated bentonite spoils.

Figure 7. Excavation in replication plot 2 of Treatment 7 in preparation for soil sampling and root evaluations.

Samples were collected from the following depths: 0 to 5 cm, 5 to 10 cm, 10 to 20 cm, 20 to 38 cm, 38 to 76 cm, and 76 to 152 cm. These sampling depths are the same as those evaluated in previous studies. The samples were placed in new polybags and transported to RRU/MSU laboratories where they were dried, disaggregated, and the following attributes (Table 7) were determined: pH, electrical conductivity (EC), and soluble concentrations of calcium, magnesium, and sodium. The sodium absorption ratio was then calculated from the cation concentrations.

The pH levels in the collected soils were very similar, with a relatively narrow range of 6.78 to 8.04. Spoils treated with H_2SO_4 and manure revealed similar pH levels to untreated spoil materials collected from an off site area adjacent to the test plots. The electrical conductivity (EC) of spoil (top 20 cm) treated with H_2SO_4 and manure was markedly reduced compared to either the control samples or the soils collected from the other treated plots. Correspondingly, the soluble concentrations of calcium, magnesium, and sodium as well as the sodium absorption

Table 7. Chemical characteristics of collected bentonite spoils from each treatment.

Treatment	Depth (cm)	Lab ID	pH	EC (µS)	Soluble Ca mg/L	Soluble Mg mg/L	Soluble Na mg/L	SAR
Control	0—5	16	8.00	2356	37	7	492	19.6
Control	5—10	13	7.44	8020	239	67	1730	25.5
Control	10—20	18	7.6	9910	314	100	2160	27.2
Control	20—38	20	7.58	8930	154	60	2060	35.6
Control	38—76	24	7.69	7780	149	77	1690	28.0
Control	76—143	8	7.25	10970	458	259	2130	19.7
$MgCl_2$ brine	0—5	21	7.41	11090	177	144	2060	27.8
$MgCl_2$ brine	5—10	1	6.78	17830	541	340	3650	30.3
$MgCl_2$ brine	10—20	25	7.34	16370	439	256	3330	31.2
$MgCl_2$ brine	20—35	22	7.84	9750	143	90	2100	33.9
$MgCl_2$ brine	35—70	9	7.18	9190	140	102	1900	29.8
$MgCl_2$ brine	70—140	14	7.51	6710	82	78	1400	26.5
Gypsum/ $CaCl_2$	0—5	2	7.06	1829	80	23	254	6.4
Gypsum/ $CaCl_2$	5—10	6	8.02	1732	31	8	324	13.4
Gypsum/ $CaCl_2$	10—20	7	7.82	1528	30	8	341	14.5
Gypsum/ $CaCl_2$	20—38	4	7.41	7460	269	102	1480	19.5
Gypsum/ $CaCl_2$	38—76	3	7.15	12830	429	211	2750	27.1
Gypsum/ $CaCl_2$	76—152	5	7.05	7460	377	183	1360	14.4
H_2SO_4/manure	0—5	17	8.04	331.2	15	2	61	4.0
H_2SO_4/manure	5—10	12	7.93	328.8	9	1	64	5.2
H_2SO_4/manure	5—10 (duplicate)	15	8.02	299	9	2	60	5.0
H_2SO_4/manure	10—20	19	7.9	344.1	6	1	63	6.2
H_2SO_4/manure	20—38	10	7.48	4007	132	35	790	15.8
H_2SO_4/manure	38—76	11	7.33	10010	322	146	2110	24.5
H_2SO_4/manure	76—152	23	7.61	11730	405	227	2450	24.1

ratios of the top 20 cm of the sulfuric acid and manure treated spoils are less than all other samples. The EC values for the $MgCl_2$ brine-treated spoils have not changed since they were last measured in 1989 (Dollhopf et al. 1990). SAR levels for the $MgCl_2$ brine treated spoils as measured in 1986, 1987, and 1989 ranged from 19.8 to 35.2. This range is nearly identical to values found in 2005 as shown in Table 6.

In 1980, the SAR levels of spoils treated with $CaCl_2$ and gypsum ranged from 16.8 to 47.7 (Dollhopf et al. 1988). Slightly lower SAR levels were found in 2005. Also in 1980, the SAR values of spoils treated with H_2SO_4 and manure ranged from 26.0 to 34.8, while data from 2005 revealed much lower SAR levels especially in the top 20 cm of the treated materials (Table 7).

Vegetation Rooting Patterns

After soil samples were collected and while the excavations were still open, rooting patterns of the vegetation were evaluated for depth of rooting, density of roots as a function of depth, and evidence of the depth of treatment. The manure incorporated into the spoils (H_2SO_4 and manure treatment) was clearly visible in the soils profile (Fig. 8). However, much of the manure had not decomposed since it was added to the spoils 25 years ago. This lack of decomposition may indicate lack of biological activity, indicating nutrient cycling is retarded in this treatment. The depth of treatment was not observable. There were abundant roots to a depth of 45 cm, with fewer root observed at deeper depths. The maximum rooting depth was approximately 103 cm.

The depth of the amended zone in the gypsum and $CaCl_2$ treated plot was clearly defined at 45 cm, and abundant roots were found in the soil profile to this depth (Fig. 9).

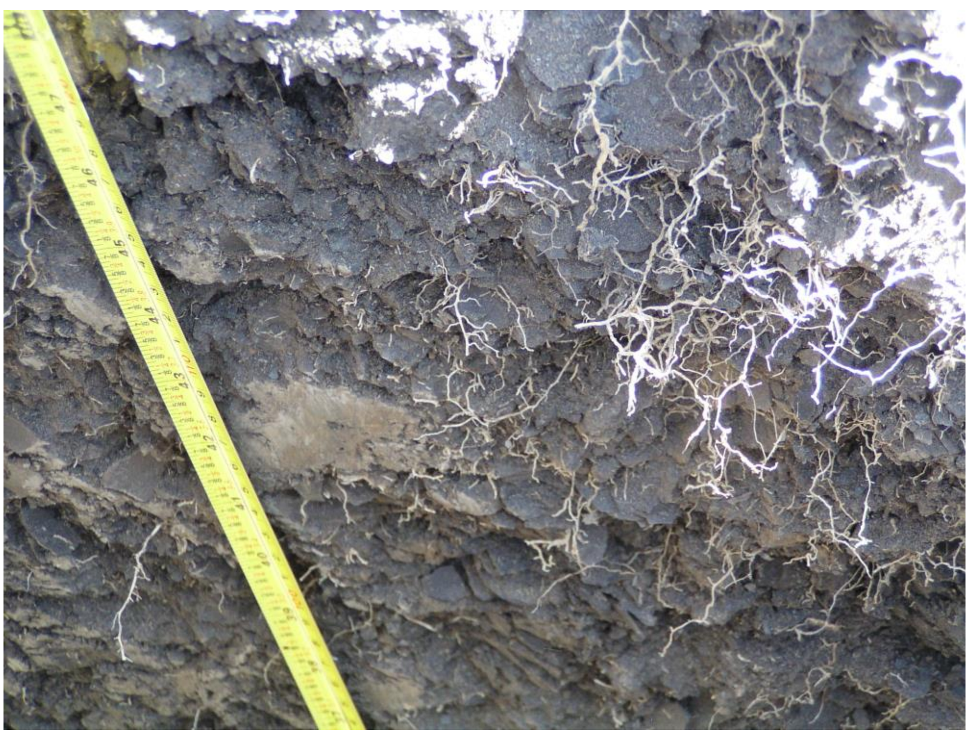

Figure 8. Rooting patterns within spoils treated with H_2SO_4 and manure.

Figure 9. Rooting patterns within spoils treated with gypsum and $CaCl_2$.

In the spoils treated with $MgCl_2$ Brine, the amended zone was visible to a depth of approximately 56 cm. Roots were abundant to 20 cm with fewer observed below this depth in the profile. The maximum rooting depth was measured at approximately 104 cm (Fig. 10).

Figure 10. Rooting patterns within spoils treated with $MgCl_2$ Brine.

Conclusions

Vegetation

Nineteen to twenty-five years after implementation of fifteen different treatments and seeding of abandoned bentonite mine spoils, the following treatments were qualitatively deemed to support the "best" vegetation: gypsum and $CaCl_2$; H_2SO_4 and manure; and $MgCl_2$ Brine. Quantitative evaluation of the vegetation growing on these experimental plots in 2005 revealed that canopy cover values for each treatment, were not significantly different, but they were markedly lower than those measured in previous years. This may indicate relatively long term degradation of some of the treatments. However, this finding is confounded due to uncontrolled livestock grazing during some periods in the last nineteen to 25 years.

Community composition did vary significantly ($P < 0.05$) among the treatments. Perennial grasses, specifically alkali sacaton (S. *airoides),* dominated the vegetation community growing on the spoils treated with $MgCl_2$ Brine. Perennial forbs, chiefly forage kochia *(K. prostrata)* accounted for the majority of the vegetation growing on the materials initially treated with H_2SO_4 and manure. Few of the seeded species were found growing on the experimental plots. Many other species have colonized the plots, but contributed little to vegetation cover or biomass. Mean Above ground biomass varied from 494 g/m^2 for plant of the acid and manure plots to 968 g/m^2 for vegetation on the plots treated with $CaCl_2$ and gypsum. Like vegetation cover, the composition of plants contributing to aboveground biomass varied among the three treatments.

One species, forage kochia shows some good long-term success on the experimental plots. It was also observed colonizing adjacent bentonite spoils that were not part of this investigation. The US Forest Service Shrub Sciences Laboratory released this introduced species in 1984 after selection from Stravopol Botanical Gardens in the former USSR. According to University of Utah Extension Service (Parker, no date), forage kochia has been seeded to improve plant community diversity, aesthetics, plant cover species richness, forage for livestock and wildlife, fire prevention, and soil stability. It suppresses or eliminates the invasion of alien annual weeds like cheatgrass, halogeton, Russian thistle, and medusahead rye. It is not highly invasive and does not spread aggressively into healthy plant communities. It does not compete well with perennial grasses.

Soils

Level of soil pH across all treatment and depths were very similar with a range of 6.78 to 8.04. The electrical conductivity (EC) of spoils (top 20 cm) treated with H_2SO_4 and manure was markedly reduced compared to either the control samples or the soils collected from the other treated plots. Correspondingly, the soluble concentrations of calcium, magnesium, and sodium as well as the sodium absorption ratios of the top 20 cm of the acid and manure treated spoils are less than all other samples. The EC and SAR values for the $MgCl_2$ Brine treated spoils have not changed since they were last measured in 1989 (Dollhopf et al., 1990). In 1980, the SAR levels of spoils treated with $CaCl_2$ and gypsum ranged from 16.8 to 47.7 (Dollhopf et al., 1988). Slightly lower SAR levels were found in 2005.

In the plots containing acid and manure, the treatment depth was not readily observable, but copious roots were present to approximately 45 cm. Little decomposition of this amendment has occurred, indicating at best, very slow or retarded nutrient cycling. The long-term success of this acid and manure treatment may be questionable.

In the plots containing gypsum and $CaCl_2$, the amended zone was clearly defined at 45cm, and abundant roots were found in the soil profile to this depth. As expected, the above ground biomass of vegetation growing on the gypsum and $CaCl_2$ treated plots was greatest owing to forage kochia.

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