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Study of Factors Affecting Shrub Establishment on the Monticello, Utah, Disposal Cell Cover

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1.0 Introduction

The design of the evapotranspiration cover at the Monticello, Utah, disposal cell was based on the concept of ecosystem engineering. Ecosystem engineering characterizes and manipulates many ecological components and processes to achieve desired goals. In the Monticello area, sagebrush (*Artemisia tridentata*) tends to form climax communities on deep loess soils, but it is transitional to piñon-juniper forests on shallower soils. The Monticello cover was designed to be sustainable over the long term and to mimic the ecology of sagebrush-wheatgrass communities growing in deep soil.

Vegetation, particularly deep-rooted shrubs, plays a key functional role in the long-term performance of the disposal cell by removing moisture stored in a thick soil "sponge" layer. Therefore, establishment of the vegetation is crucial in creating a reliable and sustainable cover. During the 6 years since the cover was planted, the vegetation community has satisfied some revegetation acceptance criteria, including those related to species diversity, the establishment of desirable perennial grasses, and total desirable plant cover. However, the cover has failed to achieve other acceptance criteria. Most importantly, the diversity and density of shrubs remain critically low, and their health (and ability to propagate) appears diminished.

The objective of this study was to identify the most likely causes for poor shrub establishment on the repository cover. This was done by measuring vegetation, soil, and wildlife parameters and comparing those measurements to nearby analog areas. In addition, records and literature reviews were conducted to clarify the contribution of such factors as plant material sources, revegetation techniques, and the seed life of critical species.

Although some sagebrush mortality was observed in 2004 (DOE 2005a) and 2005 (DOE 2005b), and the presence of small rodents was observed on the repository cover as early as 2003, wildlife predation on shrubs was not identified as a major issue until spring 2006. At that time, abnormally large numbers of montane voles (*Microtus montanus*) were observed on the repository cover, concomitant with increased numbers of dead or damaged sagebrush. Therefore, the U.S. Department of Energy (DOE) conducted a separate but related study of vole-related impacts and vole ecology (DOE 2006a). A summary of that report is included in this study because vole-related impacts are expected to remain important to future sagebrush establishment and health.

2.0 Methods

The repository cover was assessed in the field on August 14–17, 2006. Sample locations are shown on Figure 1. Three nearby analog areas were also sampled:

- The Zone A2/B Analog area, which includes portions of the repository site immediately adjacent to the cover. The same revegetation methods and materials were used in this area as on the repository cover, including live plantings and the same timing. Construction methods, including topsoil borrow sources, may have been different. This area was selected because the shrub cover appears to be denser and healthier than on the cover.
- The Rabbitbrush Analog area, which is approximately ½ mile north and northwest of the disposal cell. This area was selected because it was disturbed and revegetated at approximately the same time as the repository cover, and it contains a very healthy

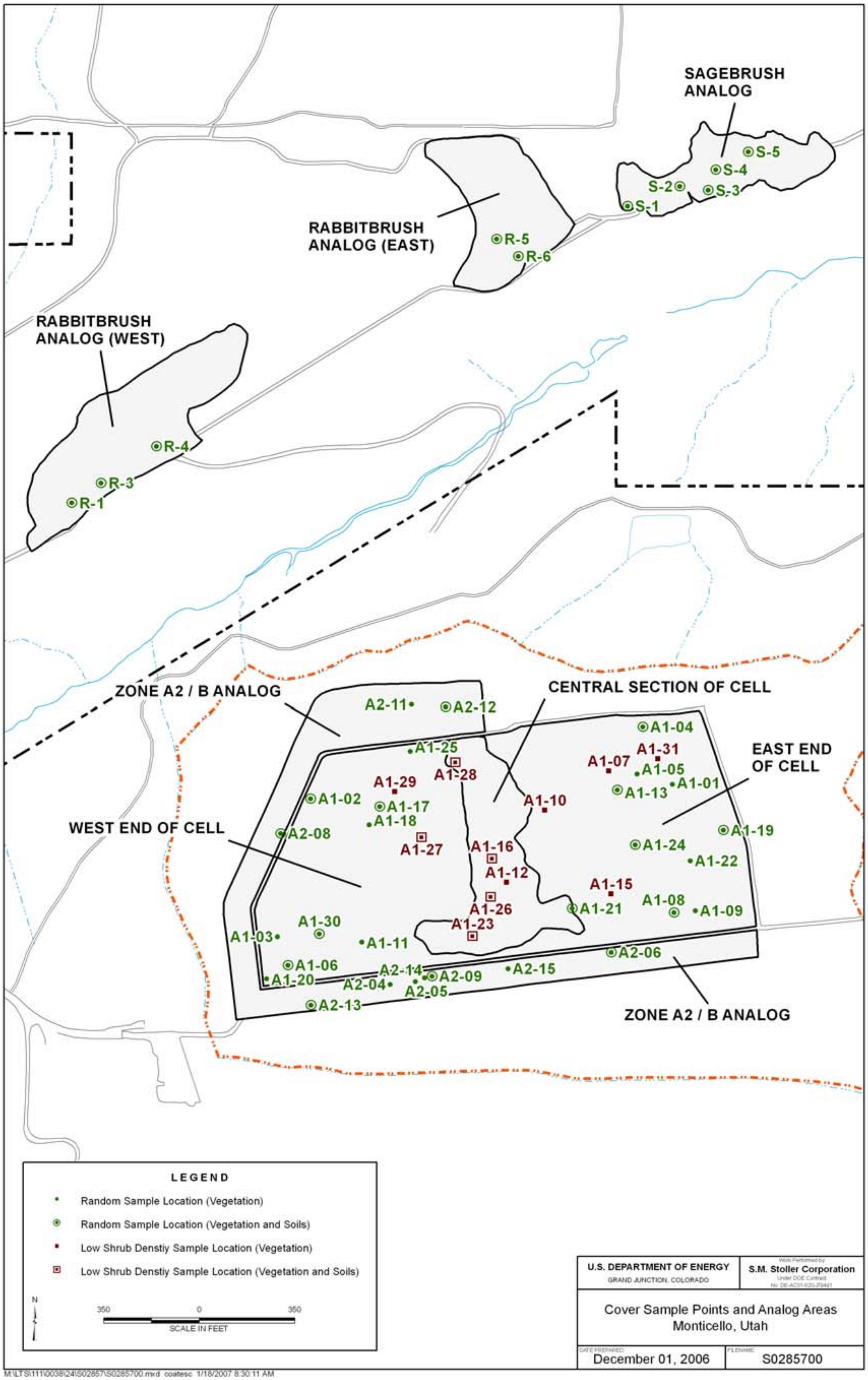

Figure 1. Sample Locations

rabbitbrush (*Ericameria nauseosa*) community. Prior to revegetation, most of the topsoil was removed from this area for use at other locations, but the native subsoil remained undisturbed. The Rabbitbrush Analog area comprises two distinct patches with relatively uniform cover.

- The Sagebrush Analog area, which is located approximately ½ mile northeast of the disposal cell and represents a mature sagebrush community. It contains shallower soils than those replicated at the repository, but the sagebrush community is dense, stable, and relatively diverse because the soil has remained undisturbed for decades, possibly longer. It is probable that the vegetation was once heavily grazed.

Although the analog areas are similar in many respects to the repository cover, the cover has a layer of rock mulch in the upper surface, and the analog areas do not. It should be kept in mind, therefore, that the areas are not exact analogs of the cover.

Fifty sample points were randomly located throughout the study areas, with a distribution of approximately one sample point per acre. At these points:

- The distances to the nearest four shrubs were measured, and the Eberhardt point-quarter method was used to calculate shrub density. (50 sampling locations.)
- Species composition, including (when possible) the subspecies of sagebrush and shrub mortality were recorded for each measured shrub. Seedling sagebrush and dead shrubs were not identified to subspecies. (200 data values.)
- Shrub volume for each measured shrub was estimated by recording the height, width (east-west), and length (north-south). For dead shrubs, only the heights were recorded. (200 data values.)
- A coring instrument was used to collect soil volume samples at depths of 1 and 2 feet (ft). These samples were laboratory-analyzed for bulk density and moisture content. (30 data points.)
- Soil fertility samples were collected at depths of 1 and 2 ft and analyzed in the laboratory. Composite samples were prepared for each analog area and for three portions of the repository cover: the east end, the west end, and the central portion, for a total of six composite samples at each depth. (30 sampling locations.)
- Shrub damage was assessed for each measured shrub. Five classes of shrub damage were recorded (see Figure 2). Not all damage is necessarily attributable to voles; therefore, vole presence was also recorded [1], along with evidence of other predators (e.g., rabbit pellets). (200 data values.)

Vegetation cover data were recorded on September 5–6, 2006, during annual vegetation monitoring at the same repository cover sampling locations. Therefore, some vegetation cover data were also available for the repository cover itself. Within the repository cover, the mean distance to the nearest *living* shrubs was calculated for each sample point. From a scatterplot of the data, the sample points could be readily separated into two groups: samples with an average

[1] Vole presence was indicated by burrows, soil casts, runways, stripping or girdling of shrub stems, and fecal pellets in the immediate area of the sampled shrub. Many burrows could be observed easily, but many could only be identified by probing around the base of the shrub to locate areas hidden by grasses and litter.

Vole Damage Assessment Form

SAMPLE ID____________

Sagebrush selected for assessment will be qualitatively evaluated for vole damage. The degree of damage noted below will be based on the observed amount of dead plant and/or girdling present. A qualitative scale of none, mild, moderate, severe, and mortality damage will be used. The presence or absence of a burrow beneath the shrub will also be noted. Finally, the presence and description of runways in the immediate area will be noted and evidence that other potential small mammals (e.g. rabbits, mice, kangaroo rats) are present will be described.

DEGREE OF DAMAGE

1. None: shrub is healthy; there is no evidence of vole damage, burrows, or runways
2. Mild: less than 20 percent of the shrub shows effects of vole damage
3. Moderate: girdling may be present; shrub shows up to 60 percent mortality
4. Severe: over 60 percent of the shrub is dead
5. Mortality: shrub is 100 percent dead

VOLE BURROWS

Is burrow present beneath shrub?	YES	NO
If yes, are soil casts present at opening	YES	NO

VOLE RUNWAYS PRESENT

1. No runways are present
2. Runways on bare ground surface are obvious and exhibit active use
3. Presence of old runways, not actively in use
4. Runways are only present below cover vegetation
5. Combo: runways are on bare ground and below vegetative cover
6. Runways connect to multiple shrubs

EVIDENCE OF OTHER PREDATORS PRESENT

Figure 2. Vole Damage Assessment Form

distance of less than 6 meters (high density) and greater than 6 meters (low density). High- and low-density samples are scattered across the cover and do not completely correspond to visually obvious areas of low shrub density. The repository cover data were also broken into groups according to the sample point location (east, central, and west [see Figure 1]). Each data point on the repository cover was therefore characterized in two ways (e.g., sample point 21 is a high-density sample point located in the central portion of the cell).

To clarify details of the revegetation effort, a records search was performed to identify seed sources, live plant sources, subspecies, and revegetation techniques. Existing data from annual monitoring reports of the repository cover were reviewed. Literature searches also addressed the ecology of voles, sagebrush and rabbitbrush varieties and subspecies, seed germination requirements, and climate data.

3.0 Results and Discussion

Results are summarized in three major groups: vegetation parameters, soil parameters, and wildlife parameters.

3.1 Vegetation Parameters

Vegetation parameters include shrub density, shrub volume, species composition, seed source, revegetation techniques, the 2005 re-seeding effort, interspecific competition, vesicular arbuscular mycorrhizae, seed germination requirements, and climate. Relevant vegetation cover data are also included. Non-parametric statistical tests were applied to quantitative vegetation data and are reported in the text where applicable (Wilcoxon Rank Sum Test for two groups; Kruskall-Wallis Test for multiple groups).

3.1.1 Shrub Density and Volume

Results of the shrub density and volume measurements are summarized in Table 1.

Table 1. Average Shrub Density and Volume

Area	Plants per Acre	Shrub Volume (cubic inches)
Repository cover, all (n=30)	115	15,488
Low density samples (n=11)	53	14,732
High-density samples (n=19)	441	16,795
East end (n=13)	191	11,500
Central portion (n=7)	40	16,992
West end (n=10)	411	19,621
Zone A2/B Analog (n=9)	496	24,500
Rabbitbrush Analog (n=5)	399	119,712
Sagebrush Analog (n=5)	2,686	4,134

Shrub density is more than 20 times higher in the Sagebrush Analog area than on the repository cover. The absence of understory grasses, probably from historical grazing, may have allowed the shrubs to reach unnaturally high densities. Shrubs may be smaller in this area because of intraspecific competition (competition from individuals of the same species) resulting from high densities, and also because the dominant plant in the analog area is mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*), a dwarf sagebrush subspecies. The repository cover supports two larger subspecies along with mountain big sagebrush (see Section 3.1.2).

In the Rabbitbrush Analog area, shrubs are denser and larger than on the cover, although they are approximately the same age. One probable explanation is that rabbitbrush, the dominant shrub in the analog area, grows faster than sagebrush. Also, the cover of understory grasses is lower in the analog area than on the repository cover, and this may reduce interspecific competition.

In the Zone A2/B Analog area, shrubs are also denser and larger than on the cover. Interspecific competition (Section 3.1.6) or soil structure (Section 3.2.4) may be partially responsible for these differences.

Within the repository cover area, shrub size may decrease slightly from west to east, but the differences were not statistically significant. Although shrubs may be smaller on the east end than in the central portion, the density of shrubs is higher on the east end. Shrubs in high-density samples do not differ significantly in size (p=.05) from shrubs in low-density samples or from the average repository cover shrub. Because density and size are not well correlated within the repository cover, it is probable that different factors affect density and size.

3.1.2 Shrub Species Composition

Live species composition and the percentages of seedlings and dead shrubs are summarized in Table 2.

Table 2. Shrub Species Composition

Area	Composition by Species, Live Shrubs (%)[a]					Seedlings (%)	Dead Shrubs (%)
	Artr va	Artr wy	Artr tr	Erna	Pera		
Repository cover (all) (n=120)	23	18	39	2	0	4 (Artr)	15
Low-density samples (n=44)	28	18	33	0	0	0	23
High-density samples (n=76)	20	18	45	3	0	7 (Artr)	8
East end (n=52)	13	31	42	2	0	2 (Artr)	10
Central portion (n=28)	29	4	29	0	0	4 (Artr)	36
West end (n=40)	30	10	43	3	0	8 (Artr)	8
Zone A2/B Analog (n=40)	10	18	38	10	0	23 (Artr)	3
Rabbitbrush Analog (n=20)	0	0	0	75	0	25 (Erna)	0
Sagebrush Analog (n=20)	70	0	0	0	5	10 (Artr)	15

[a]Artr va=*Artemisia tridentata* ssp. *vaseyana* (mountain big sagebrush); Artr wy=*Artemisia tridentata* ssp. *wyomingensis* (Wyoming big sagebrush); Artr tr=*Artemisia tridentata* ssp. *tridentata* (basin big sagebrush); Erna=*Ericameria nauseosa* (rabbitbrush); Pera=*Peraphyllum ramosissimum* (Squaw apple)

The Sagebrush Analog area is dominated by mountain big sagebrush and does not contain other subspecies. Mountain big sagebrush is less common on the east end of the repository and in the Zone A2/B Analog area than in other portions of the repository cover. Many factors may be responsible for this difference, and its significance is not known.

Seedling percentages are higher in all the analog areas than on the repository cover. No seedlings were observed at low-density sample points. This may be due to the reduced seed source from nearby mature plants in these locations. It may also be influenced by competition from weedy plants, estimated at 17 percent at the low-density sample points, compared to 9 percent at the high-density points. The differences in weedy plant cover at the time of sampling in 2006 probably reflect differences in 2004 and 2005, when seedlings would have germinated. However, this cannot be verified because vegetative cover data are not available for the specific sampling locations before 2006.

Shrub mortality is higher in the central portion of the repository cover than at the east and west ends, even though shrub density is lower. On the cover, mortality is related to vole damage (Section 3.3). Shrub mortality is lowest in the Zone A2/B and Rabbitbrush Analog areas. Shrub mortality is similar between the cover and the Sagebrush Analog area; these values may not be comparable because sagebrush wood persists for many years, and mortality values in the analog area probably represent a much longer time frame than on the cover.

3.1.3 Seed Sources and Revegetation Techniques

Records related to the repository seeding in 2000 were reviewed, and it was determined that rabbitbrush and all subspecies of sagebrush seed originated in Utah. Table 3 details the seed mix used, including seed origin. Seed sources from outside Utah may have contributed to the lack of success of some species, but other species from outside Utah (e.g., western wheatgrass from Washington) have been highly successful.

Table 3. Seed Mix Used in 2000 Revegetation of the Repository Cover

Scientific Name	Common Name	Variety	Origin	#PLS/Acre[a]
Achillea millefolium	White yarrow		NZ[b]	0.12
Achnatherum hymenoides	Indian ricegrass	Nezpar	CAN	2.00
Agropyron smithii	Western wheatgrass	Rosana	WA	3.00
Artemisia tridentata ssp. *tridentata*	Basin big sagebrush		UT	0.10
Artemisia tridentata ssp. *vaseyana*	Mountain big sagebrush		UT	0.10
Artemisia tridentata ssp. *wyomingensis*	Wyoming big sagebrush		UT	0.05
Aster tanacetifolia	Prairie aster		CA	0.05
Astragalus cicer	Cicer milkvetch	Oxley	CAN	1.60
Bromus marginatus	Mountain bromegrass	Bromar	WA	4.00
Elymus lanceolatus	Thickspike wheatgrass	Critana	WA	3.00
Ericameria nauseosa	Rabbitbrush		UT	1.50
Erigeron speciosus	Aspen daisy		UT	0.15
Hesperostipa comata	Needle and thread grass		WY	2.00
Linum lewisii	Lewis blue flax	Appar	WA	2.00
Pleuraphis jamesii	Galleta grass	Viva	TX	1.00
Purshia tridentata	Antelope bitterbrush		ID	1.00
Sphaeralcea coccinea	Scarlet globemallow		UT	0.50
Sphaeralcea grossulariifolia	Gooseberry leaf globemallow		UT	0.50

[a]#PLS/Acre=pounds of pure live seed per acre.
[b]Text on seed label reads "NZ," but the seed probably came from Nevada rather than New Zealand.

As many as 14 varieties of rabbitbrush occur naturally in Utah (Welsh et al 1993, USDA 2006, Nesom 2006). Each has different morphological and physiological traits, adapted to different areas of the state. It is not known which variety or mixture of varieties of rabbitbrush seed were used to revegetate the repository.

Repository cover seeding was completed on April 27, Zone A2 seeding on May 3, and live planting on May 5, 2000. Field notes describing the seeding and planting process indicate that revegetation of the repository cover was performed by experienced personnel (W.D. Yards and Bitterroot Restoration, Inc.), and appropriate techniques were employed[2]. The origin of the live plant stock could not be determined, but all plants were inoculated with mycorrhizae before planting.

Inadequate watering and hot weather were listed as potential concerns during planting. In the 2000 monitoring report (Collins 2000), shrub survival was estimated to be approximately 75 percent. The shrubs were planted at a density of 400 plants per acre, and their current density is approximately 100 plants per acre. While transplant shock, water stress, heat stress, or other factors associated with the revegetation process may account for part of the shrub loss (approximately 100 plants per acre), other factors are likely responsible for the loss of the additional 200 plants per acre after 2000.

3.1.4 Reseeding in 2005

In summer 2005, an interseeding effort was accomplished on the repository cover to address the shortage of shrubs and forb species. The perennial grass bottlebrush squirreltail (*Elymus elymoides*) was also included to provide springtime competition for cheatgrass (*Bromus tectorum*). Table 4 shows the seed mix used in the 2005 reseeding effort. Seed was broadcast in early April and again in July 2005. Little or no evidence of germination was observed during vegetation monitoring in 2006. Possible explanations include interspecific competition (Section 3.1.6), lack of rainfall (Section 3.1.7), and vole predation (Section 3.3).

Table 4. Seed Mix Used in 2005 Seeding of Repository Cover

Scientific Name	Common Name	Origin	#PLS/Acre
Artemisia tridentata ssp. *tridentata*	Basin big sagebrush	UT	0.50
Elymus elymoides	Bottlebrush squirreltail	WA	3.00
Ericameria nauseosa	Rabbitbrush	UT	2.00
Krascheninnikovia lanata	Winterfat	NM	1.00
Purshia tridentata	Antelope bitterbrush	OR	0.50

3.1.5 Vesicular Arbuscular Mycorrhizae

Mycorrhizae were found associated with 92 percent of the live sagebrush root samples. Eight percent of the samples (located on the repository cover and Sagebrush Analog area) did not show obvious hyphae and/or spores. The high percentage of mycorrhizae, as well as documentation that planted shrubs were inoculated, indicate that the presence or absence of mycorrhizae is not a major factor in sagebrush establishment.

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[2] The OHM subcontractor did not include follow-up watering in the planting and seeding subcontracts. Watering by OHM was limited and probably inadequate.

3.1.6 Interspecific Competition

The effects of competition were not directly measured in this study, but it is known that interspecific competition (competition between different species) does affect shrub populations. Less interspecific competition may partially explain why shrubs in the Zone A2/B Analog area are larger and have a higher density than those on the cover. Non-woody cover is higher on the repository cell (52 percent) than in Zone A2/B Analog area (43 percent)[3].

Interspecific competition may also be a factor in the low success of the 2005 reseeding effort. New seed was broadcast across the cell, and in most areas, perennial grasses were already well established. Seedlings, especially grass seedlings such as bottlebrush squirreltail, may have difficulty competing with existing plants.

While interspecific competition may have some effect on shrub density and health, it is not considered among the most important factors. Several observations support this assumption. In 2001, an area with poor seed germination and elevated densities of cheatgrass was mapped in the center of the repository cover ("cheatgrass area"). Portions of this area contain low shrub density points identified in 2006, but many of the points do not occur in the cheatgrass area. Perennial grasses (a significant component of interspecific competition) were estimated to comprise 41 percent of the cover at high shrub density sample points, compared to 35 percent at low shrub density sample points. If interspecific competition is primarily responsible for low shrub densities, this trend would be reversed. The cover of perennial grasses at individual sample points containing seedling sagebrush was similar to the cover across the repository (approximately 38 percent); this suggests that competition from perennial grasses also does not greatly affect sagebrush seedling establishment.

Species associations differ between the repository cover and the analog areas. These associations were not evaluated for potential effects on interspecific competition, but are summarized in Table 5.

Table 5. Understory Species Associated with the Study Zones

Area	Associated Herbaceous Species	Observations
Repository Cover	Wheatgrasses (western, thickspike, crested, slender, bluebunch, intermediate), cheatgrass, needle and thread grass, smooth brome, globemallow, blue flax, pigweed, prickly lettuce, Russian thistle, tall tumblemustard, salsify.	Greater density of perennial grasses than Rabbitbrush and Sagebrush Analog areas.
Zone A2/B Analog	Wheatgrasses (western, thickspike, crested, slender, bluebunch, intermediate), cheatgrass, needle and thread grass, smooth brome, curlycup gumweed, annual sunflower, blue flax, yellow and white sweetclover, globemallow, alfalfa, devil's shoestrings, tall tumblemustard, prostrate vervain, cheese mallow.	Similar to understory of repository cover, with lower density of perennial species and a greater diversity of weeds.

[3] Annual repository cover monitoring data (DOE 2006a) show that non-woody plant cover is approximately 52% on the repository cover, 49% in Zone A2, and 37% in Zone B. An estimate of the cover in the Zone A2/B Analog area (a small subset of Zones A2 and B) is 43%, the mean of the two values.

Table 5. Understory Species Associated with the Study Zones (continued)

Rabbitbrush Analog	Smooth brome, salsify, cicer milkvetch, evening primrose, globemallow, purple aster, alfalfa, broom snakeweed.	Understory is rather sparse but consists primarily of desirable forbs.
Sagebrush Analog	Fringed sagebrush, horsebrush, cheatgrass, prickly pear, broom snakeweed, globemallow, crested wheatgrass, flower of an hour, Indian ricegrass, purslane, tansymustard, fleabane.	Forbs and perennial grasses comprise less cover than repository cover, but diversity is very high. Some small juniper and piñon.

3.1.7 Seed Germination Requirements and Climate Data

Seed germination requirements for sagebrush and rabbitbrush are potentially pertinent in determining why these species did not establish well on the repository cover[4]. Although the seeds of many species (e.g., most grasses) persist for years in the soil, rabbitbrush (USDA 2006) and sagebrush (NSL 2006) seeds persist for only one season. In addition, sagebrush seed may require cold stratification to germinate. It is unlikely that the seed was stratified by the supplier prior to shipment, and seeding was done in April 2000, after natural stratification would have occurred.

Germination rates and requirements vary between rabbitbrush varieties (NSL 2006), but most varieties tend to germinate over a narrow range of moisture conditions. Mortality of seedlings is usually due to water stress after early May each year, and seedling emergence and establishment

are severely limited in dry years (USDA 2006). Table 6 shows a summary of precipitation data from Monticello between 2000 and 2005. In 2000, the 3-month period immediately following seeding was exceptionally dry, and this may be the major cause of poor sagebrush and rabbitbrush seed germination. Grass and forb seeds, which persist longer in the soil, would have emerged later, when conditions were more favorable, and the presence of these seeded species indicates that this occurred.

Table 6. Summary of Monticello Precipitation Data 2000–2005

Year	Total Precipitation (inches)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	1.58	0.83	2.90	0.03	0.49	0.22	0.97	2.29	1.95	2.95	1.22	0.20
2001	2.03	1.41	1.06	1.74	0.73	0.29	0.77	2.87	0.42	0.48	2.03	1.04
2002	0.08	0.01	0.45	0.10	Missing	Missing	2.13	0.90	1.95	1.68	1.32	0.38
2003	0.17	3.24	1.46	0.02	0.32	0.13	0.51	2.32	1.77	0.91	1.98	1.55
2004	0.63	1.70	0.20	1.34	0.00	0.71	0.74	1.55	3.69	2.01	2.30	2.94
2005	7.01	2.96	0.89	1.25	0.58	0.34	0.95	2.44	2.36	0.89	0.54	0.00
Average	1.51	1.13	1.07	0.92	0.93	0.56	1.49	1.94	1.49	1.66	1.23	1.26

Although precipitation in April 2005 was adequate to germinate rabbitbrush, the following 2 months were dry. However, young rabbitbrush plants, likely having germinated in 2004 and 2005, were observed in the Rabbitbrush Analog area and in Zone A2, indicating that favorable

[4] The lack of observed seedlings between 2000 and 2004 suggests that most of the sagebrush currently growing on the cell was planted live in 2000 and did not emerge from seed sown in 2000.

conditions existed. Climate itself may not have been a major factor preventing the germination of rabbitbrush seed from the 2005 re-seeding effort; interspecific competition by mature vegetation for moisture (Section 3.1.6) is the most likely explanation. Rainfall appears to have been adequate for germination of seed sown in July 2005, but the late-summer timing may not have been optimal.

3.2 Soil Parameters

Soil bulk density and other soil parameters affect root depth, water retention, and hydraulic conductivity throughout the root zone. Due to resource and time limitations, measurements were taken only in the upper portion of the root zone in 2006. Additional data at greater depths are required to adequately evaluate the effects of soil parameters on shrub density, growth, and survival. Preliminary results presented in the following sections represent only the upper portion of the soil profile; an incomplete picture.

Soil parameters investigated include bulk density, moisture, fertility, structure, and texture, each detailed separately in Sections 3.2.1—3.2.4. Non-parametric statistical tests were applied to the soil data, and significances are reported in the text as applicable. The Mann-Whitney U Test was used to compare two medians, and the Kruskall-Wallis Test was used to compare multiple medians.

3.2.1 Soil Bulk Density

Soil bulk density samples on the repository cover and the analog sites all have values similar to those of the area's native soils. Soil bulk density measurements are summarized in Table 7.

Table 7. Soil Bulk Density

Area	Soil Bulk Density (g/cc)			
	1-ft depth	Std. dev.	2-ft depth	Std. dev.
Repository cover (all) (n=15)	1.52	0.09	1.48	0.19
Low shrub density samples (n=5)	1.52	0.11	1.39	0.13
High shrub density samples (n=10)	1.52	0.08	1.53	0.20
East end (n=5)	1.48	0.06	1.42	0.15
Central portion (n=5)	1.51	0.10	1.39	0.11
West end (n=5)	1.58	0.08	1.70	0.14
Zone A2/B analog (n=4 [1 ft]; n=1 [2 ft])	1.70	0.15	1.57[a]	-
Rabbitbrush analog (n=5)	1.47	0.08	1.35	0.14
Sagebrush analog (n=5)	1.41	0.10	1.34	0.13

[a]Data derived from one sample point only; bulk density samples were not collected at the 1-ft depth at pit A2-12 and at the 2-ft depth at pits A2-6, A2-8, A2-9, and A2-13 because of the high percentage of gravels and cobbles.

The Zone A2/B Analog area contains denser soils than the repository cover (p=0.01) at 1-ft depth, probably because of a greater rock fraction. Repository cover soils are approximately 8 to 9 percent denser than soils in the Sagebrush Analog area at both depths (p=0.05). Differences in bulk density values as little as 0.1 gram per cubic centimeter (g/cc) can indicate more substantial differences in soil compaction. Therefore, soil compaction on the repository may be inhibiting sagebrush establishment compared to native soils. Differences between the Rabbitbrush Analog area and the repository cover soils are not statistically significant at either depth. This suggests that rabbitbrush establishment may not be substantially affected by these differences in soil compaction. It is unknown whether bulk density values may be affecting shrubs at depths greater than 2 ft because in this study, deeper samples were not taken.

At a depth of 2 ft, soils are approximately 20–22 percent denser in the western portion of the cover (p=0.05) than in the eastern and central portions (which do not differ significantly from one another). Excessive soil compaction was observed during cell construction on the western end of the cell; this issue was corrected on the eastern end. Bulk density differences may persist because of these differing construction techniques. However, at the 1-ft depth, there is no statistically significant difference in soil bulk density between the eastern, western, or central portions of the cover. No significant differences exist between the low shrub density and high shrub density samples at either soil depth. This suggests that soil bulk density, at least in the upper portion of the root zone, does not have a major effect on shrub density values. However, it may affect shrub size, as shrubs on the western portion of the repository are smaller (though denser) than shrubs in the central and eastern portions (see Section 3.1.1).

3.2.2 Soil Moisture

Soil moisture measurements did not show clear trends, probably because rainfall events occurred at random times on all sampling dates. The difference between 1- and 2-ft depths also showed no clear trends. Soil moisture measurements are in Table 8. Negative values in the percent change column indicate that soils were moister at 1 ft than at 2 ft; positive values indicate that soils were drier at 1 ft than at 2 ft.

Table 8. Soil Moisture

Area	Soil Moisture (%)		
	1-ft depth	2-ft depth	% change (1–2 ft)
Repository cover (all) (n=15)	9.59	7.62	–20.5
Low shrub density samples (n=5)	8.38	7.70	–8.1
High shrub density samples (n=10)	10.39	7.57	–27.1
East end (n=5)	10.12	7.62	–24.7
Central portion (n=5)	8.88	7.72	–13.1
West end (n=5)	10.37	7.64	–26.3
Zone A2/B analog (n=4 [1 ft]; n=1 [2 ft])	10.52	13.91[a]	+32.2
Rabbitbrush analog (n=5)	8.40	8.54	+1.7
Sagebrush analog (n=5)	11.32	9.48	–16.3

[a]Data derived from one sample point only; soil moisture samples were not collected at the 1-ft depth at pit A2-12 and at the 2-ft depth at pits A2-6, A2-8, A2-9, and A2-13 because of the high percentage of gravels and cobbles.

3.2.3 Soil Fertility

Table 9 summarizes soil fertility results. Soil pH is slightly alkaline and similar at all locations and depths, ranging from 7.8 to 8.7. Salts are also similar; soil conductivity ranges from 0.21 to 0.34 millimho per centimeter (mmho/cm). The average organic matter content is slightly higher on the repository cover than in the Rabbitbrush and Zone A2/B Analog areas, probably because of soil amendments used during revegetation. Organic matter content is similar on the cover and in the Sagebrush Analog area, probably because the analog area has built up leaf litter over time. Concentrations of soil macronutrients (nitrogen, phosphorus, and potassium) and micronutrients (sulfate, zinc, iron, manganese, copper, calcium, magnesium, sodium, and boron) are similar across areas and depths, and all are within typical ranges. For this reason, soil fertility limitations are probably not inhibiting shrub establishment.

Table 9. Average Soil Fertility Values at 1-ft and 2-ft Depths

Area	pH	Salts (mmho/cm)	Organic Matter LOI-%	Nitrates (ppm)[a]	Phosphorus (ppm)	Potassium (ppm)
Repository cover						
East end	8.1/8.4[b]	0.24/0.27	1.0/1.2	0.2/0.3	9/8	135/148
West end	8.3/8.3	0.34/0.21	1.0/1.1	1.9/1.0	9/12	129/162
Central portion	8.0/8.3	0.27/0.27	1.5/1.4	0.7/0.8	11/14	155/147
Zone A2/B Analog	8.4/8.7	0.25/0.28	0.9/0.7	0.3/1.1	7/7	117/97
Rabbitbrush Analog	8.1/8.5	0.23/0.27	0.8/0.6	0.2/0.2	3/9	91/108
Sagebrush Analog	7.8/8.5	0.28/0.30	1.4/1.1	0.3/0.3	12/4	229/151

[a]ppm=parts per million
[b]1-ft depth is listed first, followed by 2-ft depth

3.2.4 Soil Structure and Texture

Qualitative assessments were recorded for soil structure in sampling pits. The repository consists of a soil/gravel admixture approximately 4 to 15 inches deep, overlying a compacted subsoil containing weathered coarse fragments. In surface horizons, only weak structural development was noted. In subsurface horizons, soil structure was graded as “massive,” indicating that no structural development had taken place. Soil often appeared to be compacted in horizontal planes. Zone A2/B Analog soils contain a weathered rock subsoil layer below a shallow soil/gravel admixture that is 5 to 12 inches deep. Again, weak structure was observed in surface horizons, and no discernable structure was found in subsoil horizons. In the Sagebrush Analog area, all the soil profiles contained well-developed argillic horizons (zones of translocated clay accumulation that had strong blocky structure). Coarse fragments occurred in several sample pits in both the surface and argillic horizons. The Rabbitbrush Analog area contains friable soils and few coarse fragments. Soil structure was not examined at these sample locations, as an auger (versus a sharpshooter shovel) was used to collect samples. However, the soils are assumed to contain some structure, as they are composed of former subsoils.

The texture of the fine earth fraction and estimates of the coarse fragment content at the 1-ft and 2-ft depths are summarized in Table 10. The volume of coarse fragments was not quantitatively measured during soil sampling, and only general estimates were made in the field through observation. The textural class is categorized in accordance with the U.S. Department of Agriculture system. The categories—loam, clay loam, and sandy clay loam—are made on the basis of particle size differences and differences in the physical properties associated with each category. From an agricultural perspective, loams behave similarly to other loams, clay loams behave similarly to other clay loams, etc., (Brady 1974).

The most discernible difference in the six areas is the volume of coarse fragments. The surface horizons of the three repository cover areas essentially have the same texture—a gravelly loam. Differences in sand, silt, and clay composition between the three areas are minor and would not be expected to have a noticeable effect on plant growth. In contrast, differences in textural classes and in the volume of coarse fragments could make notable differences in soil properties such as permeability, available water capacity, structure, and porosity (Soil Survey Staff, Natural Resources Conservation Service 1996). The Zone A2/B Analog area has more coarse fragments than all the other areas, and the Rabbitbrush Analog area has the least. The Sagebrush Analog area has a similar volume of coarse fragments as the repository cover, but the former has a more clayey texture and stronger structure than the latter.

Table 10. Soil Texture

Area	% Sand		% Silt		% Clay		Texture	% Coarse Fragments (by volume)	
	1 ft	2 ft	1 ft	2 ft	1 ft	2 ft		1 ft	2 ft
Repository cover, east	31	38	37	23	46[a]	25	Loam/loam	5–30	8?
Repository cover, west	44[b]	31	42	23	33[a]	27	Loam/loam	5–30	8?
Repository cover, central	41	28[a]	47[a]	25	35	25	Loam/sandy clay loam	5–30	8?
Zone A2/B Analog	35	31	43	26	40	26	Loam/loam	30–50	7[c]
Sagebrush Analog	33	35	35	34[b]	33	30[b]	Clay loam/clay loam	0–30	5–30
Rabbitbrush Analog	29[a]	37	35	26	45[a]	26	Loam/clay loam	0–trace	0–trace

[a]Varies more than 2 standard deviations from the mean.
[b]Varies more than 3 standard deviations from the mean.
[c]At 2-ft depth, coarse fragments were weathered and not easily discernible; no specific observations were made on the repository cover or in the Zone A2/B Analog area.

Given the complexity in the interaction of soil properties, it is difficult to pinpoint the primary contributor to the lack of shrub establishment. The most obvious differences between the repository cover and the analog area soils appear to be associated with soil structure and coarse fragment content. Greater growth is observed in areas with well-developed subsoils (e.g., Sagebrush and Rabbitbrush Analog areas) and a higher volume of coarse fragments (e.g., Zone A2/B Analog area). More study of soil structure, particularly in the deeper horizons that were not sampled in this study, and the effects of coarse fragments on shrub growth is recommended.

3.3 Wildlife Parameters

Investigation of wildlife parameters focused mainly on montane voles. Effects from other wildlife (e.g., cottontail rabbits [*Sylvilagus* sp.]) are not regarded as major potential factors in shrub establishment between 2000 and 2006.

3.3.1 Summary of Vole Damage Assessment

A summary of the field vole data is provided in Table 11. More detailed information can be found in the separate report, *Vole Damage Assessment of the MMTS* (DOE 2006b).

Approximately 72.5 percent of the surveyed shrubs were found damaged or dead, and 67.6 percent of the damaged shrubs also had vole presence recorded. Of the 22 completely dead shrubs, 20 also had vole presence recorded. In some instances multiple vole burrows were found beneath the central trunk, and runways were typically obvious. One of the dead shrubs without vole presence was a rabbitbrush in the Zone A2/B Analog area, and the other was a sagebrush shrub from the Sagebrush Analog area.

Table 11. Summary of Shrub Damage and Vole Presence by Area (in percentages)

Damage Level	Repository Cover (n=120)		Zone A2/B Analog (n=40)		Sagebrush Analog (n=20)		Rabbitbrush Analog (n=20)		Total (n=200)	
	Shrub Damage	Vole Presence	Shrub Damage	Vole Presence	Shrub Damage	Vole Presence	Shrub Damage	Vole Presence	Shrub Damage	Vole Presence
None	26.7	11.7	37.5	5.0	15.0	0	25.0	0	27.5	8.0
Mild	45.0	39.2	60.0	25.0	15.0	0	30.0	5.0	43.5	29.0
Moderate	6.7	6.7	0	0	25.0	10.0	45.0	10.0	11.0	6.0
Severe	6.7	6.7	0	0	30.0	0	0	0	7.0	4.0
Mortality	15.0	14.2	2.5	2.5	15.0	10.0	0	0	11.0	10.0
Total	73.3	78.3	62.5	32.5	85.0	20.0	75.0	15.0	72.5	57.0

Because vole presence was higher on the repository cover, the repository cover data are described more fully. Table 12 summarizes repository cover data and compares damage within each category. The mild category of damage dominated all damage levels recorded; a significant category of damage was also shown to have associated vole presence.

Table 12. Damage Assessment of Repository Cover

Level of Damage	No. of Shrubs in Category	% of All Shrubs	No. of Shrubs with Vole Presence	% of Shrubs with Vole Presence
None	32	26.7	14	43.7
Mild	54	45	47	87
Moderate	8	6.7	8	100
Severe	8	6.7	8	100
Mortality	18	15	17	94
Total	120		94	78

Approximately 73 percent of all shrubs on the repository cover showed damage, and 78 percent showed vole presence, regardless of whether there was noted damage to the shrub. For example, 32 shrubs showed no damage, yet 14 shrubs showed vole presence. On the repository cover, of the 88 shrubs that showed damage, 90.9 percent also showed the presence of voles. The percentage of damaged shrubs showing evidence of vole presence was 44, 20, and 23.5 in the Zone A2/B, Rabbitbrush, and Sagebrush Analog areas, respectively.

Shrub damage was relatively high in all areas, but vole presence was much lower in the analog areas than on the repository cover. A combination of factors may explain this result. Rabbitbrush damage in the Rabbitbrush Analog area may be due to greater predation by cottontail rabbits and jackrabbits (*Lepus* sp.), which prefer rabbitbrush to sagebrush. In the Sagebrush Analog area, observed mortality probably occurred over a much longer time frame than on the repository cover, because sagebrush wood persists for many years. Nevertheless, other factors including drought may also have damaged sagebrush shrubs in the area, independent from vole-related damage. In 2006, a local rancher reported large vole populations in the nearby area. The Bureau of Land Management has also reported drought-related sagebrush death in many areas.

3.3.2 Summary of Vole Ecology

Montane voles utilize an often extensive runway system with numerous burrow openings. They typically eat grasses but also gnaw on the bark or taproots of woody plants. Voles do not hibernate in winter.

Voles breed promiscuously and continuously, making control difficult. Populations fluctuate in unpredictable cycles, each explosion lasting 2–4 years. It is generally recognized that imbalances in one or more aspects of the environment (common to disturbed areas) can trigger population explosions, and this may explain why voles are more abundant on the repository cover than in other areas. Populations are typically tracked by predators in classic predator-prey population curves. Therefore, predators are not able to control vole populations in the early stages of the cycle. Vole predators in the area include raptors, coyotes, and foxes. Population explosions can cause extensive damage to vegetative cover and death to stands of sagebrush. Predation on grass seeds also decreases the seed bank of desirable species.

Positive roles of voles in the ecosystem include predation on annual grasses (including cheatgrass) and dispersal of mycorrhizae. They also affect decomposition rates in the litter layer and soil chemistry and structure through their burrowing and waste products. Vole activity may have affected vegetation composition at the repository. Some understory vegetation changes measured during the 2006 annual vegetation monitoring, including an increase in Russian thistle and a decline in cheatgrass, may be attributable to vole disturbance.

3.3.3 Impact of Voles on Shrub Establishment

Voles are expected to remain a large factor in future sagebrush establishment, but they probably had little impact on shrub establishment and health on the repository cover prior to about 2005. In 2006, most of the shrub mortality observed on the cover can be reasonably attributed to voles. It would be expected that higher mortality rates would be measured in portions of the cell with higher shrub densities (e.g., the west end) than in areas with lower shrub densities (e.g., the central portion). However, the opposite trend was observed on the repository cover. The reason for this is unknown, but it may be because vole populations invaded the central portion of the cover first.

Possible reasons for greater vole damage on the repository cover than in the analog areas include:

- Greater densities of understory vegetation, including cheatgrass, on the repository cover, which provide cover from predators and food sources for voles. Because cheatgrass populations decreased in 2006, this may be less of a factor in 2007.
- The presence of large rocks in the subsurface in some portions of analog areas may be less conducive to vole establishment.
- Although the root distribution of sagebrush has not been studied at the site, roots occupying shallower soil horizons would likely be more damaged by voles than deeper roots. If roots are not penetrating as deeply in the repository cover (which would have to be determined by future study), voles could more easily damage larger percentages of the shrub roots while eating taproots during the winter in their burrows.

- Rabbitbrush is able to re-sprout from root fragments, but sagebrush is not. This ability to regenerate may change the shrub success rate to favor rabbitbrush over sagebrush.

Predation on seeds (particularly grass seeds) may have contributed to the failed reseeding effort in 2005. However, predation on cheatgrass seeds may have resulted in a positive impact; prior to 2006, cheatgrass infestations were growing exponentially on the site.

4.0 Summary

Differences in shrub density and volume were identified within portions of the repository cover and between the cover and analog areas, but density and volume differences do not appear to have the same causes.

Interspecific competition may have influenced the success of the 2005 reseeding effort but probably has not greatly affected the health and density of established sagebrush on the cover. Climate conditions and planting times are the most probable cause of the lack of shrub seed germination in 2000.

Planting techniques were professional and appropriate, but watering after planting may account for up to one-third of the shrub loss. Additional losses may have been caused by a lack of soil structure or vole predation. Soil bulk density has likely affected the health and size of sagebrush on the east end of the cover.

Mycorrhizae and soil nutrition do not appear to be important factors affecting shrub establishment on the repository cover. Soil moisture measurements are inconclusive because of random rainfall events during sampling.

4.1 Recommendations

A proposal has been submitted to the U.S. Environmental Protection Agency (EPA) for a follow-up study in 2007, to evaluate relationships between soil structure (preferential flow), saturated hydraulic conductivity, water flux, water storage profiles, and shrub ecology. The work would be jointly funded by EPA, the National Science Foundation, DOE, and the U.S. Nuclear Regulatory Commission at Monticello and other EPA Alternative Cover Assessment Program sites. This study would include sampling at depths greater than 2 ft.

Any actions that reduce the amount of dead vegetation on the repository cover would be expected to reduce vole populations as well. Possible actions would include controlled grazing (which would also disrupt vole burrows), the use of herbicide to selectively reduce cheatgrass, and controlled burning. Actions that would encourage predator populations would also reduce vole populations. Such actions could include removing large sections of fencing to allow small carnivores (and grazing mammals) easier access, and constructing raptor perches and/or nesting boxes on the site. Because of the breeding capacity of voles and their degree of establishment, chemical controls would be largely ineffective and may target unintended wildlife.

Although not specifically measured or calculated, total productivity in the Sagebrush Analog area (and therefore its ability to withdraw water from the soil) may be much higher than on the repository cover because the density is 23 times higher than that of the cover, but the shrub size is only 6 times smaller. Though the density of the shrubs in the Rabbitbrush Analog area is similar to the density in portions of the cover, the average shrub volume is three to six times the volume on the cover. As a result, the productivity is probably much greater. Shrub productivity and water use on the cover could be enhanced substantially by the establishment of a relatively small number of large rabbitbrush plants.

Live rabbitbrush planting is recommended because additional interseeding is unlikely to be successful. Rabbitbrush is less susceptible to vole damage than sagebrush, and it can re-sprout from the root crown; rabbitbrush can contribute to the development of soil structure; and individual rabbitbrush plants grow quickly. Therefore, they may provide a plausible intermediate successional community to sagebrush while fulfilling the water use role of shrubs on the cover.

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