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Liesenfeld, Zachary J., Investigation of Sagebrush Reclamation Success on Bentonite Mined Areas in the Big Horn Basin (Wyoming, USA) M.S. Ecosystem Science and Management, May 2013

The Big Horn Basin located in north central Wyoming has some of the largest deposits of high quality bentonite in the world. Historically, reclamation efforts to establish plant communities similar to conditions found in big sagebrush (*Artemisia tridentata*) grassland plant communities before mining have been limited due to the absence of shrub regulatory standards and poor response of sagebrush to reclamation efforts on bentonite mine lands. The lack of suitable shrub cover is believed to have a negative effect on sagebrush obligate species, such as the greater sage-grouse (*Centrocercus urophasianus*). The objective of this study was to determine if sagebrush communities were reestablishing on reclaimed bentonite mined lands in the Big Horn Basin under conventional reclamation techniques. Findings indicate that sagebrush establishment on reclaimed bentonite lands in the Big Horn Basin has not been successful using conventional methods. At study sites, sagebrush plants were not established in adequate densities on sites seeded within the past 15 years. However, it does appear conventionally reclaimed sites older than 15 years are undergoing natural recolonization of sagebrush to greater densities than found on the younger sites. In this study, 11 reclaimed and six native reference sites were analyzed throughout the Big Horn Basin. Five sites were reclaimed in the past 15 years, while six were reclaimed more than 15 years ago. The younger sites had a mean sagebrush density of 900 stems ha^{-1} while the older sites had a mean of 5140 stems ha^{-1}. Native reference sites had a mean sagebrush density of 10,763 stems ha^{-1}. Even the densities of the older reclaimed sites were only about half of observed sagebrush densities on native reference sites. These results indicate that conventional methods of sagebrush reestablishment used in bentonite mineland reclamation are ineffective in the short term, 15 years or less. That is, initial seeding efforts during site

reclamation result in very little sagebrush establishment. However, over longer time periods (ca. 15-30 years), natural seed dispersal of native sagebrush from undisturbed areas surrounding reclaimed mine sites appears to have resulted in greater densities of sagebrush plants. Included are sagebrush height and canopy cover to aid in better understanding natural reestablishment rates. It is also believed that other newly developed reclamation technologies may be more effective in reestablishing sagebrush communities on reclaimed bentonite mined lands.

INVESTIGATION OF SAGEBRUSH RECLAMATION SUCCESS ON BENTONITE MINED AREAS IN THE IN THE BIG HORN BASIN (WYOMING, USA)

by
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A thesis submitted to the Department of Ecosystem Science and Management
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DEDICATIONS

I would like to dedicate my thesis to my parents, Rick and Cathy Liesenfeld, for offering support, and encouragement throughout my academic career

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CHAPTER 1: LITERATURE REVIEW

INTRODUCTION

Bentonite clay is found worldwide with large deposits in Montana, South Dakota, and Wyoming. In 2007, Wyoming sodium bentonite production produced over four million tons of bentonite (Wyoming Mining Association, 2011). Large scale bentonite mining began in the Big Horn Basin area around the 1930's (Schuman et al., 1985). There are three economically important geological areas of bentonite in Wyoming including the Clay Spur areas around Upton and Newcastle, the Colony Area located in the northeast corner of Wyoming and along the east and west flanks of the Big Horn Range (Wyoming Mining Association, 2001). Bentonites producing stratigraphic units in Wyoming include the Aspen Shale, Bear River Formation, Belle Fourche Shale, Carlile Shale, Frontier Formation, Greenhorn Formation, Mowry Shale, Skull Creek Shale and Thermopolis Shale (Wyoming State Geological Survey, 2011). The highest grade of Wyoming bentonite is found primarily in the Upper Cretaceous Mowry Shale (Hosterman and Patterson, 1992). This project focused on mined areas on the Mowry Shale located in the Big Horn Basin of north central Wyoming (Figure 1.1).

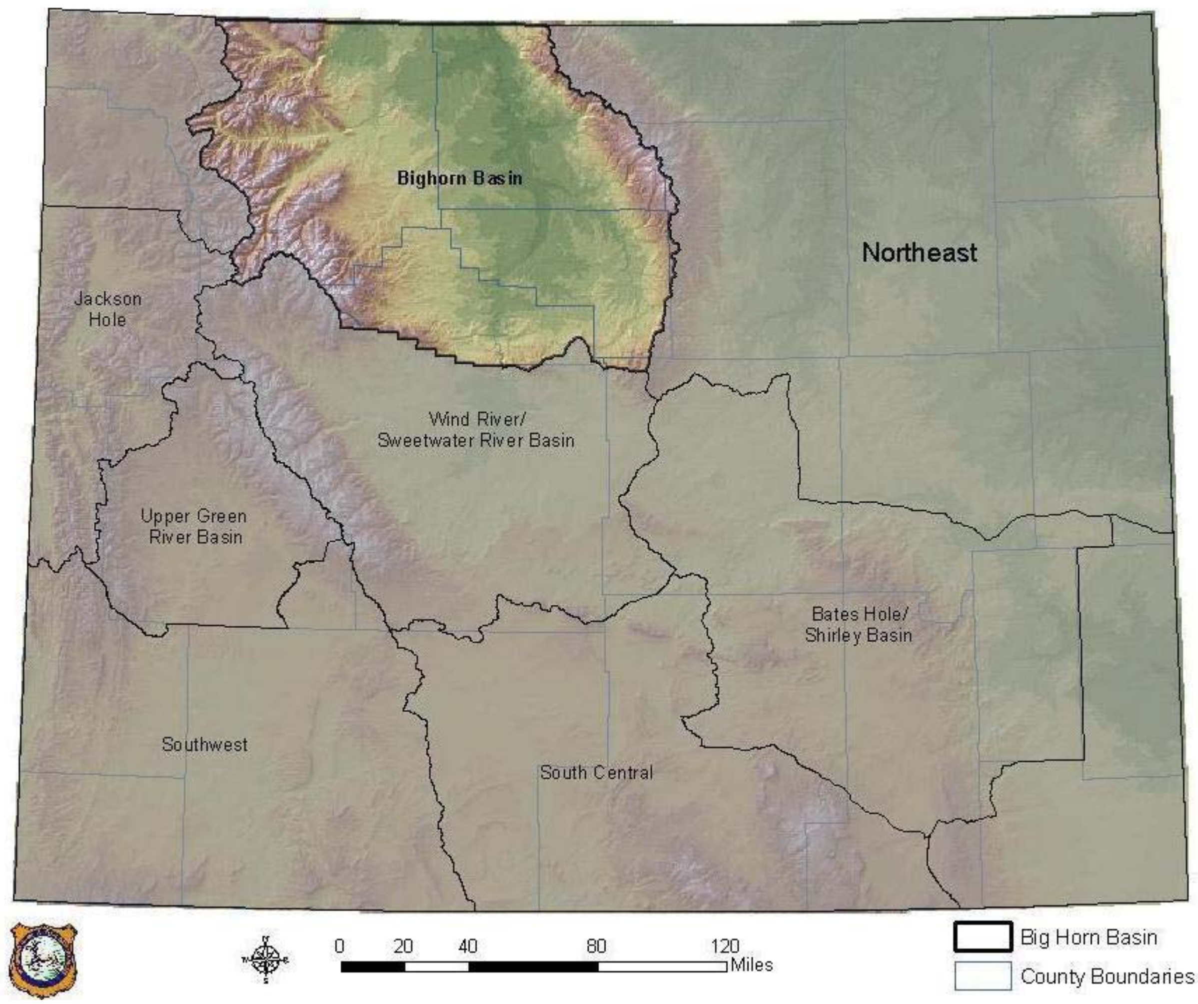

Figure 1.1.Location of the Big Horn Basin in the state of Wyoming, USA. Courtesy of Wyoming Game and Fish Department.

Wyoming bentonite is in high demand due to unique characteristics rarely found anywhere else on earth. Bentonite includes any natural material dominantly composed of clay minerals in the smectite group (Hosterman and Patterson, 1992). Wyoming bentonite is composed essentially of montmorillonite clay, also known as hydrous silicate of alumina (Hosterman and Patterson, 1992). These compounds stack together to form layers or platelets, much like a deck of cards sandwiched together. The chemical composition of bentonite found in Wyoming includes sodium rather than calcium, which is more common in bentonite found in other parts of the world. When this clay mineral is exposed to water, platelets separate, inducing swelling. The presence of sodium allows Wyoming bentonite to swell up to 16 times its original size and can absorb up to 10 times its own weight in water (Wyoming Mining Association, 2001). Major uses of Wyoming bentonite are as absorbents, drilling fluids, iron ore pelletizing, animal feeds, and sealants. Another important use for bentonite in the last few years has been as an absorbent in pet litter. Wyoming bentonite has also been used to seal reservoirs and landfills; it is also used in the production of crayons, medicines, and cosmetics (Wyoming Mining Association, 2001).

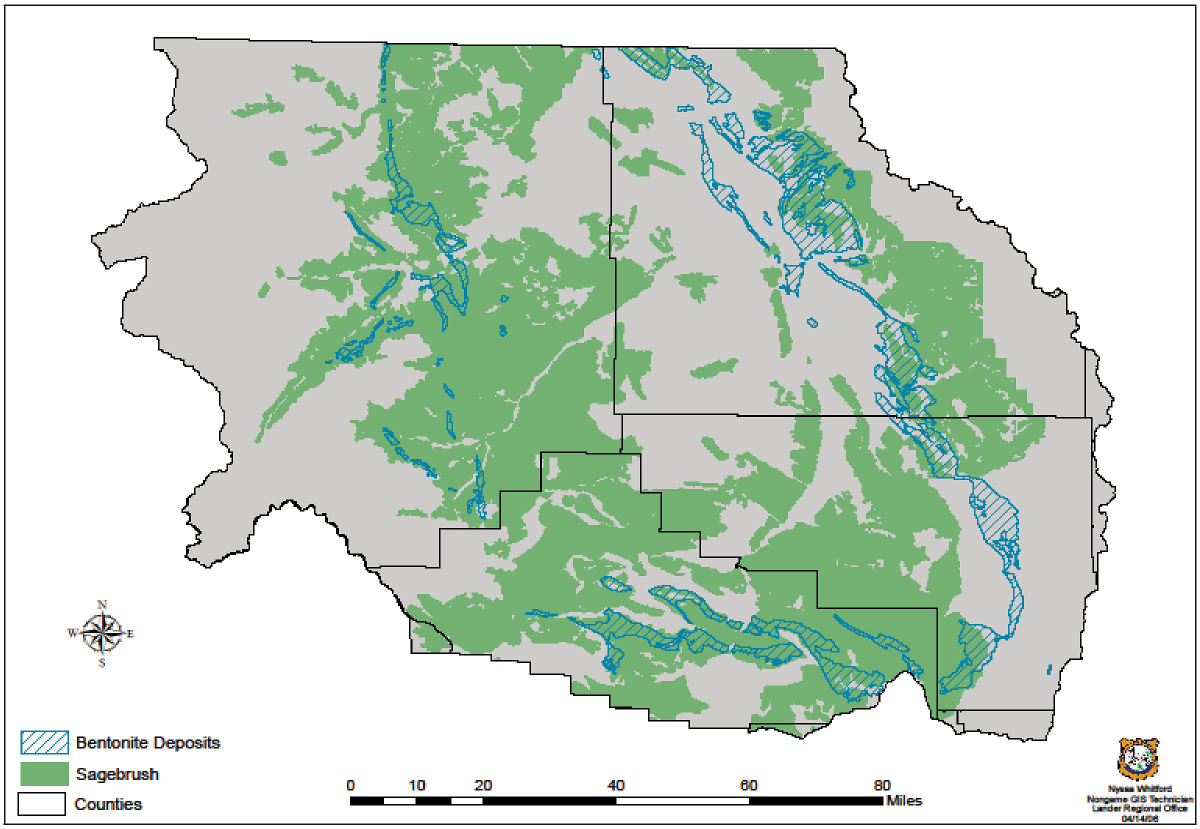

Figure 1.2. Location of bentonite beds under sagebrush shrub communities within the Big Horn Basin USA. Courtesy of Wyoming Game and Fish Department.

THE BIG HORN BASIN

The Big Horn Basin consists of the geographically isolated Big Horn River drainage and bound by the Big Horn Mountains on the east; Big Horn Mountains, Bridger Mountains and Owl Creek Mountains on the south; Absaroka Mountains on the west; and Beartooth Mountains and Pryor

Mountains on the north. The average valley elevation is 1,524 m (1,116 m min) and is composed of badland type topography and buttes (Big Horn Basin Local Sage-Grouse Working Group, 2007). Within the Big Horn Basin several environmental factors contribute to the limited amount of shrub regrowth. The Big Horn Mountains block the flow of moisture-bearing air from the east. Many of the bentonite mining sites located in this area receive only 12-25 cm of annual average precipitation, making the Big Horn Basin the driest part of the state. Most of this precipitation comes in April and May as rain (Western Regional Climate Center, 2012; Figure 1.3).

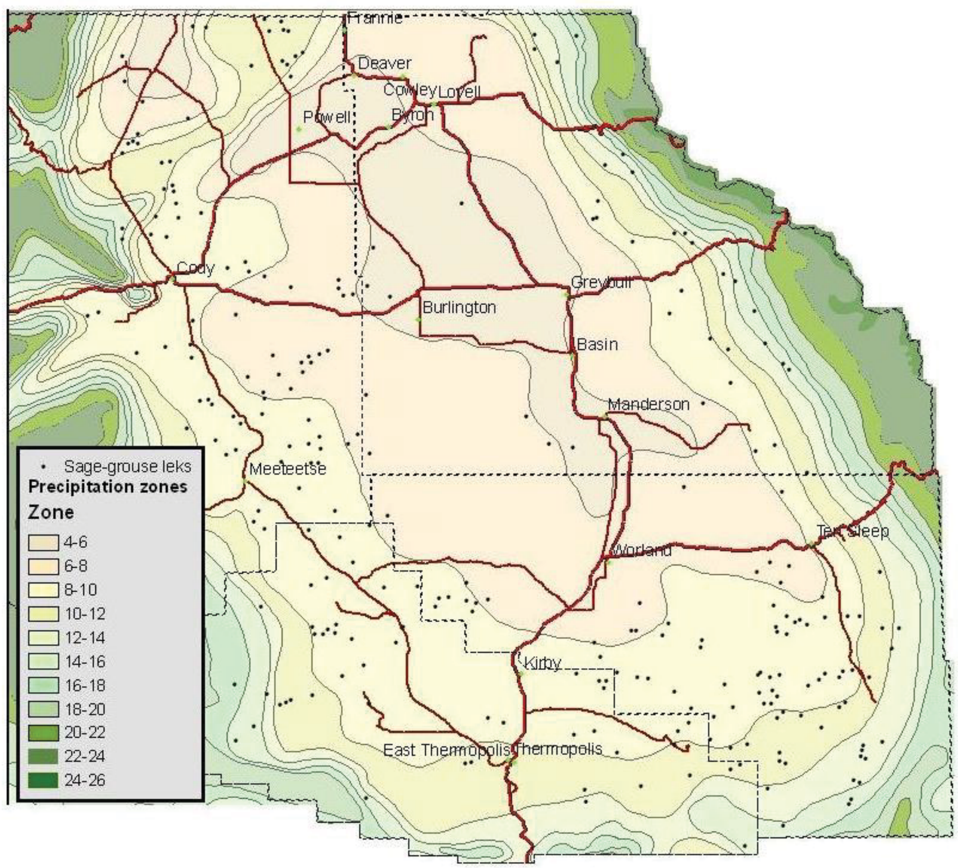

Figure 1.3. Precipitation zones (in) and distribution of active sage-grouse leks in the Big Horn Basin, USA. Courtesy of the Wyoming Game and Fish Department.

Predominant cover types within the Basin include: big sagebrush (*Artemisia tridentata*)/grassland, salt desert shrub, agricultural crop and pasture lands at lower elevations, mixed mountain shrub, mixed conifer and aspen forests at higher elevations, cottonwood-riparian corridors, and urban areas. Most bentonite mining disturbs sagebrush/grassland and salt desert shrub habitat types that are positioned on semiarid upland topography between the Big Horn Mountain foreland on the east and the Sheep Mountain Anticline to the west. Surface topographies include gentle to steeply sloping valleys, ravines, ridges, and upland slopes with variable aspects.

Mixed desert shrub communities on upland habitats are dominated by big sagebrush, spiny hopsage (*Grayia spinosa*), yellow rabbitbrush (*Ericameria nauseosus*), green rabbitbrush (*C. viscidiflorus*), and greasewood (*Sarcobatus vermiculatus*). Barren bentonite and shale outcrops are interspersed throughout, often associated with alternating beds of incompetent and resistant sedimentary rock (M-I SWACO Wyoming Mine Permit 278C, 1978). Primary land uses in the Basin include: livestock grazing, wildlife habitat, dry-land and irrigated crop production, oil and gas development, bentonite mining, recreation and urban/suburban developments. Sheep and cattle are the primary livestock species. Most ranching operations include federal or state grazing leases (Big Horn Basin Local Sage-Grouse Working Group, 2007).

HISTORICAL BENTONITE MINING TECHNIQUES AND IMPACTS

Due to the irregular distribution of minable bentonite, mine pits tend to be interspersed within non-mined areas in discontinuous patterns across landscapes and differ from other mining methods currently used in the Northern Great Plains. Bentonite pits are typically shallow, not exceeding a 10:1 stripping ratio, generally less than 15 m deep and range from one to eight ha in size (Schuman et al., 1994). Therefore, bentonite mining tends to be a more “extensive” than “intensive” land disturbance (Schuman et al., 1985). Strip mining is the preferred method of extracting bentonite from the ground. Bentonite mine pits are located throughout the Big Horn

Basin within bentonite bearing geological strata. Thus, it is critical for companies to use mining practices producing the lowest possible impact on vegetation and soils while using reclamation techniques that produce the highest success, especially when mining near sage-grouse habitat (Big Horn Basin Local Sage-Grouse Working Group, 2007).

The long-term goal of mine land reclamation and revegetation is reestablishment of a usable, healthy, and sustainable environment that meets post-mining land use objectives (Munshower, 1994; Harris et al., 1996). Techniques for extracting bentonite are summarized best by Schuman et al. (1985 pg. 43): "With current mining methods, scrapers and bulldozers remove the topsoil and replace it on regraded spoil or stockpile it for later use. The overburden is then removed, and either placed in adjoining pits, and regraded and contoured or stockpiled for later use as backfill for the open pit. The use of scrapers in a cast-back mining method results in the inversion of pre-existing strata, placing the material high in soluble salts closer to the surface. This material and poor quality bentonite may require additional overburden to insure adequate burial. The stripping of clay beds and disposal of low quality materials results in high clay material at the spoil surface, which further complicates long-term reclamation success. Current mining laws require that topsoil and suitable subsoil material be salvaged for replacement over regraded spoils."

Reclamation regulations for non-coal surface mining in Wyoming

Due to the demand for Wyoming bentonite products there has been large scale non-coal surface mining in Wyoming. This has created wide scale efforts to adequately reclaim mined sites. Historically, the state of Wyoming's non-coal reclamation standards have not required reestablishment of native shrub communities. Wyoming's current reclamation standards for non-coal surface mining require only reestablishment of about 90% of original native/perennial vegetation cover. This **does not** include a formal shrub (sagebrush) reestablishment standard (Stahl and King, 2010). Existing laws and regulations do not require the presence of native perennial shrubs such as Wyoming big sagebrush (*A. t.* Nutt. ssp. *wyomingensis* Beetle & Young) in plant communities reestablished during the reclamation of non-coal surface mines. The regulation for bond release is located in Chapter 3 of the DEQ non-coal mining rule book (2006), Section2 (d)(vi), and reads as follows:

“The administrator shall not release the entire bond of any operator until such time as revegetation is complete, if revegetation is the method of reclamation as specified in the operator’s approval plan. Revegetation shall be deemed complete when: (1) the vegetation species of the reclaimed land are self-renewing under natural conditions prevailing at the site: (2) the total vegetation cover of perennial species, (excluding noxious weed species) and any species in the approved seed mix is at least equal to the vegetation cover of perennial species (excluding noxious weed species) on the area before mining: (3) the species diversity and composition are suitable for the approved post-mining land use: (4) the requirements in (1), (2) and (3) are achieved in one growing season, no earlier than the fifth full growing season on reclaimed lands. The Administrator shall specify quantitative methods and procedures for determining whether equal total vegetation cover has been established and procedures for evaluating post-mining species diversity and composition (Wyoming Department of Environmental Quality 2006).”

Impacts on vegetation

Topsoil removal using dozers and scrapers completely removes pre-mine vegetation communities. Plant species observed on seeded reclaimed areas, on naturally reinvaded reclaimed sites, and within the native flora associated with undisturbed big sagebrush communities in the Big Horn Basin include: perennial grass species, annual forbs, annual grasses and shrubs (Table 1.1).

Table 1.1. Vegetation species by life-form found in the Big Horn Basin s0tudy area and species that have historically been included in reclamation seeding mixes.
* Dorn, Robert D. 2001. Vascular Plants of Wyoming. 3rd Ed.

Annual Grass

Scientific Name *	Common Name	Native/Introduced	Seeded
Bromus japonicus Thunb. ex Murray	Japanese brome	Introduced	
Bromus tectorum L.	cheatgrass	Introduced	
Agropyron triticeum (Gaetn.)	annual wheatgrass	Introduced	
Monroa squarrosa (Nutt.) Torrey	false buffalo grass	Native	

Perennial Grass

Scientific Name *	Common Name	Native/Introduced	Seeded
Acnatherum hymenoides (R & S) Barkw	Indian ricegrass	Native	
Agropyron cristaum (L.) Gaertn.	crested wheatgrass	Introduced	
Aristida purpurea var. *longiseta* (Steudel) Vasey	red three-awn	Native	
Bouteloua gracilis (H.B.K.) Lag	blue grama	Native	
Calamovilfa longifolia (Hook.) Scribn.	prairie sandreed	Native	
Elymus elymoides (Raf.) Sweazy	bottlebrush squirreltail	Native	
Elymus junceus (Fisch.)	Russian wildrye	Introduced	
Elymus lanceolatus var. *lanceolatus* (Hook.) Scribn. J.G. Sm.	thickspike wheatgrass	Native	x
Elymus lanceolatus var. *riparius* (Scribn. & Sm.) Dorn	streambank wheatgrass	Native	x
Elymus smithii (Rydb.) Gould	western wheatgrass	Native	x
Elymus spicatus (Pursh) Gould	bluebunch wheatgrass	Native	x
Elymus trachycaulus var. *trachycaulus* (Link) Gould ex Shinners	slender wheatgrass	Native	x
Hesperostipa comata (Trin. & Rupr.) Barkworth	needle and thread grass	Native	
Hordeum jubatum L.	foxtail barley	Introduced	
Koeleria macrantha (Ledeb.) Schultes	prairie junegrass	Native	
Leymus angustus (Trin.) Pilg.	Altai wildrye	Introduced	
Leymus cinereus (Scribn. & Mer.) A Löve	Basin wildrye	Native	x
Poa fendleriana (Steudel) Vasey	Fendler bluegrass	Native	

Poa secunda J. Presl	Sandberg bluegrass	Native	
Pucinellia airoides (Nutt.) Watson & J.M. Coult	Nuttal's alkaligrass	Native	
Schedonnardus paniculatus (Nutt.) Trel.	tumblegrass	Native	
Sporobolus airoides (Torr.) Torr	alkali sacaton	Native	
Sporobolus cryptandrus (Torr.) A. Gray	sand dropseed	Native	

Annual Forbs

Atriplex suckleyi (Torrey) Rydb.	Suckley's endopelis	Native	
Bassia scoparia (L.) Schrad.	kochia	Introduced	
Camissonia scapoidea (Nutt. ex Torr.) Raven	Paiute suncup	Introduced	
Chamaesyce glyptosperma (Englm.) Small	ribseed sandmat	Introduced	
Chenopodium album L.	Lambs quarters	Introduced	
Descurainia pinnata (Walter) Britton	western tansymustard	Introduced	
Halogeton glomeratus (M. Beib.) C.A. Mey.	halogeton	Introduced	
Helianthus annuus (L.)	annual sunflower	Native	
Lactuca serriola L.	prickly lettuce	Introduced	
Lappula redowskii auct. Non (Hornem) Greene	flatspine stickseed	Native	
Lepidium densiflorum (Schrad.)	common pepperweed	Introduced	
Lepidium perfoliatum L.	clasping pepperweed	Introduced	
Machaeranthera tanacetifolia (H.B.K.) Nees	tansyleaf tansyaster	Native	
Navarretia leucocephala Benth. ssp. *minima* (Nutt.) Day	least navarretia	Native	
Plantago patagonica (Jacq.)	woolly plantain	Native	
Polanisia trachysperma (T. & G.)	sandyseed clammy weed	Native	
Salsola kali L.	Russian thistle	Introduced	
Sisymbrium altissimum L.	tall tumblemustard	Introduced	
Thlaspi arvense L.	field penny cress	Introduced	
Tragopogon dubius Scop.	yellow salsify	Native	
Cryptantha celosioides (Eastw.) Payson	miner's candle	Native	

Perennial Forbs

Allium textile Nels. & Macbr	textile onion	Native	
Astragalus spp.	milkvetch	Native	
Calochortus nutallii Torr & Gray	Sego lilly	Native	
Castilleja angustifolia (Nutt.) G. Don var. *dubia* A. Nels	desert indian paintbrush	Native	
Eremogone congesta (Nutt.) Ikonnikov var. *congesta*	ballhead sandwort	Native	
Eremogone hookeri (Nutt.) Weber	Hooker's sandwort	Native	
Lesquerella ludoviciana (Nutt.) Wats	foothill bladderpod	Native	
Linanthus pungens (Torrey) Porter &	granite prickly phlox	Native	

Johnson			
Lomatium ambiguum (Nutt.) Coult. & Rose	Wyeth biscuitroot	Native	
Lomatium foeniculaceum (Nutt.) Coult. & Rose	desert biscuitroot	Native	
Machaeranthera canescens var. *canescens* (Pursh) Gray	hoary tansyaster	Native	
Machaeranthera grindelioides (Nutt.) Shinners	rayless tansyaster	Native	
Melilotus officinalis (L.) Pallas	yellow sweetclover	Introduced	
Musineon divarcatum (Pursh) Nutt. Ex Torr. & Gray	leafy wildparsley	Native	
Oenothera caespitosa (Nutt.)	tuffted evening primrose	Native	
Opuntia polyacantha Haw.	Prickly pear cactus	Native	
Orobanche spp.L.	broomrape	Native	
Penstemon nitidus (Dougl. ex Benth.)	waxleaf penstemon	Native	
Phlox hoodii (Richardson)	spiny phlox	Native	
Phlox multiflora (A. Nels.)	flowery phlox	Native	
Platyschkuhria integrifolia (A. Gray) Rydb.	Basin daisy	Native	
Psoralidium lancelatum (Pursh) Rydb.	lemon scurfpea	Native	
Sphaeralcea coccinia (Nutt.) Rydb.	scarlet globemallow	Native	
Suaeda nigra (Raf.) Macbr.	Pursh seepweed	Native	
Tetraneuris acaulis (Pursh) Greene	stemless four-nerve daisy	Native	
Townsendia hookeri (Beanman)	Hooker's townsend daisy	Native	
Vicia americana (Muhl. Ex Willd.)	American vetch	Native	
Xylorhiza glabriuscula (Nutt.)	smooth woodyaster	Native	

Sub-Shrubs

Artemisia pedatifida (Nutt.)	bird's foot sage	Native	
Artemisia spinescens Eaton	bud sagebrush	Native	
Atriplex gardneri (Moq.) Dietr.	Gardner's saltbush	Native	x
Gutierresia sarothrae (Pursh) Britton & Rusby	broom snakeweed	Native	

Shrubs

Artemisia tridentata (Nutt.) var. *wyomingensis* (Beetle & Young) Welsch	Wyoming Big Sage	Native	x
Atriplex canescens (Pursh) Nutt.	four-wing saltbush	Native	x
Atriplex confertifolia (Torr. & Frém.) S. Walton	shadscale saltbush	Native	
Chrysothamnus viscidiflorus (Hook.) Nutt.	green rabbitbrush	Native	
Ericameria nauseousa (Pallus & Pursh) Newson & Baird	rubber rabbitbrush	Native	
Krascheninnikovia lanata (Pursh) A. Mecuse & Smit	winterfat	Native	
Ribes aureum (Pursh)	golden currant	Native	
Sarcobatus vermiculatus (Hook) Torr.	greasewood	Native	

Tetradymia spinosa Hook&Am.	spiny horsebrush	Native	

Many native plant species have not been successfully reestablished on reclaimed bentonite mined areas since bentonite mining began in the Big Horn Basin in the 1930's. This has had a wide scale impact on many wildlife species, including species such as the greater sage-grouse.

Impacts on wildlife

Widespread bentonite mining followed by poor Wyoming big sagebrush reestablishment has led to habitat reduction for many sagebrush-obligate species that depend on these communities for forage and cover (Aldridge et al., 2008). The disturbance of habitat has led to fragmentation and disruption of normal distribution and natural movements of many species located within the Big Horn Basin (Aldridge et al. 2008; Beck et al. 2012). Big sagebrush communities provide habitat for 92 mammal, 93 bird, and 58 reptile and amphibian species (Welch, 2005). Wyoming big sagebrush provides critical resources throughout the year for pronghorn (*Antilocapra americana),* elk (*Cervus canadensis*), mule deer (*Odocoileus hemionus*), and greater sage-grouse (Olson et al., 2000; Beck et al., 2012). An M-I field survey noted that species of special management concern observed within bentonite habitat in the Big Horn Basin include: American kestrel (*Falco sparverius*), bald eagle (*Halianaeetus leucocephalus*), Brewer's sparrow (*Spizella breweri*), burrowing owl (*Athenecuni cularia*), Ferruginous hawk (*Buteo regalis*), golden eagle (*Aquila chrysaetos*), grasshopper sparrow (*Ammodramus savannarum*), lark bunting (*Calomospiza melanocorys*), lark sparrow (*Chondestes grammacus*), loggerhead shrike (*Laniuslu dovicianus*), long-earred owl (*Asio otus*), merlin (*Falco columbarius*), northern harrier (*Circus cyaneus*), prairie falcon (*Falco mexicanus*), redtailed hawk (*Buteo jamaicensis*), sage sparrow (*Amphispiza belli*), sage thrasher (*Oreoscoptes montanus*), short-eared owl (*Asio flammeus*), Swainson's hawk (*Buteo swainsoni*), and vesper sparrow (*Pooecetes gramineus*) (M-I SWACO Wyoming Mine Permit 278C, 1978).

Impacts on soil quality

During the mining process, topsoil is removed and then replaced over the backfilled pit. Impacts from these activities include destruction of soil structure, loss of vegetation, an initial increase in soil organic matter mineralization, compaction, dilution of nutrients, and loss of soil biota (Dangi et al., 2012). Soil disturbance associated with mining activities results in a decline and disruption in the structure and biomass of the soil microbial community (Dangi et al., 2012). Several studies have found a decline in fungal communities (when based on spores, propagules, and hyphae, but not biomass estimates) after a drastic soil disturbance such as surface mining (Allen and Allen 1980; Miller et al. 1985; and Stahl et al., 1988). Mummey et al. (2002a) and Classens et al. (2006) found significant reductions in soil microbial biomass resulting from disturbance associated with surface mining. However, recovery of soil microbial communities through time of disturbed and reclaimed lands is not well understood or studied (Dangi et al., 2012).

There are two ways in which topsoil is removed and replaced: 1) topsoil is stripped from one site and immediately reapplied on another site that is ready for reclamation. This is referred to as "direct haul" and helps to avoid many of the problems caused by stockpiling. However, detrimental impacts associated with soil stripping, reapplication, and tillage remain (Dangi et al., 2012). Topsoil is stored in stockpiles for various time periods until disturbed sites are ready for reclamation (Stark and Redente, 1980). Stockpiled soil may remain in storage for up to 20 years but are usually spread on reclamation sites after shorter storage periods (Dangi et al., 2012). Severe perturbations occurring from surface-mining processes can drastically impact the soil's chemical, physical, and biological attributes (Stahl et al., 2002; Ingram et al., 2005). It was found by Kein et al. (1984) and Dangi et al. (2012) that stockpiling may reduce microbial activities and by Rives et al. (1980) that mycorrhizal infection potential may be reduced. This can result in lower rates of nutrient cycling and decreased availability of nutrients. These negative impacts have been thought to reduce establishment and production of vascular plants after reapplication of stockpiled materials (Aldon, 1975; Reed et al., 1976; Reeves et al., 1979). The characteristics of impacted physical, chemical, and biotic conditions of newly reclaimed soil certainly are attributed to the limited productivity of the microbial community (Stahl et al., 1988). However, Wick et al., (2009a) reported plant community productivity and soil environmental conditions improve due to the recovery of soil aggregation and increase of soil organic matter. Successful revegetation projects are a result of a healthy regeneration of a diverse microbial community (DeGrood et al., 2005).

Greater sage-grouse habitat requirements

Greater sage-grouse are the largest grouse species in North America and once occupied 1,247,000 km^2 of sagebrush habitats in three Canadian provinces and 13 of the western United States (Schroeder et al., 2004, Braun, 2006). Disturbance and limited area of reestablished sagebrush communities are believed to have a negative effect on sagebrush obligate species, such as the greater sage-grouse (Hagen et al., 2007). This has led to negative effects on breeding, nesting, brood rearing, and wintering habitats. Structural features of sagebrush and perennial grass species are used by sage-grouse for protection from harsh weather and predators during nesting, early brood-rearing and late brood-rearing (Gregg et al., 1994; Connelly et al., 2000; Kirol et al. 2012). Forbs found in sagebrush communities provide a vital source of protein for juvenile sage-grouse growth and development as well as other nutrients, such as calcium and phosphorus, required by pre-laying females (Barnett and Crawford, 1994; Connelly et al., 2000).

Also, structural characteristics of perennial grasses such as height and canopy cover, are used by sage-grouse for predator protection during nesting and brood-rearing (Gregg et al., 1994; DeLong et al., 1995; Connelly et al., 2000).

The purpose this study was to determine if sagebrush communities were reestablishing on reclaimed bentonite mined lands in the Big Horn Basin through the use of conventional reclamation techniques. Recently, the U.S. Fish and Wildlife Service provided a listing decision stating that greater sage-grouse are warranted for protection under the Endangered Species Act of 1973, but because threats are moderate in magnitude and do not occur across their range at an equal intensity, the listing is precluded to other species under threat of extinction (U.S. Fish and Wildlife Service, 2010). According to Schroeder et al., (2004) sage-grouse inhabit around 50-60% of their historic range and very little of the sagebrush within this range has remained unaltered or undisturbed since settlement began by Euro-Americans (Knick et al., 2003). No single factor has been identified as the cause for the decline in sage-grouse populations. However, examining several disturbance factors leading to habitat loss and fragmentation are noteworthy as a combination of these factors has led to synergistic loss and fragmentation of sagebrush habitats (Hess and Beck, 2012). Present and future bentonite mining could affect approximately 1445 ha of sagebrush habitat in the Big Horn Basin (Big Horn Basin Local Sage-Grouse Working Group, 2007). Several studies have been conducted to analyze sage-grouse habitat requirements for propagation and survival. We considered a study by Connelly et al., (2000) (Table 2.6) who provide their data from several sage-grouse studies conducted across the range of this species.

This data serve as a basis for assessing adequacy of sagebrush restoration on Big Horn Basin bentonite reclamation to minimal requirements for greater sage-grouse use, survival, and propagation. Sagebrush data gathered from reclaimed bentonite lands for this study were compared to the standards reported above to gain better understanding of sagebrush community development on these lands. These assessments will help land managers make decisions regarding greater sage-grouse needs and adequate sagebrush restoration on reclaimed land.

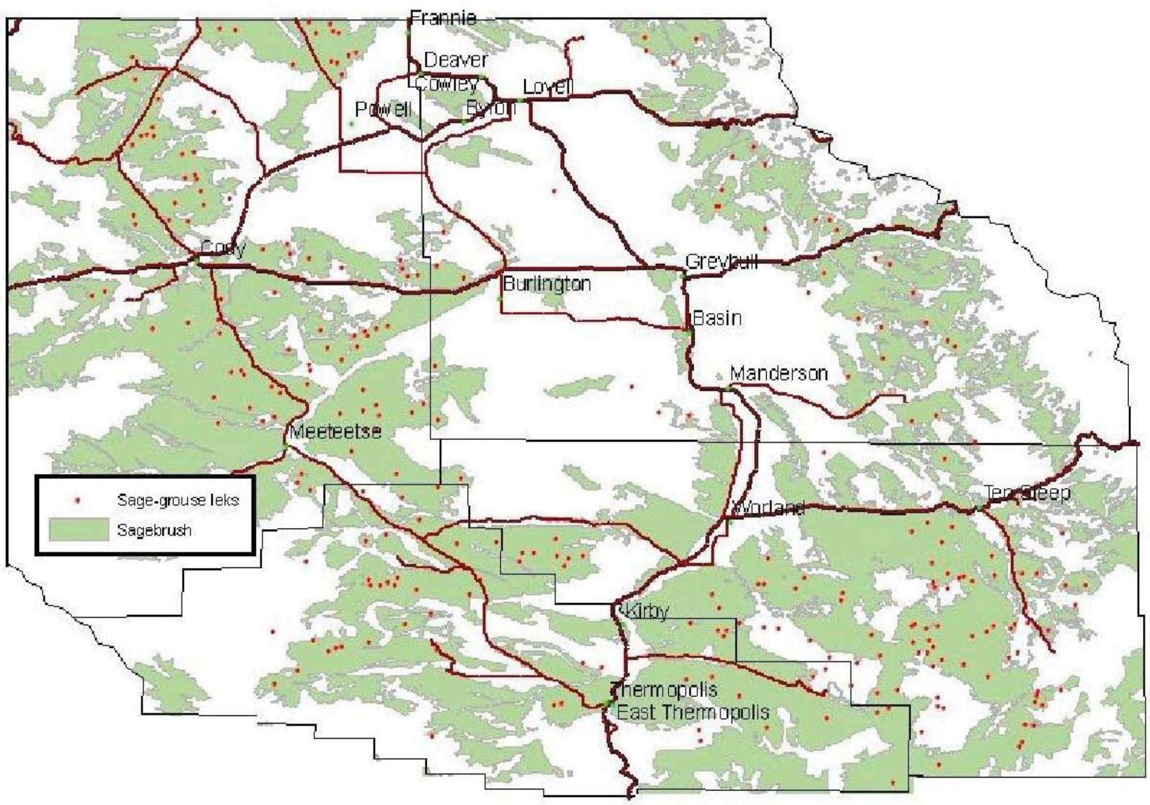

Figure 1.4. Sagebrush distribution and active sage-grouse leks within the Big Horn Basin, USA. Courtesy of the Wyoming Game and Fish Department.

BENTONITE RECLAMATION TECHNOLOGIES

Topsoil salvage and replacement

Salvage and replacement of topsoil became an accepted practice in coal mined land reclamation across northern America during the past 40 years (Schuman et al. 1985). Currently applied reclamation technology used for bentonite mining has largely been extrapolated from that developed for other types of mining. In arid and semiarid rangelands where bentonite mining has occurred, reestablishment of key vegetation species is critical to maintain function, structure, diversity, and stability of landscapes (Fortier et al., 1999). Much of the topsoil materials in the Big Horn Basin of Wyoming are clay loams (Dollhopf and Bauman, 1981 and Hemmer et al., 1977). According to Schuman et al. (1985), unsuccessful reclamation can be due to limited topsoil development as the total soil resource can be as little as 10 cm or up to 45 cm deep or greater in alluvial areas. Generally, salvage and respreading of topsoil results in a maximum of 30 cm of suitable plant growth material over the clay spoil. Thus, relatively little topsoil is available for covering contoured spoil. Cultural practices to improve the response of shrub communities incorporate such techniques as: proper topsoil handling and re-spreading techniques, inorganic amendments, organic amendments, fertilization and correct tillage, and surface preparation (Schuman et al. 1985).

Several historical studies have evaluated the thickness of topsoil material replacement in reclaiming bentonite mines and its effects on soil quality and vegetation reestablishment. Hemmer et al. (1977) analyzed seven study sites throughout Montana and Wyoming that had a topsoil thickness averaging 10 cm. This analysis concluded that 10 cm of topsoil was an insufficient depth of soil media to keep surface treatments such as gouging and deep furrowing from contaminating the topsoil with bentonitic material, reducing the quality of the topsoil present. King (1983) observed topsoil and sub soils up to 30 cm thick on mining spoils that had grass and shrub establishment. However, greater establishment rates were reported after three growing seasons on soils greater than 10 cm in depth than on those areas with minimal 10 cm or no topsoil replacement.

Seeding techniques for big sagebrush

Seeding of big sagebrush has generally resulted in marginal establishment rates on bentonite mined lands (Meyer 1990; Brown et al., 1991; Chambers et al., 1994; Booth et al., 1999). It was noted by Schuman et al. (1985) that the single most limiting characteristic of bentonite spoils is high clay content and subsequent high bulk density. Key shrub species have evolved to exploit the limited resources of these regions and are a vital component of rangeland ecosystem (Fortier et al., 1999; Welch et al. 1986). The competition for available water and soil nutrients, often combined with the presence of saline-sodic soils and low soil pH, has also contributed to limited sagebrush reestablishment on reclaimed mined areas (Sieg et al., 1983). The arid to semiarid and variable climate characterizing much of the Big Horn Basin coupled with threats from invasive species create, challenges in restoring sagebrush necessary for population persistence of sage-grouse and browsing ungulates.

Traditional sagebrush reseeding methods include the use of seed drills and broadcast applicators to distribute sagebrush seed onto disturbed areas (Vicklund, 2000). Implements such as imprinters, chains, harrows and rails are recommended by Stevens and Monsen (2004) as suitable methods to cover newly planted sagebrush seed at or near the soil surface on a firm seed bed. Shaw et al. (2005) recommends covering only lightly by soil on a proper seed bed. Drill seeded sagebrush seed should be planted no deeper than 1.6 mm in depth from the soil surface (Welch, 2005).

Much of the current bentonite reclamation efforts in the Big Horn Basin have concentrated on multi-species seed mixtures composed mainly of Gardner saltbush (*Atriplex gardneri*) and perennial grass species. Consequently, sagebrush reestablishment on bentonite reclaimed lands has generally been very limited but has been observed to occur naturally from offsite seed sources. A study by Seig et al., (1983) noted that only minimal revegetation occurred on orphan spoils for former bentonite mines in Montana after 30 years of abandonment.

WYOMING BIG SAGEBRUSH ECOLOGY

Wyoming big sagebrush is the most xeric subspecies of big sagebrush, generally growing on shallow, gravelly soil on sites receiving 20 to 30 cm of annual precipitation (Cronquist, 1994; Goodrich et al.; 1999, Monsen and McArthur, 1984). It exhibits a ragged growth habit, much like that of Basin big sagebrush (*A. t.* Nutt. ssp. *tridentata*), but most plants are less than 1 m in height with the main stems branching at, or near, ground level. Persistent leaves are narrowly cuneate and emit a pungent odor when crushed (McArthur et al., 1979). Panicles are narrower than those of Basin big sagebrush. Flowering occurs from late July to September and seeds mature in October and November (Monson and Shaw, 2000). Xeric upland sagebrush is noted to set seed only in wet years (Meikle, 2000).

Sagebrush is the common and dominant shrub species throughout much of the Intermountain area. Wyoming big sagebrush also occurs east of the Continental Divide in Montana, Wyoming, and Colorado. Prevéy et al. (2010) and Reisner (2010) state sagebrush is essential to maintaining native plants and limiting invasion of invasive plants in sagebrush communities. Wyoming big sagebrush is most common at low to moderate elevations, but may be found at elevations up to 2,700 m in sagebrush, rabbitbrush, salt desert shrub, juniper (*Juniperus* spp.) and antelope bitterbrush (*Purshia* tridentata) communities (Cronquist 1994, Welsh et al., 1987, and Schultz, 1986). Some sagebrush populations occur in drier climates and form mosaics with salt desert shrubs (McArthur et al., 1979) similar to conditions in the Big Horn Basin. However, within the Big Horn Basin many of these areas have been converted to agricultural use.

Due to semiarid conditions and disturbances that Wyoming big sagebrush communities experience from natural resource development, land managers can have enormous difficulty attempting to restore native plant communities. Natural recruitment is often limited by lack of propagules, drought, a competitive exotic understory, disruption of hydrologic functioning and changes in the soil structure and biota as a result of past disturbance (Shaw et al., 2005). During years of low precipitation, few Wyoming big sagebrush plants may establish; it may take many years before recolonization takes place (Shaw et al. 2005). Sagebrush, however, may be difficult to grow even on undisturbed soils. Sagebrush establishment, in nature, is cyclic, and even under favorable conditions, success can be anticipated in only 1 of 5 years. Soils that did not previously contain sagebrush should not be expected to grow sagebrush after mining (Sage-grouse Conservation Plan for the Big Horn Basin, 2007). Even under favorable conditions, site recovery may require 60 to 100 years on dry Wyoming big sagebrush sites; several years may pass between years with conditions favoring establishment of new seedlings (Clifton, 1981; Lowe-Dalzell et al, 2003; Wambolt and Payne, 1986). Because of these factors, big sagebrush must be artificially reseeded on sites where seed sources have been lost (Shaw et al., 2005).

Meikle (2000) stated that the recruitment of sagebrush seedlings is strongly limited by abiotic and biotic factors. These seedlings are susceptible to frost damage, drought and disease. Reviews conducted by Meyer (1994) and Mozingo (1987) provide valuable information on the reproductive biology of sagebrush. The typical seed size is around 1.0 mm X 0.7 mm. There are approximately 1.7 to 2.5 million pure sagebrush seed per 0.5 kl (NRCS Plant Guild). The seed production of a plant is subject to annual differences depending on available moisture, frost events, intra-specific competition and other factors (Meikle, 2000). Big sagebrush seeds are dispersed primarily by gravity (Shaw et al., 2005). Maximum dispersal distances are only about

30 m from the parent plant; 85 to 90 percent of all seeds fall within 1 m of the edge of the mother plant (Young and Evans 1989; Wagstaff and Welch 1991). Consequently, long-distance dispersal by wind is ineffective in recolonizing large disturbed areas (Meyer 1994).

LIMITING FACTORS ON SAGEBRUSH REESTABLISHMENT

Soil quality characteristics

Schuman et al. (1985) noted several problems with bentonite mining and reclamation practices that limit revegetation success. These are 1) topsoil contamination with bentonite, 2) poor or no topsoil redistribution, 3) compaction, restricting root penetration, and 4) initially established vegetation destroyed as a result of livestock grazing (Hemmer et al., 1977; Seig et al., 1983). Many of these problems accompanied with adverse climatic conditions and soils/spoils characteristics make bentonite mined land reclamation extremely difficult compared to that associated with extraction of other mineral resources (Schuman et al., 1985). Much consideration needs to be given to practices or methods that will loosen the spoil and promote root penetration, water infiltration, and leaching. These practices must be effective for several years to enable good vegetation establishment and initial soil formation and structural development. Care must be taken to avoid contamination of topsoil by poor quality or toxic subsoil materials (Schuman et al., 1985).

Several studies have shown that mutualistic relationships between vegetation and mycorrhizal fungi are affected by severe soil disturbance and the lack of vesicular-arbuscular fungi can hinder the reestablishment of plants (Frost et al., 2000 and Stahl et al., 1998). Unfortunately, soil physical, chemical and biotic characteristics are usually greatly altered by severe land disturbance even if the site is reclaimed and topsoiled (Pederson et al. 1978; Smith and Sobek, 1979; Severson and Gough, 1983). According to Stahl et al. (1988) mixing and movement of topsoil with toxic subsoil is the greatest hindrance to the health of mycorrhizal fungal populations within the soil profile. A number of other studies indicate that arbuscular mycorrhizal (AM) fungi play an important role in the revegetation of disturbed lands (Daft and Nicolson, 1974; Daft et al. 1975; Khan, 1978; Reeves et al., 1979; Frost et al., 2000). It was concluded that after about 12 years soil environmental conditions have improved in a number of ways, and soil organic matter had doubled or quadrupled in the 12 year span of the study. This change can have important effects on a number of soil properties that may influence AM fungi, including moisture holding capacity, soil structure, aeration, cation exchange capacity and composition and size of the soil biota (Brady, 1990; Sylvia et al., 1998). One of the reasons that sagebrush may be slow to reestablish on drastically disturbed lands is the lack of a stable soil profile and the destruction of mutualistic fungi such as arbuscular mycorrhizae (Schuman et al., 1998). Due to the importance of soil mycorrhizal fungi, it is important that soil handling practices during reclamation involve minimal disturbance and minimal mixing practices. Information presented in Dangi et al. (2012), suggests that direct-hauling of topsoil is to be preferred over long-term stockpiling, regardless of the age of reclamation sites.

Competition with other herbaceous species

Several recent studies have addressed the problem of limited shrub reestablishment by evaluating competition of sagebrush and other plant species. Vicklund et al. (2011) concluded competition from herbaceous species influences Wyoming big sagebrush reestablishment rates. Although concurrent planting of grasses, forbs, and shrubs is a common reclamation practice, this approach has often resulted in inadequate shrub establishment due to competition from herbaceous species (Blaisdell, 1949; Shaw and Monsen ,1988; Schuman et al., 1998). Competition from herbaceous species influence sagebrush reestablishment rates as invasive and non-native species, such as cheatgrass, exploit resources sooner than the native plants of the region, occupy large areas and grow at relatively faster rates thus shading sagebrush seedlings (Vicklund et al., 2011). Competition for available water and soil nutrients, often combined with the presence of saline-sodic soils and low soil pH, has also contributed to limited sagebrush reestablishment on reclaimed mined areas (Sieg et al., 1983). However, key shrub species have evolved to exploit the limited resources of these regions and are a vital component of rangeland ecosystems (Fortier et al., 1999).

CHAPTER 2:
INVESTIGATION OF SAGEBRUSH RECLAMAITON SUCCSESS ON RECLAIMED BENTONITE MINED LANDS

INTRODUCTION

Wyoming big sagebrush (*Artemisia tridentata ssp. wyomingensis*) is a subspecies of big sagebrush with its largest distribution across approximately 60 million ha in the American West (Beetle, 1960). Currently, sagebrush only covers 56% of its historic range and is extremely fragmented (Knick et al. 2003). Sagebrush steppe is the dominat vegetation type in the Big Horn Basin in north central Wyoming where large deposits of high quality bentonite are also found (Schuman et al., 1985). These deposits are currently being mined on an extensive scale. Salt desert shrub communities are also widespread throughout the Basin. Impacts from mining activities have resulted in the destruction of topsoil and loss of vegetation (Dangi et al. 2012). Historically, efforts to reestablish plant communities similar to pre-disturbed big sagebrush grassland communities on reclaimed bentonite mined sites have been limited. This is because of high clay content, high salinity, high sodicity and low permeability of the soil/spoil material, and the semiarid climate of the region (Schuman et al., 1994). Also, sagebrush has, in some cases, been planted on sites where the premining vegetation was a salt desert shrub type community. Often many reclaimed bentonite mined areas have very limited or no soil materials suitable for vegetation growth.

Bentonite mining companies have not been held to strict shrub reestablishment standards resulting in inconsistent use of sagebrush seed. Typically, bentonite mine sites reclaimed before the mid 1990s did not have sagebrush seed included in the reclamation seed mixes; while mines reclaimed in the last 15-20 years did. This has led to limited sagebrush reestablishment on reclaimed bentonite mined lands. Another important factor is a lack of requirements for reestablishment of sagebrush on reclaimed bentonite mine sites.

The Big Horn Basin encompasses 32,002 km^2 and includes portions of Big Horn, Hot Springs, Park, and Washakie counties in north-central Wyoming, USA. It is bordered by the Big Horn Mountains to the east, Absaroka Mountains to the west, Bridger and Owl Creek Mountains to the south, and both the Beartooth and Pryor Mountains to the north. The Basin's average elevation is 1,524 m (1,116 m minimum) and consists of badland type topography with intermittent buttes. The Big Horn Basin is semiarid, with average annual precipitation ranging from 13 cm to 38 cm with most precipitation occurring in April and May as rain (National Oceanic and Atmospheric Administration 2012). Predominant land uses in the sagebrush areas include wildlife and domestic livestock grazing, oil and gas extraction and bentonite mining from relatively shallow open pits. Currently, five major and several smaller companies mine bentonite in the Basin on federal, state, and private lands with governmental oversight by both the Bureau of Land Management (BLM) and Wyoming Department of Environmental Quality-Land Quality Division (WDEQ-LQD). A visual representation of a typical bentonite mining operation is given in (Fig. 2.1) which is located in the Lovell area. According to the Environmental Assessment (2012) prepared by the Cody BLM Field Office approximately 8,498 ha have been directly affected by bentonite mining in the Cody District since the 1960s. Around 5,269 ha (62%) of the 8,498 ha have been reclaimed and reseeded, leaving the balance (3,229 ha or 38%), as either under active mining, mined but pending reclamation, or as areas proposed for new mining.

Figure 2.1. Scrapers and bulldozer working on active bentonite pit in the Big Horn Basin located near the Lovell study sites. Summer 2011. Photo by Zachary Liesenfeld.

Where present, big sagebrush is critically important to ecosystem structure and function, providing habitat and forage for sagebrush obligate species such as the greater sage-grouse (*Centrocercus urophasianus)* and forage for ungulates such as, mule deer (*Odocoileus hemionus*) and pronghorn (*Antilocapra americana*) (Hagen et al., 2007, Beck et al. 2012).

The objective for this study was to determine if current and historic reclamation practices lead to successful sagebrush reestablishment on bentonite mine lands in the Big Horn Basin of Wyoming. This was accomplished through observation of vegetation characteristics on 85 reclaimed bentonite mines sites followed by the detailed examination of vegetation on 11 of the sites with greater than 1% sagebrush canopy cover. A secondary objective was to evaluate sage-grouse habitat value of the reestablished sagebrush communities. This was accomplished by comparing sagebrush community structure on reclaimed bentonite mine sites to sagebrush community structure of nearby undisturbed reference areas and to Connelly et al. (2000) sagebrush and canopy cover values in the literature.

METHODS

Field reconnaissance of reclaimed bentonite mine sites was initiated in late summer 2010 and resumed in June and July of 2011. Eighty-five reclaimed bentonite mine sites varying in age from 10 to 35 years since initial seeding were examined with the goal of assessing the historical success of sagebrush reestablishment on these sites in the Big Horn Basin. Vegetation sampling strategies were developed for reclaimed bentonite mine sites that would regularly detect sagebrush at cover values as low as 1 percent; the level that we chose as a cutoff for determining if sagebrush was successfully reestablished at a site. If a site examined in this study was found to have less than 1 % sagebrush cover, we classified it as failed sagebrush reestablishment. Sagebrush community characteristics were measured on reclaimed bentonite mine lands and compared to their representative native reference sites. Soil samples were taken and analyzed for each reclaimed site and the NRCS soils survey website provided the soil quality characteristics for native reference sites.

The amount of sagebrush on these sites was determined by preliminary line intercept transects and detailed visual observations. Fifty (58.8%) of reclaimed sites had no sagebrush reestablishment, were dominated by weeds and deemed unsuccessful reclamation. Thirty (35.3%) sites were estimated to have sagebrush cover greater than 1%. Eleven of these sites with greatest amounts of reestablished sagebrush cover were chosen for further examination of sagebrush community structure. The suitability for sage-grouse habitat was based on sagebrush height and canopy cover suggested by Connelly et al. (2000) and characteristics of nearby undisturbed sagebrush communities. Of the eleven reclaimed sites chosen for detailed structural analysis, three were located near Thermopolis, six were in the Greybull area, and two were located near Lovell, Wyoming. Two undisturbed reference sites were established in native vegetation in proximity to the reclaimed sites in each of the three areas (Thermopolis, Greybull and Lovell, Map 1).

For each site subjected to further examination, sagebrush density, sagebrush canopy cover, and sagebrush height (cm) were recorded. More study sites were chosen in the Greybull area because of its longer history of bentonite mining and more extensive development and reclamation. The inclusion of sagebrush seed into seed mixes around the mid 1990's was the major change noted in recent bentonite mining history. This has been an important change in bentonite reclamation techniques within the Big Horn Basin. Of the eleven reclaimed sites studied, five did not have sagebrush seed included in the seed mix used during the reclamation process (Table 2.1).

Table 2.1. Reclaimed sites included in the detailed community structure analysis, locations, sagebrush seeding dates, and sagebrush seed in mix.

Sagebrush Site Seeding and Dates on Reclaimed Mined Lands

WY Location	Site Names	Date Reclaimed	Sagebrush seed in mix
Greybull	Flitner	1981	-
Thermopolis	T70	1982	-
Greybull	Dump Area	1983	-
Greybull	Old Dam	1983	-
Thermopolis	T74	1983	-
Greybull	134	1993	+
Thermopolis	98T	1997	+
Lovell	LD29	2004	+
Greybull	Beaver Rim	2005	+
Lovell	Animal-Joy	2008	+
Greybull	Hinkley	2009	+

* A + symbol indicates sagebrush seed was included during reseeding. A – symbol indicates no sagebrush seed was used during reseeding.

Including the native reference sites, the Thermopolis area had a total of five study sites. Three sites were located several kilometers northeast of Thermopolis; the others were approximately eight kilometers west of town. Two undisturbed native reference sites were chosen in close proximity to each reclaimed site (one on the west and one on the northeast) for comparison purposes. These had similar soil type, slope, aspect, and precipitation to reclaimed sites. There were eight study sites in the Greybull area and four sites located in the Lovell, Wyoming area. Figure 2.2 shows locations of all 17 study sites with sage-grouse core areas highlighted in dark green and current sage-grouse distribution in light green. All of our study sites were located in areas of current distribution for sage-grouse and some were located in the proximity of sage-grouse core areas. Table 2.2 shows the UTM coordinates (NAD83) and collection dates for each reclaimed and reference sites.

Table 2.2. UTM coordinates and collection dates for each study site.

	UTM Coordinates			
Site	**Zone**	**Easting**	**Northing**	**Date Collected**
Thermopolis Reclaimed T98	12	739220	4839220	06.24.2011
Thermopolis Reclaimed T74	12	741595	4841054	06.22.2011
Thermopolis Native Reference T74	12	740686	4841758	06.22.2011
Thermopolis Reclaimed T70	12	715848	4838201	06.30.2011
Thermopolis Native Reference T70	12	715654	4838453	06.30.2011
Lovell LD 29 Reclaimed	12	731979	4956823	06.20.2011
Lovell Native Reference	12	732366	4957917	06.20.2011
Lovell Animal Joy Reclaimed	12	710270	4968420	06.20.2011
Lovell Animal Joy Native Reference	12	711284	4965894	06.20.2011
Greybull Old Dam	13	270290	4943302	06.14.2011
Greybull Hinkley	13	269401	4944102	06.13.2011
Greybull Flitner	13	270996	4938768	06.15.2011
Greybull Dump Area	13	270849	4942170	06.14.2011
Greybull Beaver Rim	13	271998	4943803	06.15.2011
Greybull Native Reference	13	270218	4948781	06.16.2011
Greybull 134 Reclaimed	13	263017	4347367	06.21.2011
Greybull 134 Native Reference	13	262904	4946987	06.21.2011

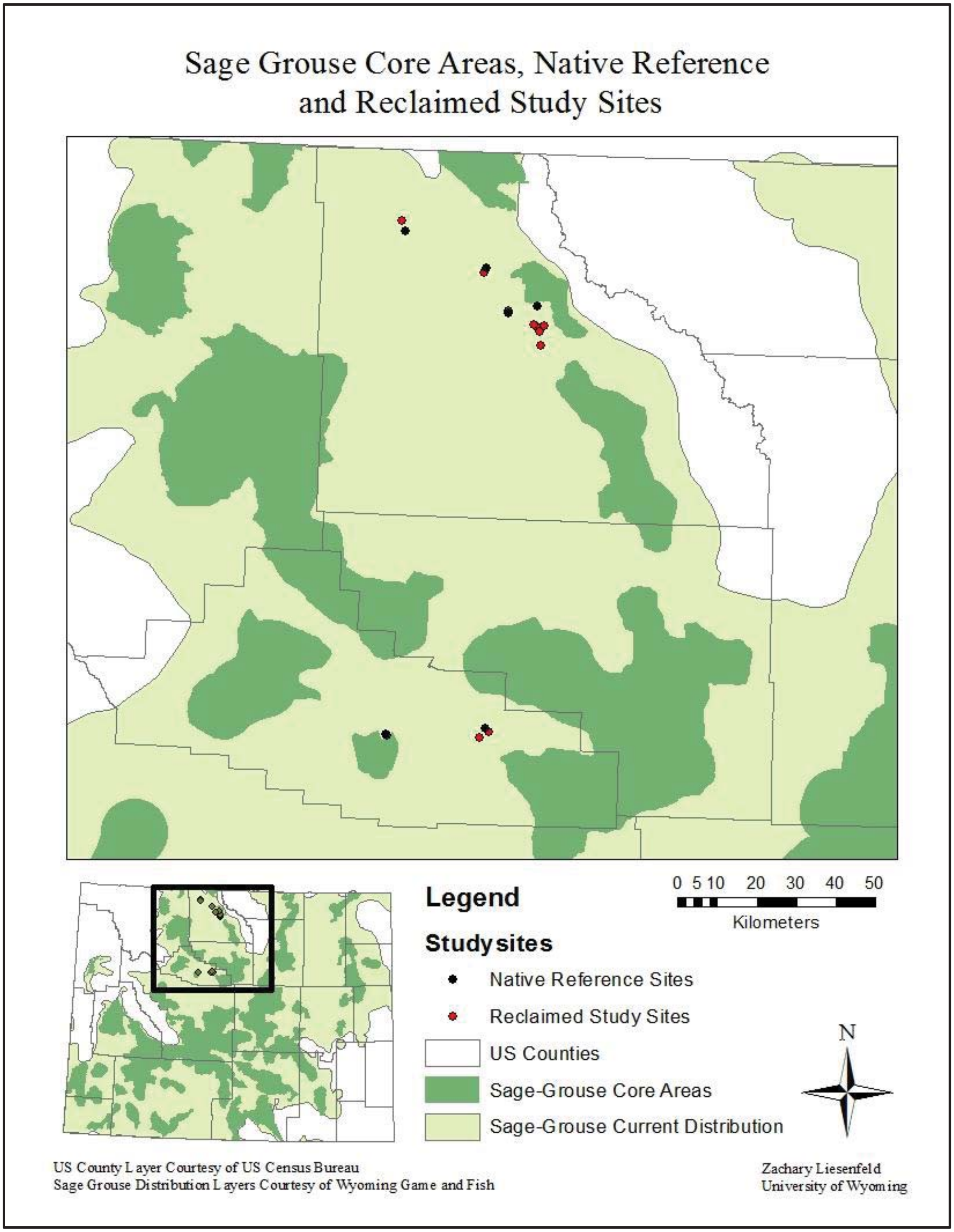

Figure 2.2. Greater sage-grouse distribution and core areas, reference, and reclaimed sites within the Big Horn Basin of north-central Wyoming, USA.

Vegetation analysis

Reclaimed sites chosen for further examination of sagebrush community structure ranged in size from 0.5 to 10 ha. Vegetation sampling methods were chosen to accurately describe overall plant communities. A combination of line intercept, point intercept, and belt transect methods were used to collect sagebrush and vegetation data (Coulloudon et al., 1999). The frequency transect design was used as the primary total transect design as it applies to a wide variety of vegetation types and is well-suited for grasses, forbs, and shrub type communities (Bonham, 1989). The frequency design is highly objective and repeatable as each secondary transect originates at a randomly selected mark along the baseline/primary transect. Randomization is restricted so about half of the transects are randomized on each side of the halfway mark of the transect (Hyder et al., 1963; Francis et al,. 1972; USDI, 1985).The same methods were used in both reference and reclaimed sites. Figures 2.3 and 2.4 show primary transects running through a reclaimed and native reference site.

Figure 2.3. GB 134 reclaimed site with transect Tape. Greybull summer 2011. Photos by Zachary J Liesenfeld.

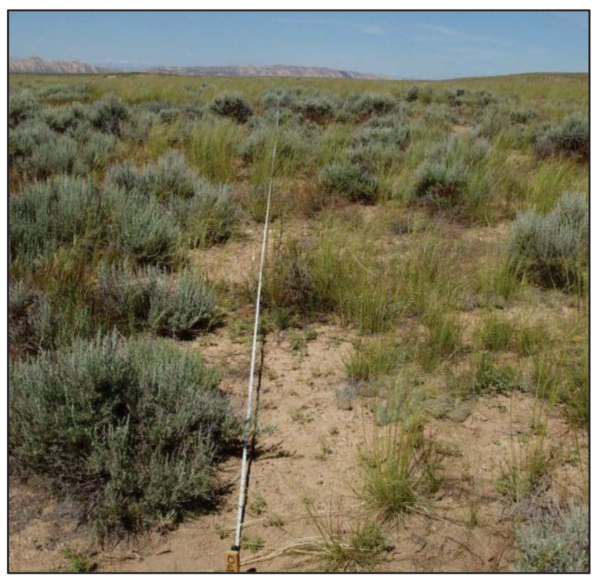

Figure 2.4. GB 134 native reference site with transect tape. Greybull summer 2012.

Primary transects were located on eleven reclaimed sites in areas with observable sagebrush reestablishment and six undisturbed native reference sites. Undisturbed reference site locations had the same basic environmental conditions as reclaimed sites and were located within 0.5 km. Primary transects were 50 m long with twenty (20), 25 m long secondary transects perpendicular to the primary transect at random 1 m designations and random right or left designations (Hironaka, 1985; Bonham, 1989). This method fulfilled our goal of 500 vegetation samples per transect, and met statistical analysis requirements for comparing the reclaimed site to the native undisturbed. This allowed for sampling to occur on smaller reclaimed sites, while having enough points to accurately sample larger sites.

Line intercept was used for shrub canopy cover as this method is suited for semiarid brunchgrass-shrub vegetation types (Brun et al., 1963; Buckner, 1985). Point intercept was used along a set of transects to estimate cover for individual species and species composition. This method is suited to vegetation types that are less than 1.5 m in height (Brown, 1954; Buckner, 1985). Sagebrush density was recorded using belt transects, which are broadly applicable and well suited for grasses, forbs, shrubs, and trees (Krebs, 1989). All vegetation species located within each transect were recorded to allow further analysis of reclaimed areas in relation to sage-grouse habitat requirements. Height, species type, and ground cover (i.e. rock, litter, and bare ground), were recorded using the point intercept method. The line intercept and belt transect density readings were used only to record sagebrush species.

Species identity and height were recorded. The goal was to characterize shrub community establishment and associated species within each reclaimed mine site. When a sagebrush species was located under the transect tape it was recorded and its, height and intercept length were recorded to calculate average height and canopy cover. Point intercept data also included ground cover readings for bare ground, litter, or rock. Belt transects were read at a 1-m width along the right side of each 25 m transect with numbers and heights of rooted sagebrush plants recorded.

Soils analysis

At each reclaimed study site, three soil pits were excavated at random locations with soil sample depths of 0-15 cm and 15-30 cm. Samples were placed and labeled in one-gallon plastic bags and transported for drying and lab analysis. Samples were analyzed for electrical conductivity (EC), pH, and texture at the University of Wyoming, Laramie Wyoming. All study sites analyzed in this study had topsoil respread before reseeding started.

Samples were analyzed for pH and EC in a saturated paste (1EC=μS/cm) using a VWR Symphony Sp80CR pH and EC meter. Particle size analysis was performed using the hydrometer method used by Gavlak et al. (2005). This analysis quantitatively determines the physical proportions of three sizes of primary soil particles that are determined by individual settling rates in an aqueous solution. Settling rates of particles are based on the principle of sedimentation described by Stokes' Law and measured using a hydrometer (Gavlak et al., 2005). A blank solution was measured with a hydrometer to account for corrections in temperature and solution viscosity. Samples were prepared and pH readings were taken using the methods used by McLean (1982). Methods published by Rhoades (1982) were followed to analyze EC.

Soils data for native reference sites were obtained from the USDA Natural Resource Conservation Services (NRCS) soil survey website using study site GPS coordinates for locations and NRCS web soil data for texture, pH, and EC measurements.

Statistical analysis

As some native undisturbed sites were used for controls for more than one reclaimed area, we chose to compare sagebrush data from each reclaimed area against its undisturbed native reference site using a two group *t*-test (Chihara and Hesterberg, 2011). The null hypothesis assumes the average measures of sagebrush on each reclaimed site were the same as the average measures of sagebrush on its representative control site, the alternative hypothesis was that they differed (α=0.05, n=20). Two group *t*-tests were conducted on the following sagebrush attributes: average height (cm), percent canopy cover and density expressed as stems ha^{-1}. When variances were not equal a weighted two group *t*-test was used, with weights being $1/\sqrt{s_i^2}$, were s_i^2 was the i^{th} variance. Eleven two group *t*-tests were conducted as this was the number of study sites compared to native reference sites. All tests were conducted with the TTEST procedure of Statistical Analysis System (SAS Institution, ver. 9.2).

RESULTS

Vegetation

For the majority of reclaimed bentonite mine pits examined in the study low density and cover values of sagebrush were observed. However, several of the older reclaimed sites, (on which sagebrush seed was not included in the seed mix) had sagebrush populations that were statistically similar to native undisturbed areas in terms of sagebrush density and cover. The mean, standard errors and P-value for each *t*-test performed on sagebrush density, canopy cover, and height are reported in Table 2.3.

Table 2.3. Statistical analysis for sagebrush height, canopy cover, and density in stems ha^{-1} with ± standard errors. Null hypothesis assumes the average measures of sagebrush on each reclaimed site were the same as the average measures of sagebrush on its representative native reference site, the alternate hypothesis that they were different (α=0.05, n=20). P-values > alpha (0.05) reveal sites with statistically comparable sagebrush characteristics between the native reference site and reclaimed sites, therefore the null is rejected and the alternative is accepted. P-values < alpha are sites that show statistically different sagebrush characteristics, here the null hypothesis is accepted. The older sites have more comparable levels of sagebrush than the younger sites to the native undisturbed areas. Asterisks indicate no P-value for native undisturbed sites.

N= 20 α=0.05

Site	Average Density Stems Ha^{-1}	P-Value	Average Canopy Cover (%)	P-Value	Average Height (cm)	P-Value
Thermopolis						
T70 (1982)	5540 ± 1313.7	<.0001	5.7 ± 1.6	<.0001	24.2 ± 5.2	0.577
T70 Reference	33720 ± 2124.5	*	17.4 ± 1.2	*	21.8 ± 0.9	*
T74 (1983)	16820 ± 1812.3	0.75	5.4 ± 0.5	0.074	24.9 ± 2.3	0.051
T98 (1997)	1820 ± 511.3	<.0001	1.9 ± 0.5	<.0001	16.4 ± 4.4	0.001
T74 Reference	16180 ± 932.7	*	14.6 ± 1.3	*	29.9 ± 1.0	*
Lovell						
LD29 (2004)	920 ± 176.8	0.039	0.2 ± 0.1	<.0001	6.8 ± 2.9	<.0001
LC29 Reference	1800 ± 361.7	*	3.5 ± 0.6	*	35.9 ± 4.8	*
AJ (2008)	620 ± 261.9	0.022	0.6 ± 0.4	0.004	0.03 ± 0.02	<.0001
AJ Reference	2200 ± 606.9	*	4.8 ± 1.5	*	31.1 ± 6.0	*
Greybull						
GB 134 (1993)	640 ± 240.7	<.0001	0.9 ± 0.5	<.0001	10.4 ± 4.6	<.0001
GB 134 Reference	7400 ± 582.2	*	15.9 ± 1.4	*	53.1 ± 2.1	*
Flitner (1981)	2560 ± 585.7	0.283	4.7 ± 1.4	0.237	33.7 ± 4.4	0.195
Old Dam (1983)	3500 ± 454.1	0.69	5.9 ± 0.8	0.494	33.6 ± 3.4	0.08
Dump (1983)	1780 ± 287.9	0.001	2.8 ± 0.6	0.002	28.1 ± 4.6	0.019
Beaver Rim (2005)	700 ± 216.9	<.0001	0.5 ± 0.2	<.0001	14 ± 4.7	<.0001
Hinkely (2009)	440 ± 132.7	<.0001	0.6 ± 0.2	<.0001	11.4 ± 3.6	<.0001
Greybull Reference	3280 ± 305.2	*	6.9 ± 1.1	*	43.6 ± 4.4	*

Sagebrush density

Sagebrush plants of varying sizes were found on all the reclaimed bentonite mine sites examined in this study. Density of sagebrush stems on most reclaimed sites, however, were extremely low (Table 2.3). Reclaimed sites chosen for closer examination in this study were those with highest sagebrush density ranging from 440-16820 stems ha^{-1}; the native undisturbed sites density ranged from 1800-33720 stems ha^{-1} (Table 2.3). In our comparisons of sagebrush density on reclaimed sites to density on nearby undisturbed sites, all comparisons but one (T74 undisturbed reference vs. T74 reclaimed, P-value = 0.75) showed undisturbed reference sites had significantly more sagebrush density than reclaimed sites.

Thermopolis sites. The highest density sagebrush stand observed in this study was the undisturbed T70 sagebrush grassland reference site with 33,720 stems ha^{-1} ± 2124.54 (Fig. 2.5). The nearby T70 bentonite mine site was reclaimed over 30 years ago (no sagebrush seed in seed mix) in 1982 had a significantly lower sagebrush density of 5,540 stems ha^{-1} ± 1313.7. At another site in the Thermopolis area, T74, the bentonite pit reclaimed in 1983 (no sagebrush in seed mix) and the adjacent undisturbed reference sites had similar sagebrush densities of 16,180 stems ha^{-1} and 16,820 stems ha^{-1} ± 932.73, respectively (Fig. 2.5, Table 2.3). The one other reclaimed bentonite mine site examined in the Thermopolis area was reseeded more recently (1997) with a mix including sagebrush seed and had sagebrush density of 1,820 stems ha^{-1} ± 511.32 , which was visually lower than sagebrush density on the other Thermopolis sites (Fig. 2.5, Table 2.3).

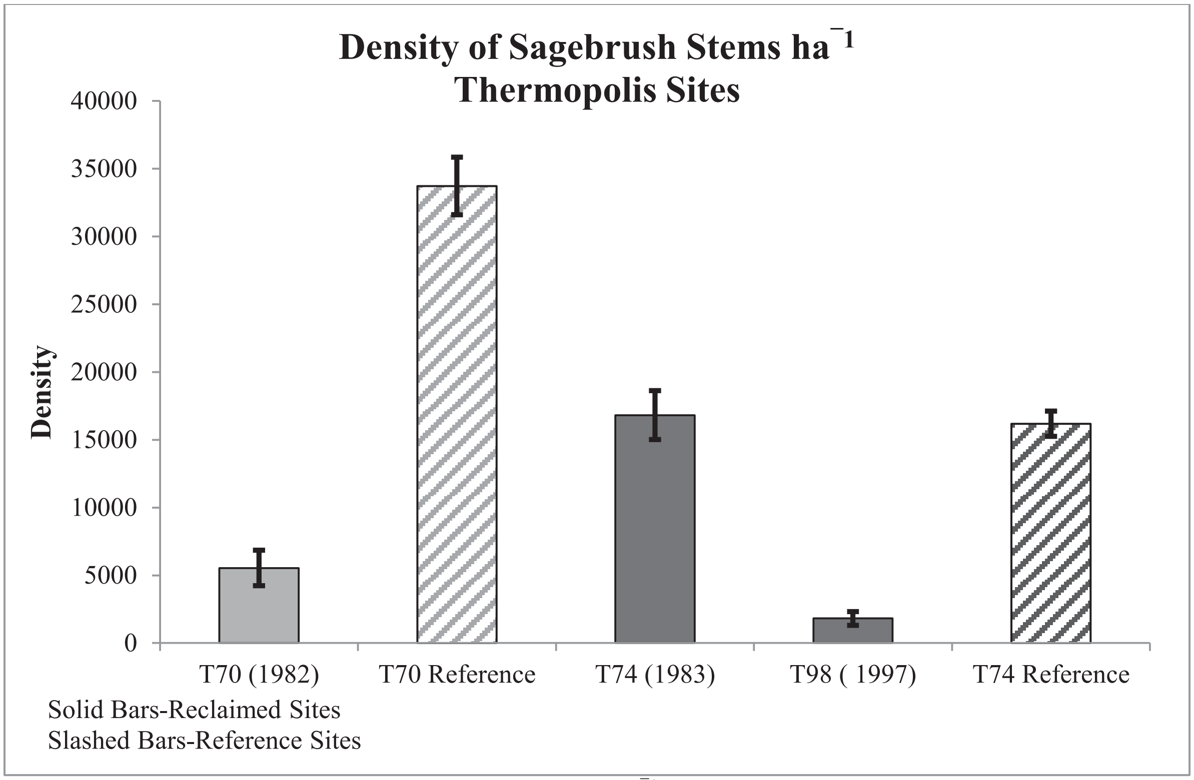

Figure 2.5. Average sagebrush densities (± SE) in stems ha^{-1} for reclaimed and reference sites. T70 (1982) compared to T70 reference; T74 (1983) and T98 (1997) compared to T74 reference.

Greybull sites. Reclaimed sites in the Greybull area had sagebrush densities lower or equal to the densities of the native reference sites. In the Greybull area, we found sites reclaimed in the early 1980's with no sagebrush seed in the reclamation seed mix had greater density of sagebrush plants than did sites reclaimed in the 1990s and 2000s using sagebrush seed. Sites reclaimed in the early 1980's without sagebrush seed in the seed mix had sagebrush densities ranging from 1,780 to 3,500 stems ha^{-1} (Fig. 2.6). Density of sagebrush on sites reclaimed in the 1990's and early 2000's (Beaver Rim, Hinckley, and GB134) had sagebrush densities ranging from 440-700 stems ha^{-1} (Fig. 2.6). Undisturbed reference sites in the Greybull area had sagebrush densities of 7,400 and 3,280 stems ha^{-1}(Fig. 2.6, Table 2.3).

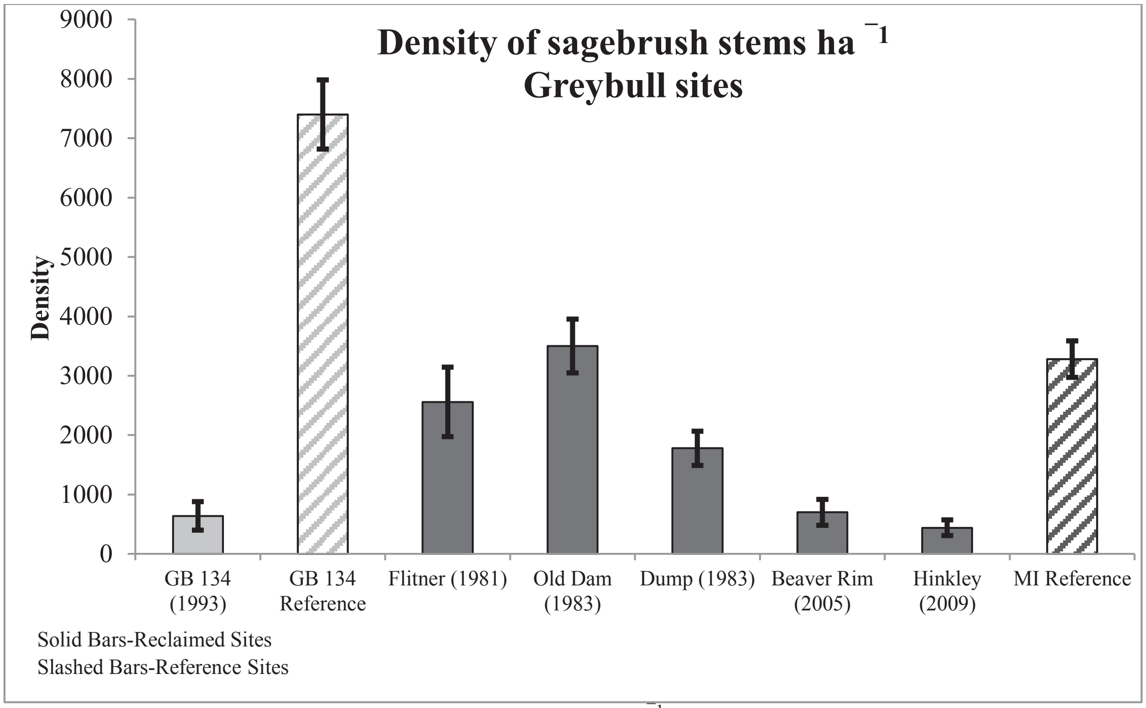

Figure 2.6. Average sagebrush densities (± SE) in stems ha^{-1} on reclaimed and native reference sites with standard error bars. GB 134 (1993) compared to GB 134 reference. Flitner, Old dam, Dump, Beaver Rim and Hinkley compared to reference.

Lovell sites. Sagebrush densities in both undisturbed reference areas and reclaimed bentonite mine sites in the Lovell area were the lowest observed in this study. Sagebrush density at the two undisturbed reference sites in the Lovell area were 1,800 and 2,200 stems ha^{-1}. Reclaimed sites examined in this area had sagebrush densities of 620 and 920 stems ha^{-1} (Fig. 2.7, Table 2.3). Sagebrush seed was used in seed mixes during reclamation of these sites.

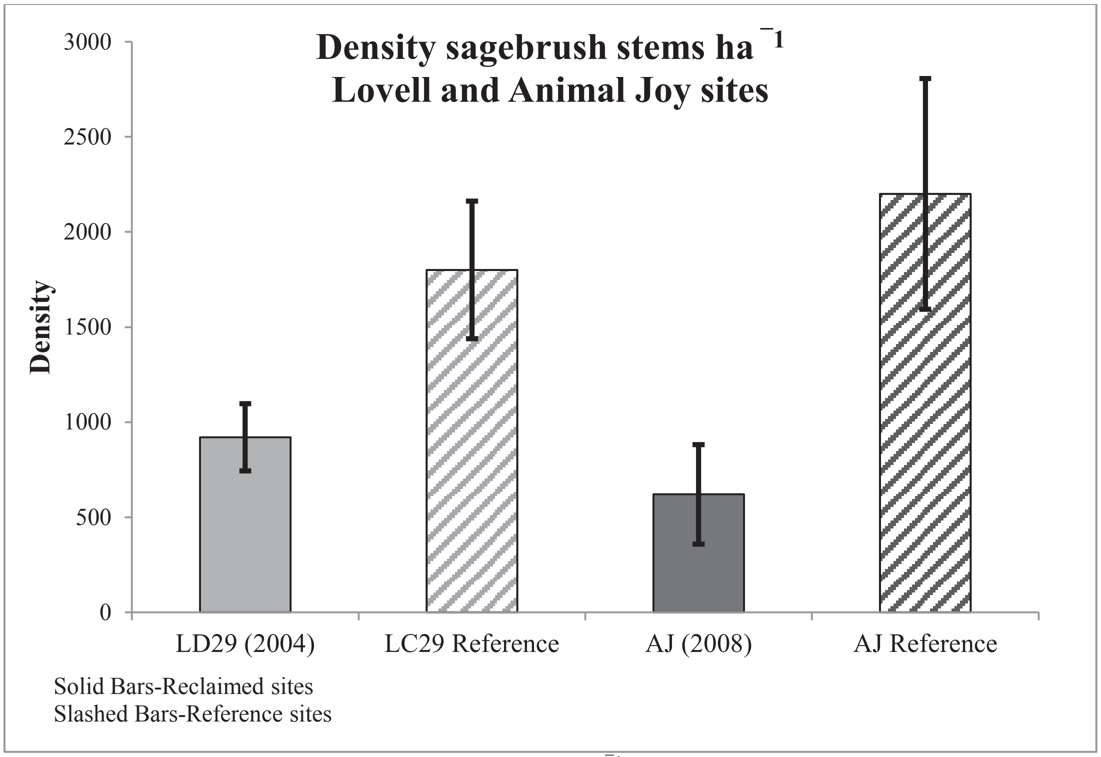

Figure 2.7. Average sagebrush (± SE) density (stems ha^{-1}) for Lovell and Animal Joy reclaimed and reference sites with standard error bars. LD29 (2004) compared to LC29 reference. AJ (2008) compared to AJ reference.

Sagebrush cover

Sagebrush canopy cover values varied from site to site. Sagebrush canopy cover on all reclaimed sites was less than 17% which was typical of reclaimed bentonite mined areas included in this study (Table 2.3). Sites chosen for further analysis in this study had the highest canopy cover of all reclaimed sites examined, ranging from 0.2% to 5.9% (Table 2.3) with the native undisturbed sites having cover values ranging from 3.5% to 17.4 % (Table 2.3). In our comparisons of reclaimed sites to undisturbed sites, all but two (T70 reclaimed vs. T70 reference and Old Dam vs. Greybull reference) showed undisturbed reference sites had significantly more sagebrush cover than reclaimed sites.

Thermopolis sites. The highest sagebrush canopy cover observed in this study was the Thermopolis T70 reference site with an average of 17.4% sagebrush cover (Fig. 2.8). The nearby

T70 bentonite mine site reclaimed over 30 year ago (no sagebrush seed in seed mix) in 1982 had a significantly lower sagebrush canopy cover of 5.7% (*P*<.0001). Another site in the Thermopolis area, T74, a bentonite pit reclaimed in 1983 (no sagebrush in seed mix) and the adjacent undisturbed reference site (T74 reference) had sagebrush canopy cover of 5.4% and 14.6%, respectively (Fig. 2.8, Table 2.3). The other reclaimed bentonite mine site examined in the Thermopolis area was reseeded more recently (1997) using sagebrush seed and had a sagebrush canopy cover of 1.9%, significantly lower than sagebrush cover at the other Thermopolis sites (Fig. 2.8, Table 2.3). The T98 site was reclaimed most recently and had the lowest sagebrush canopy cover.

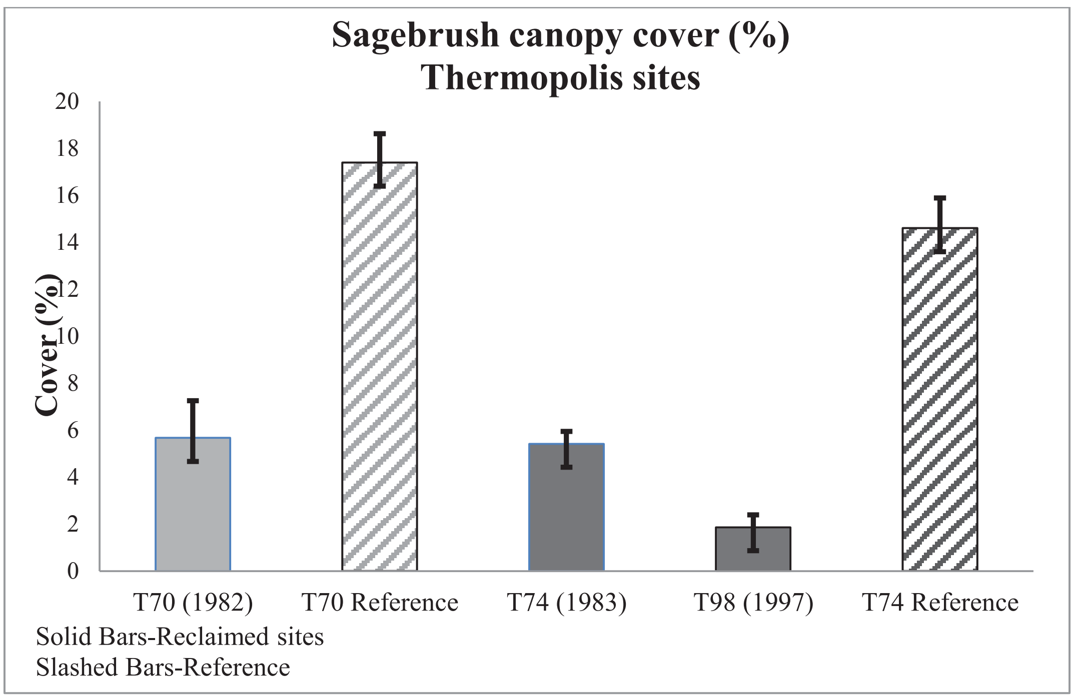

Figure 2.8. Average sagebrush (± SE) canopy cover (%) from Thermopolis. T70 (1982) compared to T70 reference; T74 (1983) and T98 (1997) compared to T74 reference.

<u>Greybull sites.</u> The reference sites in the Greybull area had average sagebrush canopy covers lower than native undisturbed reference sites. As in the Thermopolis sites, we found sites reclaimed in the Greybull area around the early 1980's with no sagebrush seed in the reclamation

seed mix had greater sagebrush canopy covers than sites reclaimed in the 1990's and 2000's that used sagebrush seed. Sites reclaimed in the early 1980's without sagebrush seed in the seed mix had sagebrush canopy cover ranging from 2.8% to 5.9% (Fig. 2.9). Sagebrush canopies on sites reclaimed in the 1990's and early 2000s (Beaver Rim, Hinckley, GB134) had sagebrush canopy covers values ranging from 0.5% to 0.9% (Fig. 2.9). Undisturbed native reference sites in the Greybull area had significantly greater sagebrush canopy cover of 6.9% and 15.9% (Fig. 2.9, Table 2.3).

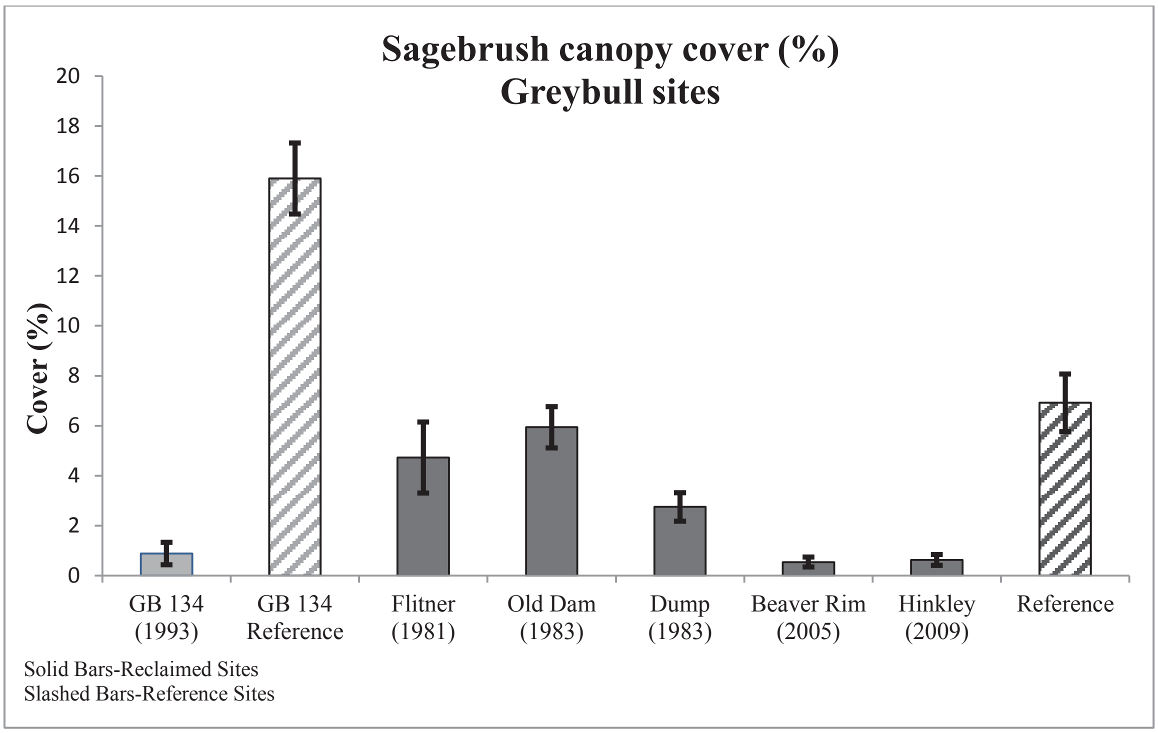

Figure 2.9. Average sagebrush (± SE) canopy cover for Greybull reclaimed and native reference sites. GB 134 (1993) compared to GB 134 reference. Flitner, Old dam, Dump, Beaver Rim, and Hinkley compared to reference with standard error bars.

<u>Lovell sites.</u> Sagebrush canopy cover in both undisturbed reference areas and reclaimed bentonite mine sites in the Lovell area were the lowest observed in this study. Sagebrush canopy cover at the two native undisturbed reference sites in the Lovell area were 0.4% and 4.8% (Fig. 2.10). Reclaimed sites examined in this area had sagebrush cover values of 0.2% and 0.6% (Fig.

2.10, Table 2.3). Sagebrush seed was included in seed mixes used during reclamation of both these sites.

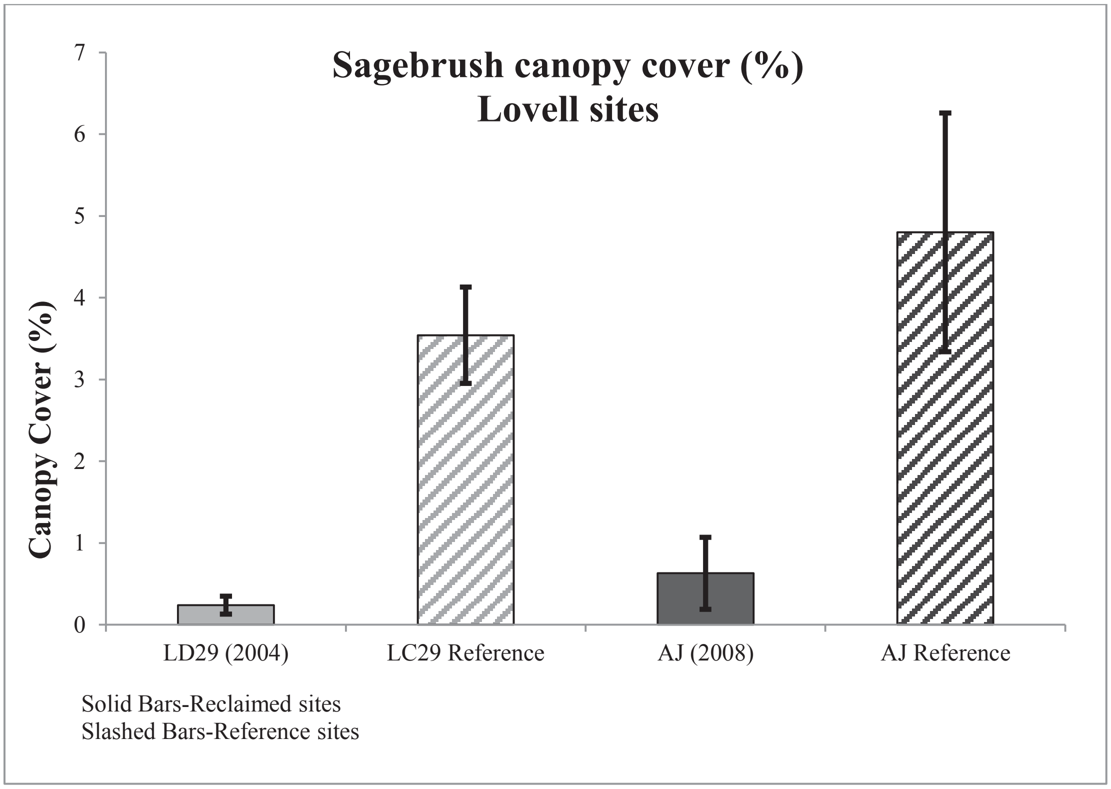

Figure 2.10. Average sagebrush (± SE) canopy cover for LD29, LC29 and Animal Joy (AJ) reclaimed and reference sites with standard error bars.

Sagebrush height

In our comparisons of sagebrush height on reclaimed sites to height on undisturbed sites, all comparisons but two (T70 reclaimed vs. T70 reference and Flitner vs. Greybull reference, Table 2.3 and Figs. 2.11, 2.12 and 2.13) showed sagebrush growing on undisturbed reference sites was significantly taller than sagebrush growing on reclaimed sites. The sagebrush height on the reclaimed sites ranged from 0.03 cm to 33.7 cm while the height on the native undisturbed sites ranged from 21.8 cm to 53.1 cm (Table 2.3).

Thermopolis sites. The tallest sagebrush observed in the Thermopolis area was the T74 reference site with an average height of 29.9 cm (Fig. 2.11). The nearby T70 bentonite mine site reclaimed over 30 years ago (no sagebrush seed in seed mix) in 1982 had a greater mean sagebrush height than the native reference site, 24.2 cm and 21.8 cm respectively (Table 2.3). Another site in the Thermopolis area, T74, reclaimed in 1983 (no sagebrush in seed mix) and the adjacent undisturbed native reference site (T74 reference) had statistically equal sagebrush height of 24.9 cm and 29.9 cm, respectively (Fig. 2.11, Table 2.3). The other reclaimed bentonite mine site examined in the Thermopolis area was reseeded more recently (1997) including sagebrush seed and had a mean sagebrush height of 16.4 cm, significantly lower than sagebrush height on the other Thermopolis sites (Fig. 2.11, Table 2.3).

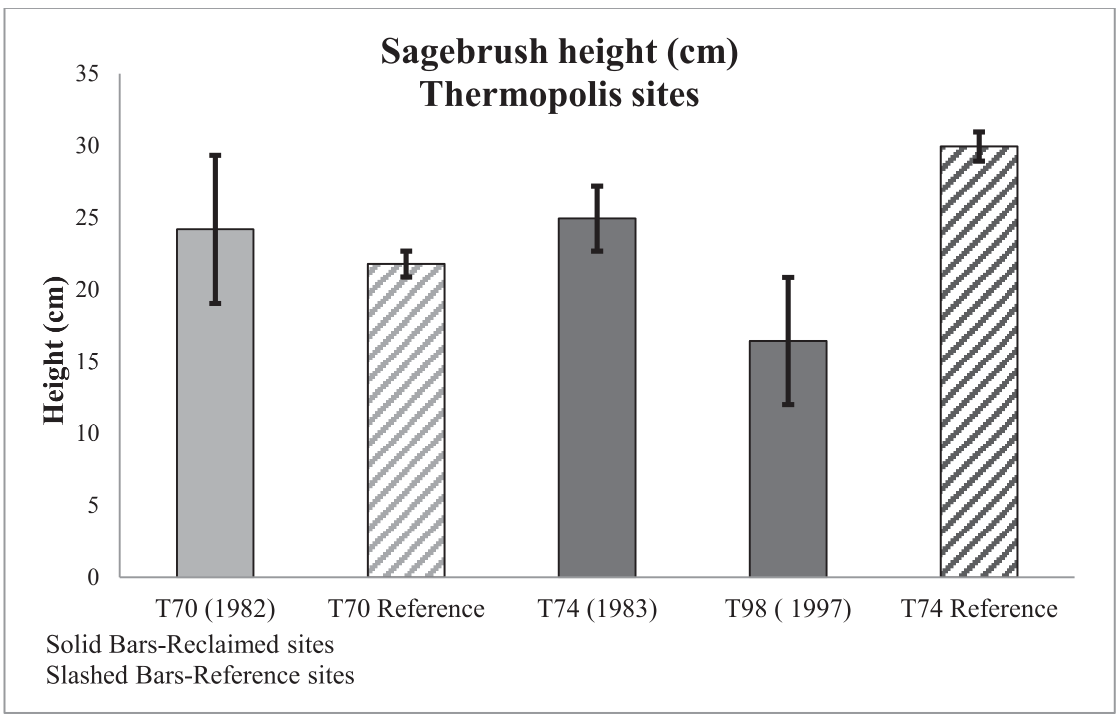

Figure 2.11. Average sagebrush heights (cm; ± SE). T70 (1982) compared to T70 reference; T74 (1983) and T98 (1997) compared to T74 reference with standard error bars.

Greybull sites. Undisturbed reference sites in the Greybull area had average sagebrush heights greater than undisturbed reference sites in the Thermopolis and Lovell area (Table 2.3). Again, the Greybull sites reclaimed in the early 1980's (no sagebrush seed in the reclamation seed mix) had greater sagebrush heights than sites reclaimed in the 1990's and 2000's using sagebrush seed. Sites reclaimed in the early 1980's without sagebrush seed in the seed mix had sagebrush heights ranging from 28.1 cm to 33.7 cm (Fig. 2.12). Sagebrush on sites reclaimed in the 1990s and early 2000's (Beaver Rim, Hinckley, GB134) had heights ranging from 10.4 cm to 14 cm (Fig. 2.12, Table 2.3). Undisturbed native reference sites in the Greybull area had sagebrush heights of 43.6 cm and 53.1 cm (Fig. 2.12, Table 2.3).

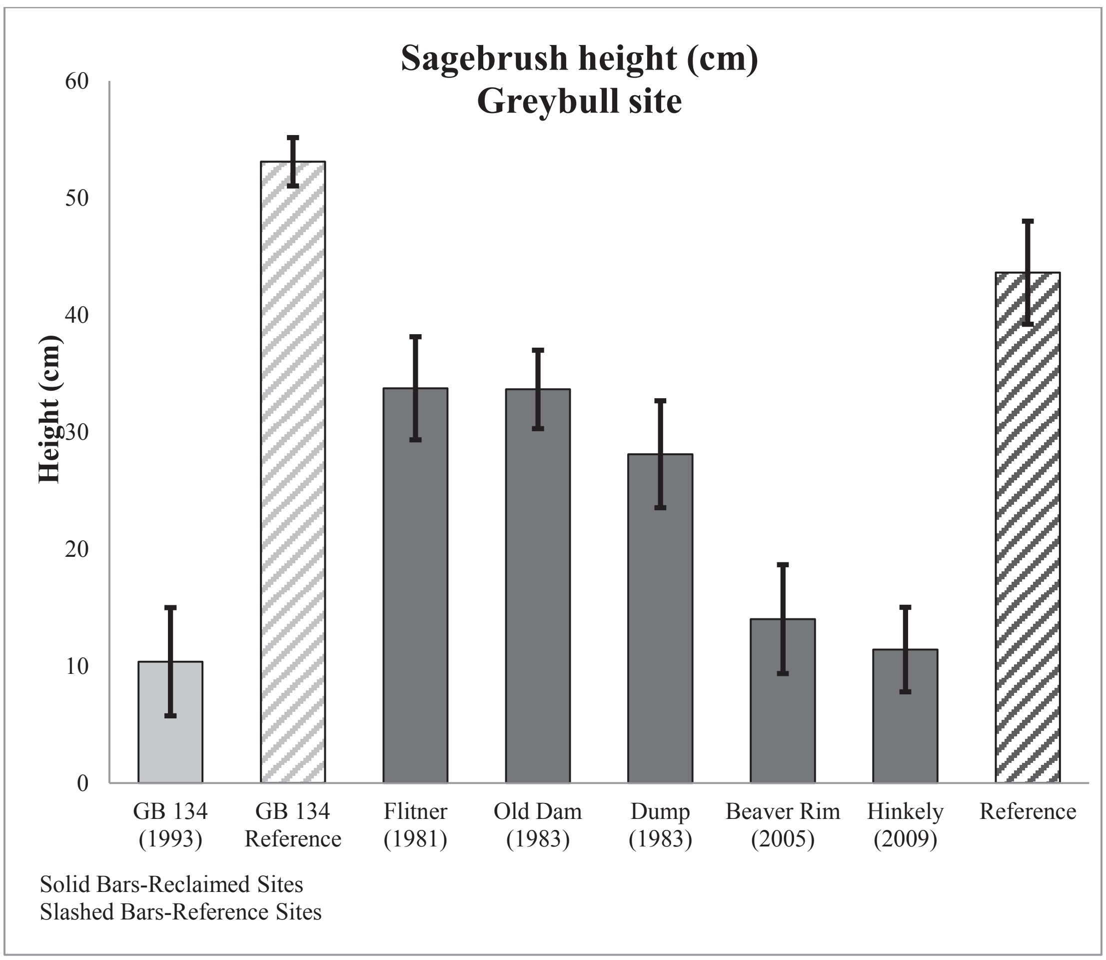

Figure 2.12. Average sagebrush (± SE) heights for Greybull reclaimed and native reference sites with standard error bars. GB 134 (1993) compared to GB 134 reference. Flitner, Old dam, Dump, Beaver Rim, and Hinkley compared to reference.

Lovell sites. Sagebrush height in both undisturbed reference areas and reclaimed bentonite mine sites in the Lovell area were the lowest observed in this study. Sagebrush height at the two native undisturbed reference sites in the Lovell area was 0.03 cm and 6.8 cm respectively (Fig. 2.13, Table 2.3). The Animal Joy (2008) site had a mean sagebrush height so low that it is difficult to visualize on a bar chart (Fig. 2.13). Reference sites examined in this area had sagebrush height of 31.1 cm and 35.9 cm (Fig. 2.13, Table 2.3). Sagebrush seed was used in seed mixes used in reclamation of these sites.

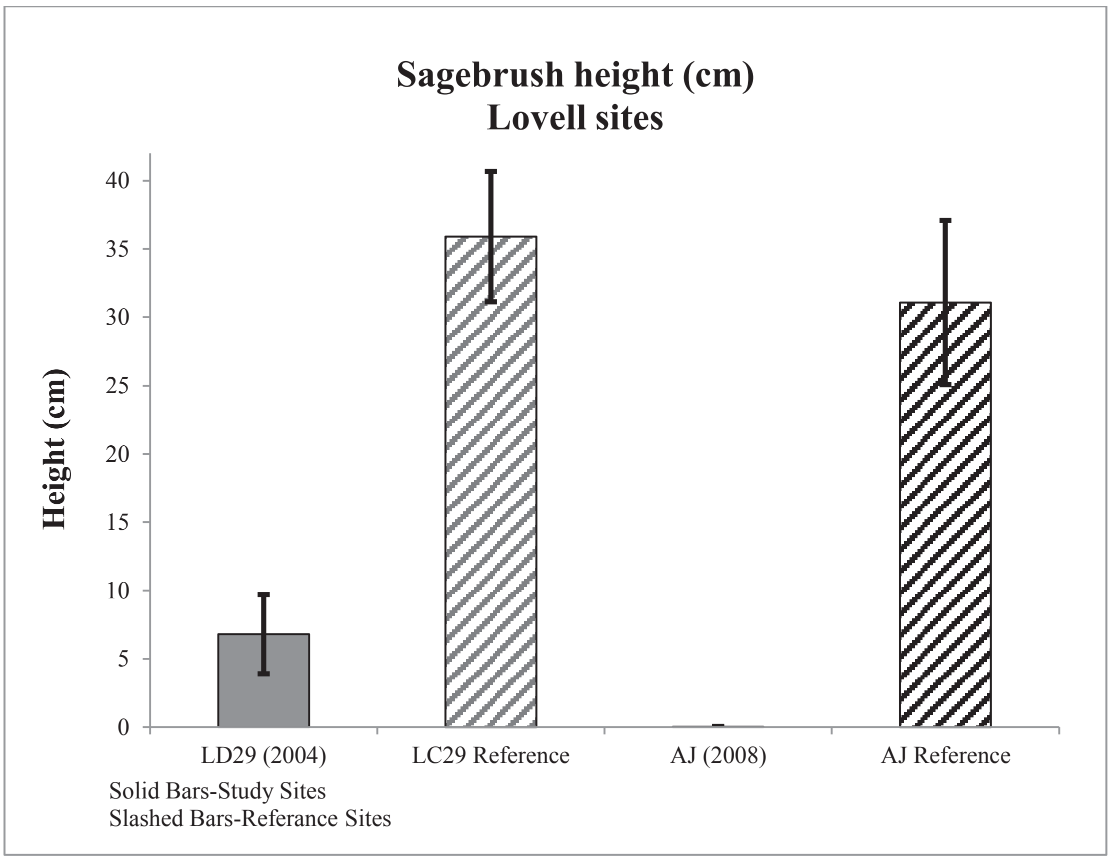

Figure 2.13. Average sagebrush (± SE) height for LD29, LC29, and Animal Joy (AJ) native reference and reclaimed sites with standard error bars.

Soils

Soils were analyzed using standard methods suggested for the Western region (Gavlak et al. 2005). Table 2.4 displays average soil sample characteristics from two sample depths (0-15 cm and 15-30 cm). Data presented for native reference sites is taken from the NRCS web soil survey, while reclaimed site data were obtained from soil samples taken from three locations within each reclaimed site. Standard deviations were large because of low sample numbers and site variability inherent in reclaimed soils. In all, three soil samples were collected at 0-15 cm and 15-30 cm from each sample location. During the excavation and collection of soil samples, no spoil or overburden from the reclamation process was noticed in the top 30 cm of topsoil.

Table 2.4. Soil samples from study sites showing sample depth, pH, EC, and texture from lab analysis.

Mine	Sites	Age	Study Sites	Soil Depth (cm)	pH	1EC=µS/cm	Texture
Thermopolis							
T70 Reclaimed	1	29	70T	0-15	7.9	2475	Sandy Clay Loam
			70T	15-30	8	3193	Loam
T70 Reference	Native	*	**43**	**0-15**	**8.2**	**2000**	**Loam**
	Native	*	**43**	**15-30**	**NA**	**NA**	*****
T74 Reclaimed	1	28	T74	0-15	8.1	354	Loam
			T74	15-30	8.3	527.1	Sandy Loam
T98 Reclaimed	2	14	T98	0-15	7.8	457.1	Clay Loam
			T98	15-30	8.3	273.3	Clay Loam
T74 Reference	Native	*	*	**0-15**	**7.9**	**1000**	**Sandy Loam**
	Native	*	*	**15-30**	**N**	**NA**	**NA**
Greybull							
GB 134 Reclaimed	1	18	G134	0-15	7.8	2293.6	Sandy Loam
			G134	15-30	7.7	2410.7	Sandy Loam
GB 134 Reference	Native	*	**53bw**	**0-15**	**8**	**1000**	**Sandy Clay Loam**
	Native	*	**53bw**	**15-30**	**8.1**	**1000**	**Sandy Clay Loam**
Flitner	1	30	MI F	0-15	8.1	310	Loamy Sand
			MI F	15-30	8.1	376.3	Sand
Old Dam	2	28	GOD	0-15	7.9	1345	Loamy Sand
			GOD	15-30	7.8	1018	Loamy Sand
Dump Site	3	28	MI D	0-15	8.2	1598	Sandy Clay Loam

			MI D	15-30	8.1	1202	Clay Loam
Beaver Rim	4	6	G-B	0-15	8.3	246.2	Loamy Sand
			G-B	15-30	8.3	514.3	Sand
Hinkley	5	2	MI H	0-15	8.1	284.9	Sandy Loam
			MI H	15-30	7.9	1077.7	Sandy Loam
Reference	Native	*	**53b1**	**0-15**	**8.1**	**1000**	**Sandy Loam**
	Native	*	**53b1**	**15-30**	**8.4**	**1000**	**Loam**
Lovell							
LD29 Reclaimed	1	7	BPM RD	0-15	5.	279.6	Sandy Loam
			BPM RD	15-30	5.1	188.3	Sandy Clay Loam
LC29 Reference	Native	*	**53ff**	**0-15**	**9.2**	**1000**	**Clay Loam**
	Native	*	**53ff**	**15-30**	**9.4**	**1200**	**Clay Loam**
A/J Reclaimed	1	3	A/JOY	0-15	7.9	400	Sandy Loam
			A/JOY	15-30	8.2	816.3	Sandy Loam
A/J Reference	Native	*	**53c7**	**0-15**	**8.5**	**1000**	**Clay Loam**
	Native	*	**53c7**	**15-30**	**8.4**	**1000**	**Clay Loam**

Table 2.5. Sagebrush density and canopy cover and soil pH and texture characteristics for reclaimed and native undisturbed reference sites at 0-15cm in depth.

Soil characteristic-sagebrush density and cover values				
Site	**Density Ha^{-1}**	**Cover (%)**	**pH**	**Texture**
Thermopolis				
T70 Reclaimed (1982)	5540	5.6	7.9	Sandy Clay Loam
T70 Reference	33720	17.4	8.2	Loam
T74 Reclaimed (1983)	1682	5.4	8.1	Loam
T98 Reclaimed (1997)	1820	1.9	7.8	Sandy Loam
T74 Reference	16180	14.6	7.9	Sandy Loam
Greybull				
GB 134 Reclaimed (1993)	640	10.4	7.8	Sandy Loam
GB 134 Reference	7400	53.1	7.9	Sandy Loam
Flitner (1981)	2560	33.7	8.1	Loamy Sand
Dump Site (1983)	1780	33.6	8.2	Sandy Clay Loam
Old Dam (1983)	3500	28.1	7.9	Loamy Sand
Beaver Rim (2005)	700	14	8.3	Loamy Sand
Hinkley (2009)	440	11.4	8.1	Sandy Loam
Reference	3280	43.6	8.1	Sandy Loam
Lovell				
LD29 Reclaimed (2004)	920	0.2	5.4	Sandy Loam
LC29 Reference	1800	3.5	9.2	Clay Loam
Animal Joy Reclaimed (2008)	620	0.6	7.9	Sandy Loam
Animal Joy Reference	2200	4.8	8.5	Clay Loam

By gathering soil samples from each reclaimed and native undisturbed reference site, I hoped to identify a relationship between soil quality and the levels of sagebrush found on study sites. Texture, pH and electrical connectivity (EC) were measured in the lab for each reclaimed site. A saturated paste was used to find EC and pH and the hydrometer method was used for particle size analysis. Time and funding were limited for an in-depth soil quality analysis, as a result this study focused on vegetation characteristics and not soil quality. After soil testing was complete I concluded that age since reclamation was the greatest factor in amounts of sagebrush on study sites and was less related to the pH, texture, and EC readings found in samples analyzed. Sagebrush plants require a pH range of 6.0-8.2 pH and have a low salinity tolerance (USDA 2012). The Wyoming Department of Environmental Quality Land Quality Division guideline indicates suitable EC levels for sagebrush growth at 0-8000 μS/cm. Soil quality characteristics found our study sites did not reveal any noticeable traits/relationships that would have lead us to believe pH, texture, and EC were influencing the level of sagebrush regrowth (Table 2.5). The older sites (1982-1993) appeared to have higher levels of soil stability and structure than the younger sites (1997-2008).

Variations in EC's are common within the geological strata typical of bentonite beds. The removal, redistribution, and possible contamination by bentonite clay are also explanations for varying EC measurements.

DISCUSSION

The goal of this study was to determine if reclamation practices used on reclaimed bentonite mine sites in the Big Horn Basin lead to successful reestablishment of sagebrush. Data gathered during this study indicate reclamation practices used on bentonite mine sites between 1980 and the mid-1990's have not resulted in reestablishment of sagebrush populations. These practices have, in some cases, facilitated the regeneration of environmental conditions favorable for natural sagebrush recruitment and establishment. Reclamation practices used in the Big Horn Basin replaced topsoil, stabilized reclaimed sites, revegetated many sites and, in some cases, created conditions suitable for natural recolonization by sagebrush. Reclaimed sites examined in this study ranged from 2 to 30 years in age, allowing us to examine sagebrush reestablishment on sites that were and were not seeded with sagebrush in the revegetation seed mix. Of the 35 reclaimed bentonite mine sites we observed, less than one-third had sagebrush cover estimated to be equal to or greater than 1%. Values for sagebrush cover in undisturbed, native sites we observed ranged from 3.5 to 17.4%, with only the two driest undisturbed sites near Lovell, having values less than 6%. The same patterns were seen in the data on sagebrush stem density. Density of sagebrush stems in undisturbed, native sites we observed ranged from 33,720 to 1,800 stems ha^{-1} with only three sites having a sagebrush stem density less than 7,000. Density of sagebrush stems on reclaimed sites ranged from 16,820 to 440 stems per ha^{-1} with only two sites having a density greater than 6,000. We found that older reclaimed sites possessed visually higher stem density and canopy cover than the younger sites examined during this study. Structural features of sagebrush and perennial grass species are used by sage-grouse for protection from harsh weather and predators during nesting and early brood-rearing (Gregg et al., 1994; Connelly et al., 2000).

During development of this study, the authors chose to closely examine the structure of sagebrush communities on reclaimed sites with at least 1% shrub cover to have sagebrush populations sizable enough to accurately characterize. Sites seeded 20 or more years ago that have not developed 1% or more sagebrush cover were considered unsuccessful sagebrush reestablishment for purposes of this study. It is important to note that many of the reclaimed bentonite mine sites initially observed had extremely limited amounts of vegetative cover (Schuman et al., 1994) and populations of sagebrush on many of these sites were limited to a few dozen plants or less. Plant community structure was analyzed in detail to assess the reestablished sagebrush communities (greater than 1% sagebrush cover) and evaluate the potential habitat value for important post mining land use of wildlife habitat, and to assess utility of reclamation techniques for future use in bentonite mine site reclamation.

Of the 11 reclaimed sites on which a minimum cover of at least 1% sagebrush was reestablished, only one, the Old Dam site near Greybull, had a sagebrush cover value statistically similar (95% confidence level) to its nearby undisturbed reference site, 5.9% vs. 6.9%, respectively (Fig. 2.9). This is an interesting observation in that the Old Dam reclaimed site was revegetated with a seed mix that did not include sagebrush seed. As previously mentioned, all sites reclaimed before 1993 were reclaimed without seeding sagebrush; so, all sagebrush reestablishment is the result of natural recolonization processes over the past 20 to 30 years. All of these older reclaimed sites had visually greater sagebrush cover values than do the younger reclaimed sites revegetated using seed mixes including sagebrush seed. Sagebrush stem density was also higher in these 11 older reclaimed sites than in the younger sites reclaimed using sagebrush seed. The large majority of sites visited in the early stages of this study had sagebrush cover values much less than 1%. Successful recolonization of sagebrush on some sites implies that viable seed of sagebrush was present on those sites and environmental conditions were favorable to seed germination and establishment. These conditions obviously occurred on only a minority of the older sites.

Native undisturbed reference sites possessed sagebrush canopy cover ranging from 3.5 to 17%. Sagebrush canopy cover on reclaimed study sites ranged from 0.2 to 5.9%. According to the minimum arid sage-grouse habitat requirement for suitable breeding, brood-rearing and wintering habitat ranges from 15 to 30%. Canopy covers on the reclaimed mined sites, regardless of age were below the minimum sage-grouse habitat standards.

Available moisture is known to be a limiting factor in the growth and establishment of sagebrush species (Sieg et al. 1983; Fortier et al., 1999; Meikle, 2000). Thermopolis sites were located in a 28-33 cm precipitation range and Greybull and Lovell at around 15-20 cm. Factors contributing to poor sagebrush response on reclaimed bentonite mines are understood, such as, low precipitation rates and timing, adverse climatic conditions (Schuman et al., 1985). Bentonite mines are typically reclaimed with topsoil associated with that particular mine, however bentonitic material located in the topsoil and poor topsoil handling (Shaw et al., 2005) have adverse effects on sagebrush establishment. The disruption of mutualistic relations between vegetation and mycorrhizal fungi could also be affecting reestablishment rates (Stahl et al. 2002).

Seeding a reclaimed site with the plant species desired in the reestablished plant community is a proven way to maximize the chances that the targeted plant community is restored (Lambert 2005). Even so, there are a number of factors important for influencing the structure of the reestablished plant community: seed quality, planting, other cultural methods used, and environmental factors. Sagebrush seed quality is important because this seed is known to be inherently short lived and of low purity (Wagstaff and Welch 1991). Availability of high quality sagebrush seed is often limited.

Improper seeding times/methods and lack of viable seed (Hemmer et al., 1977, Seig et al., 1983, Schuman et al,. 1985) are also contributing factors to low sagebrush reestablishment rates on reclaimed bentonite minelands. The short life span of sagebrush seed may be a factor in slow reestablishment rates as seed bank studies of big sagebrush indicate that seed banks are transient, with little or no seed carry-over from year to year (Young and Evans, 1989, Meyer, 1990). Early spring soon after snowmelt is usually the best time for big sagebrush seedling emergence (Monsen and Meyer, 1990). Meikle, (2000) stated recruitment of sagebrush seedlings is strongly limited by abiotic and biotic factors, and seedlings can be susceptible to frost damage, drought and disease. This study found that older sites (greater than 15 years in age) had experienced off-site seed immigration from undisturbed sagebrush stands. This is a slow process Clifton (1981); Wambolt and Payne (1986) and Lowe-Dalzell et al. (2003) collectively found that even under favorable conditions, disturbed site recovery may take 60 to 100 years in dry areas and several years may pass before conditions favoring establishment of new seedlings occur.

Natural recruitment of sagebrush on reclaimed bentonite mines is often limited by lack of propagules, drought, a competitive exotic understory such as cheatgrass, disruption of hydrologic functioning (erosion and decreased infiltration) and changes in the soil structure and biota resulting from past disturbance (Shaw et al., 2005). During years of low precipitation, few Wyoming big sagebrush plants may establish; it may be many years before recolonization takes place (Shaw et al., 2005). Sagebrush establishment, in nature, is cyclical, and even under favorable conditions, success can be anticipated in only 1 of 5 years. Soils that did not previously contain sagebrush should not be expected to grow sagebrush after mining. It is understandable then that it may take 30 years for sagebrush to recolonize areas that are greater than 0.5 ha in size due to dry conditions, poor seed viability, slow natural seed dispersal, competitive exotic species, limited available water, and disrupted soil profiles.

Soil samples collected from the study failed to provide any valuable information to explain why some sites of similar age experienced different levels of sagebrush reestablishment. It was noted during sample collection the 0-15 cm and 15-30 cm depths had very little spoil material associated with the topsoil. The majority of pH readings fell within the 6.0-8.2 pH range and relatively low salinity levels required for sagebrush growth (USDA, 2012). Sample readings of EC, pH and texture were consistent with bentonite topsoil literature. The variability of EC measurements taken from soil samples (Table 2.4) was due to the high levels of salt and sodium found within some of the geological substrates associated with bentonite deposits (Hemmer et al., 1977). Uneven distribution of these substrates and contamination of topsoil by bentonite can lead to wide variation of EC readings within a soil profile. During the re-spreading, gouging, and deep furrowing of top-soil, bentonitic material can become incorporated within the upper 10 cm of soil (Hemmer et al., 1977) increasing the salinity and sodicity of this layer, making bentonite spoils difficult to revegetate (Sieg et al., 1983). Only the Thermopolis site T70 and the Greybull site GB 134 (Table 2.4) showed EC levels between 2000-3000 μS/cm and both these sites had sagebrush growing (Table 2.5). The authors concluded from soil pH, texture, EC readings, and the amount of sagebrush found on each disturbed site, that time (15-30 years) is a key factor in sagebrush reestablishment when sagebrush seed in not included into seeding mixes. If this study would have evaluated soil quality at sites with no sagebrush growing, the soil quality at these sites may not have been amenable for sagebrush establishment, thus explaining limited sagebrush reestablishment rates.

A secondary objective of this study was to evaluate reclaimed sagebrush community habitat value for sage-grouse on bentonite minelands. Although no statistical comparisons were preformed, the average sagebrush height and canopy cover from the site examined in this study were assessed with the data for general sage-grouse habitat requirements outlined by Connelly et al. (2000) for suitable breeding, brood-rearing, and winter habitat for this species. Connelly et al.'s (2000) numbers represent values for evaluation of potential sage-grouse habitat (see Table 2.6).

Table 2.6. Connelly et al. (2000) sage-grouse habitat requirements for breeding, brood-rearing, and winter for sagebrush height and cover for arid sagebrush landscapes.

Arid Sites	**Breeding**		**Brood-rearing**		**Winter**	
	Height(cm)	Canopy Cover(%)	Height(cm)	Canopy Cover(%)	Height(cm)	Canopy Cover(%)
Sagebrush	30-80	15-25	40-80	10-25	25-35	10-30

The Big Horn Basin is one of the driest parts of Wyoming, receiving an annual average precipitation of 5-10 cm (Western Regional Climate Center 2012) and therefore falls into an arid classification. Connelly et al. (2000) data was collected from several sage-grouse studies conducted across the range of the species. The sagebrush data collected form this study did not incorporate a probabilistic sampling design using the Big Horn Basin as sampling frame, these results only refer to the actual study sites sampled.

Most reclaimed sites, regardless of when reclaimed did not meet suitable sage-grouse sagebrush habitat criteria as established by Connelly et al. (2000) (Fig. 2.6). Other attributes such as sagebrush height and perennial grass cover would have added valuable information when comparing reclaimed sites to Connelly's guidelines. About 90% of our study sites had sagebrush characteristics that did not meet these criteria. However, several studies have shown that sage-grouse prefer areas with taller grasses for nesting and greater sagebrush and herbaceous canopy cover for brood-rearing throughout their range (Gregg et al., 1994; Connelly et al., 2000; Hagen et al., 2007). It should be noted that the Connelly et al. (2000) standards were **NOT** statistically compared to sagebrush levels recorded in this study; but to gain a general idea of sagebrush cover levels on reclaimed bentonite mined lands in relation to the widely accepted habitat criteria from Connelly et al. (2000).

Even though sage-grouse and sage-grouse sign were observed on two of the reclaimed bentonite mine sites in the Thermopolis area, some characteristics of the sagebrush communities reestablished on these sites did not meet the standards proposed by Connelly et al. (2000; Table 2.6). These author's guidelines may have been developed in more typical sage-grouse habitat than that in the Big Horn Basin and thus may not pertain to very dry areas such as the Big Horn Basin.

Most reclaimed sites we examined, regardless of reclamation date, did not meet any suitable sage-grouse habitat criteria suggested by Connelly et al. (2000). The observation of sage-grouse on reclaimed and undisturbed sites with canopy cover not meeting Connelly's guidelines suggests sage-grouse are utilizing sagebrush communities with less than 15-30% canopy cover. Canopy cover from the five older reclaimed sites ranged from 2.8-5.7 % which was less than the native reference sites which ranged from 4.8-17.4 %. The six younger sites were also less than the native reference sites. Only three out of the six canopy covers from the native reference sites were close to meeting Connelly's canopy cover criteria. Hess and Beck (2012) suggest that undisturbed sagebrush areas within the Big Horn Basin meet the minimum canopy cover of 15%. However, their treated plots (burning and mowing) failed to meet the minimum canopy cover 15% (Hess and Beck 2012) suggesting that undisturbed sagebrush communities are suitable habitat while disturbed sagebrush communities fail to meet suitable habitat criteria.

The sagebrush heights (21.8-53.1 cm) on the native reference sites were similar in height to Connelly's height guidelines of 25-80 cm. All six of the older reclaimed sites in this study (Fig. 2.9, 2.11 and 2.12) had sagebrush heights (24.2-33.7 cm) close to meeting sagebrush height (21.8-53.1 cm) found on the native undisturbed reference sites. This suggests that the five older sites have sagebrush communities closer to the height criteria presented by Connelly et al. (2000). Although no statistical comparisons were performed the sagebrush heights of the six younger sites in this study are less than the native reference sites suggesting that these sites are not suitable sage-grouse habitat.

Sites examined in my study can be grouped into older sites revegetated with no sagebrush seed (1993 or earlier) applied to the site and more recently reclaimed sites (1993 or later) revegetated with sagebrush seed applied to the site as part of the seed mix. The important question arises: how does planting of sagebrush seed during initial site reclamation impact reestablishment of sagebrush? The fact that all sites reclaimed without use of sagebrush seed are much older (a longer period of time has passed since their initial reclamation) than sites reclaimed with sagebrush seed greatly complicates the comparison. All of the sagebrush growing on sites reclaimed before 1993 are the result of natural recolonization. Sagebrush growing on sites reclaimed during or after 1993 could have resulted from seed placed by humans or from natural recolonization. Because sagebrush seed is known to be viable for limited periods of time, sagebrush establishing on seeded sites more than 5 years after seeding are probably the result of natural recolonization. A large majority of sites reclaimed prior to mid-1990s have not successfully reestablished sagebrush. Around 70% of the sites we examined did not have sagebrush cover exceeding 1%. A reason for many of these reclaimed sites having very low or no sagebrush species present maybe due to the fact that the pre-disturbance site conditions consisted mainly of desert salt shrub communities. Site conditions in these areas failed to support sagebrush in the undisturbed state, therefore sagebrush reestablishment efforts were mostly unsuccessful due to poor soil quality (unsuitable for sagebrush growth) and extremely dry conditions.

Sites reclaimed before the mid-1990s that did possess good sagebrush communities were seeded with appropriate species and stabilized by effective reclamation techniques. This includes areas that had sagebrush stands present before disturbance, proper topsoil handling methods were implemented, invasive species were excluded, erosion was limited and areas with native undisturbed sagebrush communities were available to provide a native seed source. Sites reclaimed before 1990's had greater sagebrush stem density than younger sites reclaimed using sagebrush seed, but they had been reclaimed for a longer period of time (15-30 years) and have been subject to slow but steady natural recolonization by sagebrush due to the short viability and low establishment rates of this species. We concluded that currently used sagebrush planting and reestablishment methods are not very effective. However, more effective sagebrush seeding methods have been developed and should be experimented with in the Big Horn Basin.

We found that conventional sagebrush seeding techniques resulted in minimal sagebrush reestablishment within a 2-15 year period (ca. 1995-2010). Many of these reclaimed sites do not meet minimum sage-grouse habitat requirements. However, over a 15-30 year period (ca. 1980-1995) natural reinvasion occurs and sagebrush stands were closer to meeting sage-grouse habitat requirements. Therefore, we concluded that older sites examined in this study are closer to meeting minimum sage-grouse habitat requirements. This study shows conventional reclamation techniques used in the past have facilitated site conditions suitable for sagebrush regrowth over time on about 20% of the sites reclaimed. Some of these are soil stabilization, low levels of exotic invasives and physical characteristics favorable for sagebrush reestablishment.

Reclamationists in the Big Horn Basin should begin using advanced sagebrush reestablishment techniques developed for use in the Powder River Basin where sagebrush reestablishment is mandatory, such as seeding on snow banks during the winter or site specific seeding methods. This study concludes that reclaimed sites with greater levels of sagebrush density, canopy cover, and height are products of offsite seed introduction from native undisturbed sagebrush communities. This is the only explanation for the reestablishment of these stands, as sagebrush seed was not incorporated into the original seeding mix used for reclamation. Due to sagebrush having a slow growth pattern it is understandable that regrowth requires more than 15 years. By commonly incorporating sagebrush seed into seed mixes, and creating sagebrush favorable soil, slope and topographic conditions during reclamation, it is believed that sagebrush reestablishment rates will increase and the amount of time natural reinvasion requires will decrease.

CHAPTER 3:
OBSERVATIONS OF SAGEBRUSH REESTABLISHMENT FIELD TRIALS IMPLEMENTED BY BENTONITE MINE RECLAMATIONISTS

INTRODUCTION

Included in this project was an examination of several test plantings of Wyoming big sagebrush (*Artemisia tridentata ssp. wyomingensis,* Beetle & Young) implemented between 2005−2010 by industry reclamationists. These plantings were conducted to test innovative methods of reestablishing sagebrush on reclaimed bentonite mine pits. The sagebrush reestablishment trials were located on bentonite pits managed by Bentonite Performance Minerals (Lovell, Wyoming), Wyo-Ben, Inc., American Colloid (ACC) and M-I, LLC (Greybull, Wyoming). Due to the limited sagebrush response in traditional broadcast seeding methods, these trials were developed by the mining companies in an effort to find more effective ways of reestablishing sagebrush. These trials were conducted to test sagebrush response to technologies such as seed coating, supplemental watering gels, drip irrigation systems, site specific seeding, and mycorrhizal inoculation. Reports on these trials are included in this thesis to provide examples and observations of some of the methods that have been used to enhance sagebrush reestablishment on reclaimed bentonite mined lands.

Photos and data are representative of average levels of sagebrush found on these experimental sites. Many of the sagebrush reestablishment sites were small in size, with the total area being approximately $5m^2$.

FIELD TRIALS OBSERVED

Methods for reestablishing sagebrush on these sites were a combination of different techniques ranging from the use of a) pre-treated seed with a moisture holding cellulose gel called Zeba®, b) jute netting coconut mats, c) gel moisture packs, d) drip irrigation systems, e) transplanting mature sagebrush plants, f) hand seeding sagebrush seed into depressions, and swales that capture moisture and g) hand seeding of sagebrush on snow banks during the winter. The trial sites were located on reclaimed bentonite mine sites around Greybull and Lovell, Wyoming. Field data and photos were collected between July and August 2011.

To document sagebrush canopy cover in these trials a photograph of the ground surface was taken from approximately 1m in height using an Olympus E20 digital SLR camera (Olympus Corp., Tokyo, Japan) and then analyzed with Sample Point software to quantify the type of ground cover present in a $1m^2$ area (Booth et al., 2006). Sample Point is a near-earth remote sensing vegetation measuring technique designed to analyze ground cover types using high resolution images with approximately 95% accuracy (Booth et al., 2006). Five of these images were taken at each sagebrush reestablishment trial. A $1m^2$ quadrat, made from 2.5cm PVC pipe, was placed around the area to be photographed. Two images were then taken directly above the frame (Bennett et al., 2000).

Zeba® coated seeding trial (Greybull). Zeba® is based on cornstarch and forms a 'hydrogel' that can hold and release water for plant and food crops (Zeba® 2008). At the Zeba® coated seed site (Fig. 3.1) about 44 kg (11 pls [pure live seed] kg) of Wyoming Big Sagebrush seed were treated with a powder form of Zeba® coating. The treated seed was hand broadcast at approximately 4/8 pls kg ha^{-1} in May of 2008 onto bare ground. The $1m^2$ quadrat was placed around areas that had live sagebrush and a photo was taken of each quadrat. Photos were taken of five separate plots at this site.

Figure 3.1. 1m² quadrat on the Zeba® coated seed site with sagebrush, hand seeded with Zeba® coated seed onto bare ground.

Mycorrhizal inoculant and Zeba® coated seed trial (Greybull). The mycorrhizal inoculant was incorporated into this trial to facilitate growth of arbuscular mycorrhizal (AM) which is a vital component of sagebrush establishment and growth (Stahl et al. 1988). Approximately 2.4 km to the north of the Zeba® coated seeding site very similar techniques were used. Mycorrhizal inoculant and Zeba® coated seed were seeded into depressions and swales located on the reclamation site (Fig. 3.1). Approximately 36-54 bulk kg ha^{-1} of mycorrhizal inoculant and granular Zeba® coated seed was hand broadcast concurrently. The seeded area was then hand raked to lightly cover the seed. Five photos were taken using the $1m^2$ frame around established sagebrush plants.

Figure 3.2. Mycorrhizal inoculant and Zeba® coated seed site showing the 1 m^2 frame on sagebrush growing in a swale. Hand broadcasted with Zeba® coated seed onto snow banks.

Seeding rates were similar to the Zeba® coated seeding trial (Fig. 3.2). The mycorrhizal inoculant and Zeba® coated seeding trial was broadcast seeded in December 2008 onto surfaces covered with snow whereas the Zeba® coated seed trial (Fig. 3.1) was seeded in May of the same year on bare ground.

Jute netting trial (Greybull). Jute netting (woven coconut matting) provides a biodegradable ground covering that will decrease wind and water erosion while retaining soil moisture. A few kilometers to the west on a reclaimed road side, Zeba® coated seed and jute netting were placed on a disturbed hillside. Untreated sagebrush seed was hand broadcast on the disturbed area and the jute netting (Fig. 3.3) was placed over the seed and secured with landscape staples, rock and earth. This trial was conducted in the spring of 2008. The 1m^2 quadrat was placed over five representative areas of this trial and a photo was taken of each separate quadrat.

Figure 3.3. Jute netting site with three year old sagebrush plants from Zeba® coated seed are shown.

Hand broadcast Zeba® seeding trial (Greybull). On the same disturbed hillside another trial was conducted in which Zeba® coated seed was hand broadcast onto bare ground without a net covering (Fig. 3.4). This trial was conducted in 2008 with methods similar to the Zeba® coated trial mentioned earlier in the paper. Five separate, representative, $1m^2$ quadrats were photographed for this seeding trial area.

Figure 3.4. Hand broadcast Zeba® coated seed on a disturbed hillsides. Sagebrush plants after three years of growth.

<u>Gel pack and seedling trial (Greybull).</u> Gel packs are a moisture releasing product that can last from 30-90 days depending on the size. For the gel pack trial, 100 sagebrush containerized stock plants (seedlings established in a greenhouse) were hand planted with supplemental water releasing gel packs. Five sagebrush seedlings were clustered with a one half gallon Rainbird® gel-pack located up-slope of the seedlings to allow slow release of moisture into their root zones (Fig. 3.5). Circular coconut matting was placed around the base of each seedling to help with moisture retention. This trial was conducted in spring 2007. Five 1m^2 quadrats were placed around each of the trial areas, and photos were taken of each individual planting location.

Figure 3.5. Gel pack and seedlings. Sagebrush seedlings planted with water holding gel packs and coconut matting.

<u>Drip irrigation and seedling trial #1 (Greybull).</u> In the same areas as the gel pack and seedling site, approximately 1,000 sagebrush seedlings were hand planted in a patterned, linear down-slope design with a drip irrigation system set up to supply supplemental water (Fig. 3.6). This trial was implemented in May−August 2007 and 2008.

Figure 3.6. Drip irrigated hand planted sagebrush seedlings #1. Water supplied through drip irrigation system.

This site had a 1700 liter watering tank with 2.5cm diameter plastic drip line with emitters installed at 61cm intervals. The sagebrush plants were watered at least once a month over the summer (more frequently during June) with an application rate of about 0.75 liters/plant for each watering. Five separate 1m^2 quadrats were placed around growing sagebrush plants and photos were taken of each frame.

Mature sagebrush transplant trial (Greybull). Mature sagebrush transplants were removed from an area to be mined for bentonite through the use of a skid-steer and replanted on a reclaimed site. The trial was conducted in 2010. The existing sagebrush was growing with an approximate 15-20% decadent canopy (Fig. 3.7). Five separate 1m^2 quadrats were placed around growing sagebrush plants and photos were taken of each quadrat.

Figure 3.7. Mature sagebrush transplants. A skid-steer excavator was used to dig up mature sagebrush plants on site to be mined, the sagebrush were then replanted on a reclaimed mine site.

Hand broadcast seed onto snow banks trial (Lovell). Sagebrush seed was hand broadcast onto snow banks during the winter months. The seed was not treated with any type of inoculant or supplemental water. A majority of the observed seedlings were located in small depressions and swales throughout the reclaimed area (Fig. 3.8). This trial was conducted in 2007 and 2008. Five separate 1m^2 quadrats were placed around growing sagebrush plants and photos were taken of each quadrat.

Figure 3.8. Example of hand broadcasted sagebrush seed sown onto snow banks.

Drip irrigated seedling trial #2 (Greybull). This trial was also conducted in 2007 and was similar to the drip irrigated seedling trial #1 (Fig. 3.6). Approximately 1,000 sagebrush seedlings were hand planted in a patterned, linear down-slope design with a drip irrigation system being put in place to supply supplemental water (Fig. 3.9). A 1700 liter tank was used to water these seedlings every month (more frequently in June) through a 2.5 cm plastic pipe with emitters (Fig. 3.9) placed approximately every 61 cm. This trial was conducted in 2007. Five separate 1m^2 quadrat were placed around growing sagebrush plants and photos taken of each quadrat

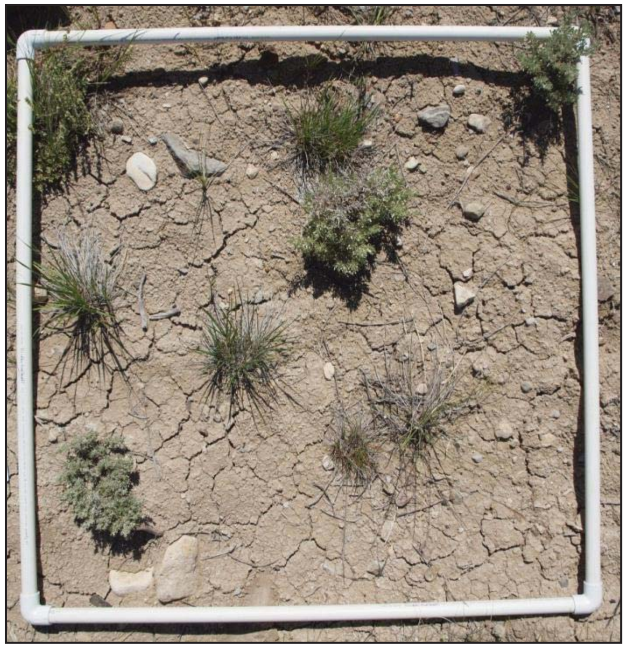

Figure 3.9. Hand planted drip irrigated sagebrush seedlings#2.

The areas in which these experiments took place were interspersed in and around sagebrush study sites analyzed earlier in this project. Most of these trials were conducted on bentonite sites reclaimed between 1990 and 2000 using more traditional methods such as broadcast or drill seeding with farm implements. Many of the soil quality characteristics within these trials were similar to soil quality found on traditionally reclaimed sites. These newer, field trial sites typically possessed less sagebrush than the traditionally reclaimed sites, which ranged in age from 10 to 30 years old. These experimental sites were younger, being 3−5 years in age.

Photos were analyzed using Sample Point software to generate aerial cover percentages. Photos were clipped to the 1 m^2 quadrats using Microsoft Paint (Microsoft Corp., Redmond, WA) and analyzed for sagebrush cover using Sample Point set at a 10X10 grid size resulting in 100 points per photograph. Each point was classified as one of eight cover categories. These were Wyoming big sagebrush, shrub, grass, forbs, litter, bare ground, rock, and shadow. A summary statistics file was created directly in the program and exported to Microsoft Excel

(Microsoft Corp., Redmond, WA) where the percent canopy cover and mean values were computed.

The primary goal was to quantify sagebrush species rather than other vegetation species. Shrubs were classified as any shrub type that was not sagebrush; grass included all grass species and forbs included all forbs species. Shadow included very dark or shadowed areas where the ground cover vegetation could not be classified. Once the statistics file was created, the average resulting percentages from the five photos were summarized into a spreadsheet.

The photographed sagebrush plants were larger and more robust than others within the disturbed area. These plants were larger in size due to site specific seeding techniques that were designed to enhance available water to the seeds by either snowdrift planting, seeding into depressions and swales, Zeba® coated seed, mycorrhizal inoculant, and Jute netting used during the implementation process.

OBSERVATIONS

Canopy cover data sets were summarized into tables for each treatment examined (Tables 3.1 through 3.9). Also shown are the percentages of litter, bare ground, rock, and shadow. Other vegetation types classified were shrubs or sub-shrubs, mostly Gardner saltbush (*Atriplex gardneri)* or four-wing saltbush (*A. canescens*) as well as grass species and forbs.

The results from the Zeba® coated seeding trial (2008) show a 10% sagebrush canopy cover after three years of growth (Table 3.1).

Table 3.1. Zeba® coated seeding trial (2008). Average canopy covers (± SE) for each cover type.

Veg/Ground Cover	%ARTR	%Shrub	%Grass	%Forbs	%Litter	%Bare	%Rock	%Shadow
Photo 1	17	0	1	5	9	48	16	4
Photo 2	11	0	1	5	25	49	5	4
Photo 3	9	0	1	14	12	43	19	2
Photo 4	1	0	0	17	6	55	21	0
Photo 5	12	0	2	8	24	44	7	3
Averages	**10±2.6**	**0**	**1±0.7**	**9.8±2.4**	**15.2±3.9**	**47.8±2.1**	**13.6±3.2**	**2.6±0.7**

The mycorrhizal inoculant and Zeba® coating seed trial (2005 and 2006) had a sagebrush canopy cover of 41.2%. Seeding during December (Table 3.2) on the surface of the snow produced approximately four times the amount of canopy cover within $5m^2$ as the areas seeded in May (Table 3.1).

Table 3.2. Mycorrhizal inoculant and Zeba® coated seeding trial (2005 and 2006). Average canopy covers (± SE) for each cover type.

Veg/Ground Cover	%ARTR	%Shrub	%Grass	%Forbs	%Litter	%Bare	%Rock	%Shadow
Photo 1	51	0	8	1	13	14	9	4
Photo 2	10	0	17	0	35	24	13	1
Photo 3	24	0	18	0	10	31	14	3
Photo 4	65	0	9	1	16	4	0	5
Photo 5	56	0	26	1	5	6	0	6
Averages ± Std Error	**41.2±10.4**	**0**	**15.6±3.3**	**0.6±0.2**	**15.8±5.1**	**15.8±5.2**	**7.2±3.1**	**3.8±0.9**

The jute netting trial sites (2008) with hand broadcast Zeba® coated seed have a 23.4% sagebrush canopy cover which was observed after three growing seasons (Table 3.3).

Table 3.3. Jute netting trial (2008). Average canopy covers (± SE) for each cover type.

Veg/Ground Cover	%ARTR	%Shrub	%Grass	%Forbs	%Litter	%Bare	%Rock	%Shadow
Photo 1	10	0	33	0	33	12	9	3
Photo 2	2	0	44	0	35	13	4	2
Photo 3	6	2	2	0	38	32	20	0
Photo 4	43	0	1	0	31	17	6	2
Photo 5	56	0	1	0	15	19	9	0
Averages ± Std Error	**23.4±10.9**	**0.4±0.4**	**16.2±9.3**	**0**	**30.4±4.0**	**18.6±3.6**	**9.6±2.8**	**1.4±0.6**

On the same site Zeba® coated seed was hand broadcast with no Jute netting; resulting in a 40.2% sagebrush canopy cover (Table 3.4), nearly double the sagebrush canopy cover on the adjacent site where jute netting was used (Table 3.3). The high litter percentage is due to the jute netting which is classified as a ground cover.

Table 3.4. Hand broadcast Zeba® seeding trial (2008). Average canopy covers (± SE) for each cover type.

Veg/Ground Cover	%ARTR	%Shrub	%Grass	%Forbs	%Litter	%Bare	%Rock	%Shadow
Photo 1	57	0	0	0	6	23	12	2
Photo 2	39	0	0	7	2	32	19	1
Photo 3	16	1	0	0	5	34	43	1
Photo 4	61	1	1	1	9	20	7	0
Photo 5	28	1	11	0	11	31	17	1
Averages ± Std Error	**40.2±8.5**	**0.6±0.2**	**2.4±2.2**	**1.6±1.4**	**6.6±1.6**	**28±2.7**	**19.6±6.2**	**1±0.3**

After 3.4 years, the gel pack and sagebrush seedling trial showed an average sagebrush canopy cover of 49.4% (Table 3.5) within the five examined $1m^2$ quadrats.

Table 3.5. Gel pack and seedling trial (2007). Average canopy covers (± SE) for each cover type.

Veg/Ground Cover	%ARTR	%Shrub	%Grass	%Forbs	%Litter	%Bare	%Rock	%Shadow
Photo 1	48	0	3	1	32	15	1	0
Photo 2	45	0	6	0	31	15	3	0
Photo 3	23	0	1	1	41	26	8	0
Photo 4	48	0	0	0	16	31	2	3
Photo 5	83	0	0	0	11	5	0	1
Averages ± Std Error	**49.4±9.6**	**0**	**2±1.1**	**0.4±0.2**	**26.2±5.5**	**18.4±4.6**	**2.8±1.4**	**0.8±0.6**

On the same site, drip irrigation and seedling trial #1 produced 10.8% sagebrush canopy cover after four years (Table 3.6).

Table 3.6. Drip irrigated and seedling trial #1 (2007 and 2008). Average canopy covers (± SE) for each cover type.

Veg/Ground Cover	%ARTR	%Shrub	%Grass	%Forbs	%Litter	%Bare	%Rock	%Shadow
Photo 1	7	0	4	2	13	70	4	0
Photo 2	8	0	3	2	23	61	3	0
Photo 3	11	0	0	0	31	56	2	0
Photo 4	15	0	1	0	15	64	5	0
Photo 5	13	0	1	0	18	59	9	0
Averages ± Std Error	**10.8±1.5**	**0**	**1.8±0.7**	**0.8±0.5**	**20±3.2**	**62±2.4**	**4.6±1.2**	**0**

The mature sagebrush transplants showed a 39.4% sagebrush canopy cover after 1.5 years since planting (Table 3.7). Litter (23.8 %) found in these quadrats was mostly decadent sagebrush canopy cover. No supplemental watering or inoculant was used.

Table 3.7. Mature sagebrush transplants trial (2010). Average canopy covers (± SE) for each cover type.

Veg/Ground Cover	%ARTR	%Shrub	%Grass	%Forbs	%Litter	%Bare	%Rock	%Shadow
Photo 1	56	0	1	2	29	4	8	0
Photo 2	33	0	21	3	30	4	9	0
Photo 3	40	0	12	3	26	9	10	0
Photo 4	29	0	5	3	12	49	2	0
Photo 5	39	0	6	4	22	15	13	1
Averages ± Std Error	**39.4±4.6**	**0**	**9±3.5**	**3±0.3**	**23.8±3.3**	**16.2±8.4**	**8.4±1.8**	**0.2±0.2**

The hand broadcast seed onto snow banks trial showed an average sagebrush cover of 8.8% for these areas after four years (Table 3.8). No inoculant, supplemental watering, or additional ground covering was provided for these seedlings.

Table 3.8. Hand broadcast seed onto snow banks trial (2007 and 2008). Average canopy covers (± SE) for each cover type.

Veg/Ground Cover	%ARTR	%Shrub	%Grass	%Forbs	%Litter	%Bare	%Rock	%Shadow
Photo 1	4	15	3	0	22	45	11	0
Photo 2	2	11	7	1	3	63	13	0
Photo 3	20	0	4	0	9	61	6	0
Photo 4	14	4	5	1	13	54	9	0
Photo 5	4	0	0	1	6	74	15	0
Averages ± Std Error	**8.8±3.5**	**6±3.0**	**3.8±1.2**	**0.6±0.2**	**10.6±3.3**	**59.4±4.8**	**10.8±1.6**	**0**

The drip irrigation and seedlings trial #2 showed sagebrush cover at 6.6% after four growing seasons (Table 3.9). This is less than the cover found at the drip irrigation and seedling trial #1 (Table 3.6) which had a 10.8% sagebrush canopy cover.

Table 3.9. Drip irrigation and seedling trial #2 (2007). Average canopy covers (± SE) for each cover type.

Veg/Ground Cover	%ARTR	%Shrub	%Grass	%Forbs	%Litter	%Bare	%Rock	%Shadow
Photo 1	7	10	3	0	12	55	13	0
Photo 2	8	0	7	3	12	62	8	0
Photo 3	4	0	6	0	6	70	14	0
Photo 4	8	0	2	1	4	81	4	0
Photo 5	6	1	6	0	14	63	10	0
Averages ± Std Error	**6.6±0.7**	**2.2±2**	**4.8±1**	**0.8±0.6**	**9.6±1.9**	**66.2±4.4**	**9.8±1.8**	**0**

DISCUSSION

The objective of this thesis chapter was to provide observations of field sagebrush seeding trials conducted by reclamationists on reclaimed bentonite mine sites and to discuss possible use of these methods in successful sagebrush reestablishment programs on reclaimed mine sites. Canopy cover observations revealed that from the $5m^2$ observed on each site, the trials using these technologies or a combination of mycorrhizal inoculant, Zeba® seed, and jute netting produced greater levels of sagebrush canopy cover (Tables 3.2, 3.3, 3.4, and 3.5) than trials using drip irrigation or seeding directly onto snow banks (Tables 3.6, 3.8, and 3.9). The transplanted sagebrush showed a cover value of 39.4% (Table 3.7) after one year but we were unable to return to these sites to further analyze the survival rate of these transplants.

Sites where jute netting, coconut mats, gel packs, sagebrush seedlings and/or drip systems were used (Tables 3.3, 3.5, 3.6, and 3.9) require intensive labor and replication on a large scale would be difficult even though a sagebrush response was present. The sites where more intensive water supplements and/or growing inoculants were used (Tables 3.2, 3.3, 3.4, and 3.5) showed greater levels of canopy cover than sites hand seeded onto snow banks or sites with drip irrigation systems (Tables 3.1, 3.6, 3.8, and 3.9). Hand seeding onto snow banks during the winter months (Table 3.8) did not produce as much sagebrush cover as other trials, although this simple method could be implemented on a larger scale.

The survival of seedlings established on sites with irrigation systems in place showed approximately a 50% survival rate after two growing seasons (King et al. 2009). Sites where gel-packs were used, a cumulative average survival rate of 74% was observed for sagebrush seedlings since the 2007 and 2008 planting (King et al. 2009). The most promising methods are from broadcast seeding with coated seeds and mycorrhizal inoculant (Table 3.2 and 3.4).

Some of the methods appear to be promising ways to reestablish sagebrush on mine land reclamation, but the cost and time requirements to implement these technologies may prohibit broad scale use. Yet, site specific implementation may establish islands of sagebrush within a reclaimed area facilitating species propagation. Some trials not producing the same levels of sagebrush may in fact be less expensive; but they may be more cost effective when trying to establish sagebrush on a larger scale.

These methods can be useful from management perspective to determine which method would best suit the area under reclamation. These trials were designed site specifically, therefore, they can be applied to specific areas in need of sagebrush reestablishment. If the area for sagebrush reclamation is small (0.5-1 ha) and funds are not a limiting factor, then the gel pack and seedling method could be implemented. On disturbed areas ranging from 1-5 ha in size jute netting, Zeba® seed with inoculant could be implemented. For example, if the area to be reestablished is larger (around 5-10 ha then a hand broadcasting of sagebrush seed onto snow banks and into depressions and swales maybe the most effective method. These reclamation methods can be used as standalone procedures or paired with other methods depending on site specific requirements. On larger areas, for example, a combination of hand broadcasting sagebrush seed with mycorrhizal inoculant onto snow banks or into depressions and swales maybe an effective method to start establishing sagebrush communities.

These eight trials give land managers ideas and tools to work with when approaching a sagebrush reestablishment project. When used as site specific methods, these have proven to reestablish sagebrush onto disturbed mined lands on a small scale (< $50 m^2$). Reestablishing islands of sagebrush within disturbance may prove to be an effective method of increasing sagebrush density that will continue to expand providing valuable wildlife habitat and site stabilization.

After spending considerable hours in the field visually evaluating these sagebrush reestablishment techniques, it was my impression that hand seeding sagebrush seed onto site specific areas or planting container grown sagebrush plants are some of the most promising methods. This is taking into consideration the labor, time and cost it required to complete one of these reestablishment methods. In order to facilitate the success of these methods proper site preparation must be adhered to, seeding should be timed around subsequent precipitation events, soil quality should be analyzed and localized seed sources should be used.

Newer technologies for sagebrush reestablishment have been developed at surface coal mines in Wyoming and are based largely on seeding under particular winter soil conditions and specialized seedbed preparation. Through the incorporation of current technologies and methods used for surface coal mining reclamation we believe sagebrush reestablishment rates can be increased in the Big Horn Basin. Reclamationists need to consider correct seeding timing around precipitation events, proper seed mixtures and correct seeding rates, the use of site specific seed sources, proper seed bed preparation and planting depth, sound topsoil handling practices, thorough predisturbance reports and appropriate post disturbance monitoring. Land managers should also be aware that areas that did not possess sagebrush communities prior to disturbance should not be expected to support sagebrush growth after mining and reclamation.

LITERATURE CITED

Aldon, E.F. 1975. Endomycrrhizae enhance survival and growth of fourwing saltbush on coal mining spoils. USDA Res. Note RM-294.

Aldridge C.L., S.E., Nielsen, H.L., Beyer, M.S., Boyce, J.W., Connelly, S.T., Knick and M.A., Schroeder. 2008. Range-Wide patterns of greater sage-grouse persistence. Biodiversity Research. Blackwell Publishing Ltd. Diversity and Distributions. 14, 983–994.

Allen, E.B., and M.F. Allen. 1980. Natural re-establishment of vesicular arbuscular mycorrhizae following strip mine reclamation in Wyoming Journal Applied Ecology 17:139–147. doi:10.2307/2402969

Barnett, J.K., and J.A. Crawford. 1994. Pre-laying nutrition of sage-grouse hens in Oregon. Journal of Range Management 47:114–118.

Beck, J.L., J.W. Connelly, and C.L. Wambolt. 2012. Consequences of treating Wyoming big sagebrush to enhance wildlife habitats. Rangeland Ecology and Management 65, 444–555.

Beetle, A.A. 1960. A study of sagebrush-section Tridentata of *Artemisia.* University of Wyoming Agricultural Experiment Station Bulletin 368.

Bennett, L.T., T.S., Judd and M.A., Adams 2000, 'Close-range vertical photography for measuring cover changes in perennial grasslands', Journal of Range Management 53: 634–641.

Big Horn Basin Local Sage-Grouse Working Group. 2007. Sage-grouse conservation plan for the Big Horn Basin, Wyoming. Wyoming Game and Fish Department, Cody, Wyoming, USA.

Blaisdell, J.P. 1949. Competition between sagebrush seedling and reseeded grasses. Ecology 30:512-519.

Bonham, C.D. 1989. Measurements for Terrestrial Vegetation, John Wiley and Sons.

Booth, D. T., J. K. Gores, G.E. Schuman and R.A. Olson. 1999. Shrub densities on pre-1985 reclaimed mine lands in Wyoming. Restoration Ecology 7 (1): 24-32.

Booth, T.D., S.E. Cox., and R.D. Berryman. 2006. Point Sampling Digital Imagery with 'Samplepoint'. Environmental Monitoring and Assessment. 9-7-108. DOI: 10.1007/s10661-005-9164-7.

Brady, N.C. 1990. The Nature and Properties of Soils, 10th ed. Macmillan Publishing Company, New York.

Braun, C.E. 1998. Sage-grouse declines in western North America: what are the problems? Transactions of Western Association of Fish and Wildlife Agencies 78: 139-156.

Braun, C.E., O.O. Oedekoven, and C.L. Aldridge. 2002. Oil and gas development in western North America: effects on sagebrush steppe avifauna with particular emphasis on sage-grouse. Transactions of the North American Wildlife Natural Resource Conference 67: 337-349.

Braun, C.E. 2006. A blueprint for sage-grouse conservation and recovery. Unpublished report. Grouse Incorporated, Tucson, Arizona, USA.

Brown, D. 1954. Methods of surveying and measuring vegetation. Commonwealth Bureau of Pastures and Field Crops. Bulletin No. 42. Common. Agriculture Bureaux Farmham Royal, Bucks, England. 223 p.

Brown, R. W., R. C. Sidle, M.C. Amacher, J. Kotuby-Amacher, B.D. Williams, and J.C. Chambers. 1991. Reclamation research results on the Borealis mine: Progress report 1987-1990. USDA Forest Service Intermountain Research Station Forestry Sciences Laboratory, Logan, UT.69 p.

Brun, J.M. and T.W. Box. 1963. Comparison of line intercepts and random point quadrats for sampling desert shrub vegetation. Journal of Range Management 16:21-25.

Buckner, D.L. 1985. Point-intercept sampling in revegetation studies: Maximizing objectivity and repeatability. Paper presented at American Society for Surface Mining and Reclamation Meeting, Denver, CO. 1985.

Connelly, J. W., K. P. Reese, R. A. Fischer, and W. L. Wakkinen. 2000. Response of a sage-grouse breeding population to fire in southeastern Idaho. Wildlife Society Bulletin 28:90–96.

Chambers, J. C., R. W. Brown, and B.D. Williams. 1994. An evaluation of reclamation success on Idaho's phosphate mines. Restoration Ecology. 2(1): 4-16.

Claassens, S., P.V. Rensburg, and L.V. Rensburg. 2006. Soil microbial community structure of coal mine discard under rehabilitation. Water Air Soil Polluant 174:355–366.

Clifton, N.A. 1981. Response to prescribed fire in a Wyoming big sagebrush/blue bunch wheatgrass habitat type. Moscow: University of Idaho. 39 p. Thesis.

Coulloudon, B., K. Eshelman, J. Gianola, N. Habich, L. Hughes, C. Johnson, M. Pellant, P. Podborny, A. Rasmussen, B. Robles, P. Shaver, J. Spehar, J. Willoughby. 1999 (revised). Sampling vegetation attributes. Interagency Technical Reference 1734-4, USDI Bureau of Land Management, National Applied Resource Sciences Center, Denver, Colorado. BLM/RS/ST-96/002+1730.

Chihara, L., and T. Hesterberg. 2011. Mathematical Statistics with Resampling and R. John Wiley and Sons, Inc. Publication. ISBN: 978-1-118-029885-5. Pg. 35-76

Clifton, N.A. 1981. Response to prescribed fire in a Wyoming big sagebrush/blue bunch wheatgrass habitat type. Moscow: University of Idaho. 39 p. Thesis.

Cronquist, A. 1994. Vol. 5. A. Cronquist, A.H. Holmgren, N.H. Holmgren, J.L. Reveal and P.K. Holmgren .Intermountain Flora. The New York Botanical Garden, Bronx, NY.

Daft, M. J., and T.H. Nicolson. 1974. Arbuscular mycorrhizae in plants colonizing coal wastes in Scotland. New Phytologist 73, 1129-1138.

Daft, M. J., E. Hackaylo, and T.H. Nicolson. 1975. Arbuscular mycorrhizas in plants colonizing coal spoils in Scotland and Pennsylvania. In: Endomycorrhizas (Ed. by F. E. Sanders, B. Mosse& P. B. Tinker), pp. 561-580. Academic Press, London.

Dangi, S.R., P.D. Stahl, A.F. Wick, L.J. Ingram, and J.S. Buyer. 2012. Soil Microbial Community Recovery in Reclaimed Soils on a Surface Coal Mine Site. Soil Science Society of America Journal. 76: 915–924.

DeGrood, S.H., V.P. Classens, and K.M. Scow. 2005. Microbial community composition on native and drastically disturbed serpentine soils. Soil Biology and Biochemistry. 37:1427–1435.

DeLong, A. K., J. A. Crawford, and D. C. DeLong, Jr. 1995. Relationships between vegetational structure and predation of artificial sage-grouse nests. Journal of Wildlife Management 59:88–92.

Dollhopf, D.J. and B.J. Bauman. 1981. Bentonite mine land reclamation in the Northern Great Plains. Montana Agricultural Experiment Station, Research Report 179, 41p.

American Colloid Company. 2012. Environmental Assessment. Gifford II Plan of Operations (WYW-155962) and Amendment to WDEQ Permit 322C for Bentonite Mining. DOI-BLM-WY-020-2010-0019-EA

Fortier, M.I., G.E. Schuman, A.L. Hild, and L.E. Vickland. 1999. Effects of seeding rates and competition on sagebrush establishment on mined lands. Project Review Seminar. Abandoned Coal Mine Land Research Program. November 17, 1999, Gillette, WY.

Francis, R. E., R.S. Driscoll, and J.N. Reppert. 1972. Loop-frequency as related to plant cover, herbage production, and plant density. U.S. Dept. of Agriculture, Forest Service Rocky Mountain Forest and Range Excrement Station, Ft. Collins, CO. Research Paper MA-94. 15 p.

Frost, S.M., P.D. Stahl, and S.E. Williams. 2000. Long-term reestablishment of arbuscular mycorrhizal fungi in a drastically disturbed semiarid surface mine soil. Arid Land Research and Management. 15:3-12

Gavlak, R. D. Horneck and R.O. Miller. 2005. Soil, Plant and Water Reference Methods for Western Region. 3rd Edition. WCC-103 Publication.

Goodrich, S., E.D. McArthur and A.H. Winward. 1999. Sagebrush ecotones and average annual precipitation. In: E.D. McArthur, W.K. Ostler and C.L. Wambolt (comps.). Proceedings: Shrubland Ecotones. USDA Forest Service, Rocky Mountain Research Station. RMRS-P-11. Ogden, UT.

Gregg, M. A., J. A. Crawford, M. S. Drut, and A. K. DeLong. 1994. Vegetational cover and predation of sage-grouse nests in Oregon. Journal of Wildlife Management 58:162–166.

Hagen, C. A., J. W. Connelly, and M. A. Schroeder. 2007. A meta-analysis of greater sage-grouse *Centrocercus urophasianus* nesting and brood-rearing habitats. Wildlife Biology 13:42–50.

Harris, J.A., P. Birch, and J. Palmer. 1996. Land Restoration and Reclamation: Principles and Practice. Addison Wesley Longman, Edinburg, UK.

Hess, J. E., and J. L. Beck. 2012. Burning and mowing Wyoming big sagebrush: do treated sites meet minimum guidelines for greater sage-grouse breeding habitats? Wildlife Society Bulletin 36:85–93.

Hess J. E., and J.L. Beck. 2012. Disturbance factors influencing greater sage-grouse lek abandonment in north-central, Wyoming. Journal of Wildlife Management 76, 1625–1634.

Hemmer, D., S. Johnson and R. Beck. 1977. Bentonite mine related reclamation problems in the Northwestern States. Montana Department of Lands (Old West Regional Grant No 1057(1164), 94 p.

Hironaka, M. 1985. Frequency approaches to monitor rangeland vegetation. Symposium on use of frequency and for rangeland monitoring. William C. Krueger, Chairman. Proc., 38th Annual Meeting, Soc. for Range Manag. Feb. 1985. Salt Lake City, UT. Society for Range Management 84-86.

Hosterman, J.W., and S.H. Patterson. 1992, Bentonite and fuller's earth resources of the United States: U.S. Geological Survey Professional Paper 1522, 1 plate, 45 p.

Hyder, D.N., C.E. Conrad, P.T. Tueller, L.D. Calvin, C.E. Poulton, and F.A. Sneva. 1963. Frequency sampling of sagebrush-bunchgrass vegetation. Ecology 44:740-746.

Ingram, L.J., G.E. Schuman, P.D. Stahl, and L.K. Spackman. 2005. Microbial respiration and organic carbon indicate nutrient cycling recovery in reclaimed soils. Soil Science Society America Journal, 69:1737–1745.

Khan, A. G. 1978. Vesicular-arbuscular mycorrhizae in plants colonizing black wastes from bituminous coal mining in the Illawarra region of New South Wales. New Phytologist 81, 53-63.

King, L.A., E. Dunklee, and J. Petty. 2009. Use of supplemental watering gels to enhance Wyoming big sagebrush establishment on Big Horn Basin bentonite reclamation. Shell Valley Consulting Associates, Inc.

King, L.A. 1983. Unpublished field data. Wyo-Ben, (Greybull, WY)

Klein, D.A., W. Metzger and B. Crews. 1984. Soil microorganisms and plant community development in disturbed ecosystems. In ecological studies of natural and established ecosystems on energy related disturbances in Colorado. E.F. Redente and C.W. Cook (eds) Progress Rep. for USDA-DOE (DE-AS02-76EV-04018) Department Range Science, CO. State University, Fort Collins, p. 37-50.

Knick, S. T., D. S. Dobkin, J. T. Rotenberry, M. A. Schroeder, W. M. Vander Haegen, and C. van Ripper, III. 2003. Teetering on the edge or too late? Conservation and research issues for avifauna of sagebrush habitats. Condor 105:611–634.

Krebs, C.J. 1989. Ecological Methodology. Harper & Row, New York.

Lowe-Dalzell, C., D, E., M, Pellant, and M. Wicklow-Howard. 2003. Post-fire establishment of sagebrush on Idaho rangelands in the Western United States. In: Allsopp, N.; Palmer, A. R.; Milton, S. J.; Kirkman, K. P.; Kerley, G. I. H.; Hurt, C. R.; Brown, C. J., eds. Proceedings of the VIIth International Rangeland Congress; 2003 July 26–August 1; Durban, South Africa. Irene, South Africa: Document Transfer Technologies: p 370–372.

Lambert, S.D. 2005. Seeding considerations in restoring big sagebrush habitat. USDA Forest Service Proceedings RMRS. p 38.

McArthur, E.D., A.C. Blauer, A.P. Plummer, and R. Stevens. 1979. Characteristics and hybridization of important intermountain shrubs. III. Sunflower family. USDA Forest

Service, Intermountain Forest and Range Experiment Station. Research Paper INT-220. Ogden, UT.

Meikle, T.W., 2000. A design Solution to Big Sagebrush Establishment: Seed Production Plots and Facilitation. Bitterroot Restoration, Inc. Corvallis, MT

Meyer, S. E. 1990. Seed source differences in germination under snowpack in northern Utah. pp. 2184-199. In: F.F. Munshower and S.E. Fisher (eds.), Proceedings Fifth Billings Symposium on Disturbed Land Rehabilitation, March 25-30, 1990, Billings, MT. Montana State University, Reclamation Research Unit Publ. No. 9003, Bozeman.

Meyer, S. E. 1994. Germination and establishment ecology of big sagebrush: implications for community restoration. In: Monsen, S. B.; Kitchen, S. G., comps. Proceedings—Ecology and Management of Annual Rangelands; 1992 May 18–22; Boise, ID. General Technical Report INT-GTR-313. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 244–251.

McLean, E.O. 1982. Soil pH; Lime requirement, Methods of soil analysis; Chemical; Microbiological properties. Al page, R.H. Miller, D.R. Keeney, Madison, WI, American Society of Agronomy, Inc. Soil Science Society of America, Inc. pp. 199-224.

M-I SWACO, LLC; 1978. Wyoming Mine Permit 278C. Wyoming Department of Environmental Quality.

Miller, R.M., B.A. Carnes, and T.B. Moorman. 1985. Factors influencing Survival of vesicular-arbuscular mycorrhiza during topsoil storage. J. Appl. Ecol.22:259–266.

Monsen, S.B., and S.E. Meyer. 1990. Seeding equipment effects on establishment of big sagebrush on mine disturbances. p. 192-199. In: 5th Billings Symp. on Disturbed Land Rehabilitation. Vol. I. Hardrock Waste, Analytical, and Revegetation. Montana State

Univ. Reclamation Res. Unit Pub. 9003. Bozeman.

Monsen, S.B. and E.D. McArthur, 1984. Factors influencing establishment of seeded broadleaf herbs and shrubs following fire, p. 112-124. In: K. Sanders and J. Durham (eds.). Rangeland Fire Effects, a Symposium. USDI, Bureau of land Management, Idaho State Office, Boise, ID.

Monson, S.B., N.L. Shaw. 2000. Development and use of Plants Resources for Western Wildlands. USDA Forest Service Proceedings RMRS. p 21. 2001

Mozingo, H. 1987. Shrubs of the Great Basin. University of Nevada Press, Reno.

Mummey, D.L., P.D. Stahl, and J.S. Buyer. 2002a. Microbial biomarkers as an indicator of ecosystem recovery following surface mine reclamation. Appl. Soil Ecol. 21:251–259.

Munshower, F.F. 1994. Practical handbook of disturbed land revegetation. Lewis Publication. Boca Raton, FL.

National Oceanic and Atmospheric Administration, 2012. NOAA satellite and information service. NNDC climate data online.

Olson, R.A., J.K. Gores, D.T. Booth, and G.E. Schuman. 2000. Suitability of shrub establishment on Wyoming mined lands reclaimed for wildlife habitat. Western North American Naturalist 60: p 77-92.

Pederson, T. A., A.S. Rogowski, and R. Pennock JR. (1978). Comparison of morphological and chemical characteristics of some soils and mine soils. Reclamation Review 1, p 143-156.

Prevéy, J. S., M. J. Germino, N. J. Huntly, and R. S. Inouye. 2010. Exotic plants increase and native plants decrease with loss of foundation species in sagebrush steppe. Plant Ecology 207:39–51.

Reed, D.J., H.K. Koucheki, and J. Hodgson. 1976. Vesicular-arbuscular mycorrhizal fungi in natural vegetation systems. The occurrence of infection. New Phytologist. 77:641-653

Reeves, F.B., B.D. Wagner, T. Moorman and J. Keil. 1979. The role of endomycorrhize in revegetation practices in the semiarid west: 1. A comparison of incidence of Mycorrhizae in severely disturbed vs. natural environments. American Journal of Botany 66:6-13

Resiner, M. D. 2010. Drivers of plant community dynamics in sagebrush steppe ecosystems: cattle grazing, heat and water stress. Dissertation, Oregon State University, Corvallis, Oregon, USA.

Rhoades, J.D. 1892. Soluble Salts. Methods of soil analysis; Chemical; Microbiological properties. Al page, R.H. Miller, D.R. Keeney, Madison, WI, American Society of Agronomy, Inc. Soil Science Society of America, Inc. p. 167-180.

Rives, C.S., M.E. Bajwa, A.E. Liberta, and R.M. Miller. 1980. Effects of topsoil; storage during surface mining on the viability of VA mycorrhiza. Soil Science 129:253-257

SAS Institute Inc. 2009. Base SAS® 9.2 Procedures Guide. Cary, NC: SAS Institute Inc.

Schroeder, M.A., Aldridge, C.L., Apa, A.D., Bohne, J.R., Braun, C.E., Bunnell, S.D., Connelly, J.W., Diebert, P., Gardner, S.C., Hilliard, M.A., Kobriger, G.D., McAdam, S.M., McCarthy, C.W., McCarthy, J.J., Mitchell, D.L., Rickerson, E.V. and Stiver, S.J. 2004. Distribution of sage-grouse in North America. Condor 106:363-376.

Schultz, L. M. 1986. Taxonomic and geographic limits of *Artemisia* subgenus *Tridentata* (Beetle) McArthur (Asteraceae: Anthemideae). In: McArthur, E. D.; Welch, B.L., eds. Proceedings—symposium on the biology of *Artemisia* and *Chrysothamnus*; 1984 July 9–13; Provo, UT. Gen. Tech. Rep. INT-200. Ogden, UT:U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 20–29.

Schuman G. E., E. J. DePuit, J. A. Smith, and L. A. King. 1985. Reclamation of bentonite mined lands in the Northern Great Plains. Environmental Geochemistry and Health. Volume 7.

Schuman G.E., E.J. DePuit, and K.M. Roadifer. 1994. Plant responses to gypsum amendments of sodic bentonite mine spoil. Journal of Rangeland Management 47:206-209.

Schuman, G.E., D.T. Booth, and J.R. Cockrell. 1998. Cultural methods for establishing Wyoming big sagebrush on mined lands. Journal of Range Management 51:223-230.

Severson, R. C. and L.P. Gough. (1983). Rehabilitation materials from surface coal mines in the western U.S.A. I. Chemical characteristics of spoil and replaced cover soil. Reclamation and Revegetation Research 2, 83-102.

Sieg, Carolyn Hull., D.W. Uresk and R.M. Hanson. 1983. Plant-soil relations on bentonite mine spoils and sagebrush-grasslands in the Northern Great Plains. Journal of Range Management. Vol. 36, No. 3. Pp. 289-294.

Shaw, N.L. and S.B. Monsen. 1988. Use of sagebrush for improvement of wildlife habitat. pp.19-35. In H.G. Fisser (ed.) Proceedings, Seventeenth Wyoming Shrub Ecology Workshop, University of Wyoming, Laramie, WY.

Shaw, N.L, A.M. DeBolt, and R. Rosentreter. 2005. Reseeding Big Sagebrush: Techniques and Issues. USDA Forest Service Proceedings RMRS –P- 38.

Smith, R. M. and A.A.Sobek. 1979. Physical and chemical properties of overburdens, spoils, wastes and new soils. In: Reclamation of Drastically Disturbed Lands (Ed. by F. W. Schaller & P. Sutton), pp. 162-179. American Society of Agronomy, Madison, Wisconsin.

Stahl, P.D., S.E. Williams, and M. Christensen. 1988. Efficacy of native Vesicular arbuscular mycorrhizal fungi after severe soil disturbance. New Phytologist 110:347–354.

Stahl, P.D., G.E. Schuman, S.M. Frost and S.E. Williams 1998. Arbuscular mycorrhizae and water stress of Wyoming big sagebrush seeding. Soil Science Society of America Journal 62:1309-1313

Stahl, P.D., B.L. Perryman, S. Sharmasarkar, and L.C. Munn. 2002. Stockpiling vs. exposure to traffic: Best management of topsoil on in-situ uranium well fields. Restoration Ecology. 10:129–137.

Stahl, P.D. and L. King. 2009. Improving sagebrush reclamation in bentonite mining areas of the Big Horn Basin (CESU) Project Narrative. Wyoming Reclamation Research Center. University of Wyoming

Stark, J.M., and E.F. Redente. 1980. Production potential of stockpiled topsoil. Piceance Restoration Symposium. p 304-308. Soil Science.

Stevens, R., and M. B. Stephen. 2004. Guidelines for restoration and rehabilitation of principal plant communities. In: Monsen, B. Stehpen, R. Stevens; Shaw, Nancy L., comps. Restoring Western Ranges and Wildlands. Gen. Tech. Rep. RMRS-GTR-136-Vol-1. For Collins, CO: U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station: 199-224.

Sylvia, D.M., J. J. Fuhrmann, P. G. Hartel, and D. A. Zuberer. 1998. Principles and Applications of Soil Microbiology. Prentice Hall, New Jersey.

USDA, 2012. NRCS, PLANTS Database, plants.usda.gov. National Plant Data Center, Baton Rouge, LA 70874-4490 USA. September 2012.

USDI, Bureau of Land Management. 1985. Rangeland monitoring - Trend studies TR4400-4.

U. S. Fish and Wildlife Service. 2010. Endangered and Threatened Wildlife and Plants; 12-

month findings for petitions to list the greater sage-grouse (*Centrocerus urophasianus*) as threatened or endangered. Federal Register 75:13909–14014.

Vicklund L. 2000. Historical sagebrush establishment practices in the Powder River Basin. In: 2000 Billings land reclamation symposium. Bozeman (MT): Montana State University. Reclamation Research Unit. Publication No. 00-01 (compact disc). p 330–337.

Vicklund L.E., G.E. Schuman and M.C. Mortenson. 2011. Effects of Wyoming big sagebrush seeding rate and grass competition on long-term density and canopy volume of big sagebrush and wildlife habitat. Presented at the National meeting of American Society of Mining and Reclamation, Bismarck, ND. Science Leading to Success.

Wambolt, C. L. and G.F. Payne. 1986. An 18-year comparison of control methods for Wyoming big sagebrush in southwestern Montana. Journal of Range Management 39: 314–319.

Wagstaff, F. L. and B.L. Welch. 1991. Seed stalk production of mountain big sagebrush enhanced through short-term protection from heavy browsing. Journal of Range Management 44: 72–74.

Welch, B. L., E.D. McArthur, D.L. Nelson, J.C. Pederson, and J.N. Davis. 1986. 'Hobble Creek'—a superior selection of low-elevation mountain big sagebrush. Research Paper INT-370. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. p 10.

Welch, B. L. 2005. Big sagebrush: a sea fragmented into lakes, ponds, and puddles. General Technical Report RMRS-GTR. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Welsh, S.L., N.D. Atwood, S. Goodrich, and L.C. Higgins (eds.). 1987. A Utah Flora. Great Basin Naturalist Memoirs 9. Brigham Young University, Provo, UT.894 p.

Western Regional Climate Center. 2012. http://www.wrcc.dri.edu/narratives/WYOMING.htm

Wick, A.F., L.J. Ingram, and P.D. Stahl. 2009. Aggregate and organic matter dynamics in reclaimed soils as indicated by stable carbon isotopes. Soil Biology and Biochemistry 41:201–209.

Wyoming Department of Environmental Quality (Land Quality Division): http://deq.state.wy.us/lqd/. Accessed September 2012.

Wyoming Mining Association. 2011. Bentonite Mining. http://www.wma-minelife.com/bent/bentmine/bentmine.htm. Accessed October 2011.

Wyoming State Geological Survey. 2011. Bentonite. http://www.wsgs.uwyo.edu/AboutWSGS/bentonite.aspx. Accessed October 2011.

Young, J. A. and R.A. Evans. 1989. Dispersal and germination of big sagebrush (*Artemisia tridentata*) seeds. Weed Science. 37:201–206.

Zeba®. 2008. More food, Using less Resources. A Sustainable Technology White Paper. http://www.zeba.com/company/20319_sustain%20_brochure.pdf. Accessed October 2012.