EVALUATION OF CULTURAL METHODS FOR ESTABLISHING WYOMING BIG SAGEBRUSH ON MINED LANDS[1]

J.R. Cockrell, G.E. Schuman, and D.T. Booth[2]

Abstract: Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) is one of the most widely distributed and adapted shrub species in Wyoming and the region. However, its reestablishment on mined lands has proven difficult because of low seedling vigor, its inability to compete with herbaceous species, poor seed quality, and altered edaphic conditions. Field research evaluating the effect of topsoil management, mulching practice, and plant competition have shown that all of these factors significantly influence early initial sagebrush establishment. Greater sagebrush establishment occurred on fresh topsoil compared to 5 year old stockpiled topsoil. Stubble and surface applied mulch and elimination of herbaceous species competition also significantly increased big sagebrush establishment in the first growing season. However, a cool, wet second year growing season (April-September) resulted in large increases in sagebrush seedling density across all treatments. These large increases resulted in some changes in response to imposed treatments; however, greater sagebrush seedling densities were still evident on fresh compared to stockpiled topsoil and competition still significantly reduced seedling density on the fresh topsoil treatment. Mulch type showed limited effects on sagebrush seedling density in the later phases of the study. This research indicates that big sagebrush seed viability may be longer than previously thought and that seed dormancy, safe site development, and climatic conditions play an important role in germination and establishment of this species.

Additional Keywords: Topsoil, Mulching, Plant Competition, *Artemsia tridentata*

Introduction

Wyoming big sagebrush (*Artemesia tridentata* ssp. *wyomingensis*) occurs across the West and east to the Black Hills (Beetle and Johnson 1982). Although controversy exists over its value (Colbert and Colbert 1983, Tessman and Kleinman 1989), the mining industry is encouraged or required to restore Wyoming big sagebrush on mined lands if it existed in the pre-mined ecosystem. Establishment of big sagebrush on reclaimed mined lands can be accomplished by direct seeding or transplantation. Luke and Monsen (1983) found that direct seeding was the most cost effective method; however, the reliability of direct seeding for shrub reestablishment is not good. Many theories exist as to the reasons for poor establishment of big sagebrush from direct seeding, including poor seed viability (Harniss and McDonough 1976, Young and Evans 1989), seed dormancy, seed harvest methods, and seedbed microclimate (McDonough and Harniss 1974, Meyer and Monsen 1992).

Herbaceous species competition may be another reason for the variable success of direct seeded sagebrush. Blaisdell (1949) reported that grasses outcompeted sagebrush when seeded from two years before to one year after seeding sagebrush and Jones (1991) was able to show increased survival of big sagebrush by removing other vegetation competition. Cook and Lewis (1963) and Sturges (1977) noted that competition effects are probably related to sagebrush seedlings inability to compete for water. Another issue identified as a factor that might reduce sagebrush seedling establishment is the lack, of or reduced level of vesicular-arbuscular mycorrhizae (VAM)

[1]Paper presented at the 1995 National Meeting of the American Society for Surface Mining and Reclamation, Gillette, Wyoming, June 5-8, 1995.

[2]J.R. Cockrell, Graduate Research Assistant,Univ. of Wyoming, Laramie, G.E. Schuman, Soil Scientist, D.T. Booth, Rangeland Scientist, USDA, ARS, High Plains Grasslands Research Station, 8408 Hildreth Road, Cheyenne, WY 82009 USA.

Proceedings America Society of Mining and Reclamation, 1995 pp 784-795
DOI: 10.21000/JASMR95010784

https://doi.org/10.21000/JASMR95010784

inoculum present in the post-mining soil. Soil salvage and storage can greatly influence the level of VAM inoculum present (Allen and Allen 1980, Smith et al. 1987, Rives, et al. 1980, Gould and Liberta 1981, Williams et al. 1981, Persson and Funke 1988, Christensen and Allen 1979, Douds and Schenck 1991). Topsoil salvage can result in mixing of soil horizons, altering edaphic conditions and resulting in dilution or reduction of potential inoculum (DePuit 1988, Stahl et al. 1988, White et al. 1989). Storage (stockpiling) of topsoil has been demonstrated to significantly reduce the VAM inoculum potential of the soil even when stockpiled for as little as six months (Allen and Allen 1980, Smith et al. 1987, Williams et al. 1981, Persson and Funke 1988). Most rangeland shrubs form VAM associations and some, including big sagebrush, are often considered to be obligately mycorrhizal (Allen 1982). Call and McKell (1981) reported greater shoot growth from inoculated sagebrush seedlings compared to those not inoculated. VAM associations result in improved nutrient uptake, especially phosphorus (Sylvia and Williams 1992) and improved resistance to drought (Sylvia et al. 1993).

The objectives of the research reported herein were to evaluate the efficacy of direct-applied topsoil for enhanced sagebrush establishment through VAM introduction, to evaluate the value of various mulch types in improving sagebrush seedling establishment through safe site enhancement, and to determine if competition from concurrently seeded perennial grasses reduced sagebrush establishment.

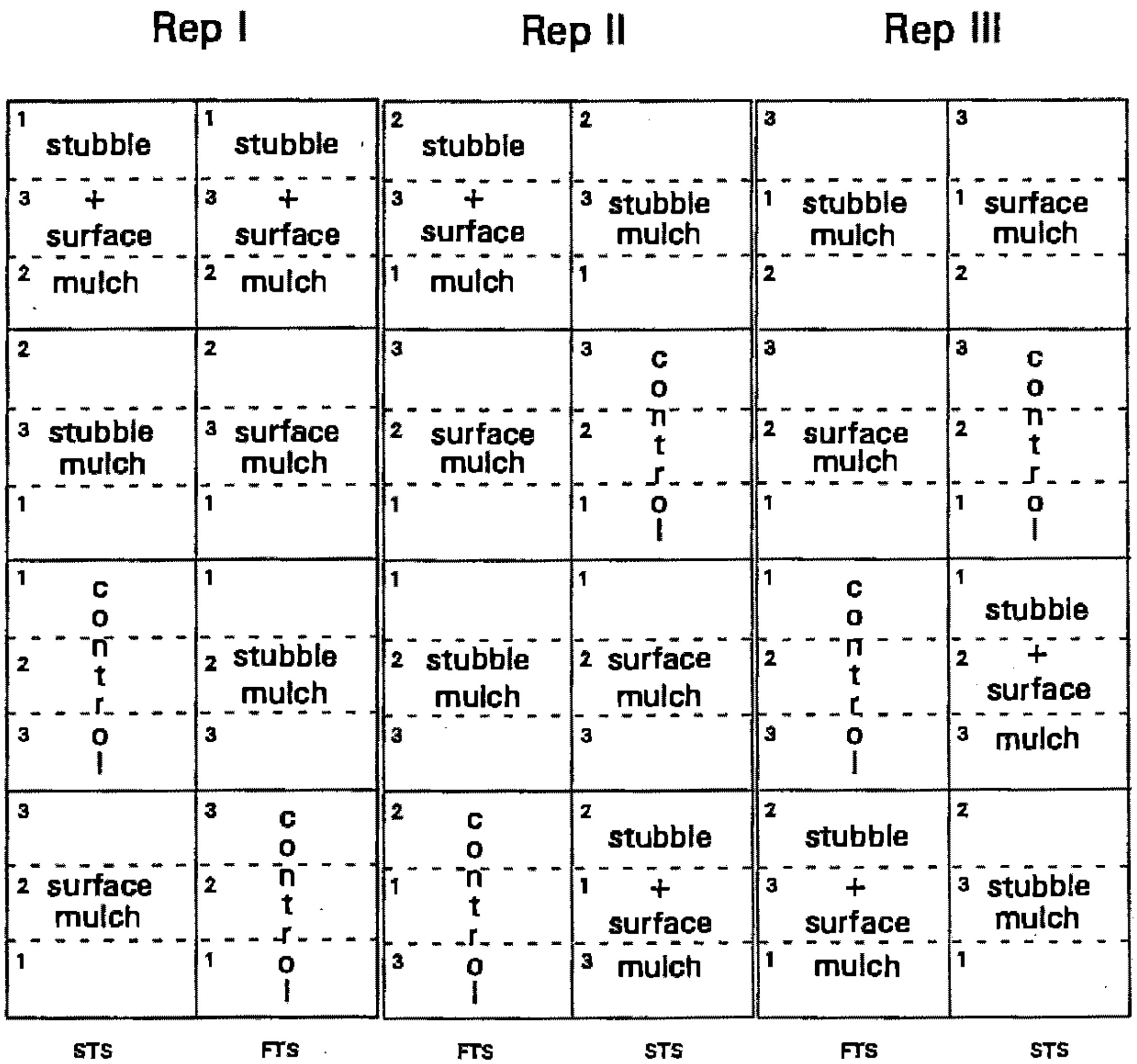
Field Site and Methods

The research was located at the North Antelope Coal Mine, in Campbell county, approximately 100 km south of Gillette, Wyoming. The site has a cool, semiarid continental climate. Precipitation ranges from 250 to 330 mm annually, with approximately 70% occurring from April through August. Monthly mean temperatures range from a low of -5° C in January to a high of 22.5° C in July. The fresh topsoil was composed of a complex of the Shingle (loamy, mixed, calcareous, mesic, shallow, Ustic Torrorthents)and Samsil series (clayey, montmorillinitic, calcareous, mesic, shallow, Ustic Torrorthents). The stockpiled topsoil came from an area that was mapped as Bidman-Briggsdale complex. Both the Bidman and Briggsdale series are fine, montmorillinitic, mesic, Ustollic Paleargids.

The project was initiated in August 1990 on approximately 1.2 ha of leveled coal mine spoil. Treatments included: (1) topsoil management; fresh stripped and stockpiled topsoil that had been stored for 5 years; (2) mulch type; stubble mulch, surficially applied straw mulch that was crimped, stubble and surface applied straw, and no mulch; and (3) competition; no perennial grass seeded, 16 kg PLS/ha of perennial grass, and 32 kg PLS/ha of perennial grass seeded. Each topsoil treatment plot was 15 by 60 m with mulch subplots being 15 by 15 m and competition sub-subplots being 15 by 5 m. All treatments were assigned at random in a randomized block, split-split plot design with three replications (Figure 1). The plots were established in August 1990 and topsoil placed on the regraded and ripped spoil material. Topsoil replacement depth averaged 30 cm and was accomplished in September 1990.

Baseline topsoil and spoil samples were collected in April 1991. Topsoil samples were collected for depth increments 0-7.5 cm and 7.5 cm to the spoil interface. Samples of the surface 7.5 cm of spoil were also collected. These samples were analyzed for electrical conductivity (EC) (Rhoades 1982); calcium, magnesium, sodium and potassium (Rhoades 1982); total Kjeldahl nitrogen (Schuman et al. 1973) and sodium bicarbonate-extractable phosphorus (Olsen et al. 1954). Vesicular-arbuscular mycorrhizal spores levels were assessed using sucrose floatation methods and counted (Allen et al. 1979).

In late April 1991, 'Steptoe' barley was seeded at 60 kg/ha on the plots which had been assigned to the stubble mulch or stubble + surface applied straw mulch treatments. In mid-July the barley was clipped to reduce seed maturation and subsequent year competition from volunteer barley plants. Annual weeds on the other mulch treatment plots were controlled with herbicide and tillage.



Grass Seeding Rate:

1 = 0 lbs PLS/hectare

2 = 16 kg PLS/hectare

3 = 32 kg PLS/hectare

FTS = fresh topsoil

STS = stored topsoil

Figure 1. Field plot diagram of Wyoming big sagebrush establishment study.

In late November, the competition treatments were imposed by drill seeding a mixture of 'Rosanna' western wheatgrass [*Pascopyrum smithii* (Rybd.) A. Love], 'San Luis' slender wheatgrass [*Elymus trachycaulus* (Link) Gould ex Skinners], and 'Critana' thickspike wheatgrass [*Elymus lanceolatus* (Scribner & J.G. Smith) Gould] composed of equal seed numbers of each of the grasses. The grass seeding was made as a dormant seeding after soil temperatures had dropped below that conducive to germination. The competition sub-subplots were seeded at 0, 16, or 32 kg PLS/ha. Wheat straw, 1000 kg/ha, was added to the stubble + surface mulch treatment and anchored to the surface with a vertical disk crimper. Wheat straw at the rate of 4500 kg/ha was applied and anchored to the soil surface on the surface mulch treated plots. In early March 1992, all plots were broadcast seeded with sagebrush (2.63 kg PLS/ha). The sagebrush was seeded at this time to reduce the potential for spurious germination during the winter if surface temperatures were adequate and to reduce the length of time seed might be displaced by wind. Rice hulls were mixed with the sagebrush seed to improve seed flow. The sagebrush seed was collected in the Powder River Basin area of Wyoming in early December 1991 and threshed with a debearder (Booth, et al. 1995).

In late March 1992, nine 1 m^2-quadrats were established in each mulch by grass competition subplot, for a total of 216 quadrats. The quadrats were established in three belts of three quadrats with each belt lying in an east-west direction. These quadrats were used to asscss grass and sagebrush seedling numbers in 1992 and sagebrush seedling numbers in 1993 and 1994. Sagebrush seedling numbers were evaluated in June and October 1992 and 1993 and in September 1994.

In the June of 1993, sagebrush seedlings located outside of the quadrats were excavated, their roots fixed and stained to evaluate percentage mycorrhizal infection (Kormanick and McGraw 1982; Giovenetti and Mosse 1980).

Since many of the quadrats had no sagebrush seedlings present, particularly in the early phases of the study, data analysis required innovative adaptation to enable evaluation of the treatments. Analysis of variance was accomplished on the sagebrush seedling means of the 9 quadrats collected on each replicate sub-subplot. This is a conservative evaluation of the data; therefore, it strengthens interpretations resulting from any statistical differences observed. The data were analyzed as a split-split plot design. The main plots were fresh and stockpiled topsoil and the four mulch types were randomly assigned within each topsoil source and the three herbaceous species competition treatments were randomly assigned to sub-subplots within each of the mulch subplots (Figure 1). Least-significant-difference was used to evaluate treatment mean comparisons. All statistical comparisons were evaluated at $P \leq 0.05$.

Results and Discussion

Spores of VAM were 2600 and 4100/g soil in the stockpiled and fresh topsoil, respectively. Even though this difference was significant at the $P \leq 0.05$ level of probability it was expected that the difference in spore numbers between the two topsoil sources would be much greater (Allen and Allen 1980; McMahon and Warner 1984). Baseline chemical and nutrient parameters generally showed the fresh topsoil to have significantly higher concentrations of soluble ions and nitrogen and phosphorus (Table 1).

Sagebrush seedling densities exhibited a significant three way interaction (topsoil management x mulch type x grass competition) for all five dates of sagebrush seedling density measurements (Figures 2-6). Sagebrush seedling densities exhibit differing responses to the treatments in the early phases (Spring and Fall 1992, Spring 1993) of the study compared to the later phases (Fall 1993 and 1994). We believe the large increase in seedling density that occurred between the first of June count (Spring 1993) and the early October count (Fall 1993) reflects the wet and cool spring and summer of 1993 (Table 7). Precipitation in 1993 was almost double that in 1992 and 1994 and the April through June average monthly temperature was about 2°C cooler than 1992. Fresh topsoil resulted in >40% more sagebrush seedlings than stockpiled topsoil and in the early phases of the study the differences were generally 1-2 orders of magnitude greater for the fresh topsoil treatment. Sagebrush seedling data clearly show that topsoil source is important in sagebrush establishment, but this study has not clearly deliniated the specific benefits derived from the fresh topsoil. Mycorrhizal infection in sagebrush seedlings excavated in June 1993 from the two topsoil

Table 1. Chemical and nutrient concentrations in fresh and stockpiled topsoil.

Soil Mgmt	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	TKN	P
		--------mg/kg--------				
Fresh	342a	108a	79a	23a	950a	7.2a
Stockpiled	170b	67b	84a	26b	740b	6.3b

Values within a column with the same letter are not significantly different at the 0.05 level of probability.

treatments was not different (Table 8) even though the topsoil had different VAM spore levels at the initiation of the study. Loree and Williams (1984) found that native grass species became inoculated with VAM within a year of establishment on stockpiled topsoil. VAM inoculum levels may have been or became adequate for infection of the sagebrush seedlings on the stockpiled topsoil; or, seedlings not infected died. This may have resulted in a non-representative sample of the sagebrush seedlings. Further evaluation of the role of VAM on sagebrush seedling establishment will be necessary. It appears that fresh topsoil did not act as a seedbank for the sagebrush because an adjacent companion study showed no sagebrush seedlings on fresh topsoil during this same period where sagebrush had not been seeded (D.T. Booth et al. 1994, unpublished data). Soil moisture in the surface 30 cm of the fresh topsoil was significantly higher than that observed in the stockpiled topsoil during May-July 1992 (J.R. Cockrell 1992, unpublished data), which also could account for the greater seedling establishment in the fresh compared to stockpiled topsoil.

Table 2. Sagebrush seedling density as affected by topsoil management, mulch type, and grass competition, Spring 1992.

	Topsoil Management					
	Fresh			Stockpiled		
Competition (kgPLS/ha)	0	16	32	0	16	32
Mulch Type						
stubble	5.78a	1.11b	0.04b	0.11a	0a	0a
surface	7.37a	.07b	0b	0.04a	0a	0a
stubble + surface	1.59a	1.56a	0.63a	0.11a	0a	0.04a
control	0a	0a	0.04a	0a	0a	0a

Means within a mulch and topsoil with the same letter are not significantly different, $P \leq 0.05$.

Table 3. Sagebrush seedling density as affected by topsoil managment, mulch type, and grass competition, Fall 1992.

	Topsoil Management					
	Fresh			Stockpiled		
Competition (kgPLS/ha)	0	16	32	0	16	32
Mulch Type						
stubble	5.15a	0.52b	0.07b	0a	0a	0.04a
surface	6.07a	0b	0.15b	0a	0a	0a
stubble + surface	1.41a	1.11a	0.37a	0.30a	0.04a	0a
control	0a	0a	0a	0a	0a	0a

Means within a mulch and topsoil with the same letter are not significantly different, $P \leq 0.05$.

Table 4. Sagebrush seedling density as affected by topsoil management, mulch type, and grass competition, Spring 1993.

	Topsoil Management					
	Fresh			Stockpiled		
Competition (kgPLS/ha)	0	16	32	0	16	32
Mulch Type						
stubble	6.30a	2.04b	1.81b	1.63a	0.04a	0.15a
surface	8.74a	0.30b	0.89b	0.44a	0.04a	0.93a
stubble + surface	4.07a	2.48a	1.52a	1.56a	0.33a	0.11a
control	1.26a	0.56a	0.22a	0.37a	0.14a	0.04a

Means within a mulch and topsoil with the same letter are not significantly different, $P \leq 0.05$.

Table 5. Sagebrush seedling density as affected by topsoil management, mulch type, and grass competition, Fall 1993.

	Topsoil Management					
	Fresh			Stockpiled		
Competition (kgPLS/ha)	0	16	32	0	16	32
Mulch Type						
stubble	9.67a	3.93b	2.93b	5.41a	2.11a	1.93a
surface	13.48a	1.00b	1.22b	2.74a	1.81a	2.18a
stubble + surface	8.04a	2.89b	1.63b	4.59a	2.15a	1.70a
control	7.52a	1.37b	0.52b	1.81a	0.52a	0.19a

Means within a mulch and topsoil with the same letter are not significantly different, $P \leq 0.05$.

Table 6. Sagebrush seedling density as affected by topsoil management, mulch type, and grass competition, Fall 1994.

	Topsoil Management					
	Fresh			Stockpiled		
Competition (kgPLS/ha)	0	16	32	0	16	32
Mulch Type						
stubble	8.15a	9.82a	7.11a	3.44a	2.78a	3.26a
surface	12.11a	4.63b	5.33b	2.40a	3.52a	5.07a
stubble + surface	9.11a	3.78b	4.26b	3.30a	3.85a	2.52a
control	7.22a	5.88a	4.56a	4.48a	2.52a	1.70a

Means within a mulch and topsoil with the same letter are not significantly different, $P \leq 0.05$.

Table 7. Monthly precipitation and mean monthly temperature, North Antelope Coal Company, Gillette, WY, 1992-1994.

Month	1992 Precip (cm)	°C	1993 Precip (cm)	°C	1994 Precip (cm)	°C
Jan	0	-0.6	0	-7.2	0.20	-3.3
Feb	0.68	2.2	0.38	-7.7	0.15	-6.1
Mar	3.15	4.4	1.47	2.2	0.41	3.3
Apr	0.76	7.7	6.48	5.5	2.79	6.6
May	2.26	13.2	5.94	12.7	2.87	14.9
Jun	6.43	16.5	14.15	14.3	8.36	18.2
Jul	7.75	17.6	9.70	17.1	4.93	19.8
Aug	2.95	18.2	10.13	18.2	0.81	20.9
Sep	1.75	15.4	2.29	12.1	1.22	16.0
Oct	0.41	8.8	2.36	6.1	5.49	7.2
Nov	0.89	-0.6	0.36	-2.2	0.58	0
Dec	1.19	-6.6	0.10	-1.7	0.05	-1.7
Total	28.22		53.36		27.86	

Mulch greatly affected sagebrush seedling establishment in the early phases of the study. No sagebrush seedlings were evident in the first year where no mulch was applied. The stubble and surface straw mulch had several fold greater sagebrush establishment over the stubble + surface mulch in the early phases of the study. The stubble + surface mulch is believed to have reduced seed-soil contact. Stubble mulch has been shown to affect seedling microclimate through reduced diurnal temperature fluctuations and increased soil moisture (Schuman, et al. 1980). However, seedling counts taken in the Fall 1993 and 1994 were not different between mulched and unmulched plots.

Grass seedling competition reduced sagebrush seedling densities throughout the duration of the study. These difference were most consistent on the fresh topsoil treatment and on the stubble and surface straw mulch treatments where sagebrush seedling densities were the greatest. Grass seedling numbers counted in the Fall 1992 reflect the herbaceous competition. The 0, 16 and 32 kg PLS/ha grass seeding rates resulted in 0, 196, and 250 grass seedlings/m^2 (J.R. Cockrell, 1992, unpublished data). No differences in grass seedling densities between topsoil source and mulch were evident.

Table 8. VAM infection percentage of sagebrush seedlings as affected by topsoil management, mulch type, and grass competition.

Treatment	% Infection	Number of Seedlings Evaluated
Topsoil Mgmt		
Fresh	66	66
Stockpiled	76	66
Mulch Type		
Stubble	73	36
Surface	71	36
Surface + Stubble	72	36
Control	67	24
Grass Competition (kg PLS/ha)		
0	73	69
16	68	63
32	--a	--a

[a]Insufficient sagebrush seedlings available for evaluation.

The increase in sagebrush seedling establishment from a single seeding over the 3 years evaluated poses numerous questions. First, did the seed that was sown in March 1991 remain viable for the three year period and continue to germinate as safe sites developed and conditions became adequate for germination. We are confident that seed did not blow in from nearby undisturbed sagebrush-grasslands, because control plots on the adjacent study show no sagebrush seedlings during these 3 years. Young and Evans (1989) reported that Artemisia tridentata tridentata does not maintain seed viability for more than a few months. However, *Artemisia tridentata wyomingensis* has been shown to have some seed dormancy (McDonough and Harniss 1974; Booth et al. 1995). Bai and Romo (1994) also reported that fringed sage (*Artemisia frigida* Willd.) seed buried in the soil in vials exhibited longevity from 3 1/2 to 5 years. They concluded that continuous germination over time may enable fringed sage to occupy safe sites as they develop. They also concluded that as fringed sage seed aged its requirements for germination became less specific. Industry reclamation specialists in the Powder River Basin have observed increased sagebrush seedling numbers over a period of 2-3 years after seeding. It is also posssible that a portion of the increase observed over time could result from missing the very small sagebrush seedlings when making the seedling counts; however, this would not account for the magnitude of the change observed.

As noted earlier, the sagebrush seedling densities observed in the latter phases of the study do not exhibit as much response to the cultural and management treatments as they did in the important firs and second years. We cannot fully explain the perceived long-term seed viability as indicated by increasing seedling densities in years two and three. Observed sagebrush seedling densities would result in a more than adequate density of Wyoming big sagebrush on mined lands if one assumes that all of the seedlings survive and reach maturity. However, data do not exist to evaluate long-term survival in relation to initial establishment.

Conclusions

Results of this research have shown that topsoil management, mulching practices, and herbaceous species competition all influence sagebrush establishment on mined lands. Mulching reduces the effects of rapid changes in temperature and conserves moisture in the seed site environment. Fresh stripped topsoil enhances overall reclamation success because it possesses better chemical, physical, and biological properties than does stockpiled topsoil. These qualities influence water infiltration, water storage, nutrition, soil structure and VAM inoculum potential which all enhance the potential success of plant establishment. Topsoil management to prevent or limit topsoil stockpiling should be practiced. Herbaceous plant competition greatly reduced early sagebrush seedling establishment; therefore, seeding practices may need to be modified where big sagebrush is an important component of the postmine plant community. We recommend sagebrush be sown in islands or strips with no herbaceous species. These islands or strips need to be small and systematically located to ensure protection and stability of the topsoil resource from loss due to water erosion.

Acknowledgement

This work was supported in part by the Abandoned Coal Mine Lands Research Program at the University of Wyoming. This support was administered by the Wyoming Department of Environmental Quality from funds returned to Wyoming from the Office of Surface Mining of U.S. Department of Interior. The authors also express their appreciation to Dr. Gary V. Richardson, Biometrician for his assistance in experimental design and data analysis and to Scott Belden, Environmental Supervisor, North Antelope Coal Company for his cooperation and assistance.

References

Allen, M.F. 1982. Influence of vesicular-arbuscular mycorrhizae on water movement through *Bouteloua gracilis* (H.B.K.) lag ex Stued. New Phytol. 91: 191-196.
http://dx.doi.org/10.1111/j.1469-8137.1982.tb03305.x

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

Allen, M.F., T.S. Moore, Jr., M. Christensen, and N. Stanton. 1979. Growth of vesicular-arbuscular and non-mycorrhizal *Bouteloua gracilis* in a defined medium. Mycologia 71: 666-669.
http://dx.doi.org/10.2307/3759083

Bai, Yuguang and J.T. Romo. 1994. Germination of previously buried seeds of fringed sage (*Artemisia frigida*). Weed Sci. 42:390-397.

Beetle, A.A. and K.L. Johnson. 1982. Sagebrush in Wyoming. Wyoming Agr. Exp. Stn. Bull. 779, Laramie.

Blaisdell, J.P. 1949. Competition between sagebrush seedlings and reseeded grasses. Ecology 30: 512-519.
http://dx.doi.org/10.2307/1932454

Booth, D.T. 1995. Wyoming big sagebrush seed quality related to debearder operation during seed cleaning and storage. In: Proc. 5th International Rangeland Congress, Salt Lake City, UT (In press)

Call, C.A. and C.M. McKell. 1981. Vesicular-arbuscular mycorrhizae--a natural revegetation strategy for disposed processed oil shale. Recl. and Reveg. Res. 1: 337-347.

Christensen, M. and M.F. Allen. 1979. Effect of VA mycorrhizae on water stress tolerance and hormone balance in native western plant species. Final Report to the Rocky Mountain Institute of Energy and Environment, Laramie, WY.

Colbert, T.A. and M.A. Colbert. 1983. Revegetating with sagebrush, who's right? Rangelands 5: 33-35.

Cook, C.W. and C.E. Lewis. 1963. Competition between big sagebrush and seeded grasses on foothill ranges in Utah. J. Range Manage. 16: 245-250.
http://dx.doi.org/10.2307/3895334

DePuit, E.J. 1988. Productivity of reclaimed lands-rangeland. pp. 93-129. In: L.R. Hossner (ed.) Reclamation of Surface Mined Lands, Vol. II, CRC Press, Baco Raton, FL.

Douds, D.D. Jr. and N.C. Schenck. 1991. Germination and hyphal growth of VAM during and after storage in soil at five matrix potentials. Soil Biol. Biochem. 23: 177-183.
https://doi.org/10.1016/0038-0717(91)90132-4

Giovannetti, M. and B. Mosse. 1980. An evaluation of techniques for measuring vesicular-arbuscular mycorrhizal infection in roots. New Phytol. 84: 489-500.
http://dx.doi.org/10.1111/j.1469-8137.1980.tb04556.x

Gould, A.B. and A.E. Liberta. 1981. Effects of topsoil storage during surface mining on the viability of vesicular-arbuscular mycorrhizal fungi. Mycologia 73: 914-922.
http://dx.doi.org/10.2307/3759802

Harniss, R.O. and W.T. McDonough. 1976. Yearly variation in germination in three subspecies of big sagebrush. J. Range Manage. 29: 167-168.
http://dx.doi.org/10.2307/3897421

Jones, G.P. 1991. Seedling survival and adult plant water relations of black sagebrush and big sagebrush in the Laramie Basin. Ph.D. Diss., University of Wyoming, Laramie.

Kormanick, P.P. and A.C. McGraw. 1982. Quantification of vesicular-arbuscular mycorrhizae in plant roots. pp. 37-45. *In*: N.C. Schenck (ed.) Methods and principles of mycorrhizal research. Am. Phytopath. Soc., Minneapolis, MN.

Loree, M.A.J. and S.E. Williams. 1984. Visicular-arbuscular mycorrhizae and severe land disturbance. pg 1-14. *In*: Proc. VA Mycorrhizae and Reclamation of Arid and Semiarid Lands. August 17-19, 1982, Dubois, WY. Wyoming Agr. Exp. Stn. Scient. Rpt. No. SA1261, Laramie.

Luke, F. and S.B. Monsen. 1983. Methods and costs for establishing shrubs on mined lands in southwestern Wyoming. pp. 286-292. *In*: Proceedings, Symposium on the biology of *Atriplex* and related chenopods. USDA Forest Service, Gen. Tech. Rpt. INT-172, Ogden, UT.

McDonough, W.T. and R.O. Harniss. 1974. Effects of temperature on germination in three subspecies of big sagebrush. J. Range. Manage. 27: 204-205.
http://dx.doi.org/10.2307/3897032

McMahon, J.A. and N. Warner. 1984. Dispersal of mycorrhizal fungi: Processes and agents. pp. 28-41. In: S.E. Williams and M.F. Allen (eds.) VA mycorrhizae and reclamation of arid and semiarid lands. Univ. Wyo. Agr. Exp. Stn. Rept. AS1261, Laramie.

Meyer, S.E. and S.B. Monsen. 1992. Big sagebrush germination patterns: Subspecies and population differences. J. Range. Manage. 45: 87-93.
http://dx.doi.org/10.2307/4002533

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939, United States Government Printing Office, Washington, D.C.

Persson, T.J. and B.R. Funke. 1988. Microbiology of stored topsoil at North Dakota stripmining sites. Arid Soil Res. and Rehabil. 2: 235-250
https://doi.org/10.1080/15324988809381178

Rhoades, J.D. 1982. Soluble salts. pp. 167-179. *In*: A.L. Page et al. (eds.) Methods of Soil Analysis, Part 2. Agron. Monograph 9, American Society of Agronomy, Madison, WI.

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 Sci. 129: 253-257.
http://dx.doi.org/10.1097/00010694-198004000-00009

Schuman, G.E., M.A. Stanley and D. Knudsen. 1973. Automated total nitrogen analysis of soil and plant samples. Soil Sci. Soc. Am. Proc. 37: 480-481.

Schuman, G.E., E.M. Taylor, Jr., F. Rauzi, and G.S. Howard. 1980. Standing stubble versus crimped straw mulch for establishing grass cover on mined lands. J. Soil and Water Cons. 35: 25-27.

Smith, P.L., E.F. Redente, and E. Hooper. 1987. Soil organic matter. pp. 185-214. In: R.D. Williams and G.E. Schuman (eds.) Reclaiming minesoils and overburden in the western United States: Analytical parameters and procedures. Soil Conservation Soc. Am., Ankeny, IA.

Stahl, P.D., S.E. Williams, and M. Christensen. 1988. Efficacy of native vesicular-arbuscular mycorrhizal fungi under severe soil disturbance. New Phytol. 110: 347-354.
http://dx.doi.org/10.1111/j.1469-8137.1988.tb00271.x

Sturges, D.L. 1977. Soil water withdrawl and root characteristics of big sagebrush. Am. Midl. Nat. 98: 257-274.

Sylvia, D.M., L.C. Hammond, J.M. Bennett, J.H. Haas, and S.B. Linda. 1993. Field response of maize to a VAM fungus and water management. Agron. J. 85: 193-198.
http://dx.doi.org/10.2134/agronj1993.00021962008500020006x

Sylvia, D.M. and S.E. Williams. 1992. Vesicular-arbuscular mycorrhizae and environmental stress. *In*: Mycorrhizae in sustainable agriculture. Am. Soc. Agron. Special Publ. 54., American Society of Agronomy, Madison, WI.

Tessman, S.A. and L.H. Kleinman. 1989. Should the mining industry be required to increase the amount of sagebrush planted at reclaimed sites--point/counterpoint. The Wyoming Mining Claim. 15(2): 8-11.

Williams, S.E., M.A.J. Loree and P.C. Singleton. 1981. The effect of long term storage on fertility and biological activity of topsoil. Abstract. In: Proceedings of the Fifth North American Conference on Mycorrhizae. August 1981, Quebec City, Quebec, Canada.

White, J.A., L.C. Munn and S.E. Williams. 1989. Edaphic and reclamation aspects of vesicular-arbuscular mycorrhizae in Wyoming Red Desert soils. Soil Sci. Soc. Am. J. 53:86-90.
http://dx.doi.org/10.2136/sssaj1989.03615995005300010016x

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