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Canopy Growth and Density of Wyoming Big Sagebrush Sown with Cool-Season Perennial Grasses

Ann L. Hild

Department of Renewable Resources, University of Wyoming, Laramie, Wyoming, USA

Gerald E. Schuman

High Plains Grasslands Research Station USDA-ARS, Cheyenne, Wyoming, USA

Laurel E. Vicklund

Belle Ayr Coal Mine, Foundation Coal West, Inc., Gillette, Wyoming, USA

Mary I. Williams

Department of Renewable Resources, University of Wyoming, Laramie, USA

Post-mining revegetation efforts often require grass seeding and mulch applications to stabilize the soils at the same time as shrub seeding, creating intraspecific competition between seeded shrubs and grasses that is not well understood. Artemisia tridentata *Nutt. ssp.* wyomingensis *(Beetle and Young) (Wyoming big sagebrush) is the dominant premining shrub on many Wyoming mines. The Wyoming Department of Environmental Quality, Land Quality Division requires reestablishment of 1 shrub m^{-2} on 20% of post-mined lands in Wyoming. Reclamationists seldom document the impacts of grass competition on shrub canopy size after reclamation plantings become established even though shrub canopy development is important to vegetative structural diversity. In 1999, we initiated a study at the Belle Ayr Coal Mine near Gillette, Wyoming, to evaluate the influence of grass competition on establishment and growth of Wyoming big sagebrush. Combinations of three*

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Address correspondence to Ann L. Hild, Department of Renewable Resources, Dept. 3354, University of Wyoming, Laramie, Wyoming 82071. E-mail: annhild@uwyo.edu

sagebrush seeding rates (1, 2, and 4 kg pls ha^{-1}) and seven cool-season perennial grass mixture seeding rates (0, 2, 4, 6, 8, 10, and 14 kg pls ha^{-1}) were seeded during winter 1998–1999. Shrub density and grass cover were assessed from 1999 to 2004. We monitored sagebrush canopy size in 2001, 2002, and 2004. All sagebrush seeding rates provided shrub densities $\geq$1 shrub m^{-2} after six growing seasons. Grass production $\geq$75 g m^{-2} was achieved by seeding grasses at 6 to 8 kg pls ha^{-1}. Canopy growth of individual sagebrush plants was least in the heaviest grass seeding rate. Reduced grass seeding rates can aid in achieving Wyoming big sagebrush density standards and enhance shrub canopy growth.

Keywords *Artemisia tridentata* ssp. *wyomingensis*, coal mine reclamation, seeding rates, shrub, structural diversity, structure

The goal of mine land reclamation in the western United States is to develop a stable, productive and diverse plant community that meets postmine land uses (SMCRA, 1977). 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 & Monsen, 1988; Schuman et al., 1998). In general, high grass seeding rates create dense stands with low vigor (DePuit et al., 1980), and can limit seedling establishment due to inter- and intraspecific competition (Bergelson & Perry, 1989). In recent studies, grass limited *Artemisia tridentata* Nutt. ssp. *wyomingensis* (Beetle & Young) (Wyoming big sagebrush) (Eissenstat & Caldwell, 1988; Schuman et al., 1998) and *Artemisia tridentata* ssp. *vaseyana* (mountain big sagebrush) initial seedling establishment (Richardson et al., 1986).

Reclaimed mine land standards in Wyoming require a minimum of 1 shrub m^{-2} on 20% of disturbed lands where the postmine land use is grazing and wildlife habitat, and shrubs comprise at least 20% of the pre-mine undisturbed plant community (Wyoming Department of Environmental Quality (WDEQ), 1996). Even though research demonstrates competition from herbaceous species influences Wyoming big sagebrush establishment, the regulations require topsoil stabilization using a permanent vegetative cover that is as productive or more productive than pre-mine conditions. These two reclamation requirements result in a potential limitation that must be better understood in order to successfully establish a diverse plant community containing shrubs. Recent studies (for example Schuman et al., 1998; Stahl et al., 1998) provided improved cultural techniques for sagebrush reestablishment on coal mined lands. In general, reducing grass seeding rates may enhance Wyoming big sagebrush densities (Kleinman, 1996). However, the consequences of combined sagebrush and grass seeding rates on shrub canopy size are not known.

Success in mine land reclamation has historically been assessed by comparing post-mining species richness and abundance to predisturbance baseline standards. However, during the last decade, ecologists have departed from species composition to assess ecosystem integrity. Instead they target three attributes thought to be critical to ecosystems: composition, structure and function (Chen & Yaffee, 1999; Costanza, 1992; Hobbs & Norton, 1996; Interagency Ecosystem Management Task Force, 1995; Noss, 1990; U.S. Fish and Wildlife Service, 1994). By considering structure and function, this approach reduces dependence on vegetative composition. Vegetative structure (the vertical arrangement of vegetation) has profound influence on communities by providing microsites, visual barriers, spatial patterning and cumulative habitat characteristics. Woody shrubs such as sagebrush can strongly influence the microenvironment and soils surrounding them. Although the Wyoming DEQ does not require that mines document vegetative structure, reclamationists recognize its importance (Whisenant, 1999). In shrubland systems, it is clear that shrub density does not adequately describe aboveground shrub production, shading, microsite formation, or shrub size. By documenting canopy size of shrubs over time in reclamation plantings, we may better describe structural development of reclaimed sites that is critical to the return of ecosystem function.

This study was conducted to evaluate the establishment and subsequent canopy growth of Wyoming big sagebrush when sown with a mixture of cool-season perennial grasses on reclaimed land at the Belle Ayr Coal Mine near Gillette, Wyoming. Three seeding rates of Wyoming big sagebrush and seven grass seeding rates were used to evaluate the influence of sagebrush seeding rate and grass competition upon establishment of Wyoming big sagebrush and shrub canopy volume. We addressed three questions:

1. Does grass seeding density influence Wyoming big sagebrush emergence and initial establishment?
2. Do Wyoming big sagebrush seeding rates determine Wyoming big sagebrush seedling densities?
3. Is the growth of Wyoming big sagebrush, especially canopy development, affected by grass or sagebrush seeding rates or their interaction?

Materials and Methods

Site Description

The study site was located within a 36-hectare (ha) area at Foundation Coal West, Inc., Belle Ayr Coal Mine, 29 km southeast of Gillette, Wyoming. The Belle Ayr Mine is situated in the Powder River Basin between the Black Hills and Big Horn Mountains (44°17′ N, 105°30′ W; elevation 1460 m) and has a continental climate. Mean air temperature and average annual precipitation are 6.7°C and 376 mm (Belle Ayr Coal Mine Annual Report, 2000). Rolling plains, terraces and sloping alluvial fans along streams characterize the landscape. Premining vegetation of the Powder River Basin included localized concentrations of shrubs in a matrix of cool- and warm-season perennial grasses typical of northern mixed-grass prairie (Glassey et al., 1955). Wyoming big sagebrush is common on shallow soils while *Artemisia cana* (silver sagebrush) is commonly found within drainages. Local soils were formed from both Tertiary and Upper Cretaceous shale, sandstone and limestone. These soils often have a carbonate horizon 40–76 cm deep in the profile (Glassey et al., 1955). Annual precipitation records (Figure 1) were obtained from the Belle Ayr Mine meteorological site located about 4 km from the study site. Air temperature, soil temperature, and edaphic properties are reported in Williams et al. (2002).

Plot Layout and Seeding Treatments

Approximately 56 cm of topsoil (7-year-old stockpile) was spread onto 70 m of graded spoil in December 1997. In spring 1998, the site was seeded to *Hordeum vulgare* var. 'Steptoe' (barley) and then mowed in early summer and in early fall 1998 to provide a standing stubble mulch.

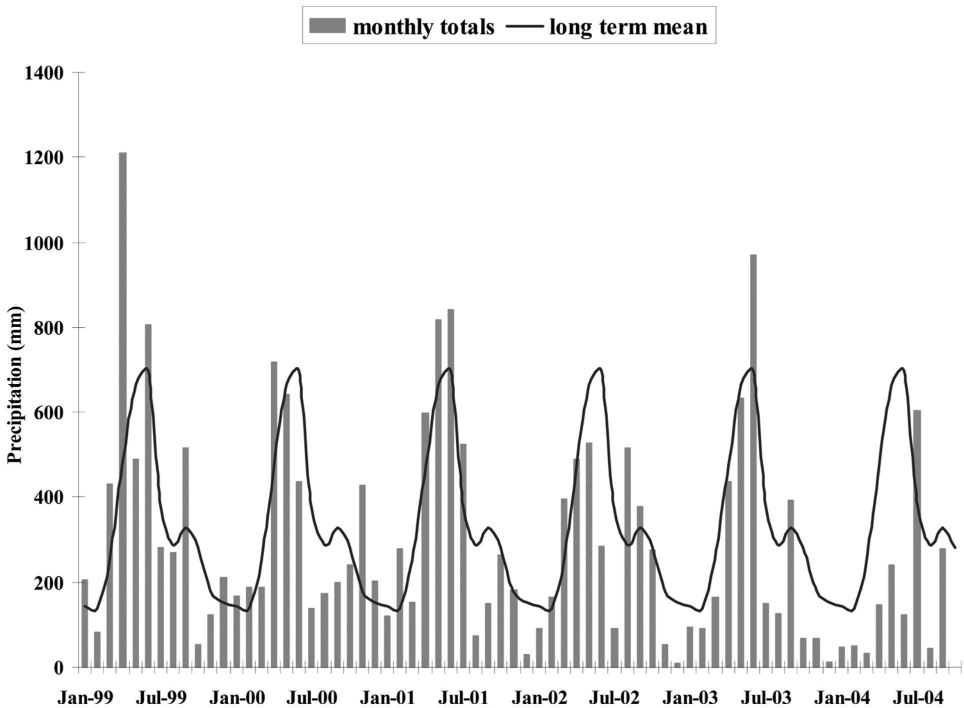

Figure 1. Monthly precipitation totals (bars) from 1999 to 2004 and 80-year long-term mean precipitation (line) at Belle Ayr Mine, Foundation Coal West, Inc., a formerly mined land reclamation site near Gillette, Wyoming.

Seven grass seeding rates 0, 2, 4, 6, 8, 10, and 14 kg pls ha^{-1} (0, 187, 374, 561, 750, 935, and 1309 pls m^{-2}), were randomly assigned to 6.5- × 27-m main plots within each of four rectangular 27- × 45.5-m replicate blocks. Seeding was accomplished in December 1998 using a 1.5 m wide double disk drill. Three cool-season (C_3) perennial grasses [*Pascopyrum smithii* (Rydb.) A. Love, 'Barton' (western wheatgrass), *Elymus lanceolatus* (Scribner & J.G. Smith) Gould, 'Critana' (thickspike wheatgrass), and *Elymus trachycaulus* (Link) Gould ex Shinners, 'Pryor' (slender wheatgrass)] were seeded at equal seed numbers into the stubble mulch at 1.5 to 2.0 cm depth. The three grass species are commonly used in mine reclamation and are the dominant C_3 species on pre-mine lands in northeastern Wyoming.

In March 1999 each grass treatment plot was divided into three rectangular 6- × 9-m subplots, which were randomly assigned to one of three Wyoming big sagebrush seeding rates (1, 2, and 4 kg pls ha^{-1}; 350, 700, and 1400 pls m^{-2}). Sagebrush seeding rates between 2.2 and 3.9 kg pls ha^{-1} have been shown to be successful for establishing Wyoming big sagebrush in the past (Gores, 1995; Quinney et al., 1996). A local Wyoming big sagebrush seed source (88% viability and 23% pls) collected in December 1997 was seeded using a precision broadcast seeder. Cracked corn was mixed with the sagebrush seed to accomplish uniform seed distribution and flow through the seeder. Because of abundant volunteer forb cover derived from soil seed banks in 1999 (Williams et al., 2002), the study area was mown to an 18-cm height and the plant material removed from the plots by hand after the first sagebrush seedling count (30 June 1999). Nearest mature sagebrush native vegetation was more than 1000 m from the study plots and immature sagebrush seedings were more than 600 m from the plots. Because sagebrush recruitment from native stands, even stands immediately adjacent to plots is an unlikely seed source (Johnson & Payne, 1968), there was little chance that native sagebrush seed from these distances were wind-transported to our study plots. Additionally, seeds can remain viable 3–4 years after seeding and can demonstrate delayed germination (Monsen & Richardson, 1986; Schuman et al., 1998; Williams et al., 2002).

Vegetation Measurements

Prior to seedling emergence in 1999, six square 1-m^2 quadrats were permanently marked within each treatment subplot. Sagebrush seedlings in each 1-m^2 quadrat were counted on 11 sampling dates (30 June, 3 August, 31 August, and 25 October 1999; 5 June and 18 September 2000; 18 June and 3 October 2001; 20 June and 27 September in 2002; and 25 August 2004). Results from sagebrush seedling density counts in 1999 and 2000 are reported elsewhere (Williams et al., 2002) and are summarized here only for comparison purposes. To better understand the effects of grass competition on sagebrush establishment and to strengthen any seeding recommendations, we assessed seedling density in the research plots over four subsequent years (2001–2004).

Sagebrush seedling canopy volume was documented on three sampling dates (18 June 2001, 20 June 2002 and 25 August 2004) to evaluate the effects of grass competition (seeding rates) on canopy growth. Canopy of all sagebrush seedlings within each of three sample subplots in each treatment were documented by measuring the widest canopy width, the canopy width perpendicular to the first width, and plant height. Canopy volume was calculated for each sagebrush plant using the formula for an elliptical cone and volume was also totaled for each plot to obtain values per m^2. Canopy volume reported as a unit-area measure reflects structural habitat changes over time. Canopy volume of individual sagebrush plants is also important to community structural development. In even-aged stands such as in reclamation plantings, shrub size and age are uniform, because plots lack a nearby seed source for natural recruitment. For this reason, we examined the relationship of seeding rates to variability in the canopy volume of individual sagebrush plants.

Seedling survival (%) was calculated within each treatment subplot by dividing final sagebrush densities (August 2004) by the initial seedling densities (June 1999). This calculation uses the highest sagebrush seedling densities which occurred in June 1999.

Experimental Design and Data Analysis

Analysis of variance (ANOVA) was conducted on sagebrush density, survival and canopy volume data using a split-plot randomized block design (Proc GLM, SAS Institute, 1999). Grass seeding treatments were main plots and Wyoming big sagebrush seeding rates were subplot level treatments. Data were assessed for conformance to assumptions of analysis of variance, including parametric data distribution. Because the survival data is expressed as a percent, survival analysis residuals were found to be nonnormal. Consequently F-test probabilities for survival analysis are derived from analysis of variance of log-transformed data. For all analyses, where F-test probabilities were significant ($P < 0.05$), Fishers protected least significant difference (FLSD) was used for mean separation.

Results

Sagebrush Density

Sagebrush densities documented after six growing seasons (1999 through August 2004) exceeded the 1 shrub m^{-2} standard within all three sagebrush seeding rates. In August 2004 sagebrush densities were 1.0, 2.8, and 4.5 plants m^{-2} in the 1, 2, and 4 kg pls ha^{-1} sagebrush seeding rates, respectively (Figure 2). Sagebrush densities within the three sagebrush seeding rates varied with sampling date ($P \leq 0.0001$) and some late germination occurred in higher seeding rates after the initial winter 1999–2000 (Figure 2 and Williams et al., 2002). Sagebrush density differed among the three sagebrush seeding rates on the first eight sampling dates. In the 2002 and 2004 growing seasons, densities resulting from the three rates do not differ, primarily as a result of decreased densities in the 2 and 4 kg ha^{-1} rates. Although not significantly different in 2004, the density of sagebrush in the 2 and 4 kg ha^{-1} rates are well above two seedlings m^{-2} and exceed the critical one shrub m^{-2} density

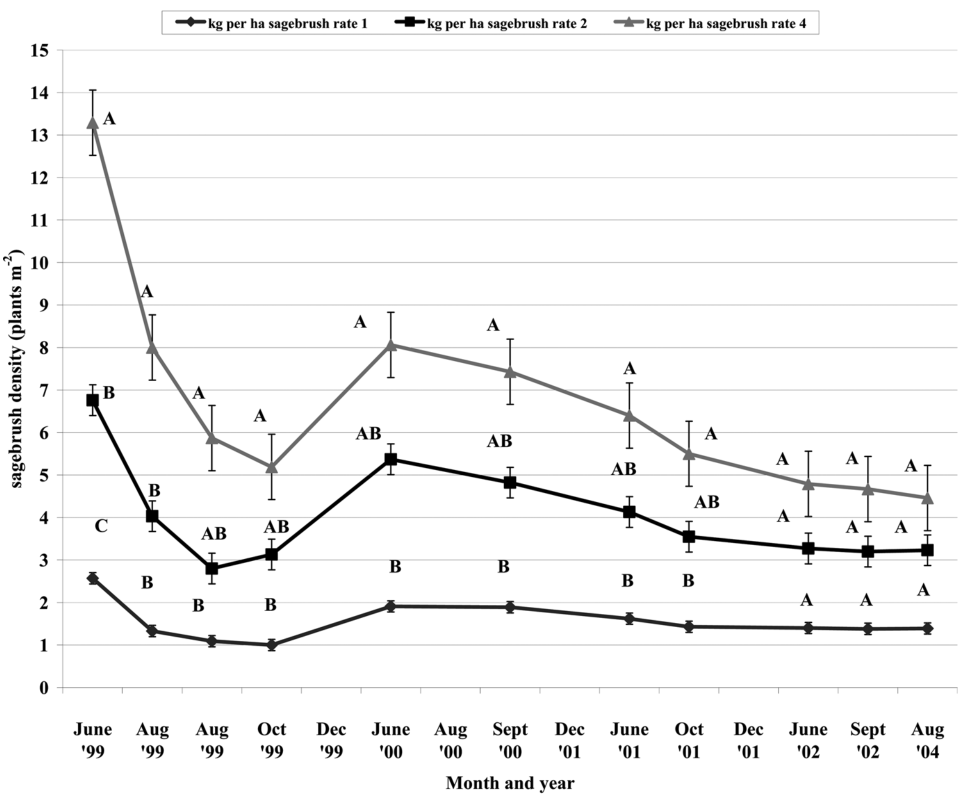

Figure 2. Sagebrush seedling density in three sagebrush seeding rates over six study years. Within each sampling date, sagebrush seeding rate means with the same letter do not differ ($p > 0.05$, LSD).

standard. When averaged across the sampling dates, sagebrush densities were greatest in the 4 kg pls ha^{-1} sagebrush seeding rate (6.7 seedlings m^{-2}) when compared to the 1 (1.5 plants m^{-2}) or 2 (4.0 plants m^{-2}) kg pls ha^{-1} rates ($P \leq 0.0001$). Sagebrush densities did not differ among the seven grass seeding rates regardless of sampling date ($P > 0.05$).

Sagebrush Canopy Volume by Unit Area

In general, sagebrush canopy volume per unit area increased six-fold from 2001 (220.2 cm^3 m^{-2}) to 2004 (1316.5 cm^3 m^{-2}). Sagebrush canopy volume differed among each of the three years sampled ($P = 0.0070$) but did not differ among sagebrush seeding rates or grass seeding rates.

Canopy Volume of Individual Sagebrush Plants

The mean canopy volume of individual sagebrush plants after six growing seasons was 230 cm^3. Size of sagebrush plants differed among the seven grass seeding rates and among the three years (grass rate $P \leq 0.0001$; year $P \leq 0.0001$). In 2001, canopy volume of individual sagebrush seedlings was 64 cm^3; in 2002 volume more than tripled to 218 cm^3 and by 2004 individual plant canopy volume averaged 421 cm^3.

When averaged across the three years and the three sagebrush seeding rates, individual sagebrush plant canopy volume was greatest in plots without grass and least in the highest (14 kg ha^{-1}) grass seeding rate (Figure 3). In addition, canopy volume of plants was greater in the 2 and 4 kg ha^{-1} grass seeding rates than in the 14 kg ha^{-1} rate. Sagebrush canopies in other grass rates (6, 8, and 10 kg ha^{-1}) were intermediate and not different from other grass seeding rates.

Sagebrush Survival

Sagebrush survival (from June 1999 to August 2004) did not differ among the three sagebrush seeding rates, the seven grass seeding rates, or their interaction. Survival of sagebrush seedlings in the three sagebrush and seven grass seeding rates was variable and ranged from 22 to 72% (Table 1).

Discussion

Our initial reports on seedling densities (Williams et al., 2002) suggested that sagebrush densities were only minimally influenced by grass seeding rates, agreeing with other studies (Johnson & Payne, 1968; Gores, 1995; Quinney et al., 1996; Booth et al., 1999; Partlow et al., 2004). However, our study emphasizes two things: the importance of long-term data collection on studies involving plant community dynamics and the apparent increased influence of grass seeding rates on sagebrush growth as the vegetation matures. Our grass seeding rates were intended to represent rates that had minimal competitive effects upon established sagebrush density (Schuman et al., 1998). Even though the 14 kg pls ha^{-1} grass seeding rate had 30–50% fewer sagebrush, sagebrush density did not differ among grass seeding rates. Since aboveground herbaceous production did not differ among the grass seeding rates $\geq$4 kg ha^{-1} in 2000 and $\geq$2 kg ha^{-1} in 2001 (Vicklund et al., 2004), lower grass seeding rates can be used to achieve soil protection and soil stability that are critical to controlling

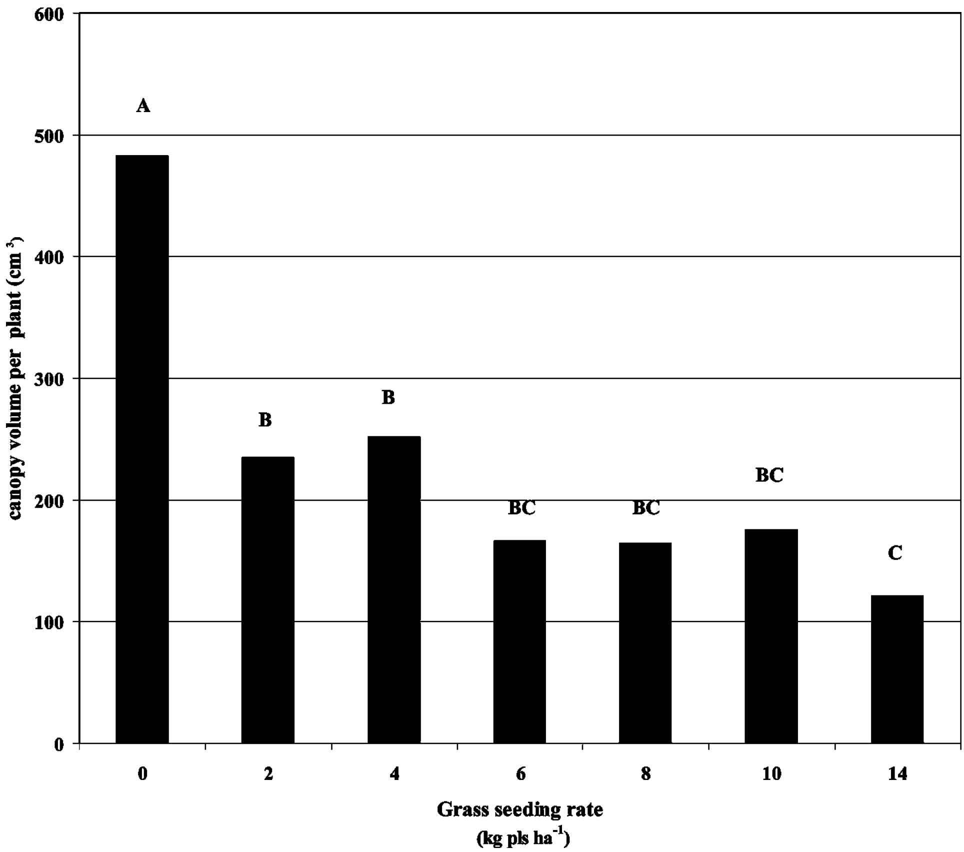

Figure 3. Sagebrush seedling canopy volume (per individual plant) within seven grass seeding rates (averaged across three sagebrush seeding rates and three years). Means with the same letters do not differ ($p > 0.05$, LSD).

Table 1. Wyoming big sagebrush survival (%) after six growing seasons in three sagebrush and seven grass seeding rates at a mine reclamation site near Gillette, Wyoming

	Sagebrush seeding rate (kg pls ha^{-1})			
Grass seeding rate (kg pls ha^{-1})	1	2	4	Mean
		survival (%)		
0	72.5	50.6	52.1	58.4
2	42.9	47.8	36.0	42.2
4	57.9	27.7	39.6	41.7
6	41.4	46.2	43.2	43.6
8	42.3	52.4	28.3	41.0
10	52.1	41.7	22.2	38.6
14	33.6	61.4	33.0	42.6
Mean	48.9	46.8	36.3	44.0

Survival is calculated as percent survival from June 1999 to August 2004, planted March 1999.

erosion (Zielinski, 1994). By the time sagebrush plants entered their sixth year, their collective canopy volume ($cm^3\,m^{-2}$) was not influenced by grass seeding rates, but the size of individual plants was greatly reduced by the highest grass seeding rate. Because sagebrush densities were not as dramatically impacted, the seven grass seeding rates are not critically different in their potential to achieve shrub density standards for bond release. Our density results concur with earlier suggestions that over the long term, differences in initial seedling densities may decline and densities from different sagebrush seeding rates may converge toward a density threshold for the site (Schuman & Belden, 2002).

The influence of grass seeding rates on the canopy of individual sagebrush plants is an important consideration for long-term community development and sustainability. If canopy volume per plant continues to increase from levels identified in Figure 3 for the next six years, our results suggest that even with comparable densities of sagebrush across the grass seeding rates, vegetative structure derived from the canopy of sagebrush should differ greatly among the grass seeding rates by the 10th year after seeding (2008). This effect may be diminished in future years by mortality associated with thinning of sagebrush as they mature and compete with grasses, thus serving to equalize canopy volumes among the grass treatments. However, once established, sagebrush plants may limit grass growth (Rittenhouse & Sneva, 1976) rather than being lost to mortality.

Wildlife browse can significantly reduce shrub size and survival (Schuman & Belden, 2002; Partlow et al., 2004). Wildlife use of sagebrush at our site was minimal and browsing was not common. Our results demonstrate the competitive effects of grasses in the absence of heavy browsing by wildlife. Sampling over the 10-year period would help to clarify this interaction.

Irrespective of mortality, the uniformly small size of sagebrush seedlings at higher grass rates provides less diversity in canopy structure than can be achieved by seeding grasses at lower rates. Shrub canopy cover is commonly reported in non-mined Wyoming big sagebrush stands and can be as high as 40% (Muscha et al., 2004; Welch & Criddle, 2003). Canopy measures can provide a more realistic measure of canopy structure that reflects long-term survival and community development. Because individual sagebrush plants were larger at lower grass seeding rates, we suggest that canopy structure will be more developed in the lower grass seeding rates over the long-term. Structural development of reclaimed sites is critical to the return of ecosystem function by facilitating animal use and providing safe sites for seedlings of other species (Paruelo et al., 1998; Parmenter & MacMahon, 1983). By considering canopy growth, we were able to capture initial canopy development to better document the impact of grass competition on return of structure to shrubland reclamation seedings.

Concurrent planting of grass and shrub species did not suppress shrub establishment or survival over the six growing seasons relative to plots not seeded with grasses. The differences in shrub density between the three sagebrush seeding rates continues to diminish over time as sagebrush plants are lost each year. It will be interesting to see if sagebrush seedling densities of the two highest sagebrush seeding rates remain above the shrub density achieved by the 1 kg ha^{-1} sagebrush seeding rate during the next four years of the 10-year bond period.

Using the sagebrush seedling densities found in our study and long term survival rates for seeded big sagebrush documented in other studies, we assessed the potential of achieving the Wyoming shrub density standard. Our data suggested that grass seeding rates of 6 or 8 kg pls ha^{-1} and sagebrush seeding rates of 2 or 4 kg pls ha^{-1} would satisfy the Wyoming shrub density standard (Fortier, 2000; Williams et al., 2002; Vicklund et al., 2004). In 2004, sagebrush densities for the 2 and 4 kg pls ha^{-1} sagebrush seeding rate demonstrated that these seeding rates should continue to exceed the density standard, even considering published survival rates of 33 % (Kiger et al., 1987) and 59% (Schuman & Belden, 2002). It is likely that this trajectory will prevail during the next four years of the 10-year bonding period, barring any unusual climatic or physical perturbations. The 2004 data suggests that seeding Wyoming big sagebrush at 1 kg ha^{-1} will not ultimately fulfill the density standard, even assuming our highest survival rate (75%) that we observed in the first six years. We must continue to evaluate the interaction of grass seeding rates on Wyoming big sagebrush density and canopy growth in order to understand thoroughly the effects of reduced grass seeding rates on soil stability (erosion protection) and to follow long-term effects of grass competition on sagebrush community development.

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