Restoring Wyoming Big Sagebrush

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Abstract—The widespread occurrence of big sagebrush can be attributed to many adaptive features. Big sagebrush plays an essential role in its communities by providing wildlife habitat, modifying local environmental conditions, and facilitating the reestablishment of native herbs. Currently, however, many sagebrush steppe communities are highly fragmented. As a result, restoring big sagebrush is considered a priority in the conservation and rehabilitation of sagebrush steppe ecosystems. Wyoming big sagebrush can often be difficult to establish, because many environmental factors act to restrict its emergence and persistence. On fire rehabilitation projects in Idaho, Wyoming big sagebrush seed is typically aerially broadcast over the soil surface. This method has had some success; however, several alternative seeding treatments, such as cultipacking, have resulted in the establishment and persistence of Wyoming big sagebrush. In addition, transplanting bareroot and containerized stock may be useful for restoring shrub stands in critical areas.

Keywords: *Artemisia tridentata*, revegetation, rehabilitation, seeding, shrub-steppe

In the Western United States, big sagebrush (*A. tridentata* Nutt.) steppe communities dominate over 60 million ha (Wambolt and Hoffman 2001) and provide essential habitat and forage for many species (West 2000). Fragmentation of sagebrush steppe communities has occurred through excessive livestock grazing, conversion to agricultural cropland, invasion of exotic plants, and increasing frequency of large fires (Anderson and Inouye 2001; Knick 1999; Knick and Rotenberry 1997; Noss and others 1995). More than 350 species of plants and animals associated with sagebrush ecosystems have been identified as species of conservation concern due to declining habitats or populations (Wisdom and others 2003).

Big sagebrush is important because of its wide distribution and the extent of disturbance within its range. It provides both food and cover for sage-grouse (*Centrocercus urophasianus* Bonaparte) year round (Connelly and others 2004). This paper presents a review of the literature on big sagebrush taxonomy and characteristics, germination requirements, relevance in rehabilitation projects, and methods for improving its establishment in seedings and transplantings. It will focus primarily on Wyoming big sagebrush (*A. t.* Nutt. ssp. *wyomingensis* Beetle and Young).

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Big Sagebrush Taxonomy and Characteristics

There are five subspecies of big sagebrush. These include basin big sagebrush (*A. t.* Nutt. ssp. *tridentata*), Wyoming big sagebrush, mountain big sagebrush (*A. t.* Nutt. ssp. *vaseyana* [Rydb.] Beetle), xeric big sagebrush (*A. t.* Nutt. ssp. *xericensis* Winward ex R. Rosentreter & R. Kelsey), and subalpine big sagebrush (*A. t.* Nutt. ssp. *spiciformis* [Osterhout] Kartesz and Gandhi) (Wambolt and Frisina 2002; West and Young 2000). The distribution of the subspecies is regulated by seasonal precipitation patterns, elevation, and soil conditions (McArthur 2000; McArthur and others 1979, 1995; Monsen and Shaw 2000).

The dominance and ubiquitous occurrence of big sagebrush can be attributed to many factors. One factor is the production of seasonally dimorphic leaves. Ephemeral leaves, larger and often irregularly lobed, develop in spring and are shed in summer following moisture stress (West and Young 2000). Persistent leaves are typically three-lobed, smaller, develop in late spring, and remain on the shrubs through winter (West and Young 2000). A second major factor contributing to the widespread occurrence of big sagebrush is an efficient two-component root system (West and Young 2000). Its fibrous root system captures water and nutrients near the soil surface, permitting plants to take advantage of summer precipitation (West and Young 2000). The taproot, in turn, allows for utilization of water and nutrients deep within the soil profile and below the principal rooting zone of associated herbaceous species (West and Young 2000).

Several additional adaptive features influence the distribution and persistence of big sagebrush subspecies. These include, but are not limited to, variable growth forms, response to fire, the production of allelopathic substances in roots and leaves, the ability to conduct photosynthesis at low temperatures, temperature requirements for seed germination, seed dispersal strategies, seed size, and structure and timing of seed maturation (Blaisdell and others 1982; Kelsey 1986; Meyer and Monsen 1992; Peterson 1995).

Big sagebrush plants are capable of producing seed in their second year and will continue to produce some seed annually, except during years of severe moisture stress (Meyer and Monsen 1992). Plants flower in fall, following the summer drought period, and the fruits (achenes) mature from midfall to early winter (Meyer 2003). Achenes are small (about 1 by 1.5 mm) and shiny with a deciduous pappus (Meyer 2003). They are dispersed by gravity and wind, but do not possess any special adaptations for wind dispersal (Meyer 1994). Seeds may be blown by wind across crusty snow surfaces and dispersed by animals and water (Tisdale and Hironaka 1981; Young and Evans 1989a). Maximum dispersal distance of seeds can be up to 30 m; however, most seeds (85 to 90 percent) fall within 1 m of the shrub canopy (Meyer 1994; Young and Evans 1989a).

Big sagebrush seeds are surface or near-surface emerging and are sensitive to microsite conditions (Meyer 1994). Germination occurs in late winter to early spring, soon after snowmelt, in areas where snow accumulates (Meyer and Monsen 1992; West and Young 2000). A semi-gelatinous pericarp and hypocotyl hairs aid in the adhesion of the achene to the soil surface and permit the radicle to penetrate the soil (Young and Martens 1991). The achene's small size reduces the surface area for moisture loss (Young and Martens 1991). Achenes typically exhibit high seed viability and germination capacity at maturity (Meyer 2003).

Wyoming Big Sagebrush

Wyoming big sagebrush is the most xeric subspecies of big sagebrush. It generally occurs on shallow soil in areas receiving 200 to 300 mm of annual precipitation (Cronquist 1994; Monsen and Shaw 2000). Wyoming big sagebrush plants exhibit a ragged, irregular growth form, and most plants grow to less than 1 meter in height. The main stem is often branched into two or three twisted portions at or near ground level (Winward and Tisdale 1977). Persistent leaves are narrowly cuneate to cuneate with the margins curved outward, and exhibit a strong, pungent odor when crushed (McArthur and others 1979). The plants flower from late July to September, and seed maturation occurs in October and November (Monsen and Shaw 2000).

Germination and Establishment Ecology

Many environmental factors act to reduce sagebrush establishment and persistence. Seed germination is substantially limited by water stress, and a principal cause of seed mortality is early or prolonged drought (Meyer 1994). The successful establishment of large cohorts of big sagebrush shrubs can result from recruitment pulses that are associated with rare events of highly favorable precipitation (Watson and others 1997; West and others 1979; Williams and Hobbs 1989). High seed densities and synchronous germination can result in intense competition between big sagebrush seedlings. Intraspecific competition or self-thinning probably accounts for much of the initial mortality (Meyer 1994). Competition between sagebrush plants within a stand may also affect flowering and seed set, particularly in dry years (Meyer 1994).

Competition with herbaceous species may also impact the success of sagebrush seedings. However, reports on sagebrush seedling competitiveness with seeded wheatgrasses are contradictory. During the time period when sagebrush was being controlled on rangelands, managers often remarked on the ability of sagebrush to reestablish in perennial grass seedings (Meyer 2003). Conversely, researchers have demonstrated that competition with introduced and native grasses seeded before or with big sagebrush can reduce Wyoming big sagebrush establishment (Blaisdell 1949; Fortier 2000; Schuman and others 1998). Similarly, sagebrush seedings in areas with exotic annual grass competition have had little success (Meyer 2003). Competitive effects are probably related to the inability of sagebrush seedlings to compete for soil moisture during establishment (Cook and Lewis 1963; Sturges 1977). Blaisdell (1949) found higher grass yields on plots that were seeded with grass prior to or 1 year after sagebrush, and that prior grass establishment often prevented the establishment of sagebrush seedlings. However, when grasses were seeded 2 or 3 years following sagebrush seeding, grass yields were reduced and grass competition did not have an effect on sagebrush (Blaisdell 1949).

Sagebrush seedlings have high first-year survival rates, even through summer drought periods, on mine sites where there is little competition (Meyer 1994). Schuman and others (1998) found that grass competition reduced sagebrush seedling densities in a mined-land reclamation study using direct-placed topsoil. They concluded that successful establishment of big sagebrush may require seeding big sagebrush without grasses or with very low grass seeding rates (Schuman and others 2000).

Commercially available sagebrush seed is often not from locally or regionally adapted seed sources. Nonadapted seeds may respond differently to normal germination cues and germination may occur at an inappropriate time, resulting in seeds that fail to germinate or persist (Monsen and Meyer 1990). Using seedlots with the source or geographic origin of the seed verified (Source Identified) and matched to the site may be a key factor for achieving successful shrub establishment (McArthur and others 1995; Meyer and Monsen 1992). Commercially available seed often contains a mixture of sagebrush subspecies (Dalzell 2004). Currently, the Association of Seed Analysts does not provide guidelines or testing methods for differentiating sagebrush subspecies in purchased seed (AOSA 2003). Applying the big sagebrush subspecies matched to the restoration site is essential because big sagebrush subspecies exhibit differences in seedling establishment traits (McArthur and others 1995), growth rates (Welch and McArthur 1984), habitats (Winward and Tisdale 1977), and moisture (Barker and McKell 1983; Kolb and Sperry 1999), temperature (Harniss and McDonough 1976), and germination requirements (Meyer 1994).

Seed bank studies of big sagebrush indicate seed banks are transient, with very little seed carryover from one year to the next (Meyer and Monsen 1992). Most of the big sagebrush seeds produced in autumn are absent from the soil seed bank by late spring of the following year (Young and Evans 1989a). Wyoming big sagebrush seeds are, in general, short lived and do not survive fires (Young and Evans 1989a). Young and Evans (1989a) found that no mountain big sagebrush or basin big sagebrush seedlings emerged from germination tests of 1,000 soil surface samples taken from a burned area. In contrast, however, some Wyoming big sagebrush seeds applied with mulch cover on mined lands in Wyoming remained viable in the seed bank for up to 4 years (Schuman and others 1998).

Sagebrush seeds are highly viable with little or no dormancy at dispersal, but may have strong light requirements for germination (Meyer 2003; Young and Evans 1989b). The light requirement is removed through stratification (moist chilling), and most seeds are germinable by late winter or early spring (Meyer 2003).

Use of Big Sagebrush in Rehabilitation Projects

Reestablishing big sagebrush is considered a priority in the conservation and rehabilitation of sagebrush steppe ecosystems (USDI BLM 2002a). In addition to providing habitat for sage-grouse and other sagebrush obligate species, big sagebrush also plays an essential role in these communities by directly modifying local environmental conditions, thus providing a more favorable environment for seed germination and seedling survival (Schlesinger and Pilmanis 1998). Shrubs also help to retain soil nitrogen, increase organic matter, and create favorable environments for microorganisms, resulting in fertile islands or patches that develop over time (Cross and Schlesinger 1999; West 2000). By trapping blowing snow and moderating temperatures, big sagebrush facilitates the establishment of native herbs, and their canopy protects native herbs from over-utilization (West 2000). Wyoming big sagebrush also develops mycorrhizal fungi associations, which aid in nutrient extraction and cycling (West 2000).

The establishment of big sagebrush is often difficult due to poor seed quality (Harniss and McDonough 1976; Young and Evans 1989a), low seedling vigor, exposure to unfavorable seedbed conditions (McDonough and Harniss 1974; Meyer and Monsen 1992), competition with herbaceous species (Blaisdell 1949; Sturges 1977), and inadequate moisture (Cook and Lewis 1963; Sturges 1977). Improved seed cleaning, handling, and purchasing requirements have made higher quality seed easier to obtain (Meyer and Monsen 1992; Olson and others 2000). Also, seedbed conditions can be manipulated to reduce competition and facilitate seed germination (McArthur and others 1995; Welch and others 1992). Ultimately, however, environmental factors still play a central role in determining the success of big sagebrush restoration projects.

Seeding treatments can have a strong influence on the emergence and survival of big sagebrush seedlings. On Bureau of Land Management (BLM) fire-rehabilitation projects in Idaho, Wyoming big sagebrush seed is typically aerially broadcast over the soil surface by helicopter (USDI 2002b). Aerial broadcasting is often desirable over other methods, because large areas can be seeded quickly and the seed can be placed on the soil surface (Monsen 2000). This seeding method has had some success (Monsen 2000); however, results from a recent study in southern Idaho indicate that aerially seeding Wyoming big sagebrush had limited effect on shrub establishment (Dalzell 2004). In this study, seeding did not increase the density or cover of Wyoming big sagebrush on seeded plots compared to adjacent unseeded plots (Dalzell 2004). In fact, shrubs failed to establish on 23 of the 35 (66 percent) study sites sampled (Dalzell 2004).

Another key factor in the establishment and persistence of sagebrush seedlings is the timing and amount of winter snowfall. The recommended time for planting big sagebrush is in fall, just before the first winter snowfall. This is the time when big sagebrush would naturally be dispersing seed onsite (Meyer 1994). Snow cover can facilitate the establishment of big sagebrush—particularly in areas with reliable, long-term snow cover—by compacting or firming the soil surface and assisting in keeping the seed in contact with the soil. However on drier and warmer sites, winter snowfall may be inadequate to facilitate these physical processes to ensure successful big sagebrush emergence and establishment (Meyer 2003). Wyoming big sagebrush sites are typically windswept and relatively dry in both autumn and winter (Meyer and Monsen 1992). These environmental conditions are not favorable for sagebrush emergence or establishment.

Increasing Shrub Establishment

There are several alternatives to aerial seeding that have been shown to increase big sagebrush establishment and persistence. For example, seeding equipment that compacts the soil surface, such as cultipacking, chaining, and imprinting, can increase big sagebrush seedling establishment. Monsen and Meyer (1990) obtained significantly greater initial seedling emergence, compared to broadcasting, by seeding with the Oyer compact row seeder. This device compacts the soil and then presses the seed into the surface. Intermediate seedling emergence results were achieved by using the Brillion cultipacker seeder (Monsen and Meyer 1990). Using this device, the seed is broadcast over the surface and pressed into the soil (Pyke 1994). The cultipacker is a circular cylinder or set of wheels that are rolled over the soil surface to place the seed in contact with the soil near the soil surface (Pyke 1994).

The U.S. Department of the Interior, Bureau of Land Management's Lower Snake River District in Idaho achieved successful sagebrush establishment using a seeder that incorporates a fertilizer spreader, anchor chain or tire drags, and a vine-roller cultipacker (Boltz 1994). This sagebrush seeder covered the seed and firmed the soil surface on silt loams, but it was less effective on gravelly and stony areas (Boltz 1994).

Another option for establishing big sagebrush is to transplant bareroot or containerized stock. Stock that is 12 to 20 cm tall is transplanted in early spring (McArthur and others 1995). First year survival rates for transplanted stock are often 80 percent or higher (Welch and others 1992). Seedlings are typically transplanted only in small, critical areas due to the cost of using planting stock. Transplant stock can be grown from small amounts of seed from specific areas similar to the planting sites. Transplant stock is available locally or regionally from private contracted nurseries and from USDA Forest Service nurseries.

A similar method, the "mother plant" technique, combines transplanting and natural seed dispersal. The mother plants are planted as bareroot or containerized stock on key locations throughout the rehabilitation site. Within 3 to 5 years, established mother plants mature, disperse seed, and provide an established seed source for unseeded areas (Welch and others 1992). However, successful sagebrush establishment and subsequent dispersal also depends on the species composition in the unseeded areas.

Big sagebrush is considered an obligate vesicular-arbuscular mycorrhizal (VAM) plant (Wicklow-Howard

1994). Arbuscular mycorrhizae can improve the ability of plants to extract nutrients and water from the soil, thereby improving the host species' survival and growth on severely disturbed lands (Wicklow-Howard 1994). In a greenhouse study, Stahl and others (1998) found that sagebrush seedlings grown in topsoil with mycorrhizal inoculum exhibited significantly greater tolerance to drought stress than non-mycorrhizal seedlings. Arid land disturbances such as fire, mining, overgrazing, off-highway vehicle use, and cultivation significantly reduce the mycorrhizal inoculum potential (MIP) of the soil (Wicklow-Howard 1989). Efforts to add commercially available VAM fungal inoculum to the soil or to use VAM-inoculated plants on disturbed areas have met with limited success (Wicklow-Howard 1994).

To increase big sagebrush establishment, it is imperative that alternative seeding methods are considered in lieu of aerially seeding Wyoming big sagebrush, particularly if the seed is not adequately covered. Although transplanting bareroot and containerized stock is regarded as costly, this expense may be acceptable when considering the current failure to establish sagebrush using aerial seeding (Dalzell 2004). Because areas that have been depleted of sagebrush for several years may lack the proper mycorrhizal fungi in the soil, containerized stock should be inoculated with compatible fungi. Bareroot and containerized stock could be transplanted in small, critical areas and in areas currently dominated by introduced seeded grasses. Planting big sagebrush can also facilitate the restoration of highly palatable selections of sagebrush, such as Gordon Creek Wyoming big sagebrush, or local germplasms that are best suited for the site conditions (Welch and others 1992).

Another alternative method is to transplant big sagebrush shrubs on areas where fertile islands existed prior to burning, focusing on areas where native vegetation and shrub skeletons remain. The transplanted shrubs will assist in the formation of "islands of fertility" (Cross and Schlesinger 1999). These shrub islands will serve as habitat islands for animal species by providing shrub cover to reduce the risk of predation (Longland and Price 1991), providing temporary refuges to facilitate animal dispersal and the maintenance of a metapopulation, a group of spatially separated subpopulations that are interlinked and maintained by occasional dispersal (Longland and Bateman 2002). Areas that are positioned adjacent to the shrub islands and have remaining native vegetation could be left unseeded; thus reducing the mechanical disturbance of the soil surface by some seeding equipment and reducing the likelihood of exotic plant invasion, biological soil crust destruction, and subsequent wind erosion. In addition, the islands would serve as a seed source for the replenishment of native species with unavailable or limited commercial seed supplies. The shrub islands would not only provide a seed source for animals to harvest, consume, and disperse, but also provide a refuge for seed dispersers (Longland and Bateman 2002). In addition, these islands are sites with high vesicular arbuscular mycorrhizal activity. Ultimately, the development of fertile shrub islands would serve as inoculum focal points from which shrubs, VAM, and other species could spread (Allen 1987).

As previously mentioned, establishment of big sagebrush seedlings is impacted by competition. Seeding introduced grasses such as crested wheatgrass (*Agropyron cristatum*) and intermediate wheatgrass (*Elymus hispidus*) with big sagebrush has prevented shrub seedlings from establishing (Richardson and others 1986). Direct competition for available soil moisture and nutrients exists between seeded grasses and big sagebrush because of similar root distributions and growth periods (Cook and Lewis 1963; Sturges 1977). In contrast, studies have shown that stands of native bunchgrasses permitted big sagebrush recruitment (Booth and others 2003; Frischknecht and Bleak 1957). Frischknecht and Bleak (1957) reported that seeded stands of bluebunch wheatgrass (*Pseudoroegneria spicata*) were more likely to permit sagebrush seedling recruitment than seeded stands of crested wheatgrass. In addition, Booth and others (2003) found that the native perennial bunchgrass squirreltail (*Elymus elymoides*) permitted big sagebrush recruitment and also suppressed cheatgrass.

Seeds of several important native bunchgrasses are available. However, sources of other bunchgrasses adapted to the Interior Western United States, such as Great Basin wildrye (*Leymus cinereus*), bluebunch wheatgrass, Sandburg bluegrass (*Poa sandbergii*), bottlebrush squirreltail, and the needlegrasses (*Hesperostipa*) are just beginning to be marketed. Additional research is needed to develop appropriate seedbed preparation methods, planting techniques, and equipment for the establishment of individual native species and populations. Also, further research could focus on seeding big sagebrush in mixed seedings of native species and investigating the ability of these seedings to permit sagebrush establishment and compete with invasive species.

Successful rehabilitation following wildland fire is essential to mitigate the effects exotic, invasive plants have on ecosystems, decrease the frequency of large fires, provide suitable wildlife habitat, and halt the conversion of diverse sagebrush steppe communities to communities dominated by exotic, invasive plants. To increase big sagebrush establishment, it is imperative that other seeding methods be considered, utilized, monitored, and evaluated instead of the commonly used aerial seeding technique. If current sagebrush restoration efforts do not result in more consistent establishment and persistence of this important shrub, large areas of sagebrush-steppe may be lost, and rehabilitation may no longer be a viable option (West 2000).

References

Allen, M. F. 1987. Ecology of vesicular-arbuscular mycorrhizae in an arid ecosystem: use of natural processes promoting dispersal and establishment. In: Sulvia, D. M.; Hung, L. L.; Graham, J. H., eds. 7th North American conference on mycorrhizae: proceedings; 1987 May 3–8; Gainesville, FL: University of Florida: 133–135.

Anderson, J. A.; Inouye, R. S. 2001. Landscape-scale changes in plant species abundance and biodiversity of a sagebrush steppe over 45 years. Ecological Monographs. 71: 531–556.

Association of Official Seed Analysts (AOSA). 2003. *Artemisia* seed testing working group workshop. Unpublished document on file at: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Boise, ID. 7 p.

Barker, Jerry R.; McKell, Cyrus M. 1983. Habitat differences between basin and Wyoming big sagebrush in contiguous populations. Journal of Range Management. 36: 450–454.

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

Blaisdell, J. P.; Murray, R. B.; McArthur, E. D. 1982. Managing Intermountain rangelands—sagebrush-grass ranges. Gen. Tech. Rep. INT-134. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 41 p.

Boltz, M. 1994. Factors influencing postfire sagebrush regeneration in south-central Idaho. In: Monsen, S. B.; Kitchen, S. G., comps. Ecology, management, and restoration of intermountain annual rangelands: proceedings; 1992 May 18–22; Boise, ID. Gen. Tech. Rep. INT-GTR-313. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 281–290.

Booth, M. S.; Caldwell, M. M.; Stark, J. M. 2003. Overlapping resource use in three Great Basin species: implications for community invasibility and vegetation dynamics. Journal of Ecology. 91: 36–48.

Connelly, J. W.; Knick, S. T.; Schroeder, M. A.; Stiver, S. J. 2004. Conservation assessment of greater sage-grouse and sagebrush habitats. Report. Cheyenne, WY: Western Association of Fish and Wildlife Agencies. 610 p.

Cook, C. W.; Lewis, C. E. 1963. Competition between big sagebrush and seeded grasses on foothill ranges in Utah. Journal of Range Management. 16: 245–250.

Cronquist, A. 1994. Vol. 5. Asterales. In: Cronquist, A.; Holmgren, A. H.; Holmgren, N. H.; Reveal, J. L.; Holmgren, P. K., eds. Intermountain flora: vascular plants of the Intermountain West, U.S.A. Bronx: The New York Botanical Garden. 496 p.

Cross, A. F.; Schlesinger, W. H. 1999. Plant regulation of soil nutrient distribution in the northern Chihuahuan Desert. Plant Ecology. 145: 11–25.

Dalzell, C. R. 2004. Post-fire establishment of vegetation communities following reseeding on southern Idaho's Snake River Plain. Boise, ID: Boise State University. 112 p. Thesis.

Fortier, M. I. 2000. Wyoming big sagebrush establishment on mined lands: seeding rates and grass competition. Laramie: University of Wyoming. 66 p. Thesis.

Frischknecht, N. C.; Bleak, A. T. 1957. Encroachment of big sagebrush on seeded range in northeastern Nevada. Journal of Range Management. 10: 165–170.

Harniss, R. O.; McDonough, W. T. 1976. Yearly variation in germination of three subspecies of big sagebrush. Journal of Range Management. 29: 167–168.

Kelsey, R. G. 1986. Emergence, seedling growth and crude turpenoid concentration in a sagebrush garden. In: McArthur, E. D.; Welch, B. L., comps. Symposium on the biology of *Artemisia* and *Chrysothamnus*: proceedings; 1984 July 9–13; Provo, UT. Gen. Tech. Rep. INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 358–365.

Kolb, K. J.; Sperry, J. S. 1999. Differences in drought adaptation between subspecies of sagebrush (*Artemisia tridentata*). Ecology. 80: 2373–2384.

Knick, S. T. 1999. Requiem for a sagebrush ecosystem? Northwest Science. 73: 53–57.

Knick, S. T.; Rotenberry, J. T. 1997. Landscape characteristics of disturbed shrubsteppe habitats in southwestern Idaho (U.S.A.). Landscape Ecology. 12: 287–297.

Longland, W. S.; Bateman, S. L. 2002. The ecological value of shrub islands on disturbed sagebrush rangelands. Journal of Range Management. 55: 571–575.

Longland, W. S.; Price, M. V. 1991. Direct observations of owls and heteromyid rodents: can predation risk explain microhabitat use? Ecology. 72: 2261–2273.

McArthur, E. D. 2000. Sagebrush systematics and distribution. In: Entwistle, P. G.; DeBolt, A. M.; Kaltenecker, J. H.; Steenhof, K., comps. Sagebrush steppe ecosystems symposium: proceedings; 1999 June 23–25; Boise, ID. BLM/ID/PT-001001+1150. Boise, ID: U.S. Department of the Interior, Bureau of Land Management: 9–14.

McArthur, E. D.; Blauer, A. C.; Plummer, A. P.; Stevens, R. 1979. Characteristics and hybridization of important Intermountain shrubs. III. Sunflower family. Res. Pap. INT-220. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 82 p.

McArthur, E. D.; Stevens, R.; Monsen, S. B. 1995. Adaptation and success of big sagebrush and rubber rabbitbrush on disturbed sites. In: Schuman, G. E.; Vance, G. F., eds. 12th annual national meeting of the American Society for Surface Mining and Reclamation: proceedings; 1995 June 3–8; Gillette, WY. Lexington, KY: American Society for Surface Mining and Reclamation: 811–823.

McDonough, W. T.; Harniss, R. O. 1974. Effects of temperature on germination in three subspecies of big sagebrush. Journal of Range Management. 27: 204–205.

Meyer, S. E. 1994. Germination and establishment ecology of big sagebrush: implications for community restoration. In: Monsen, S. B.; Kitchen, S. G., comps. Ecology, management, and restoration of Intermountain annual rangelands: proceedings; 1992 May 18–22; Boise, ID. Gen. Tech. Rep. INT-GTR-313. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 244–251.

Meyer, S. E. 2003. *Artemisia* L. In: Bonner, F. T.; Nisley, R. G., eds. Woody plant seed manual. Washington, DC: U.S. Department of Agriculture, Forest Service. Online: http://ntsl.fs.fed.us/wpsm/ [February 15, 2005].

Meyer, S. E.; Monsen, S. B. 1992. Big sagebrush germination patterns: subspecies and population differences. Journal of Range Management. 45: 87–93.

Monsen, S. B. 2000. Establishment of big sagebrush (*Artemisia tridentata*) in semiarid environments. In: Entwistle, P. G.; DeBolt, A. M.; Kaltenecker, J. H.; Steenhof, K., comps. Sagebrush steppe ecosystems symposium: proceedings; 1999 June 23–25; Boise, ID. BLM/ID/PT-001001+1150. Boise, ID: U.S. Department of the Interior, Bureau of Land Management: 81–86.

Monsen, S. B.; Meyer, S. E. 1990. Seeding equipment effects on establishment of big sagebrush on mine disturbances. In: Fifth Billings symposium on disturbed land rehabilitation. Vol. I.; 1990 March 25–29; Billings, MT. Reclamation Research Unit Publ. 9003. Bozeman: Montana State University: 192–199.

Monsen, S. B.; Shaw, N. L. 2000. Big sagebrush (*Artemisia tridentata*) communities—ecology, importance and restoration potential. In: Schuman, G. E.; Richmond, T. C.; Neuman, D. R., eds. Sagebrush establishment on mined lands: ecology and research: proceedings; 2000 March 20–24; Billings, MT. Reclamation Research Unit Publ. 00-01. Bozeman, MT: Montana State University: 255–270.

Noss, R. F.; LaRoe, E. T., III; Scott, J. M. 1995. Endangered ecosystems of the United States: a preliminary assessment of loss and degradation. Biol. Rep. 28. Washington, DC: U.S. Department of the Interior, National Biological Service. 81 p.

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

Peterson, J. G. 1995. Ecological implications of sagebrush manipulation. W-101-R-2. Helena: Montana Department of Fish, Wildlife, and Parks, Wildlife Management Division. 49 p.

Pyke, D. A. 1994. Rangeland seedings and plantings: exotics or natives. In: Edge, W. D.; Olson-Edge, S. L., eds. Symposium on sustaining rangeland ecosystems: proceedings; 1994 August 29–31; La Grande, OR. Special Rep. 953. Corvallis: Oregon State University: 32–44.

Richardson, B. Z.; Monsen, S. B.; Bowers, D. M. 1986. Interseeding selected shrubs and herbs on mine disturbances in southeastern Idaho. In: McArthur, E. D.; Welch, B. L., eds. Symposium on the biology of *Artemisia* and *Chrysothamnus*: proceedings; 1984 July 9–13; Provo, UT. Gen. Tech. Rep. INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 134–139.

Schlesinger, W. H.; Pilmanis, A. M. 1998. Plant-soil interactions in deserts. Biogeochemistry. 42: 169–187.

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

Schuman, G. E.; Booth, D. T.; Olson, R. A. 2000. Enhancing Wyoming big sagebrush establishment with cultural practices. In: Schuman, G. E.; Richmond, T. C.; Neuman, D. R., eds. Sagebrush establishment on mined lands: ecology and research: proceedings; 2000 March 20–24; Billings, MT. Reclamation Research Unit Publ. 00-01. Bozeman, MT: Montana State University: 32–42.

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

Sturges, D. L. 1977. Soil water withdrawal and root characteristics of big sagebrush. American Midland Naturalist. 98: 257–274.

Tisdale, E. W.; Hironaka, M. 1981. The sagebrush-grass region: a review of the ecological literature. Bull. 33. Moscow: University of Idaho, Forestry, Wildlife, and Range Experimental Station. 31 p.

U.S. Department of the Interior, Bureau of Land Management (USDI BLM). 2002a. Management considerations for sagebrush (*Artemisia*) in the Western United States: a selective summary of current information about the ecology and biology of woody North American sagebrush taxa. Washington, DC: U.S. Department of the Interior, Bureau of Land Management. 73 p.

U.S. Department of the Interior, Bureau of Land Management (USDI BLM). 2002b. Unpublished fire records and maps. On file at: U.S. Department of the Interior, Bureau of Land Management, Idaho State Office, Boise, ID. Various paging.

Wambolt, C. L.; Frisina, M. R. 2002. Montana sagebrush guide. Helena, MT: Montana Department of Fish, Wildlife and Parks. 71 p.

Wambolt, C. L.; Hoffman, G. R. 2001. Mountain big sagebrush age distribution and relationships on the northern Yellowstone winter range. In: McArthur, E. D.; Fairbanks, D. J., comps. Shrubland ecosystem genetics and biodiversity: proceedings; 2000 June 13–15; Provo, UT. RMRS-P-21. Ogden, UT: U.S. Department of the Interior, Forest Service, Rocky Mountain Research Station: 330–335.

Watson, I. W.; Westoby, M.; Holm, A. McR. 1997. Continuous and episodic components of demographic change in arid zone shrubs: models of two *Eremophila* species from Western Australia compared with published data on other species. Journal of Ecology. 85: 833–846.

Welch, B. L.; McArthur, E. D. 1984. Growth rate of big sagebrush as influenced by accessions, sites, subspecies, and years. In McArthur, E. D.; Welch, B. L., comps. Symposium on the biology of *Artemisia* and *Chrysothamnus*: proceedings; 1984 July 9–13; Provo, UT. Gen. Tech. Rep. INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 342–346.

Welch, B. L.; Nelson, E. D.; Young, S. A.; Sands, A. R.; Wagstaff, F. J.; Nelson, D. L. 1992. 'Gordon Creek'—a superior, tested germplasm of Wyoming big sagebrush. Res. Pap. INT-461. Ogden, UT: Forest Service, Intermountain Research Station. 7 p.

West, N. E. 2000. Synecology and disturbance regimes of sagebrush steppe ecosystems. In: Entwistle, P. G.; DeBolt, A. M.; Kaltenecker, J. H.; Steenhof, K., comps. Sagebrush steppe ecosystems symposium: proceedings; 1999 June 23–25; Boise, ID. BLM/ID/PT-001001+1150. Boise, ID: U.S. Department of the Interior, Bureau of Land Management: 15–26.

West, N. E.; Rea, K. H.; Harniss, R. O. 1979. Plant demographic studies in sagebrush-grass communities of southeastern Idaho. Ecology. 60: 376–388.

West, N. E.; Young, J. A. 2000. Intermountain valleys and lower mountain slopes. In: Barbour, M. G.; Billings, W. D., eds. North American terrestrial vegetation. 2d ed. Cambridge, UK: Cambridge University Press: 255–284.

Wicklow-Howard, M. C. 1989. The occurrence of vesicular-arbuscular mycorrhizae in burned areas of the Snake River Birds of Prey Area, Idaho. Mycotaxon. 34: 253–257.

Wicklow-Howard, M. C. 1994. Mycorrhizal ecology of shrub-steppe habitat. In: Monsen, S. B.; Kitchen, S. G., comps. Ecology, management, and restoration of Intermountain annual rangelands: proceedings; 1992 May 18–22; Boise, ID. Gen. Tech. Rep. INT-GTR-313. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 207–210.

Williams, K.; Hobbs, R. J. 1989. Control of shrub establishment by springtime soil water availability in an annual grassland. Oecologia. 81: 62–66.

Winward, A. H.; Tisdale, E. W. 1977. Taxonomy of the *Artemisia tridentata* complex in Idaho. Bull. 19. Moscow, ID: University of Idaho, Idaho Forestry, Wildlife and Range Experimental Station. 15 p.

Wisdom, M. J.; Rowland, M. M.; Suring, L. H.; Schueck, L.; Wolff Meinke, C.; Wales, B. C.; Knick, S. T. 2003. Procedures for regional assessment of habitats for species of conservation concern in the sagebrush ecosystem. March 2003 Report, Version 1. La Grande, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 151 p.

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

Young, J. A.; Evans, R. A. 1989b. Reciprocal common garden studies of the germination of seeds of big sagebrush (*Artemisia tridentata*). Weed Science. 37: 319–324.

Young, J. A.; Martens, E. 1991. Importance of hypocotyl hairs in germination of *Artemisia* seeds. Journal of Range Management. 44: 438–442.

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