Strategies to Enhance Plant Structure and Diversity in Crested Wheatgrass Seedings

Mike Pellant
Cindy R. Lysne

Abstract—Crested wheatgrass (*Agropyron cristatum* sensu amplo [L.] Gaertn.) is an introduced, caespitose grass that has been seeded on millions of acres of Western rangelands. In some areas, crested wheatgrass seedings overlap with critical sage-grouse (*Centrocercus urophasianus*; *C. minimus*) habitat, raising the question of how plant diversity might be restored in these closed plant communities. A three-step process is described to reduce crested wheatgrass competition, introduce desired species, and manage to maintain desired species for use long term. Crested wheatgrass is a strong competitor with other species and a prolific seed producer, which hinders treatments to reduce its influence and improve conditions for establishment of desirable seeded species. Herbicides, burning, mechanical treatments, livestock grazing, droughts, and combinations of these are effective to varying degrees in reducing crested wheatgrass competition. Once crested wheatgrass competition is reduced, either seed or seedlings can be used to increase diversity in these seedings. Post-establishment management and monitoring are essential components of the strategy to maintain plant diversity into the future.

Introduction

Use of introduced species invokes a range of emotions from unequivocal support to outright opposition and has even been linked to fascism and racism (Simberloff 2003). In the Western United States, the planting of introduced perennial wheatgrasses for rangeland rehabilitation has and continues to be practiced after disturbances such as wildfires, on cropland taken out of production, and to increase forage production for livestock. Given the focus of this symposium on the restoration of habitat for sage-grouse, using crested wheatgrass (*Agropyron cristatum* sensu amplo [L.] Gaertn.) to meet certain land-use objectives must be evaluated relative to the millions of acres already planted to these grasses and their continued use in rangeland rehabilitation projects.

This paper will focus on a review of the characteristics, use, and control techniques for crested wheatgrass and other closely related introduced, caespitose bunchgrasses (Siberian wheatgrass [*Agropyron fragile*], and Russian wildrye [*Psathyrostachys juncea*]), prior to reintroducing plant diversity. Crested wheatgrass and its close relatives were introduced from Eurasia and selected for land rehabilitation in the Central and Western United States. The areas where crested wheatgrass has been extensively used in the Western United States overlap closely with historic sage-grouse distribution in the low elevation rangelands where annual precipitation ranges from 8 to 12 inches annually (USDA NRCS 2004). The first part of this paper will include a review of the historical use, competitive characteristics, and concerns regarding the use of crested wheatgrass, especially with regard to sage-grouse habitat. The remainder of this paper will emphasize potential treatments to reduce crested wheatgrass competition, where acceptable functional or structural vegetation components required by sage-grouse are not present, prior to increasing the diversity of desirable herbs and shrubs.

Crested Wheatgrass: Introduction, Uses, and Issues in Western Ecosystems

The first collections of crested wheatgrass were made in 1897 to 1989 and again in 1906 from the dry steppes of Eastern Russia (Dillman 1946; Rogler and Lorenz 1983). These collections were classified as crested wheatgrass and desert wheatgrass (*Agropyron desertorum*) and were distributed to 15 experiment stations throughout the West. Minimal use of these introduced grasses occurred until the 1930s when a combination of cheap labor (for example, Civilian Conservation Corps), the "dust bowl" in the Midwest, and the need to reestablish perennial vegetation on abandoned farmlands prompted their increased use. Crested wheatgrass, primarily the caespitose bunchgrasses, were used extensively to revegetate abandoned croplands that were subject to wind erosion in the Northern Great Plains (Holechek 1981; Young and Evans 1986). The first planting of crested wheatgrass in the Intermountain area occurred in eastern Idaho in 1932 (Hull and Klomp 1966). As the need for plants to reclaim abandoned cropland increased, the production of seed of crested wheatgrass also increased (Sharp 1986). With greater demands for red meat production from Western rangelands during World War II, Congress allocated funds to convert unproductive sagebrush rangelands to more productive introduced grasslands (Young and McKenzie 1982). Researchers for the Forest Service developed a series of bulletins on rangeland seeding, emphasizing the use of

Mike Pellant is Coordinator, Great Basin Restoration Initiative, Nevada State Office, Bureau of Land Management, Boise ID 83709, U.S.A.; e-mail: Mike_Pellant@blm.gov. Cindy R. Lysne is Environmental Specialist, Power Engineers, Inc., Boise, ID 83707; e-mail: clysne@powereng.com

In: Shaw, Nancy L.; Pellant, Mike; Monsen, Stephen B., comps. 2005. Sage-grouse habitat restoration symposium proceedings; 2001 June 4–7; Boise, ID. Proceedings RMRS-P-38. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

crested wheatgrass and other introduced wheatgrasses in Idaho (Hull and Pearse 1943), Nevada (Robertson and Pearse 1943), and Utah (Plummer and others 1943).

Following World War II, the pace of rehabilitation accelerated again during the 1950s and early 1960s when millions of acres of Central and Western rangelands were seeded to crested wheatgrass. The objectives of these seedings included increasing forage for livestock, weed control, watershed stabilization, and reducing wildfire hazards. The use of crested wheatgrass to biologically suppress halogeton (*Halogeton glomeratus*), a nonnative poisonous forb, was funded by Congress in 1952 and ultimately paid for a major portion of crested wheatgrass seedings in Nevada and other Great Basin States (Young and Evans 1986).

The rehabilitation of degraded rangelands with crested wheatgrass was also accelerated by the development of equipment to control competitive plants and distribute seed effectively across a wide range of edaphic conditions. In particular, the development of the rangeland drill in the early 1950s hastened the ability of land managers to seed large acreages to crested wheatgrass, while the brushland plow provided managers with a tool for sagebrush removal prior to seeding (Young and McKenzie 1982). By the early 1970s, referred to by Young and Evans (1986) as the "golden age" of seeding crested wheatgrass, an estimated 12.4 million acres were seeded to this species (Dewey and Asay 1975). A recent report (USDI 2001) on the condition of public lands managed by the Bureau of Land Management in the Western United States indicates that approximately 5 million acres of rangelands have been seeded (USDI 2001), the majority of which we estimate included crested wheatgrass in the seed mixture. However, since this information is based in large part on inventory information collected in the mid-1970s, the acreage of public lands seeded in part with crested wheatgrass is expected to exceed this figure.

The use of crested wheatgrass has come under increasing scrutiny since the 1970s. Legislation, such as the Surface Mining Control and Reclamation Act (PL 95-87, 1977), required the use of native species for mine reclamation. The National Environmental Policy Act of 1969 (Pub. L. 91-190, 42 U.S.C. 4321-4347) required the preparation of an impact analysis on activities funded by the government; this included the use of introduced species in seedings. Federal agency guidance on this subject has also changed. Prior to 1984, the Bureau of Land Management's guidance on post-wildfire seeding encouraged the use of introduced grass species given their cost, ease of establishment, and erosion prevention capability (USDI BLM 1981). More recently, Presidential Executive Order 13112 on Invasive Species (Clinton 1999) directs Federal agencies to use native species when feasible to restore ecosystems where invasive species are a problem. Finally, the BLM's Great Basin Restoration Initiative (GBRI) gives preference to the use of native species in seeding projects, "pending seed availability, cost and chance for success." (USDI BLM 2000).

Competitive Characteristics of Crested Wheatgrass

An understanding of the competitive characteristics of crested wheatgrass is essential in order to develop strategies to increase plant diversity in seedings dominated by this species. The same features that make crested wheatgrass appealing to land managers (for example, provide soil stability and compete with and control invasive species) can also result in community dominance of this species, displacement of native species, and reduced plant diversity (Broersma and others 2000; D'Antonio and Vitousek 1992; Marlette and Anderson 1986; Roundy and others 1997). Although some studies reported that crested wheatgrass is not "mobile" and does not deter the reestablishment of native species (Broersma and others 2000; Krzic and others 2000), several other studies have shown that established stands have spread beyond the original seeded area (Hull and Klomp 1966; Marlette and Anderson 1986). Other studies have shown that crested wheatgrass seedings resulted in near monospecific stands (Hull and Klomp 1966; Looman and Heinrichs 1973; Schuman and others 1982).

There are several characteristics of crested wheatgrass that contribute to its competitiveness with both invasive species and native vegetation. At the seedling stage, crested wheatgrass has an advantage over some native plants, due in part to its ability to efficiently capture nutrients and water (Bakker and Wilson 2001; Schuman and others 1982). Established crested wheatgrass plants were more efficient at securing phosphorus than native bluebunch wheatgrass (*Pseudoroegneria spicatum*) when both species were grown in association with big sagebrush (*Artemisia tridentata*) (Caldwell and others 1985). Big sagebrush was also negatively affected by the ability of crested wheatgrass to rapidly extract soil water during the same period that sagebrush requires this resource (Cook and Lewis 1963; Eissenstat and Caldwell 1988; Sturges 1977). Other studies have shown the competitive advantage of crested wheatgrass during the initial stages of plant establishment for Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) and antelope bitterbrush (*Purshia tridentata*) (Blaisdell 1949; Fortier 2000;Hall and others 1999; Schuman and others 1998). Native grasses may also reduce shrub seedling establishment; however, the effect is less than that exhibited by crested wheatgrass (Eissenstat and Caldwell 1988; Hubbard 1957). For example, Frischknecht and Bleak (1957) reported that seeded stands of bluebunch wheatgrass were more likely to permit sagebrush seedling recruitment than seeded stands of crested wheatgrass.

Another attribute that favors crested wheatgrass establishment is its prolific seed production. Marlette and Anderson (1986) germinated seed from a crested wheatgrass monoculture planting and reported around 500 crested wheatgrass seedlings per m^2. Pyke (1990) compared the demography of crested wheatgrass and bluebunch wheatgrass and found crested wheatgrass to have a decided advantage over the native grass in seed production, seed bank carryover, seed dispersal, and seedling survival. Seed production for crested wheatgrass ranged from 1,772 seeds per m^2 in a wet year to 1,037 seeds per m^2 in a dry year. Bluebunch wheatgrass seed production during this same period ranged from 26 seeds per m^2 in the wet year to no seed production in the dry year. In a recent study, Romo (2005) found an average return of 2 percent of crested wheatgrass seeds sown while Heidinga and Wilson (2002) reported a 4 percent return. For example, seed production rates of 1,000 per m^2 with a 3 percent rate of return would result in an initial count of 30 crested wheatgrass seedlings per m^2.

Carryover of germinable seed for more than 1 year is another competitive characteristic of crested wheatgrass. Under ideal seed storage conditions in a lab, crested wheatgrass seeds remained germinable for over 20 years (Ackigoz and Knowles 1983). Seed life is much shorter in the natural environment; however, crested wheatgrass has been observed by the authors to germinate in the second and, in a few cases, the third growing season after the seed was planted.

Sage-Grouse and Crested Wheatgrass

Crested wheatgrass has been planted or has the potential for establishment (Rogler and Lorenz 1983) over a large portion of the historic and current range of sage-grouse (Connelly and others 2004). The question of the quality of crested wheatgrass seedings as habitat for sage-grouse is difficult to answer since it depends on both spatial and temporal scales that are rarely monitored (Connelly and others 2004). The size of the seeding, juxtaposition on the landscape in relation to suitable habitat, species composition of the seeding, and sagebrush cover are other factors that affect the utility of crested wheatgrass seedings as sage-grouse habitat. A recent review of sage-grouse habitat needs and associated habitat threats does not directly identify introduced seedings as a factor in the decline of sage-grouse (Wambolt and others 2002). They indicated that the extreme reduction in canopy cover of sagebrush, and associated loss in understory plant diversity typical of some introduced species seedings, can significantly reduce sage-grouse habitat quality throughout the year.

Understory plant diversity is important to sage-grouse in the spring and summer, whereas sagebrush provides essential cover and forage in the winter and late fall (Connelly and others 2000; Wambolt and others 2002). Brood-rearing habitats with an array of plant species provide a diversity of insects important to sage-grouse, especially during brood rearing (Connelly and others 2000; Drut and others 1994). The recently published "Guidelines for Sage-Grouse Habitat" (Connelly and others 2000) identified grass height (over 18 cm) and canopy cover (greater than 15 percent for breeding and brood-rearing habitats) as important habitat requirements for nesting sage-grouse. Therefore, crested wheatgrass, in the appropriate proportions, could provide similar habitat structure compared to native bunchgrasses. Connelly and others (2000) recommend that nonnative species that are functionally equivalent to natives be used in restoration projects if native forbs and grasses are unavailable.

Another situation where the use of crested wheatgrass may be necessary is the restoration of habitat that is severely degraded and dominated by aggressive invasive species (Pyke 1994). Beginning in the 1930s numerous studies were conducted that showed the superior competitive ability of crested wheatgrass with cheatgrass in the Intermountain area (Hull 1974; Hull and Holmgren 1964; Hull and Pehanec 1947; Hull and Stewart 1948). Recently, the establishment of crested wheatgrass as a "bridge" plant community to replace cheatgrass-dominated lands for future restoration to a more diverse plant community has been proposed as an alternative to seeding a full complement of native species in one treatment. This strategy, also referred to as "assisted succession" (Cox and Anderson 2004), will be discussed later in this document.

It is known that sage-grouse will not thrive in large homogenous stands of a single plant species (Crawford and others 2004). The modification of composition and structure of existing crested wheatgrass seedings to increase plant diversity for sage-grouse should be implemented only after considering social impacts, economic considerations, and land-use objectives. This synthesis paper was not produced to support the replacement of crested wheatgrass with native species. It is intended to provide a review of existing science and knowledge that can be used to increase diversity and structure of crested wheatgrass seedings to benefit sage-grouse, other wildlife species, and livestock. Local land-use plans, science, and public input should be incorporated into the decisionmaking process when selecting crested wheatgrass seedings to implement the strategies described in this paper.

Steps Required to Enhance Structure and Diversity in Crested Wheatgrass Seedings

The competitive characteristics of crested wheatgrass, discussed in the previous section, illustrate the difficulty in designing treatments to increase plant diversity in crested wheatgrass seedings. This grass is extremely resistant to grazing by herbivores. It has a variable response to mechanical or chemical treatments and a large viable seed reserve in the soil that must be considered in any control treatment. Increasing plant diversity in established stands of crested wheatgrass is presented as a three-step process.

Step 1. Reduce competition of crested wheatgrass to facilitate the establishment and persistence of the desired species.
Step 2. Introduce the desired plant(s) as seed or seedlings.
Step 3. Implement appropriate management and monitoring to maintain plant diversity of the seeding.

The discussion that follows focuses on step 1, because the knowledge and literature on seed or plant application (step 2) and managing restored seedings (step 3) are generally available.

Step 1: Reduce Crested Wheatgrass Competition

Grazing by domestic livestock, mechanical or chemical treatments, and fire are potential treatments that can be implemented singly or in combination to reduce crested wheatgrass competition prior to introducing desired plants to a seeding. Periodic droughts also offer opportunities, again singly or in combination with the above treatments, to reduce crested wheatgrass competition.

Livestock Grazing—The design of livestock grazing systems to maintain crested wheatgrass and reduce encroachment of sagebrush into these seedings has been studied for almost as long as crested wheatgrass has been used.

Much of this early research focused on grazing systems and utilization levels to maintain the productivity of seedings and minimize the return of sagebrush in seeded areas (Cook and others 1958; Hull and Klomp 1974) Sagebrush was considered an "invader" in crested wheatgrass seedings because it reduced the productive capability and economic returns from seedings in direct proportion to the ratio of shrub to grass. Rittenhouse and Sneva (1976) determined that each 1 percent increase in Wyoming big sagebrush canopy cover was associated with a 3.3 to 5.2 percent decline in crested wheatgrass production in eastern Oregon. This early research can now be used "in reverse" to develop grazing systems to reduce crested wheatgrass competition in order to increase plant diversity, especially shrubs, in seedings.

Since crested wheatgrass can withstand heavy grazing (Caldwell and others 1981; Cook and others 1958; Hull 1974; Laycock and others 1981), reducing competition using only livestock may be insufficient to permit establishment of desirable seeded species. In general, high levels of utilization by livestock during the growing season reduces the vigor of crested wheatgrass and may lead to mortality of some, but not all, plants (Cook 1973; Wilson and Partel 2003). Early summer grazing may be detrimental to crested wheatgrass due to lower carbohydrate (Trlica and Cook 1972) and nitrogen reserves (de Kroon and Bobbink 1997) of grazed plants. Other studies have demonstrated that heavy use alone (up to 70 percent) did not significantly affect stands of crested wheatgrass (Frischknecht and Harris 1968; Lodge and others 1972; Springfield 1963). Heavy utilization by livestock was also cited by some of these authors as necessary to reduce development of crested wheatgrass "wolf plants." Wolf plants are crested wheatgrass plants that contain a higher proportion of dead stems than consistently grazed plants and, as a result, are not preferentially selected by livestock.

Olson and others (1988a,b) found that grazing to reduce vigor, cause mortality, or reduce establishment of new crested wheatgrass seedlings is most effective if the treatment is done during or immediately after tiller elongation (internode elongation) and results in removal of the apical meristem. These same studies showed that grazing crested wheatgrass before internode elongation had little effect on reducing tiller replacement and could increase tiller density if grazing intensity and timing were not closely monitored. Olson and others (1988b) indicated that short-duration grazing at a conventional stocking rate in eastern Oregon increased tiller density of crested wheatgrass. This study also demonstrated that most crested wheatgrass tillers are produced in the fall, overwinter, and flower the following growing season. If an adjacent crested wheatgrass plant was removed, the tiller production and resource uptake of its neighbor was increased. Thus, attempts to reduce crested wheatgrass by livestock grazing are influenced by growing season conditions, level of utilization in relation to plant phenology, degree of use of neighboring plant, and the dynamics of tiller production.

It is well established that crested wheatgrass is adapted to withstand heavy livestock use with minimal mortality. How does livestock grazing affect the recruitment and establishment of crested wheatgrass? Most crested wheatgrass recruitment occurs between the rows of established plants in a seeding (Salihi and Norton 1987). The success of recruitment in the interspaces is reduced by the impacts of livestock trampling since cattle (*Bos* sp.) generally avoid stepping on plant tussocks (Balph and Malechek 1985). As crested wheatgrass plants age, elevated tussocks develop because of the plant's caespitose growth form, further increasing cattle avoidance of stepping on the mature plants. This results in increased mortality of seedlings that are trampled (Salihi and Norton 1987), and accelerates soil erosion and compaction (Balph and others 1985) in the interspace areas. In another study, Krzic and others (2000) stated that long-term grazing of crested wheatgrass did not result in degradation of soil properties, with one exception: soil compaction was greater in seedings grazed in spring compared to native rangeland. Salihi and Norton (1987) measured less than 1 percent crested wheatgrass seedling survival in grazed plots compared to 12 percent survival in ungrazed plots.

The combination of properly timed livestock use to reduce vigor and survival of mature crested wheatgrass plants along with the trampling of new recruits in the interspace areas should result, over time, in a reduction in both numbers and vigor of mature crested wheatgrass plants and their recruitment potential. The decision to use these intensive grazing treatments must be weighed against the detrimental effects of heavy grazing on soil properties, weed entry and/or expansion, and erosion potential as well as the management objectives for the seeding.

Another benefit of livestock use at the appropriate time and intensity in crested wheatgrass seedings is to facilitate the return of sagebrush. As mentioned earlier, control of "reinvading" sagebrush in crested wheatgrass seedings was the focus of past research on treatments to physically remove the sagebrush or livestock management systems to maintain the crested wheatgrass productivity and minimize the reinvasion of sagebrush. It is well established that sagebrush encroachment in seedings is less under light to moderate spring livestock use, but increases under high crested wheatgrass utilization levels for this same period (subject to climatic, grazing management system, and initial treatment variables) (Frischknecht and Harris 1968; Hull and Klomp 1974; Laycock and Conrad 1981; Robertson and others 1970). For example, crested wheatgrass utilization levels of 80 percent on a Utah seeding resulted in loss in vigor of crested wheatgrass and an increase in sagebrush (Frischknecht and Harris 1968). By comparison, fall grazing by cattle resulted in less sagebrush encroachment in seedings when compared to heavy spring livestock use (Laycock and Conrad 1981). However, grazing by sheep (*Ovis aries*) in fall often resulted in reduced production or mortality of sagebrush (Frischknecht 1978).

Therefore, assuming that there is a sagebrush seed source in or near the target crested wheatgrass seeding, a grazing system that promotes heavy spring livestock use over a period of years could promote an increase of sagebrush in crested wheatgrass seedings. Angell (1997) found that this same grazing management system would also promote the survival of juvenile sagebrush plants due to decreased soil water depletion by crested wheatgrass. He found that only the short duration, double stocking rate treatment in spring resulted in an increase in juvenile sagebrush plants when compared to the continuous grazing and moderate short duration grazing treatments. In a similar study, Owens and Norton (1990) found that juvenile sagebrush survival was greater in a pasture that received high intensity use for repeated short durations (short duration grazing system) during the growing season when compared to a traditional continuous growing season treatment.

Thus, once juvenile sagebrush plants are established in a seeding, continued heavy livestock use will accelerate sagebrush growth and potentially increase additional sagebrush recruitment. This strategy is predicated on concentrated heavy use of crested wheatgrass and may require temporary fencing to concentrate livestock in a smaller portion of a larger seeded pasture. The temporary fence could then be moved to another portion of the seeding to increase sagebrush establishment over a larger area, if desired. Other considerations in applying this strategy to increase sagebrush in crested wheatgrass seedings are the effects of soil compaction, potential for weed entry, increased soil erosion, and effects on residual native grasses and forbs in the heavy use areas. Introduction of sagebrush seed may be required if a seed source is not already present in or immediately adjacent to the treatment area.

Drought and Livestock Grazing—Periodic droughts provide another window of opportunity to reduce crested wheatgrass density, especially when combined with properly timed, heavy levels of livestock use. Tiller regrowth of crested wheatgrass was limited by clipping and drought over a 2-year period (Busso and Richards 1995). They cautioned that repeated late spring grazing under droughts lasting 2 or more years could reduce the persistence of crested wheatgrass in a stand. Conversely, light or moderate grazing (around 40 percent) of crested wheatgrass in a drought was found to enhance production and survival because of a decrease in the leaf area and associated respiration (Mohammad and others 1982). In this same study, no plant recovery occurred when water stress was severe and crested wheatgrass defoliation was 80 percent.

Crested wheatgrass has the potential to recover rapidly after a drought due to the high accumulation of total nonstructural carbohydrate reserves accumulated in the plant organs during times of stress (Busso and others 1990). Thus, any benefits in reduction in competition of crested wheatgrass achieved by livestock grazing during droughts may be lost quickly if treatments to increase diversity are not implemented in a timely manner. Another concern with using drought and livestock to reduce competition of crested wheatgrass is the opportunity for an increase in invasive species during periods between droughts and the average or above average precipitation periods following droughts (Svejcar 2003). Heavy livestock use may also increase the potential for loss of biological soil crusts and residual native plants in the seeding (Anderson and others 1982; Kimball and Schiffman 2003). Even with these concerns, livestock grazing during multi-year droughts may reduce crested wheatgrass competition sufficiently to allow successful reintroduction of desired species.

Herbicide Application—The application of an appropriate herbicide at the proper time can reduce perennial grass density (Nelson and others 1970; Whisenant 1999). A number of different herbicides are effective in reducing vigor or causing mortality of crested wheatgrass. Glyphosate (*N-[phosphonomethyl]glycine*) is a contact herbicide that stunts or kills the entire plant upon application. Application of glyphosate (trade name Roundup™) reduced crested wheatgrass cover from 12 to 4 percent in 1 year and had no effect in the second year of a 2-year study in Utah that looked at the utility of several treatments to reduce competition prior to seeding native species (Cox and Anderson 2004). This difference in effect between years, probably due to timing of application, illustrates the importance of applying contact herbicides at the appropriate phenological stage. In Canada, a spring application of glyphosphate reduced crested wheatgrass by 50 percent, which was adequate control to establish a native warm season grass seeded at a high application rate (Bakker and others 1997).

Wilson and Partel (2003) applied multiple herbicide treatments to maximize the mortality of crested wheatgrass in Canadian grasslands. A total of 13 glyphosphate applications over 6 years significantly reduced cover of crested wheatgrass; however, the surviving plants in the herbicide treatment area produced 42 seedheads per m^2 compared to 12 seedheads per m^2 in the control. Crested wheatgrass seedlings emerging from the seedbank were not significantly different between the herbicide treatment and control (average density of 284.4 seedlings per m^2). Even though crested wheatgrass was not eliminated with the herbicide treatments in this study, Bakker and others (2003) reported that native species diversity and abundance were enhanced on these study sites. They reported that the careful application of glyphosate by wicking or spraying prior to the active growth of warm season native species can suppress crested wheatgrass and promote native species establishment. They recommend considering cultivation prior to seeding and applying multiple control treatments (herbicide and intensive grazing) in hot dry years to further reduce crested wheatgrass competition if herbicide application alone is not adequate.

Another Canadian project evaluated multi-year application of glyphosphate to reduce crested wheatgrass competition before seeding native species (Ambrose and Wilson 2003). Glyphosphate was applied as a spray in the spring of the first year and applied with a wick applicator in the 3 subsequent years. Surprisingly, emergence of crested wheatgrass seedlings from the seedbank was not decreased by 4 years of glyphosphate treatments, due primarily to the tripling in number of seed heads on surviving plants in the herbicide plots compared to the control plots. The impacts of releasing crested wheatgrass from intraspecific competition with glyphosphate and thereby increasing seed production on remaining plants must be considered when selecting treatments to reduce crested wheatgrass competition.

When Romo and others (1994) investigated the effects of a combination of fall burning followed by a spring application of glyphosate on crested wheatgrass mortality in Canada, they found that burning had little effect on crested wheatgrass survival, while glyphosphate applied early in the growing season on the burned crested wheatgrass reduced cover from 78 to 35 percent on one site and from 81 to 55 percent on another site. In another study, Romo and others (1994) applied mowing in the fall to reduce crested wheatgrass vigor followed by an application of glyphosate on individual plants and recorded 100 percent crested wheatgrass mortality. They also observed total elimination of crested wheatgrass with an application of 25 percent glyphosphate in early spring when two to four leaves per tiller were present.

Another consideration in using glyphosphate to reduce crested wheatgrass is the differential effect that this herbicide appears to have on different species of crested wheatgrass. Lym and Kirby (1991) found that 'Fairway' crested wheatgrass was less susceptible to glyphosphate in terms of yield than was 'Nordan' crested wheatgrass. Also glyphosate generally does not interfere with the establishment of seeded species (Bakker and others 1997; Masters and Sheley 2001) since it is bound to the soil once applied and is not available for uptake by plants. On the negative side, since glyphosphate is a contact herbicide, it has no residual effect on crested wheatgrass regrowth and may need to be applied multiple times in the same growing season or over multiple years, depending on climatic conditions and plant phenology and growth patterns.

Paraquat (1,1´-dimethyl-4,4´-bipyridinium ion) is another herbicide that has been used to treat crested wheatgrass. Sneva (1970) found that paraquat applied for 3 consecutive years did not significantly reduce crested wheatgrass yield in the fourth year. In this study, clipping crested wheatgrass to ground level in May of each year was more effective in reducing the percent of apical meristems than was the herbicide application. Atrazine and simazine were evaluated as tools to rejuvenate weed infested seedings in Nevada (Eckert 1979). The reduction of weedy competition in the stand by these herbicides resulted in slightly more crested wheatgrass seed production and minimal mortality on treated compared to control sites. Crested wheatgrass seedling production was significantly greater in the atrazine treated plots compared to the control, indicating that the reduction in weedy competition not only favored seed production but greatly enhanced seedling establishment.

In summary, herbicides can be very effective in controlling crested wheatgrass, especially when combined with other treatments such as burning or mowing. Label restrictions on their use should be closely followed in order to minimize adverse effects. If complete crested wheatgrass mortality is not obtained (usually the case), the seed production on surviving plants increases significantly and provides significant competition with desirable plants introduced on the treated areas. As Whisenant (1999) points out, effective herbicide use requires knowledge of individual site characteristics and knowledge of herbicide effects on the individual species and the environment.

Mechanical Treatments—Mechanical treatments can be used to either physically remove crested wheatgrass biomass (for example, mowing) to reduce plant vigor or cause mortality, or uproot plants and cause direct mortality (for example, plowing). Mechanical removal of live crested wheatgrass foliage will be discussed first, followed by an overview of equipment that can be used to cause direct mortality. Clipping studies to simulate grazing have been previously discussed in the **Livestock Grazing** section of this paper, and the reader is encouraged to review that information as it applies to the effects of mowing described in this section.

Lodge (1960) compared mowing in the fall, burning in spring and fall, and double disking in the fall. He found that mowing had little effect on floristic composition or in reducing basal area of crested wheatgrass in Canada. Double disking was the only treatment that significantly reduced crested wheatgrass basal area (from 6.6 percent on the control to 2.7 percent in the treatment areas); this treatment effect disappeared within 2 years. A clipping study to reduce crested wheatgrass competition was conducted in northern Utah by Cook and others (1958). They hand-clipped crested wheatgrass plants at 1- and 3-inch stubble heights throughout the growing season over a 5-year period. The 1-inch clipping height and more frequent clipping treatments reduced yield, vigor, and seed production of crested wheatgrass more than did the 3-inch clipping height and less frequent clipping treatments. Seed production, as expressed by number of spikes per plant, was not significantly affected by clipping height; however, increasing the frequency of harvesting decreased the number of spikes produced. Finally, this study documented that frequency and season of clipping were the most influential factors affecting viable seed production. At the end of the 5-year study period, control plants produced 1,834 viable seeds per plant, while clipping once in mid-June or early July for 5 years reduced the number of seeds per plant to nearly zero.

Lorenz and Rogler (1962) compared several mechanical techniques to "renovate" stands of crested wheatgrass in North Dakota. Plowing in spring eliminated crested wheatgrass production for 2 years, while a spring scarification treatment (heavy field cultivation that uprooted about one-third of the plants) significantly reduced yields in only the first year following treatment. In subsequent years the scarified treatment produced more herbage than the control plot in one year and similar yields in the remaining years of the study. The authors urged caution with the plowing treatment due to the potential for increased wind erosion.

Bakker and others (1997) rototilled crested wheatgrass plots in May on a sandy site in Canada, reducing cover of crested wheatgrass from around 40 percent on control plots to 20 percent on the treatment plots in August of the same year. Finally, Cox and Anderson (2004) investigated the effectiveness of two tillage treatments and a herbicide treatment in reducing crested wheatgrass competition prior to seeding native species. Tillage treatments were done in February in 2 consecutive years on a crested wheatgrass seeding in an arid (average annual precipitation of 7 inches) portion of Utah. The tilling treatment was done with a cultivator that removed all vegetation and mixed the soil to a 7-inch depth, while the harrowing treatment was done with a field harrow that uprooted some, but not all plants. Tillage was more effective than harrowing in reducing crested wheatgrass cover in this study. The control plots averaged 12 to 4 percent crested wheatgrass cover during the 2-year study compared to 1 to 2 percent cover on tilled and 4 to 7 percent cover on harrowed plots.

Another category of mechanical equipment, the interseeders and transplanters, remove plant competition in narrow bands and seed (interseeder) or plant seedlings (transplanter) in a one-pass operation (Giunta and others 1975; Stevens 1994; Stevens and others 1981; Wiedemann 2005). Scalping to reduce plant competition is generally done with either modified disks or a plow pulled behind a tractor. The seeder or transplanter is mounted immediately behind the disk or plow. Recommended widths for scalping crested wheatgrass prior to seeding shrub seeds are 40 to 60 inches (Van Epps and McKell 1978). This width should be adjusted according to density, vigor, and growth form of existing vegetation, the species to be interseeded, and local site conditions (Stevens 1994). A side benefit of scalping is that the scalp captures and holds additional moisture from snow and rain, which enhances seedling establishment and growth (Stevens 1994). An indepth description of interseeders and transplanters can be found in Chapter 28 of Restoring Western Ranges and Wildlands (Monsen and others 2004b).

Other equipment not specifically addressed in studies cited above that could be used to reduce crested wheatgrass competition includes pipe harrows, anchor chains with welded railroad rails (for example, Ely and Dixie Sager chains), and the disk chain (Monsen and others 2004a). Effectiveness of these types of equipment in providing crested wheatgrass control is expected to be moderate to excellent, although published studies to support their use for crested wheatgrass control are few.

In summary, the use of mechanical equipment to reduce crested wheatgrass competition will vary in effectiveness, dependent upon a wide array of factors. Some cautions on the use of plows or disks include increased chance of soil erosion and weed entry, loss of residual native plants and biological crusts, and treatment costs.

Step 2: Introduce Desired Species

The challenges in controlling crested wheatgrass competition, described in Step 1, must be resolved prior to implementing the seeding or planting treatments outlined in Step 2. The benefits of increasing plant diversity in grass monocultures include improved habitat, greater species richness and community diversity, improved aesthetics, more soil cover (Stevens 1994), and increased diversity of birds, mammals, reptiles, and insects (Reynolds 1980).

Most of the treatments implemented in the past to increase diversity in crested wheatgrass stands have involved interseeding or transplanting single species or a few species such as big sagebrush, rubber rabbitbrush (*Chrysothamnus nauseosus*), fourwing saltbush (*Atriplex canescens*), antelope bitterbrush, Lewis flax (*Linum perenne*), Palmer penstemon (*Penstemon palmeri*), western yarrow (*Achillea millefolium*), and globemallow (*Sphaeralcea* spp.) (Monsen and Shaw 1983; Pendery and Provenza 1987; Stevens 1994). However, single rows of shrubs or forbs in monocultures of crested wheatgrass may not meet all of the resource (for example, sage-grouse habitat) or management objectives for a particular area.

Step 2 involves the selection of adapted species to plant and appropriate equipment to implement the planting. It is essential to select the species and seed mixtures that meet resource objectives and are adapted to the ecological site(s) that will be seeded. Nonadapted seeds may respond differently to germination cues and germination may occur at an inappropriate time, resulting in seeds that fail to germinate or persist (Meyer 1994). Additional considerations for seed mixture development include the potential for interspecific interactions among the species in the seed mixture during the establishment phase, the ability of plants to coexist, and the ability of the species to regenerate itself on the site (Archer and Pyke 1991; Pyke 1994; Pyke and Archer 1991).

If the objective of the crested wheatgrass treatment(s) is to restore ecosystem functioning and biological diversity to a site, this will often require the use of native species (Lesica and Allendorf 1999). Native species introduced into a crested wheatgrass seeding may facilitate recruitment of additional native species. For instance, Frischknecht and Bleak (1957) found that seeded stands of bluebunch wheatgrass were more likely to permit sagebrush seedling recruitment than seeded stands of crested wheatgrass. Introduced species may also increase the diversity of a crested wheatgrass seeding, improving it as habitat for sage-grouse. Dryland alfalfa (*Medicago sativa*) and small burnet (*Sanguisorba minor*) are introduced forbs that are preferred by sage-grouse that can be successfully reintroduced into crested wheatgrass seedings. It is important to select site-adapted species (native or introduced) that are competitive in the posttreatment environment and that will be maintained over the long term with livestock management systems.

The selection of a seed mixture should not be done without consideration of how seed will be distributed during the planting process. Rangeland drills vary considerably in their ability to seed native species. If suitable equipment is not available to properly seed a species in the proposed seed mix, the mix should be changed or the proper equipment secured. Another factor to consider is that some site preparation treatments, such as plowing or disking, may create an unfavorable planting seedbed that requires additional treatments. Harrowing or cultipacking after these surface disturbing treatments may be required to mitigate these unsatisfactory seedbed surfaces (Whisenant 1999).

Direct seeding by drilling or aerially broadcasting seed is relatively inexpensive, widely applicable, and under appropriate seedbed conditions, provides good plant establishment (Whisenant 1999). Applying seed with a rangeland drill is considered the best method for establishing species with large, hard seeds because the seed is placed in contact with the soil and at an appropriate depth (Hull 1948; Pyke 1994). However, seeding many native species with the standard rangeland drill is problematic given the lack of control of seeding depth, variable seed coverage with soil, and absence of a mechanism to improve soil to seed contact. Surface obstructions such as rocks, steep slopes, and soddy vegetation also limit the effectiveness of rangeland drills in establishing any seed mixture, especially native forbs and grasses. One unknown in the use of rangeland drills to seed diverse seed mixtures into crested wheatgrass seedings is the effectiveness of these drills in cutting through the dead plant crowns and the shallow root mass of the seeding. If this is a problem, the deep furrow rangeland drill (Hull and Stewart 1948), which has a double furrow opener, may be more effective in soddy conditions than the rangeland drill, which has a single furrow opener. The single disk or double disk opener on the rangeland drill does create a furrow that can capture and store water for seedlings. However, the soil disturbance created by this drill also opens the plant community for the entry of other invasive species.

Another option for ground application seeding into treated crested wheatgrass stands is the use of a minimum till drill that creates less soil disturbance than the rangeland drill. The Truax and Amazon drills are minimum till drills that can place seed at different depths, and their press wheels improve soil to seed contact. An overview of rangeland drills, manufacturer's specifications, and contact information is the Revegetation Equipment Catalog available online at http://reveg-catalog.tamu.edu (Wiedemann 2005). This catalog also contains similar information on most of the equipment discussed in this paper. The reader is encouraged to utilize this Web site for all treatments requiring the use of equipment.

Aerial broadcasting is often easier and less expensive than ground application methods because large areas can be seeded quickly and topography or slopes are generally not a limiting factor (Monsen 2000). Aerially broadcasting seed followed by cultipacking, harrowing, or dragging a chain over the surface, where slope or surface rock is not limiting, places the seed in contact with the soil; however, seeding depth is not uniform (Pyke 1994; Stevens 2004). Livestock trampling has been suggested as another alternative for covering seed that has been aerially applied. Eckert and others (1986) found that heavy livestock trampling appeared to favor the emergence of sagebrush and weedy annual forbs, but was detrimental to the emergence of perennial grasses and forbs. Aerial seeding native species mixes into treated crested wheatgrass stands without some sort of incorporation into the soil is not advised. Given the high cost of seed and the different seedbed requirements of native species (seeding rates are generally doubled on aerial seedings), seeding with rangeland drills is recommended over aerial seeding with or without seed coverage.

Alternatives to ground or aerial application of seed include transplanting individual plants from existing populations ("wildings") or planting container stock or bare-root seedlings grown from seed. In arid and semiarid environments, transplanting young plants may be a more reliable, albeit a considerably more expensive method for establishing native species in crested wheatgrass seedings. Transplanting young plants bypasses the high-risk germination and seedling stage. In addition, transplanting may enhance the success of species that do not establish rapidly from seed and provide larger plants that are more capable of coping with competition and herbivory (Archer and Pyke 1991; Van Epps and McKell 1980; Whisenant 1999). If small islands of native species are desired in a crested wheatgrass seeding or if greater native plant diversity is desired in an existing native species seeding, transplanting wildings, bare-root, or containerized stock of desired forbs or shrubs may be a good option. However, costs of treating larger acreages this way will generally be prohibitive.

The use of livestock to disseminate seed of desired species via dung (Auman and others 1998; Doucette and others 2001; Ocumpaugh and others 1996; Welch 1985) into crested wheatgrass seedings is another option since livestock preferentially graze these areas. Seeds ingested by cattle are deposited in a moist, nutrient-rich medium that may facilitate germination and establishment of ingested seeds and may result in patches of desirable species (Archer and Pyke 1991). Fecal-seeding offers a nonintrusive, relatively low cost method of seeding small areas (Archer and Pyke 1991; Shinderman and Call 2001). Seeding response can be slow and sporadic, and there is the potential for the introduction and spread of exotic species by livestock (Auman and others 1998; De Clerck-Floate 1997; Lyon and others 1992; Pleasant and Schlather 1994). A study by Auman and others (1998) found that cattle dung provided favorable conditions for the germination of crested wheatgrass as well as cheatgrass. Also, livestock grazing would need to be closely monitored to ensure that livestock did not overutilize and eliminate the very plants they were dispersing (Archer and Pyke 1991).

Step 3: Posttreatment Management

The long-term success of any project implemented to increase plant diversity in crested wheatgrass seedings is dependent on applying appropriate management during the establishment and postestablishment period. Documentation of implementation practices and the effectiveness of treatments must be conducted via a well designed monitoring program in order to adjust management now and design more effective projects in the future (for example, implement an adaptive management program). An adaptive management program is not possible without good implementation information combined with sound effectiveness monitoring.

Livestock Management—It is essential that livestock grazing and rest intervals are matched with the phenology and life history attributes of desired plant species (Archer and Pyke 1991; Holechek 1983). Grazing should be restricted until plants are adequately established and sexually reproducing (Pyke 1994). Many plants require at least 2 years, and as many as 5 years, to become established with adequate root systems to endure grazing (Pyke 1994; Stevens 1994; Vallentine 1989; Vallentine and others 1963; West and Hassan 1985). Areas seeded to shrubs must be protected from grazing during the establishment period (Ganskopp and others 1999; Richardson and others 1984). Plant seedlings are particularly sensitive to herbivory because they have low nutrient and energy reserves and shallow, low-density root systems relative to adult plants (Archer and Pyke 1991; Holechek 1983).

Once the plant establishment period (period of time when livestock were excluded from the project area) has passed, an appropriate livestock management plan must be followed to maintain the diversity restored in the crested wheatgrass seeding (Archer and Pyke 1991). If plant diversity is increased in a crested wheatgrass seeding to benefit sage-grouse, additional livestock or recreation management changes may be necessary to maintain structure, composition, and forage quality to meet seasonal habitat requirements. Impacts of livestock grazing can be positive, negative, or neutral to sage-grouse, depending on the timing and intensity of livestock grazing and which seasonal habitat is being considered (Crawford and others 2004). Heavy livestock grazing can reduce grass competition and increase sagebrush density (Crawford and others 2004; Vallentine 1989) or it can decrease big sagebrush seedling survival under certain management systems (Owens and Norton 1990). In general, the season and duration of livestock use and the stocking rate should be managed to promote optimum growth of forbs, grasses, and sagebrush to maximize habitat values for sage-grouse (Beck and Mitchell 2000).

Monitoring—Monitoring involves the orderly collection of data, analysis, and evaluation of data. Combined with experience, monitoring is a powerful tool to improve the effectiveness of restoration efforts now and into the future. Implementation monitoring includes summarizing how, what, where, and when treatments were actually implemented. The timing of treatments, conditions during application of treatments (for example, was the soil dry or frozen when seeding occurred), and posttreatment events (for example, Mormon cricket density was high the first year following seeding) are all important factors in evaluating treatment effectiveness. The origin and percent of pure live seed of each species in the seed mixture should also be documented in the project file to improve the accuracy of seeding establishment interpretations.

Effectiveness monitoring measures the success of the treatments that were implemented relative to the project objectives. Implementation monitoring provides the context to evaluate the effectiveness of the treatments. It is important that project objectives be developed before selecting monitoring protocols. The sage-grouse guidelines developed by Connelly and others (2000) provide a good starting point to develop sage-grouse habitat objectives in crested wheatgrass seedings proposed for treatments to increase their diversity.

Monitoring information, if collected appropriately, provides the framework to implement an adaptive management program to improve restoration practices in the future. Adaptive management acknowledges uncertainty and imperfect knowledge in implementing projects (Walters 1986), and encourages research and management to be conducted simultaneously (Smallwood and others 1999; Walters and Holling 1990). An adaptive management approach would be especially helpful in identifying treatments that are effective in reducing crested wheatgrass competition (Step 1). To maximize the utility of this approach, different treatments would be implemented and evaluated on the same project, promoting a better understanding of treatment effectiveness. At a minimum, adequate monitoring data should be collected to determine if short- and long-term management objectives are met when restoring diversity of crested wheatgrass seedings.

Summary

This review identifies some of the actions that can be taken to increase plant diversity in crested wheatgrass seedings for sage-grouse and other uses. The importance of proper planning and posttreatment management has been stressed as an essential component of a three-step process to convert parts of existing crested wheatgrass seedings into more diverse plant communities. This three-step process and the treatments associated with it could be used as part of a more ambitious strategy to first convert cheatgrass monocultures (Allen 1995; Pellant 1990; Tausch and others 1995) into perennial grasslands followed by the steps described above to increase plant diversity in these crested wheatgrass grasslands, for example, assisted succession as described by Cox and Anderson (2004). This strategy provides a bridge between the difficult conversion of exotic annual grasslands into native plant communities.

It is important to remember that crested wheatgrass seedings have been an important management tool used to increase livestock production, reduce weed problems and wildfires, and mitigate soil erosion potential following disturbances since they were first established in the late 1930s. Regardless of whether our objectives now are to increase plant diversity in selected crested wheatgrass seedings or as part of a larger strategy to reduce cheatgrass domination in the Intermountain region, the application of good science and professional experience tempered with results from monitoring studies should guide our actions. Sage-grouse, other wildlife species, and all resource uses will benefit from an objective-based approach (both at the site and landscape levels) to restoring plant diversity to selected crested wheatgrass seedings. As always, social, economic, and political values will provide the context for these important restoration decisions.

Acknowledgment

The authors thank Nancy Shaw and Danielle Scholten for the reviews and edits of this manuscript.

References

Ackigoz, E.; Knowles, R. P. 1983. Long-term storage of grass seeds. Canadian Journal of Plant Science. 63: 669–674.

Allen, E. B. 1995. Restoration ecology: limits and possibilities in arid and semiarid lands. In: Roundy, B. A.; McArthur, E. D.; Haley, J. S.; Mann, D. K., comps. Wildland shrub and arid land restoration symposium: proceedings. Gen. Tech. Rep. INT-GTR-315. Ogden, UT: U.S. Department. of Agriculture, Forest Service, Intermountain Research Station: 7–15.

Ambrose, L. G.; Wilson, S. D. 2003. Emergence of the introduced grass *Agropyron cristatum* and the native grass *Bouteloua gracilis* in a mixed-grass prairie restoration. Restoration Ecology. 11: 110–115.

Anderson, D. C.; Harper, K. T.; Holmgren, R. C. 1982. Factors influencing development of cryptogamic soil crusts in Utah deserts. Journal of Range Management. 35: 180–185.

Anderson, J. E.; 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.

Angell, Raymond F. 1997. Crested wheatgrass and shrub response to continuous or rotational grazing. Journal of Range Management. 50: 160–164.

Archer, S.; Pyke, D. A. 1991. Plant-animal interactions affecting plant establishment and persistence on revegetated rangeland. Journal of Range Management. 44: 558–565.

Auman, B. S.; Call, C. A.; Wiedmeier, R. D. 1998. Crested wheatgrass establishment in livestock dung deposited on degraded rangeland vegetation types in the Intermountain West, USA. Arid Soil Research and Rehabilitation. 12: 317–333.

Bakker, J.; Wilson, S. 2001. Competitive abilities of introduced and native grasses. Plant Ecology. 157: 117–125.

Bakker, J. D.; Christian, J.; Wilson, S. D.; Waddington, J. 1997. Seeding blue grama in old crested wheatgrass fields in southwestern Saskatchewan. Journal of Range Management. 50: 156–159.

Bakker, J. D.; Wilson, S. D.; Christian, J. M.; Li, X.; Ambrose; L. G.; Waddington, J. 2003. Contingency of grassland restoration on year, site, and competition from an introduced grass. Ecological Applications. 13: 137–153.

Balph, David F.; Malecheck, John C. 1985. Cattle trampling of crested wheatgrass under short-duration grazing. Journal of Range Management. 38: 226–227.

Beck, J. L.; Mitchell, D. L. 2000. Influences of livestock grazing on sage-grouse habitat. Wildlife Society Bulletin. 28: 993–1002.

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

Bleak, A. T.; Miller, Warren G. 1955. Sagebrush seedling production as related to time of mechanical eradication. Journal of Range Management. 8: 66–69.

Broersma, K.; Krzic, M.; Thompson, D. J.; Bomke, A. A. 2000. Soil and vegetation of ungrazed crested wheatgrass and native rangelands. Canadian Journal of Soil Science. 80: 411–417.

Busso, C. A.; Richards, J. H. 1995. Drought and clipping effects on tiller demography and growth of two tussock grasses in Utah. Journal of Arid Environments. 29: 239–251.

Busso, C. A.; Richards, J. H.; Chatterton, N. J. 1990. Nonstructural carbohydrates and spring regrowth of two cool-season grasses: interaction of drought and clipping. Journal of Range Management. 43: 336–343.

Caldwell, M. M.; Eissenstat, D. M.; Richards, J. H.; Allen, M. F. 1985. Competition for phosphorus: differential uptake from dual-isotope labeled interspaces between shrub and grass. Science. 229: 384–386.

Caldwell, M. M.; Richards, J. H.; Johnson, D. A.; Nowak, R. S.; Dzurec, R. S. 1981. Coping with herbivory: photosynthetic capacity and resource allocation in two semiarid *Agropyron* bunchgrasses. Oecologia. 50: 14–24.

Clinton, W. J. 1999. Executive Order 13112—invasive species. Federal Register. 64: 6183–6186.

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

Connelly, J. W.; Schroeder, M. A.; Sands, A. R.; Braun, C. E. 2000. Guidelines to manage sage-grouse populations and their habitats. Wildlife Society Bulletin. 28: 967–985.

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.

Cook, C. Wayne. 1973. Forage utilization, daily intake, and nutrient value of desert range. In: Proceedings: 3rd workshop of the United States/Australia Rangelands Panel; 1973 March 26–April 5; Tucson, AZ. Denver, CO: Society for Range Management: 47–50.

Cook, C. Wayne; Stoddart, L. A.; Kinsinger, Floyd E. 1958. Responses of crested wheatgrass to various clipping treatments. Ecological Monographs. 28: 237–273.

Cox, R. D.; Anderson, V. J. 2004. Increasing native diversity of cheatgrass-dominated rangeland through assisted succession. Journal of Range Management. 57: 203–210.

Crawford, J. A.; Olson, R. A.; West, N. E.; Mosley, J. C.; Schroeder, M. A.; Whitson, T. D.; Miller, R. F.; Gregg, M. A.; Boyd, C. S. 2004. Ecology and management of sage-grouse and sage-grouse habitat. Journal of Range Management. 57: 2–19.

D'Antonio, C. M.; Vitousek, P. M. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics. 23: 63–87.

De Clerck-Foate, R. 1997. Cattle as dispersers of hounds-tongue on rangeland in southeastern British Columbia. Journal of Range Management. 50: 239–243.

de Kroon, H.; Bobbink, R. 1997. Clonal plant dominance under elevated nitrogen deposition, with special reference to *Brachypodium pinnatum* in chalk grassland. In: de Kroon, H.; van Groenendael, J. The ecology and evolution of clonal plants. Leiden, The Netherlands: Backhuys Publishers: 359–379.

Dewey, D. R.; Asay, K. H. 1975. The crested wheatgrasses of Iran. Crop Science. 15: 844–849.

Dillman, A. C. 1946. The beginnings of crested wheatgrass in North America. Journal of the American Society of Agronomy. 38: 237–250.

Doucette, K. M.; Wittenberg, K. M.; McCaughey, W. P. 2001. Seed recovery and germination of reseeded species fed to cattle. Journal of Range Management. 54: 575–581.

Drut, M. S.; Crawford, J. A.; Gregg, M. A. 1994. Brood habitat use by sage-grouse in Oregon. Great Basin Naturalist. 54: 170–176.

Eckert, Richard E., Jr. 1979. Renovation of sparse stands of crested wheatgrass. Journal of Range Management. 32: 332–336.

Eckert, R. E., Jr.; Peterson, E. E.; Meurisse, M. S.; Stephens, J. L. 1986. Effects of soil morphology on emergence and survival of seedlings in big sagebrush communities. Journal of Range Management. 39: 414–420.

Eissenstat, D. M.; Caldwell, M. M. 1988. Competitive ability is linked to rates of water extraction: a field study of two aridland tussock grasses. Oecologia. 75: 1–7.

Fortier, M. I. 2000. Wyoming big sagebrush establishment on mined lands: seeding rates and grass competition. Laramie, WY: 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.

Frischknecht, N. C.; Harris, L. E. 1968. Grazing intensities and systems on crested wheatgrass in central Utah: response of vegetation and cattle. Tech. Bull. 1388. Washington, DC: U.S. Department of Agriculture. 47 p.

Frischknecht, Neil C. 1978. Biological methods: a tool for sagebrush management. In: Sagebrush symposium: proceedings; 1978 April; Logan, UT. Logan: Utah State University, College of Natural Resources: 121–128.

Ganskopp, D. T.; Svejcar, T.; Taylor, F.; Farstvedt, J.; Painter, K. 1999. Seasonal cattle management in 3 to 5 year old bitterbrush stands. Journal of Range Management. 52: 166–173.

Giunta, B. C.; Christensen, D. R.; Monsen, S. B. 1975. Interseeding shrubs in cheatgrass with a browse seeded-scalper. Journal of Range Management. 28: 398–402.

Hall, D. B.; Anderson, V. J.; Monsen, S. B. 1999. Competitive effects of bluebunch wheatgrass, crested wheatgrass, and cheatgrass on antelope bitterbrush seedling emergence and survival. Res. Pap. RMRS-RP-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 7 p.

Heidinga, L.; Wilson, S. D. 2002. The impact of an invading alien grass (*Agropyron cristatum*) on species turnover in native prairie. Diversity and Distributions. 8: 249–258.

Holechek, J. L. 1981. Crested wheatgrass. Rangelands. 3: 151–153.

Holechek, J. L. 1983. Considerations concerning grazing systems. Rangelands. 5: 208–211.

Hubbard, R. L. 1957. The effects of plant competition on the growth and survival of bitterbrush seedlings. Journal of Range Management. 10: 135–137.

Hull, A. C., Jr. 1948. Depth, season, and row spacing for planting grasses on southern Idaho range lands. Journal of the American Society of Agronomy. 40: 960–969.

Hull, A. C., Jr. 1974. Species for seeding arid rangeland in southern Idaho. Journal of Range Management. 27: 216–218.

Hull, A. C., Jr.; Holmgren, R. C. 1964. Seeding southern Idaho rangelands. Res. Pap. INT-10. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 31 p.

Hull, A. C., Jr.; Klomp, G. J. 1966. Longevity of crested wheatgrass in the sagebrush-grass type in southern Idaho. Journal of Range Management. 19: 5–11.

Hull, A. C., Jr.; Klomp, G. J. 1974. Yield of crested wheatgrass under four densities of big sagebrush in Southern Idaho. Tech. Bull. 1483. Washington, DC: U.S. Department of Agriculture, Agricultural Research Service. 38 p.

Hull, A. C., Jr.; Pearse, C. K. 1943. How to reseed southern Idaho rangelands. Res. Pap. INT-2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.

Hull, A. C., Jr.; Pehanec, J .F. 1947. Cheatgrass—a challenge to range research. Journal of Forestry. 45: 555–564.

Hull, A. C., Jr.; Stewart, G. 1948. Replacing cheatgrass by reseeding with perennial grass on southern Idaho ranges. American Society of Agronomy Journal. 40: 694–703.

Kimball, S.; Shiffman, P. M. 2003. Differing effects of cattle grazing on native and alien plants. Conservation Biology. 17: 1681–1693.

Krzic, M.; Broersma, K.; Thompson, D. J.; Bomke, A. A. 2000. Soil properties and species diversity of grazed crested wheatgrass and native ranges. Journal of Range Management. 53: 353–358.

Laycock, W. A.; Conrad, P. W. 1981. Responses of vegetation and cattle to various systems of grazing on seeded and native mountain rangelands in eastern Utah. Journal of Range Management. 34: 52–58.

Lesica, P.; Allendorf, F. W. 1999. Ecological genetics and the restoration of land communities: mix and match? Restoration Ecology. 7: 42–50.
Lodge, R. W. 1960. Effects of burning, cultivating, and mowing on the yield and consumption of crested wheatgrass. Journal of Range Management. 13: 318–321.
Lodge, R. W.; Smoliak, S.; Johnston, A. 1972. Managing crested wheatgrass pastures. Publ. 1473. Ottawa: Agriculture Canada. 20 p.
Looman, J.; Heinrichs, D. H. 1973. Stability of crested wheatgrass pastures under long-term pasture use. Canadian Journal of Plant Science. 53: 501–506.
Lorenz, Russell J.; Rogler, George A. 1962. A comparison of methods of renovating old stands of crested wheatgrass. Journal of Range Management. 15: 215–219.
Lym, R. G.; Kirby, D. R. 1991. Effect of glyphosate on introduced and native grasses. Weed Technology. 5: 421–425.
Lyon, D. J.; Baltensperger, D. D.; Rush, I. G. 1992. Viability, germination, and emergence of cattle-fed jointed goatgrass seed. Journal of Production Agriculture. 5: 282–285.
Marlette, G. M.; Anderson, J. E. 1986. Seed banks and propagule dispersal in crested wheatgrass stands. Journal of Applied Ecology. 23: 161–175.
Masters, R. A.; Sheley, R. L. 2001. Principles and practices for managing rangeland invasive plants. Journal of Range Management. 54: 502–517.
Meyer, Susan E. 1994. Germination and establishment ecology of big sagebrush: implications for community restoration. In: Monsen, Stephen B.; Kitchen, Stanley G., comps. Proceedings—ecology and management of annual rangelands symposium: proceedings; 1992 May 18–21; Boise, ID. Gen. Tech. Rep. INT-GTR-313. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 244–251.
Mohammad, Noor; Dwyer, Don D.; Busby, F. E. 1982. Responses of crested wheatgrass and Russian wildrye to water stress and defoliation. Journal of Range Management. 35: 227–230.
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. BLM/ID/PT-001001+1150. Boise, ID: U.S. Department of the Interior, Bureau of Land Management: 81-88.
Monsen, S. B.; Shaw, N. L. 1983. Seeding antelope bitterbrush with grass on south-central Idaho rangelands—a 39 year response. In: bitterbrush and cliffrose symposium: proceedings. Gen. Tech. Rep. INT-152. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 126–136.
Monsen, Stephen B.; Stevens, Richard; Shaw, Nancy L., comps. 2004a. Restoring Western ranges and wildlands. Gen. Tech. Rep. RMRS-GTR-136-vol-1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 1–294 plus index.
Monsen, Stephen B.; Stevens, Richard; Shaw, Nancy L., comps. 2004b. Restoring Western ranges and wildlands. Gen. Tech. Rep. RMRS-GTR-136-vol-3. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 669–884 plus index.
Nelson, J. R.; Wilson, A. M.; Goebel, C. J. 1970. Factors influencing broadcast seeding in bunchgrass range. Journal of Range Management. 23: 163–170.
Ocumpaugh, W. R.; Archer, S.; Stuth, J. W. 1996. Swithgrass recruitment from broadcast seed vs. seed fed to cattle. Journal of Range Management. 49: 368–371.
Olson, B. E.; Richards, J. H. 1988a. Tussock regrowth after grazing: intercalary meristem and axillary bud activity of tillers of *Agropyron desertorum*. Oikos. 51: 374–382.
Olson, B. E.; Richards, J. H. 1988b. Annual replacement of the tillers of *Agropyron desertorum* following grazing. Oecologia. 76: 1–6.
Owens, M. K.; Norton, B. E. 1990. Survival of juvenile basin big sagebrush under different grazing regimes. Journal of Range Management. 43: 132–135.
Pellant, M. 1990. The cheatgrass-wildfire cycle—are there any solutions? In: McArthur, E. D.; Romney, E. M.; Smith, S. D.; and Tueller, P. T., comps. Cheatgrass invasion, shrub die-off, and other aspects of shrub biology and management symposium: proceedings. Gen. Tech. Rep. INT-GTR-276. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 11–18.
Pendery, B. M.; Provenza, F. D. 1987. Interplanting crested wheatgrass with shrubs and alfalfa: effects of competition and preferential clipping. Journal of Range Management. 40: 514–520.
Pleasant, J. M. T.; Schlather, K. J. 1994. Incidence of weed seed in cow (*Bos* sp.) manure and its importance as a weed source for cropland. Weed Technology. 8: 304–310.
Plummer, A. P.; Hurd, R. M.; Pearse, C. K. 1943. How to reseed Utah rangelands. Res. Pap. INT-1. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.
Pyke, D. A. 1990. Comparative demography of co-occurring introduced and native tussock grasses: persistence and potential expansion. Oecologia. 82: 537–543.
Pyke, D. A. 1994. Rangeland seedings and plantings: exotics or natives. In: Edge, W. D.; Olson-Edge, S. L., eds. Proceedings—symposium on sustaining rangeland ecosystems. Special Rep 953. Corvallis, OR: Oregon State University: 32–44.
Pyke, D. A.; Archer, S. 1991. Plant-plant interactions affecting plant establishment and persistence on revegetated rangeland. Journal of Range Management. 44: 550–557.
Reynolds, T. 1980. Save some sage. Idaho Wildlife. 2: 10–13.
Richardson, B. Z.; Monsen, S. B.; Bowers, D. M. 1984. Interseeding selected shrubs and herbs on mine disturbances in southeastern Idaho. In: McArthur, E. D.; Welch, B. L., comps. Biology of *Artemisia* and *Chrysothamnus* symposium: 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.
Rittenhouse, L. R.; Sneva, F. A. 1976. Expressing the competitive relationship between Wyoming big sagebrush and crested wheatgrass. Journal of Range Management. 29: 326–327.
Robertson, J. H.; Neal, D. L.; McAdams, K. R.; Tueller, P. T. 1970. Changes in crested wheatgrass ranges under different grazing treatments. Journal of Range Management. 23: 27–34.
Robertson, J. H.; Pearse, C. K. 1943. How to reseed Nevada rangelands. Res. Pap. INT-3. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.
Rogler, G. A.; Lorenz, R. J. 1983. Crested wheatgrass—early history in the United States. Journal of Range Management. 36: 91–93.
Romo, J. T. 2005. Emergence and establishment of *Agropyron desertorum* (Fisch.) (crested wheatgrass) seedlings in a sandhills prairie of central Saskatchewan. Natural Areas Journal. 25: 26–35.
Romo, J. T.; Grilz, P. L.; Delanoy, L. 1994. Selective control of crested wheatgrass (*Agropyron cristatum* [L.] Gaertn. and *A. desertorum* Fisch.) in the Northern Great Plains. Natural Areas Journal. 14: 308–309.
Roundy, B. A.; Shaw, N. L.; Booth, D. T. 1997. Using native seeds on rangelands. In: Shaw, N. L.; Roundy, B. A., comps. Using seeds of native species on rangelands: proceedings. Gen. Tech. Rep. INT-GTR-372. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 1–8.
Salihi, D. O.; Norton, B. E. 1987. Survival of perennial grass seedlings under intensive grazing in semi-arid rangelands. Journal of Applied Ecology. 24: 145–151.
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: 226–230.
Schuman, G. E.; Rauzi, F.; Booth, D. T. 1982. Production and competition of crested wheatgrass-native grass mixtures. Agronomy Journal. 74: 23–26.
Sharp, L. A. 1986. Crested wheatgrass: its values, problems and myths. In: Johnson, K. L., ed. Crested wheatgrass: its values, problems, and myths symposium: proceedings. Logan: Utah State University: 3–6.
Shinderman, Matthew J.; Call, Christopher A. 2001. Establishment of forbs in cattle dungpats deposited in vegetation gaps

in a degraded sagebrush community. Ecological Restoration. 29: 99–106.

Simberloff, D. 2003. Confronting introduced species: a form of xenophobia? Biological Invasions. 5: 179–192.

Smallwood, K. S.; Beyea, J.; Morrison, M. L. 1999. Using the best scientific data for endangered species conservation. Environmental Management. 24: 421–435.

Sneva, Forrest A. 1970. Paraquat—effects of growing season applications. Journal of Range Management. 23: 451–452.

Springfield, H. W. 1963. Cattle gains and plant responses from spring grazing on crested wheatgrass in northern New Mexico. Production Res. Rep. 74. Washington, DC: U.S. Department of Agriculture, Forest Service. 46 p.

Stevens, R. 1994. Interseeding and transplanting to enhance species composition. In: Monsen, S. B.; Kitchen, S. G., comps. Ecology and management of annual rangelands: proceedings; 1992 May 18–21; Boise, ID. Gen. Tech. Rep. INT-GTR-313. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 300–306.

Stevens, R. 2004. Establishing plants by transplanting and interseeding. In: Monsen, Stephen B.; Stevens, Richard; Shaw, Nancy L., comps. Restoring Western ranges and wildlands. Gen. Tech. Rep. RMRS-GTR-136-vol-3. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 739–744.

Stevens, R.; Moden, W. L., Jr.; McKenzie, D. W. 1981. Interseeding and transplanting shrubs and forbs into grass communities. Rangelands. 3: 55–58.

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

Svejcar, T. 2003. Applying ecological principles to wildland weed management. Weed Science. 51: 266–270.

Tausch, R. J.; Chambers, J. C.; Blank, R. R.; Novak, R. S. 1995. Differential establishment of perennial grass and cheatgrass following fire on an ungrazed sagebrush-juniper site. In: Roundy, B. A.; McArthur, D. E.; Haley, J. S.; Mann, D. K., comps. Wildland shrub and arid land restoration symposium: proceedings. Gen. Tech. Rep. INT-GTR-315. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 252–257.

Trlica, M. J., Jr.; Cook, C. Wayne. 1972. Carbohydrate reserves of crested wheatgrass and Russian wildrye as influenced by development and defoliation. Journal of Range Management. 25: 430–435.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA NRCS). 2004. The PLANTS database, version 3.5. Baton Rouge, LA: National Plant Data Center. (Online: http://plants.usda.gov). [August 29, 2005].

U.S. Department of the Interior (USDI). 2001. National rangeland inventory, monitoring, and evaluation report—FY 2001. Denver, CO: U.S. Department of the Interior, Bureau of Land Management, National Science and Technology Center. 12 p.

U.S. Department of the Interior, Bureau of Land Management. 1981: Idaho Instruction Memorandum ID-81-312. Boise, ID: U.S. Department of the Interior, Bureau of Land Management, Idaho State Office.

U.S. Department of the Interior, Bureau of Land Management (USDI BLM). 2000. The Great Basin Restoration Initiative: healing the land. U.S. Department of the Interior, Bureau of Land Management. (Online: http://www.fire.blm.gov/library.htm). [August 29, 2005].

Vallentine, J. F. 1989. Range development and improvements. 3d ed. New York: Academic Press. 524 p.

Vallentine, J. F.; Cook, C. W.; Stoddart, L. A. 1963. Range seeding in Utah. Extension Circular 307. Logan, UT: Utah State University. 20 p.

Van Epps, G. A.; McKell, C. M. 1978. Major criteria and procedures for selecting and establishing range shrubs as rehabilitators of disturbed lands. In: Hyder, D. N., ed. Proceedings of the First International Rangeland Congress; 1978 August 14–18; Denver, CO. Denver, CO: Society for Range Management: 352–354.

Van Epps, G. A.; McKell, C. M. 1980. Revegetation of disturbed sites in the salt desert range of the Intermountain West. Land Rehabilitation Series 5. Logan, UT: Utah Agricultural Experiment Station.

Walters, C. J. 1986. Adaptive management of renewable resources. New York: McGraw-Hill.

Walters, C. J.; Holling, C. S. 1990. Large-scale management experiments and learning by doing. Ecology. 71: 2060–2068.

Wambolt, Carl L.; Harp, Aaron J.; Welch, Bruce L.; Shaw, Nancy; Connelly, John W.; Reese, Kerry P.; Braun, Clait E.; Klebenow, Donald A.; McArthur, E. Durant; Thompson, James G.; Torell, L. Allen; Tanaka, John A. 2002. Conservation of greater sage-grouse on public lands in the Western U.S.: implications of recovery and management policies. PACWPL Policy Pap. SG-02-02. Caldwell, ID: Policy Analysis Center for Western Public Lands. 41 p.

Welch, D. 1985. Studies in the grazing of heather moorland in Northeast Scotland. Journal of Applied Ecology. 22: 461–472.

West, N. E.; Hassan, M. A. 1985. Recovery of sagebrush-grass vegetation following wildfire. Journal of Range Management. 38: 131–134.

Whisenant, S. G. 1999. Repairing damaged wildlands: a process-oriented, landscape-scale approach. New York: Cambridge University Press. 312 p.

Wiedemann, H. 2005. Revegetation equipment catalog. Revegetation Equipment Development Council; U.S. Department of Agriculture, Forest Service; and U.S. Department of the Interior, Bureau of Land Management. (Online: http://reveg-catalog.tamu.edu). [August 29, 2005].

Wilson, S. D.; Partel, M. 2003. Extirpation or coexistence? Management of a persistent introduced grass in a prairie restoration. Restoration Ecology. 11: 410–416.

Young, J. A.; Evans, R. A. 1986. History of crested wheatgrass in the Intermountain area. In: Johnson, K. L., ed. Crested wheatgrass: its values, problems, and myths: proceedings. Logan, UT: Utah State University: 21–25.

Young, J. A.; McKenzie, D. 1982. Rangeland drill. Rangelands. 4: 108–113.

Rose pusseytoes