Downy Brome (Bromus tectorum) and Japanese Brome (Bromus japonicus) Biology, Ecology, and Management

Literature Review

K. George Beck
Professor of Weed Science
Department of Bioagricultural Sciences and Pest Management
Colorado State University

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INTRODUCTION

Downy brome (*Bromus tectorum* L.) is a member of the grass family, Poaceae (Cronquist et al. 1977; Whitson et al. 1996). It normally behaves as a winter annual that germinates following fall rains and overwinters in a vegetative state (USDA 1970). Downy brome, also known as cheatgrass, downy chess, bronco grass, Mormon oats, and Junegrass, was introduced into the United States from Europe in the mid-19th century (Fleming et al. 1942; Klemmedson and Smith 1964). The genus name, *Bromus*, was apparently derived from the ancient Greek words *bromos*, which means a kind of oat, and *broma*, which means food (USDA 1948). The specific epithet, *tectorum*, came from the Latin, *tector*, meaning one who overlays, and *tectum*, which mean roof (Harper 1879).

Japanese brome (*Bromus japonicus* Thunb.) also is a member of the Poaceae (Whitson et al. 1996). It typically behaves as a winter annual that germinates in fall, survives the winter as "rosettes" (Baskin an Baskin 1981) i.e., in a vegetative state similar to downy brome. *Bromus arvensis* is a recognized taxonomic synonym and its associated common name is field brome (USDA Plants Database).

Description

<u>Botanical characteristics for identification</u>

Downy brome usually grows from 4 to 30 inches tall (Whitson et al. 1996). Leaf blades and sheaths are light green and covered with find, soft hairs (Hitchcock 1950; Figures 1 and 2). Sheaths and closed and ligules are short (Figure 3). The inflorescence forms panicles that are dense, soft, drooping, with nodding


Figure 2


Figure 3

spikelets, and 2 to 6 inches long (Figures 4 and 5). Glumes are villous (covered with soft, unmated hairs) with the second longer than the first (Figure 6). Lemmas are toothed, lanceolate, and covered with long, soft hairs. Awns are 0-.38 to 0.63 inches long and the panicle may or may not be purplish. The entire plant will develop a purplish color after being subject to low temperatures or moisture stress.

Japanese brome usually grows 8 to 48 inches all (Great Plains Flora Association 1986; Harrington 1964; Hickman 1993; Johnson and Nichols 1970; Welsh et al. 1987; Whitson et al. 1996). Sheaths are hairy and leaves are glabrous or hairy (Figures 7 and 8). The inflorescence is an open panicle 4.5 to 8 inches long with three to five usually drooping branches (Figure 9). Spikelets at 0.25 inches wide and about 0.5 inches long while awns are 0.25 to 0.75 inches long (Figure 10).

ORIGIN, HISTORY, CURRENT DISTRIBUTION

<u>Origin</u>

Downy brome is native to much of Europe, the northern rim of Africa, and southwestern Asia (Kostivkovsky and Young 2000; Novak and Mack 2001). Outlier populations occur in Tibet, Kashmir, and southern Pakistan (Pierson and Mack 1990). Downy brome has been introduced into Australia, New Zealand, Japan, temperate South America (Upadhyaya et al. 1986), Britain (Stace 1997), and North America where it is not restricted

Figure 4

to grasslands but rather occurs on widely to varying degrees throughout the contiguous United States except in Florida and Alaska (Hitchcock and Chase 1971). It also has been introduced into Hawaii (Upadhyaya et al. 1986). USDA Plants Database, however, indicates that downy brome exists in all state of the U.S. including Florida and Alaska. Downy brome success in the Great Basin and similar western landscapes is related to its evolution on the *Artemisia* steppes of Central Asia (Young and Evans 1978; Young et al. 1972). Japanese brome is native to Europe and Asia

<u>How and When Arrived in United States</u>

Downy brome most likely was introduced into the United States accidentally as a contaminant of grains and packing material (Mack 1981). The first report of downy brome in North America occurred in about 1790 in Lancaster County, Pennsylvania (Muhlenberg 1793), but it cannot be verified. The first record of downy brome in a U.S. flora was by Wood (1863) and indicated that the species was synonymous with *Bromus sterilis* Torr. Torrey (1843) reported *B. sterilis* in New York but his description matches that of *B. tectorum*. *Bromus tectorum* was first reported in Gray's Manual of Botany in 1889 – it was the authoritative19th century resource for flora of the northeastern U.S. The first herbarium specimen was collected in 1859 in eastern Pennsylvania (Novak and Mack 2001). By 1898, downy brome had been collected repeatedly from Vermont to Washington, D.C. (Novak and Mack 1981). Downy brome was collected in 1875 on Guadalupe Island off the coast of Baja, CA (Mack 1981). The first report of downy brome in western North America was in 1889 at Spences Bridge, British Columbia. By 1900, downy brome has been collected in many western North American

Figure 5

locales, indicating that it had been introduced simultaneously at several widely separated sites including Ritzville, WA in 1893, Provo, UT in 1894, Pullman, WA in 1897, and Klamath Falls, OR in 1902 (Mack 1981). Mack further states that downy brome range expansion was extremely rapid from a few isolated pre-1900 locales to occupying its new range in the Intermountain in about 40 years by the 1930s. Such rapid expansion undoubtedly was facilitated by humans via discarded packing material (Dewey 1897), livestock bedding thrown out along railroad sidings, adulterated and contaminated grains, in transported livestock, and even from the occasional purposeful sowing (Mack 1981).

Genetic research by Novak and Mack (2001) showed the downy brome introduction into North America occurred independently multiples times but mostly from Europe and the western Mediterranean (Spain and Morocco). There is some evidence that downy brome was introduced to the eastern U.S. and then transported west with migration although, separate introductions into eastern and western North America also is possible. Novak and Mack (2001) found substantial evidence to show multiple introductions into western North America directly from Europe. At least seven independent introductions occurred and most of these source populations were from central Europe (Germany and the Czech Republic). Owing to its origins, downy brome was introduced into western North America already adapted to the local conditions followed by a time of excessive livestock grazing on land that had not evolved with such (Mack 1981). These two factors provided the means for the rapid expansion to its current range in the western U.S. Downy brome's success in the western U.S. has been due to phenotypic plasticity and not the result of genetic variation (Novak et al. 1991; Novak et al. 1993; Novak 1994). Annual environmental variation yields substantial variation in population characteristics such as recruitment, survivorship, and fecundity (Mack and Pyke 1983). For example, downy brome may


Figure 6

Figure 7

exist within a site as an ephemeral monocarpic, an annual monocarpic, and winter annual monocarpic species at the same time.

<u>Historic and current uses</u>

During the 19th century, downy brome was sown as a forage but only occasionally (Mack 1981). Its successful expansion in the western U.S. ultimately translated into downy brome providing much of the spring-utilized forage in the Pacific Northwest and the Intermountain regions by the late 1940s (Hull and Pechanec 1947). During this period in Idaho, for example, downy brome comprised up to 95% of the vegetation on about 3.9 million acres; was the principal vegetation on another 1.9 million acres; and provided 25% of the vegetation on an additional 9.9 to 14.8 million acres (Stewart and Hull 1949).

Downy brome is quite palatable to livestock and is readily used by cattle (*Bos taurus*), sheep (*Ovis aries*), and horses (*Equus caballus*) (Rice 2005). Mule deer (*Odocoileus hemionus*) display a strong preference for downy brome in fall and spring (Austin et al. 1994) while Goodrich (1999) indicated that bighorn sheep (*Ovis canadensis*) fed heavily on downy brome during the winter but claimed it cannot provide for their nutritional needs. Rice (2005) indicated that downy brome provides little forage for elk (*Cervus elaphus*). While many species utilize downy brome as a forage, downy brome production varies widely annually due to climate and primarily precipitation. It is not unusual for downy brome forage production to range tenfold over time and space; for example, Hull and Pechanec (1947) found downy brome forage yield to vary from 300 to 3,500 lb/A depending upon year and location. Thus, downy brome is not a reliable forage for livestock producers or wildlife managers but it can be taken advantage of in spring during high downy brome production years.

Figure 8

Japanese brome is highly palatable and livestock graze heavily on it in the fall

and early spring (Stubbendieck et al. 1985; Valentine 1961). Japanese brome also is an important component of whitetail deer (*Odocoileus virginianus*) diets and is readily grazed by bison (*Bison bison*) in fall (Howard 1994). Similar to downy brome, however, Japanese brome forage yield varies annually with precipitation and cannot be considered a reliable forage for livestock producers or wildlife managers (Stubbendieck et al. 1985; Valentine 1961).

Current North American distribution

Downy brome currently is found in all 50 U.S. states and all Canadian provinces except New Foundland and Labrador (USDA-Plants Database; Figure 11). The downy brome problem is most pronounced in the western U.S. where infestations were described as follows by Pellant and Hall in 1994: Downy brome occupies 1) 16.9 million acres of BLM-administered lands either as a monoculture or an understory component in Oregon, Washington, Nevada, Utah, and Idaho; 2) Another 62 million acres of public rangeland also classified as being lightly infested (less than 10% cover) or susceptible

to invasion. In 2003, Rice (2005) estimated that 56 million acres were infested with downy brome in 17 western states. Mack (1981), however, reported over 101 million acres of western rangeland were infested with downy brome. The downy brome problem has not decreased over the past 29 years but the discrepancy demonstrates the need for systematic mapping of invasive weed species in North America.

Japanese brome is an introduced species to the United States where it now can be found in every state except Hawaii and Alaska and in the Canadian provinces of British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, and Prince Edward Island (USDA-Plants Database; Figure 12).

BIOLOGY

Life History

Downy brome phenology

Downy brome is a self-pollinated winter annual species that reproduces solely from seed (Allen and Meyer 2002; Bartlett et al. 2002; Hulbert 1955; McKone 1985). Downy brome typically behaves as an annual or winter annual species (Mack and Pyke 1983). In the Intermountain West, downy brome usually germinates in the later summer into fall in response to precipitation. Recruitment, however, can occur anytime from fall through late spring within a few days of precipitation (Harris and Goebel 1976; Hulbert 1955; Klemmedson and Smith 1964; Mack 1984; Mack and Pyke 1983; Young et al. 1969). Resumption of hot, dry weather following fall emergence of downy brome can cause seedlings to desiccate and die (Harris 1967; Mack and Pyke 1984). Mack and Pyke (1984) found that about 0.7 inches of precipitation over a 2-week period in late August and Early September coincided with downy brome emergence. However, no additional precipitation until the third week of September caused many seedlings to die. They also found that death rate declined with later emerging seedlings and that few plants died over the winter regardless of emergence date.

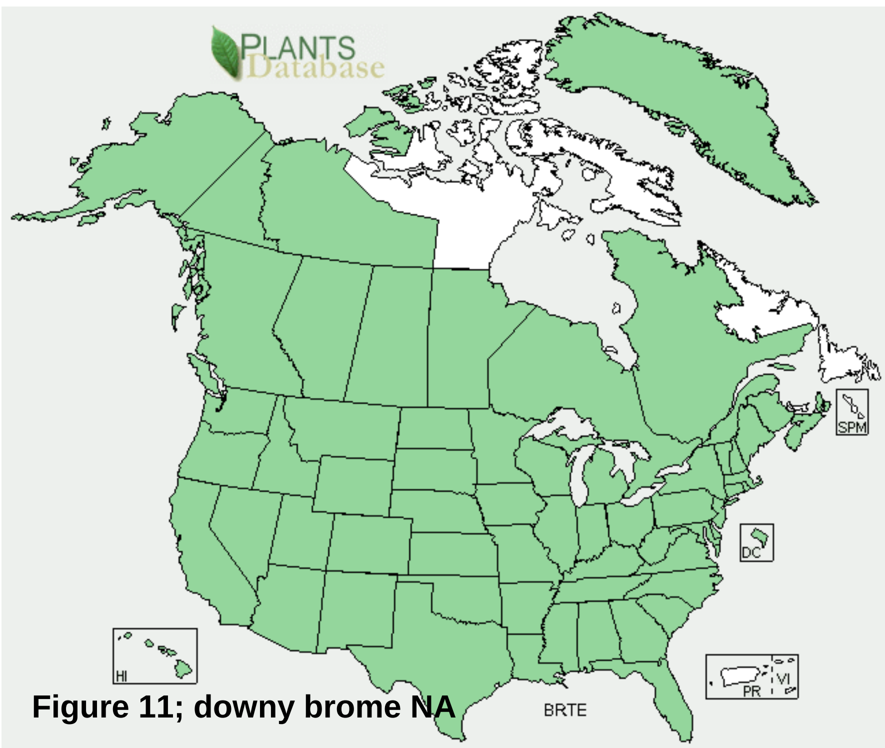

Figure 11; downy brome NA

Fall emerging downy brome plants overwinter in a semidormant state (Klemmedson and Smith 1964). Growth resumes in spring with the onset of warmer weather and growth usually is profuse and of short duration. Studies conducted near Lewiston and Boise, ID showed that phenological development varied among years and locations due to climate and site characteristics (Hulbert 1955; Klemmedson and Smith 1964). Downy brome typically formed panicles in late April to early May and anthesis occurred within 7 days. Downy brome reached the soft-dough seed development stage my mid- to late-May and plants turned purplish from early May to early June and then turned brown. Plants died shortly after seeds ripened. Phenological development in Colorado follows a similar pattern but is influenced by elevation. Recruitment varies with location and can be dramatic. In 2009 for example, recruitment first was observed in early August along the Front Range whereas, recruitment in northwest CO and in many other western CO locations had failed to occur even into late October (K.G. Beck, personal observation).

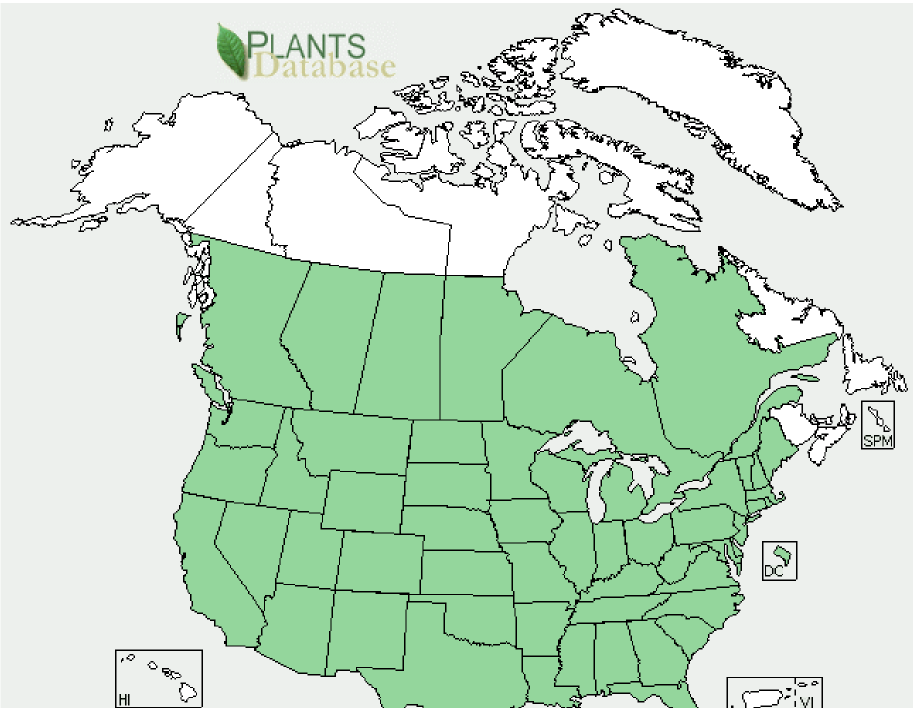

Figure 12; Japanese brome NA

<u>Japanese brome phenology</u>

Japanese brome usually germinates in the fall and overwinters in a vegetative growth stage (Anderson et al. 1990; Baskin and Baskin 1981; Finnerty and Klingman 1962; Whisenant 1990b). It resumes vigorous vegetative growth in spring and panicles begin to emerge in early May then seeds are ripe by late June or early July (Baskin and Baskin 1981). Plants die soon after seeds ripen but seeds remain on dead shoots until fall or winter when they are dispersed. Only occasionally are seedlings found in spring. Because seed is dispersed over the winter and most seedlings emerge in September or October, seedlings are derived from the previous year's seed crop (Baskin and Baskin 1981).

Downy brome germination and seedling emergence

Downy brome germination is influenced by light, temperature, and moisture conditions and their effects in turn are influenced by downy brome seed age. Freshly harvested seed is highly viable and displays high germination percentage at temperatures from 50 to 60 F (Hulbert 1955; Steinbauer and Grigsby 1957; Thill et al. 1980). Newly developed seed, however, germinates poorly at temperatures above 60 F, which is caused by a postharvest dormancy or after-ripening period. Temperatures (soil and air) often exceed 60 F in late June into July when seeds are first shed and the after-ripening period provides an ecological advantage to downy brome by avoiding precocious germination shortly after dispersal and subsequent seedling desiccation and death during hot, dry summer conditions. Laude (1956) observed delayed germination of downy brome over time. He found, under controlled greenhouse conditions, that downy brome germination steadily increased over a 5-month period from 0 to 81%. Hulbert (1955) observed an interaction between light and temperature of downy brome seed and this probably was the first indication of the after-ripening requirement. He reported that optimum germination temperature of 4-week-old seed was 60 F and the optimum temperature for 7-week-old and 1-year-old seed was 68 F, which approximated the after-ripening period. Hulbert also found that the influence of light on downy brome germination to be complex. Light influenced germination least at optimum temperatures and most at temperatures that were less suitable and these effects disappeared in 1-year-old seed.

After-ripening occurs under natural field conditions on the soil surface or in litter. Thill et al. (1980) found that freshly harvested downy brome seed did not germinate at 86 F. They stored dry seeds for 4 or 7 days at 122 F and discovered that germination was increased by 23 and 18% compared to seeds stored at 32 F. Similar results occurred with downy brome seed was stored 2 and 4 weeks at 68 to 104 F. They concluded that after-ripening can occur under field conditions in 1 to 2 weeks if soil surface temperatures are hot (e.g. 122 F or more) or in 2 to 4 weeks at more moderate soil surface temperatures (e.g. 68 to 104 F). Soil surface temperatures in Colorado in late June and July easily can reach these temperatures especially at lower elevations or on south facing slopes at higher elevations.

After-ripening can be accelerated by exposing seed to cold temperatures as well. Steinbauer and Grigsby (1957) found that chilling downy brome seeds to one week overcame the postharvest dormancy. Initial germination of freshly harvested seed was 93% at 60 F but only 34% at 68 F and only 2% at alternating day/night temperatures of 86 and 68 F. When they stored downy brome seed at 41 F for 1 week, germination exceeded 92% and was similar to downy brome stored for 8 weeks at room temperature (about 70 F).

After-ripening under field conditions likely will have occurred in any given year by late summer or early fall regardless of environmental conditions (Allen et al. 1995).

Once after-ripening has occurred, downy brome germinates over a wide range of temperatures and moisture potentials. For example, germination of 1-year-old seed stored at room temperature (after-ripening would have occurred over this time and storage conditions) was similar at constant temperatures of 50, 60, and 68 F or at alternating day/night temperatures of 50/32, 60/32, and 77/50 F (Thill et al. 1979).

Seedbed characteristics such as litter cover, microtopography, and soil texture directly influence the microenvironment (e.g. light, temperature, and moisture), which in turn influences downy brome germination (Evans and Young 1970; Evans and Young 1972; Young and Evans 1973). Evans and Young (1972) dispersed seed evenly on bare, smooth soil or in pits and found much greater emergence from pits than on smooth soil (6,470 v 67 seedlings/m^2) – even when seeds were buried (7,500 v 2,290 seedlings/m^2). Downy brome can successfully germinate and establish on bare soils, however, in the mesic areas of the northern mixed-grass prairies and Pacific bunchgrass biomes but in drier environments, downy brome requires conditions that are not as harsh as bare soil (Young et al. 1972) and must be covered by soil or litter (Evans and Young 1972; Evans and Young 1987). Additionally, downy brome seed mass can provide the necessary litter to support successful germination and establishment (Young et al. 1987).

Downy brome germination is high (95% or more) and quite rapid when soil moisture and temperature are favorable (Hull and Hansen 1974). Downy brome seeds also are relatively insensitive to moisture and temperature stress (Goodwin et al. 1996). Pyke and Novak (1994) indicated that downy brome germination is uninhibited down to soil matric potential of -15 bars (-1.5 MPa) but time to germination may increase as soil moisture potential decreases. Goodwin et al. (1996) supported this claim; downy brome began germinating in 1 or 2 days at 0 bars (0 MPa) but took 2 to 5 days at – 10 bars (-1 MPa). The internal water potential of downy brome seed can decrease to -16 bars (-1.6 MPa) between 10 and 60 hours after imbibitions starts (McDonough 1975). This allows the germinating seed to effectively extract water from the surrounding soil or litter matrix even when soils are quite dry.

Japanese brome germination and seedling emergence

Japanese brome seed is shed during winter and acquires an induced dormancy (Baskin and Baskin 1981). Japanese brome seed must undergo an after-ripening period over the following summer. Freshly harvested seed during the winter displayed over 90% germination under controlled conditions but when placed onto soil in the field for 4 months, germination decreased to about 21%. One hundred percent of seed that after-ripened during the summer germinated over a very wide range of alternating temperatures under a 14-hour daylength or in complete darkness. Thus, as long as soil moisture is adequate, Japanese brome seed with germinate once after-ripening has occurred.

Litter is very important to successful Japanese brome germination and establishment. High quantities of litter foster increased soil moisture and compensates for low precipitation. If litter and precipitation are low, germination and subsequent seedling establishment are decreased.

Downy brome seedling establishment

High amounts of litter favor downy brome seedling establishment although, seedlings are relatively tolerant of drought up to 10 days (Frazier 1994). Downy brome emergence and establishment occurs in late summer into fall but can occur anytime up until about mid-May. Seedling recruitment was concentrated in fall but almost continuous germination and establishment occurred in Washington from fall through mid-May (Mack and Pyke 1983). Most of these populations incurred low death risk but those that germinated in late summer were killed by drought or extended periods of snow cover. Most plants, however, survived to produce seed. Loss of seed production from fall recruits that were devastated from drought or extended snow cover was compensated by late-winter/spring germination. Even spring recruits as young as 45 days old produced at last one viable seed by June. Seed production by spring recruits, while not as much as fall cohorts, is enough to ensure continued site occupation by downy brome.

Downy brome seedling growth occurs over a fairly narrow range of soil temperatures starting when just above freezing and ceasing when soil temperatures exceed 60 F (Young 2000). Downy brome growth rate increases from a low (air) temperature limit between 37 and 45 F to an upper limit that occurs between 81 and 88 F while optimum growth occurs between 50 and 68 F (McCarlie et al. 2001). Downy brome can withstand extremely cold temperatures and survived -10 F in Minnesota with only minimal injury to leaves (Hulbert 1955).

Downy brome has finely divided, fibrous root system with an average of seven main roots per plant (Spence 1937). Reports of rooting depth vary widely and probably are more related to experimental methodology than environment (Hulbert 1955). Several researchers reported that downy brome is a shallow-rooted grass that penetrates soil to 13 inches or less (Klemmedson and Smith 1964; Piemeisel 1938; Spence 1937; Tisdale 1947). Other researchers reported rooting depths of over 39 inches in root box studies (Harris 1967) and over 59 inches deep under field conditions (Hironaka 1961; Hulbert 1955). Harris (1977) indicated that downy brome roots grow 7 to 8 inches deep before lateral roots develop and lateral roots then tend to grow more downward than horizontally. Lateral root growth was reported to be 8 to 12 inches (Hulbert 1955).

Downy brome root density and root biomass studies showed that most roots are found in the top 8 to 12 inches of soil (Cline et al. 1977). These researchers reported root biomass of about 15 oz/yd^2 (470 g/m^2) in the surface 4 inches of soil and 2.6, 1.6, and 0.97 oz/yd^2 (80, 50, and 30 g/m ^{2}) at depths of 4 to 8, 8 to 12, and 12 to 16 inches, respectively. Hulbert (1955) reported no difference in root biomass between early- and late-fall sown downy brome or from experimental populations with different downy brome densities [46 to 92 plants/yd^2 (50 to 100 plants/m^2) compared to 1,830 to 3,660 plants/yd^2 (2,000 to 4,000 plants/m^2). He also showed that nitrogen fertilizer (80 lb/A of nitrate fertilizer) increased downy brome biomass 240% in the top 4 inches of soil. Hulbert (1955) also reported that root biomass throughout the remainder of the soil profile was about twice that in nitrogen fertilized plots compared to non-fertilized plots.

Harris (1967) reported that downy brome roots grow rapidly following germination and grew throughout the winter. This rapid growth allowed downy brome root tips to be in more favorable soil growing temperatures than slower growing bluebunch wheatgrass (*Pseudoroegneria spicata*). He also found that downy brome roots continued to grow at soil temperatures of 37 F while rots of bluebunch wheatgrass stopped growth between 46 and 50 F.

In a pure stand of downy brome, moisture depletion throughout the soil profile was greatest in the top 12 to 16 inches and below 16 inches, soil moisture depletion did not vary with depth (Cline et al. 1977). Soil moisture depletion to the permanent wilting point (- 15 bars) occurred at approximately the same depth in sparse [46 to 92 plants/yd^2 (50 to 100 plants/m^2)] as in dense stands [1,830 to 3,660 plants/yd^2 (2,000 to 4,000 plants/m^2)] (Hulbert 1955). Ehlhardt (1983) studied early downy brome root growth using mannitol solutions to create a gradient of matric potentials ranging from 0 to -12 bars (0 to -1.2 MPa). At 0 bars, downy brome roots averaged 2 inches in length while at -9.6 bars root length averaged 0.5 inches. Little or no root growth occurred at -12 bars. Downy brome roots will continue to grow in very dry soils.

Downy brome roots have poorly developed endodermis and suberized casparian strips to insulate against hot, dry soil and drought (Harris 1977). High air temperatures cause leaf water potentials to drop and roots cannot absorb soil moisture fast enough to keep plants from desiccating. Downy brome ensures species survival over hot summer months by completing its life cycle before the onset of hot summer temperatures.

Downy brome plant density and soil fertility (Hulbert 1955) influences shoot growth but shoot growth remains similar regardless of slope exposure (Hinds 1975). Total shoot production did not vary between north and south aspects but seed production was greater on north aspects presumably because of greater available soil moisture. Hulbert (1955) evaluated the influence of downy brome density on its shoot biomass, tiller number, and seed production. Downy brome produced relatively constant biomass per unit area [13 to 19 oz/yd^2 (400 to 600 g/m^2)] at densities ranging from 46 to 1,830 plants/yd^2 (50 to 2,000 plants/m^2). Seed production averaged 34,767 seeds/yd^2 (38,000 seeds/m^2) across the range of densities. Tiller production per unit area was greatest at highest plant densities - 732 tillers/yd^2 (800 tillers/m^2) at low densities compared to 3,385 tillers/yd^2 (3,700 tillers/m^2) at the highest densities. The number of tillers per plant, however, increased markedly at downy brome density decreased; tillers per plant increased from 1.9 to 13.3 as downy brome density decreased from 1,802 to 55 plants/yd^2 (1,970 to 60 plants/m^2).

Japanese brome seedling establishment

Japanese brome seedling establishment and subsequent stand density is highly dependent upon litter (Whisenant and Uresk 1990). This is especially the case in years where fall precipitation is low but this relationship is almost insignificant in years with high fall precipitation. In most situations and years, Japanese brome seedling establishment is facilitated by large quantities of litter. Uresk (1984) observed that Japanese brome density outside Badlands National Park in South Dakota was far less than inside the park and attributed the difference to grazing by domestic livestock outside the park, which decreased litter production. During years of high precipitation, litter is of less importance to Japanese brome germination and seedling establishment.

Reproduction

Downy brome flowering

Downy brome has perfect flowers (Harper et al. 1992) and is primarily cleistogamous (Novak and Mack 1993), usually autogamous (Hulbert 1955; McKone 1985; Novak et al. 1991) but can be xenogamous (Thill et al. 1984; Young et al. 1987). Young and Evans (1975) and Young et al. (1987) suggest that downy brome's capacity to cross breed in response to changing environmental conditions allows it to maintain plant community dominance by selecting for those individuals or ecotypes that are highly competitive under those conditions. Young et al. (1972) suggested that lodicule rigidity, anther exsertion and pollen vitality, stigma exsertion and receptivity increase as environmental resources (available nutrients and water) per individual increase and improve the chance of cross breeding in that generation. This is especially evident following fire where resources and increased intraspecific competition are decreased. Cross breeding under these conditions yields individuals with increased genetic capacity to exploit varied microenvironments. More recent studies, however, have shown that downy brome is almost always a self-fertilizing species (McKone 1985; Allen and Meyer 2002; Bartlett et al. 2002). Allozyme analysis showed no occurrence of heterozygosity (Novak et al. 1993) and genetic studies on seed dormancy also showed that downy brome strictly self-fertilizes (Bartlett et al. 2002).

Downy brome vernalization

Downy brome displays specific daylength and temperature requirements (must be vernalized, i.e., exposed to cold temperatures over winter) to flower normally (Finnerty and Klingman 1962). Continuous exposure to long or short days inhibited flowering. Whereas, plants exposed to short days for 1 month followed by long days flowered normally. Vernalized plants exposed to 9- or 10-hour days failed to flower, however, exposure to 15-hour days allowed normal panicle development. Imbibed downy brome seeds can be vernalized over winter months (Finnerty and Klingman 1962; Mack and Pyke 1983). Thus, spring recruited downy brome seedlings are capable of flowering and producing seed. This attribute (i.e. vernalization as seed) ensures species survival and plant community dominance when fall recruits succumb to drought or extreme winter weather. Plants that germinate and establish in fall, however, usually produce the most seed (Mack and Pyke 1983).

Downy brome seed production

Downy brome produces copious quantities of seed, typically producing over 70 millions seeds/A (Hull and Pechanec 1947). Seed production per unit area is relatively constant but downy brome density influences seed production per plant (Hulbert 1955). Individual plants at high downy brome density (9,835 plants/yd^2 equivalent to 10,750 plants/m^2) produced about 25 seeds per plant whereas open grown plants averaged 400 seeds per plant and an isolated individual growing under optimum environmental conditions produced about 5,000 seeds per plant (Piemeisel 1938; Young et al. 1987). Downy brome produces so many seeds that subsequent plant densities are not a function of seed production but rather due to the number of safe sites for it to germinate and establish (Young et al. 1969). Even in years of unfavorable conditions, downy brome will produce enough seed to perpetuate its populations (Hulbert 1955; Tisdale and Hironaka 1981; Young 2000).

Downy brome soil seed longevity

Hulbert (1955) found that downy brome seeds stored under dry conditions in a laboratory were 95 to 100% viable after 11.5 years, which suggested the potential to create a seed bank under field conditions. However, Hulbert (1955) and Klemmedson and Smith (1964) concluded that because of the rapid and high percentage of seeds that germinate the fall following production, that seed longevity was very short. Several researchers, however, reported that downy brome seed can persist for more than one season (Bund et al. 1954; Chepil 1946; Wicks et al 1971; Young et al. 1969). Under field conditions, seeds that overwinter on the soil may acquire an induced dormancy (as opposed to endogenous dormancy), which allows populations to survive from one year to the next (Young et al. 1969). Rarely do downy brome seeds persist in soil more than 2 to 3 years (Bund et al. 1954; Hulbert 1955), however, Wicks et al. (1971) found that some seed survived burial for 5 years and soil texture had no influence on seed longevity.

Downy brome seed dispersal

Most downy brome seed falls near the parent plant but some seed may be dispersed short distances by wind or water (Zouhar 2003). Long distance dispersal of downy brome seeds is facilitated by humans, livestock and other domestic animals, and wild animals. Awns on seeds attach to clothing, fur, hooves, feathers (Hulbert 1955) or can be dispersed by vehicles and machinery (Young 2000). Rodents and harvester ants can move seeds short distances during caching (Daubenmire 1970; Mull and MacMahon 1996). Cropland, especially winter cereals and dryland hay, can be sources of downy brome seed for neighboring lands including natural areas and rangeland (Upadhyaha et al. 1996; Young 2000). Young (2000) indicates that downy brome seed can remain viable for many years in hay bales and subsequent feeding of infested bales could result in dispersal by livestock.

Downy brome rate of spread

The average annual rate of spread by downy brome is 14%. This is based upon information from Utah as to its first historic occurrence in that state to contemporary infestations levels (Rice 2005).

Japanese brome flowering

Apparently, Japanese brome does not have to be vernalized to flower (Baskin and Baskin 1981). Plants that were exposed to cold temperatures over the winter and plants that were held in a heated greenhouse all flowered normally although, as the number of hours of exposure to cold temperatures increased, the time to flowering decreased. Daylength is an important determinant for Japanese brome flowering. It requires long days to flower and exposure only to short days inhibited flowering (Baskin and Baskin 1981). A minimum of 12 hours of daylight are needed to induce flowering, however, Japanese brome must be exposed to short days before long days to flower as normally occurs over all and winter months.

Japanese brome seed production

Japanese brome produces huge quantities of seed. Whisenant (1990) measured seed production in excess of 86,000 seeds/yd^2 (94,000 seeds/m^2), which is equivalent to over 416,000,000 seeds/A. The most seed was produced from plants growing in the highest quantities of litter. As with downy brome, seed production by Japanese brome per plant is influenced by plant density with the greatest number of seeds being produced by plants at the lowest density. Plants growing sparsely tiller more than plants growing densely and thus, produce more seed.

Japanese brome soil seed longevity

Japanese brome apparently has not been assessed in a classic seed burial experiment. Actual soil seed longevity is unknown, however, Baskin and Baskin (1981) found that most seeds germinate the year following their production – owing to being shed in winter and acquiring a secondary dormancy that is broken the following summer during after-ripening – but found that a few seeds germinated 2 years after production. Its soil seed longevity, therefore, can be at least 2 years. Whisenant (1990) found that most Japanese brome seed was within the top 1.25 inches of mineral soil or in litter.

ECOLOGY

Downy brome habitat requirements/site characteristics

Downy brome often is described as occupying sites characterized by disturbance such as roadsides, cultivated lands, abandoned lands, fire, and overgrazed rangeland, but it can establish in a broad spectrum of habitats and soil conditions (Rice 2005). By 1947, downy brome was the prominent vegetation along an elevational gradient from the salt desert shrub through the sagebrush (*Artemisia* spp.) steppe up into the ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) zones (Hull and Pechanec 1947). In 1949 (Stewart and Hull 1949) and 1966 (Beatley 1966) downy brome was only a very minor member of the black greasewood-shadscale (*Sarcobatus vermiculatus-Atriplex confertifolia*) and salt desert shrub associations. Currently, downy brome is common in these plant communities (Brown 1971; Hunter 1991; West 1988; West and Ibrahim 1968; Young et al. 1987; Young 2000). Downy brome associations in these plant communities include budsage (*Artemisia spinescens*), bottlebrush squirreltail (*Elymus elymoides*), Sandberg bluegrass (*Poa secunda*), and Indian ricegrass (*Achnatherum hymenoides*) (Blackburn et al. 1969a; Blackburn et al. 1969b). Downy brome also associates with blackbrush (*Coleogyne ramosissima*) (Callison and Brotherson 1985; Harper et al. 2001), galleta (*Pleuraphis jamesii*)(West and Ibrahim 1968), and many others (Zouhar 2003).

Today, downy brome is most widespread in the sagebrush steppe plant communities of the Intermountain West (Young 2000), particularly in years of high precipitation (Banner 1992). In the sagebrush steppe and bunchgrass zones of the Intermountain West, downy brome can be found in and often dominates vast tracts in big sagebrush (*Artemisia tridentata*) and bluebunch wheatgrass (Blackburn et al. 1969; Brown 1971; Hansen and Hoffman 1988; Hironaka et al. 1983; Hopkins 1979a; Hopkins 1979b; Hopkins et al. 1983; McClean 1970; Mueggler and Stewart 1980; Thilenius et al 1995; Young et al. 1976), Thurber needlegrass (*Achnatherum thurberianum*) (Young et al. 1976), needle-and-thread (*Heterostipa comata*) (McClean 1970; Young et al. 1976), western wheatgrass (*Pascopyrum smithii*) (Blackburn et al. 1969; Hansen and Hoffman 1988; Thilenius et al. 1995), basin giant wildrye (*Elymus cinereus*) (Blackburn et al.

1969; Young et al. 1976), Idaho fescue (*Festuca idahoensis*), rough fescue (*F. altaica*), bottlebrush squirreltail, low sagebrush (*A. arbuscula*) (Hironaka et al. 1983; Hopkins 1979a; McClean 1970; Mueggler and Stewart 1970; Terwilliger and Tiedeman 1978; Tisdale 1994), spiny hopsage (*Grayia spinosa*), and rabbitbrush (*Chrysothamnus* spp.) (Blackburn et al. 1968) plant communities. Downy brome also dominates sites occupied by silver sagebrush (*A. cana*) and blue grama (*Bouteloua gracilis*) in Wyoming (Thilenius et al. 1995). In pinyon-juniper and mountain brush lands, downy brome associates with Rocky Mountain juniper (*Juniperus scopulorum*) (Hansen and Hoffman 1988; Terwiller and Tiedeman 1978) western juniper (*J. occidentalis*) (Driscoll 1964; Franklin and Dyrness 1973), singleleaf pinyon (*Pinus monophylla*) (Everett 1985; Lewis 1971), Colorado pinyon (*P. edulis*), Gambel oak (*Quercus gambelii*) (Hess and Wasser 1982; Muldavin et al. 1996), Emory oak (*Q. emoryi*) (Warren et al. 1992), antelope bitterbrush (*Purshia tridentata*) (Driscoll 1964; Franklin and Dyrness 1973; Mueggler and Stewart 1980; Young et al. 1976), curlleaf mountain mahogany (*Cercocarpus ledifolius*) (Franklin and Dyrness 1973; Lewis 1971; Young et al. 1976), skunkbush sumac (*Rhus trilobata*) (Mueggler and Stewart 1980; Thilenius et al. 1995), snowberry (*Symphoricarpos* spp.) (Young et al. 1976), serviceberry (*Amelanchier pallida*), and mountain big sagebrush (*A. tridentata* ssp. *vaseyana*) (Harper et al. 2001; Young et al. 1976) plant communities. Zouhar (2003) indicates that downy brome has invaded 18 ecosystems, 16 BLM physiographic regions, 59 Kuchler plant associations, 30 Society of American Forester cover types, and 104 Society for Range Management rangeland cover types.

<u>Downy brome and disturbance</u>

Downy brome invasions often are associated with disturbance (Evans and Young 1970; Ogle and Reiners 2002). Cultivation and subsequent abandonment, overgrazing, overstory removal, and repeated fires can act independently or interact and allow downy brome to invade and dominate plant communities and landscapes (Evans and Young 1985; Hull and Pechanec 1947; Miller et al. 1999). Invasion by downy brome may be enhanced by disturbance but it is not required for downy brome to establish and gain a foothold (Goodrich and Gale 1999). Downy brome also can thrive in areas without historic cultivation or grazing by domestic livestock (Goodrich and Gale 1999; Svejcar and Tausch 1991).

<u>Downy brome and climate</u>

Downy brome exists under a multitude of climatic conditions and can be found in low elevation salt-desert shrub communities that receive 6 inches of annual precipitation up into high elevation coniferous forests that receive 25 inches or more of annual precipitation (Daubenmire 1970). It tends to be most invasive in areas that receive 12 to 22 inches of precipitation yearly that peaks in late winter or early spring (Pyke and

Novak 1994). Downy brome is more invasive in Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis*) and pinyon-juniper belts than in cooler, more mesic areas occupied by mountain big sagebrush and low sagebrush at elevations above 5,280 ft (Goodrich et al. 1999; Tisdale 1994a; Tisdale 199b;Tisdale 1994c). Mountain big sagebrush communities are susceptible to downy brome invasion on warm exposures (south and southwest aspects). Downy brome is adapted to extreme drought and when growing under such conditions, it produces much smaller plants that still set seed to produce another generation and perpetuate its presence (Stewart and Hull 1949).

Downy brome and elevation

In eastern Idaho, downy brome is most abundant between 2,000 and 6,000 foot elevations but has been found up to 9,000 in that state (Stewart and Hull 1949). Downy brome has been found growing at or above 13,100 ft in the United States (Hunter 1991). Land managers at Rocky Mountain National Park in Colorado indicate that downy brome has been "moving upslope" for the past 10 to 15 years (J. Connor, Natural Resource Specialist RMNP, personal communication). Beatley (1966) stated that in 1966 downy brome occupied the sagebrush or pinyon-juniper zones at the Nevada Test Site at elevations of 5,000 to 7,500 ft while red brome (*Bromus madritensis* ssp. *rubens*) dominated lower elevation sites from 4,000 to 5,000 ft. Downy brome has since then expanded its range to lower elevation sites in Nevada.

Downy brome and soils

Downy brome will grow on almost any soil but is most dominant on deep, loamy or coarse textured soils (Doescher et al. 1986; Link et al. 1994; Young 2000). Downy brome is commonly found on deep, sandy soils associated with vast tracts of big sagebrush on flat uplands and valley bottoms in mountain and foothill areas (Beatley 1966). It also tolerates calcareous and saline soils but does not grow as well as on other soils (Blackburn et al. 1968; McClean 1970). Downy brome is competitive on low fertility soils and on eroded B and C horizon soils and on soils low in nitrogen (Dakheel et al. 1993; Klemmedson and Smith 1964; Young 2000). Downy brome thrives, however, under conditions where available nitrogen in soils is increased (Dakheel et al. 1993; Harris 1967; Harris and Goebel 1976; Lowe et al. 2002). Some researchers have suggested that increased available nitrogen and the relative abundance of nitrate nitrogen compared to ammonium nitrogen plays a key role for the continued dominance of western landscapes by downy brome (Stark and Hart 1999; Young et al. 1995).

Downy brome successional status

Downy brome is facultative relative to successional status and can behave both as an early seral species and late seral dominant species at many locations where perennial grasses and forbs dominate (Zouhar 2003). Downy brome is especially prevalent in the early stages of fire succession or after other disturbances that remove shrubs, trees, and perennial grasses (Evans 1988; Evans and Young 1985; Hull and Pechanec 1947; Miller et al. 1999; Sowder 1960). Downy brome can outcompete many other non-native common or invasive weeds such as Halogeton (*Halogeton glomeratus*), tumblemustard (*Sisymbrium altissimum*), and Russian thistle (Salsola kali) (DeFlon 1986; Piemeisel 1951). At some locations, downy brome can be replaced by other, perhaps more invasive species such as bur buttercup (*Ranunculus testiculatus*), St. Johnswort (*Hypericum perforatum*), Dalmatian toadflax (*Linaria dalmatica*), yellow starthistle (*Centaurea solstitialis*), spotted knapweed (*C. stoebe* ssp. *micranthos*), diffuse knapweed (*C. diffusa*), squarrose knapweed (*C. virgata* ssp. *squarrosa*), rush skeletonweed (*Chondrilla juncea*), and leafy spurge (*Euphorbia esula*) (Harris 1990; Roche 1999). In addition, downy brome may be replaced by other invasive weedy grasses such at interrupted windgrass (*Apera interrupta*), corn brome (*Bromus squarrous*), little lovegrass (*Eragrostis minor*), poverty grass (*Sporobolus vaginiflorus*), ventenata (*Ventenata dubius*) that also can occupy downy brome infested landscapes (Northam and Callihan 1994).

Japanese brome habitat requirements/site characteristics

Japanese brome invades disturbed sites (Osborn and Allan 1949; Reed 1952; Ratliff and Denton 1991) and undisturbed sites (Karl et al. 1999; Whisenant 1990). Japanese will grow on many soil types including sand (Brand 1980), silt (Carlson et al. 1990), clay (Blank et al. 1992), and on claypan (Haferkamp et al. 1993). Japanese brome grows best in fine textured soils with high amounts of litter (Whisenant 1989). Although, litter is less important in years with above average precipitation. Japanese brome does not tolerate alkaline soils (Unger 1978). Japanese brome generally is found on mesic sites (Gartner et al. 1978; O'Conner et al. 1991). In the western United States, Japanese brome is found in prairie, pinyon-juniper, sagebrush steppe, and desert shrub-grassland plant communities (Howard 1994). Howard (1994) also indicates that Japanese brome can be found in 22 ecosystems, 16 BLM physiographic regions (including the Wyoming Basin, the Southern Rocky Mountains, the Colorado Plateau, the Great Plains, and Rocky Mountain Piedmont), 23 Society of American Foresters cover types, and 68 Society for Range Management cover types.

Impacts

Fire

It has been long known that downy brome is highly adapted to a regime of frequent fires (Leopold 1941; Pickford 1932). Downy brome has very fine leaves and shoots, accumulates fine litter, dries completely in early summer, and provides a highly flammable, fine and often continuous fuel (Billings 1952; Stewart and Hull 1949; Young 1989). Downy brome changed the historic fire frequency in the Great Basin from once every 70 to 100 years to once every 3 to 5 years (Knapp 1966; Whisenant 1990). The decrease in interval between wildfires causes increased risk to human life and property, and also places desirable plant and animal communities at risk (Beck et al. 2008).

Downy brome and wildlife

After wildfires, downy brome can dominate the plant community because it is fire adapted and recovers from the soil seed bank and from seed transported in after fires (Hulbert 1955; Young et al. 1969; Young et al. 1972). Increased fire frequency caused by downy brome has an indirect effect on animal communities by destroying the structure of native plant communities, especially sagebrush habitats (Rice 2005). Sagebrush does not resprout after fire and such communities are often inextricably altered after fire. Shrubs become more widely dispersed after fire with a decreased chance to fill in spaces and concomitant reduction in cover for hiding, nesting, and foraging by brush-dependent species such as sage grouse (*Centrocercus urophasianus*), Brewer's (*Spizella brewerii*) and sage sparrows (*Amphispiza belli*), and sage thrashers (*Oreoscoptes montanus*) (Knick 1999; Knick and Rotenberry 1997; Miller and Edleman 2001). About three times as many small mammals were found in a shrub-dominated unburned area of antelope bitterbrush as in a downy brome dominated burned area (Gano and Rickard 1982). The mammals included pocket mice (*Pergnathus* spp.), deer mice (*P. maniculatus*), grasshopper mice (*Onychomys leucogaster*), harvest mice (*Reithcodontomys megalotis*), and one species of ground squirrel (*Spermophilus* sp.).

In another study on impacts to animals caused by downy brome, native birds from the Pacific Northwest rangeland were given a choice between downy brome and medusahead (*Taeniatherum caput-medusae*) and two native perennial grass species (Goebel and Berry 1976). The birds showed a strong preference for the native grass seed and researchers concluded that by preferentially feeding on native species and avoiding exotic grasses, the birds could be indirectly contributing to the continued degradation of native rangelands.

Downy brome and natural plant communities

After downy brome is established, it readily competes with seedlings of native perennial range grasses such as bluebunch wheatgrass (Harris 1967) and annual forbs (Young and Evans 1973). Harris (1967; 1977) and Harris and Wilson (1970) evaluated competition between downy brome and bluebunch wheatgrass and between downy brome and crested wheatgrass (*Agropyron cristatum*). Downy brome stands from 0 to 5%, 45 to 50%, and 95 to 100% cover were labeled as sparse, moderate, and dense, respectively. Bluebunch wheatgrass survival 1 year after sowing in sparse, moderate, or dense downy brome stands was 86, 69, and 39%, respectively. Bluebunch wheatgrass dry weight 9 months after seeding was 5.8 times greater in sparse than in dense downy brome stands. In sparse downy brome, roots for bluebunch wheatgrass penetrated the soil to 37 inches whereas their roots only grew to 20 to 24 inch depths in dense downy brome, while downy brome roots grew to an average depth of 41 inches. The rapid and continuous growth of downy brome roots over the winter placed root tips in warmer soil allowing for continued growth and earlier resumption of rapid spring growth over bluebunch wheatgrass. Continuous downy brome root growth depleted soil moisture and nutrients for slower growing bluebunch wheatgrass roots. Crested wheatgrass roots penetrated the soil almost as rapidly as downy brome roots suggesting that crested wheatgrass would be a better competitor with downy brome than bluebunch wheatgrass. In a more recent study, however, Melgoza and Nowak (1991) found that roots of rabbitbrush (*Chrysothamnus viscidiflorus*) and needle-and-thread grew similarly compared to downy brome for 2 years after a fire.

Downy brome and soil C:N

Early seral species, or weeds – especially annual weeds – often dominate previously disturbed landscapes. Increased nitrogen availability due to disturbance in semiarid climates has been shown to delay succession by allowing annuals to establish and maintain dominance of the recovering plant community. McClendon and Redente (1991) conducted an experiment in the Piceance Basin in western Colorado where they disturbed the soil by scraping off the top 2 inches and mixing the next 14 inches by cultivating, which decreased the soil seed reserve by an estimated 90%. They provided annual additions of nitrogen and phosphorous for a period of 5 years and compared the resulting plant communities to similarly disturbed plots where no amendments were made. Annual weeds dominated the nitrogen treated and control (no amendments) plots for 3 years but in control plots during the fourth year, perennial grasses and perennial and biennial forbs increased while annual weeds decreased. This effect was more pronounced during the fifth year. However, annual weeds such as Russian thistle (*Salsola iberica*), downy brome, and kochia (*Kochia scoparia*) continued to dominate the nitrogen treated plots 5 years after the experiment began.

Because of the influence that high amounts of available nitrogen has on succession by favoring weedy annual species, decreasing available soil nitrogen has been evaluated as a means to stimulate old-fields to a late seral state. Paschke et al. (2000) examined increasing soil carbon through amendments as a mechanism to decrease available soil nitrogen (alter the C:N). Experiments were conducted on the shortgrass steppe of eastern Colorado in early-, mid-, and late-seral plant communities that previously had been cultivated and on one uncultivated site that served as a control. Secondary succession takes about 50 years to occur in this region of Colorado (Coffin et al. 1996; Reichardt 1982). This process is usually characterized by transition from plant communities dominated by annual forbs and annual grasses to herbaceous perennials (Lauenroth and Milchunas 1992). High soil nitrogen conditions were created with annual fertilizer amendments while low nitrogen was created with sucrose additions at 3,374 lb/A/yr (1,425 lb C/A/yr) to immobilize soil nitrogen. The sucrose applications were divided into three equal soil applications each year. Decreasing the available soil nitrogen with carbon additions decreased the relative biomass of downy brome and other weedy annuals and increased the relative biomass of perennial species (grasses, forbs, shrubs, and succulents). Decreasing available soil nitrogen stimulated the rate of succession in early-, mid-, and late-seral plant communities and minimized changes in the uncultivated site. Conversely, increased available soil nitrogen shifted species compositions in the direction of early-seral conditions. The authors concluded that carbon additions may be a useful aid in the rehabilitation of degraded rangeland to late-seral conditions but warned that the cost of using sucrose to do so was prohibitive.

Downy brome and soil symbionts

Arbuscular mycorrhizal fungi (AMF) are common in terrestrial ecosystems and form obligatory symbioses with most higher plants (Mosse et al. 1981; Read et al. 1976). AMF play a vital role n the mineral nutrition of host plants (Trappe 1981) and increase the amounts of accumulated macro- and micronutrients (Killham 1985; Read et al. 1985; Smith et al. 1986). Additionally, AMF colonization of herbaceous species improved drought tolerance (Allen and Allen 1984; 1986). AMF act to extend the root system of the host plant, which is beneficial to the latter due to the increased efficiency by which the soil volume is exploited (Koucheki and Read 1976; Schubert and Hayman 1986). In exchange, the fungal symbiont(s) receives carbon from the host plant (Paul et al. 1985; Snellgrove et al. 1982). Seedling recruitment and species diversity decline in the absence of AMF, especially during secondary succession (Gange et al. 1990; Grime et al. 1987). AMF fungal benefits to host plants potentially are great in nutrient poor or deficient soils or in extreme environments where the symbiosis acts to overcome plant stress (Allen and Allen 1984; Bethlenfalvay et al. 1984; Miller 1979; Molina et al. 1978). In stressful environments, higher plants that are mycorrhizal are likely to experience a competitive advantage over those that are non-mycorrhizal (Doerr et al. 1984; Filler 1985). While AMF can be beneficial to higher plants that are mycorrhizal, AMF can be parasitic to non-mycorrhizal plants (Schmidt and Reeves 1984). Secondary succession in sagebrush ecosystems includes early-seral species that are nonmycorrhizal (Goodwin 1992). When composition of the plant community is primarily non-mycorrhizal, AMF fungi decline (Reeves et al. 1979) and AMF populations remain low until mycorrhizal plants re-establish (Biondini et al. 1985; Miller 1987).

Downy brome is a facultative mycorrhizal species and when it grows in a mycorrhizal plant community, AMF colonize its roots but when growing in a non-mycorrhizal community, downy brome too is non-mycorrhizal (Pendleton and Smith 1983; Trappe 1981). Downy brome may not benefit from an AMF associate during revegetation/restoration efforts, but it is clear that when native plants, especially late-seral species, are included in the seed mix, that AMF inoculation of soil from neighboring uninvaded sites is beneficial to native mycorrhizal plants (Rowe et al. 2007).

MANAGEMENT

Weed management strategies

There are three general weed management strategies. *Prevention* includes steps taken by land managers to avoid acquiring a weed problem. These may include keeping vehicles, implements, and other equipment free of weed seeds to prevent seeds from being re-distributed around the mined site that is being reclaimed. Sow only certified, high quality, weed-seed free desirable plant seeds and also use only certified weed-seed-free mulch when including such is part of the reclamation process. A powerful prevention technique is vigilance to detect small infestations and controlling them so they do not become large acreage problems. *Eradication* is the second weed management strategy and equates to the total removal of a weed from a defined geographic area (large or small) not be to seen at that location again unless it is re-introduced. It is a lofty goal and often not achievable with widespread weeds like downy and Japanese bromes. *Control* is the third weed management strategy and is the decrease of weed populations from an area such that land management goals and objectives can be met. *Prevention* and *control* are the most often practiced weed management strategies.

Control methods

There are four general categories of weed control methods and these are combined, or integrated, into a successional weed management approach to place the greatest stress on the weed population and the least stress to the desirable plant community. Control methods used are dependent upon the status of the undesirable plant community and the onset of site recovery/reclamation. The four control methods are *chemical, mechanical/physical, biological*, and *cultural*. Chemical control involves the use of herbicides or growth regulators to directly suppress, kill, or inhibit weeds. Mechanical control includes physical methods to disrupt weed growth such as Handpulling or hand operated equipments such as hoes or shovels, tillage, mowing, burning, flooding, or any other physical method that successfully kills or suppresses weeds. Biological weed control involves using organisms to suppress and decrease weed populations and typically evolved natural enemies are used. Properly managed livestock (i.e., for weed suppression not for production of livestock) also can be used for biological weed control. Biological weed control is most appropriate for large populations of weeds, especially in remote areas or difficult terrain. Cultural weed control is steps taken to introduce and/or enhance competition from desirable plants to keep weeds from reinvading. These control methods are most often combined to create a successional weed management approach.

Successional weed management

Ecologically-based weed management, sometimes referred to as successional weed management, is an approach where land managers determine the composition of the existing plant community and decide upon a species composition that will allow achievement of land management goals and objectives and what changes then are necessary to arrive at the desired plant community (Sheley et al. 1996). Successional weed management is a process to develop weed management programs based upon our current understanding of succession. This approach recognizes that plant communities are constantly changing and uses technology to enhance natural vegetation processes and mechanisms that regulate vegetation change. It directs weed infested plant communities on a trajectory to attain a desirable plant community to achieve land management goals and objectives. Successional weed management exploits the three primary drivers of succession; site availability, differential species availability, and differential species performance. The corresponding management components are *designed disturbance* (correlating with site availability), *controlled colonization* (correlating with differential species availability), and *controlled species performance* (correlating with differential species performance). Management input over time (Table 1) and monitoring results allows for an adaptive management approach (using the successional weed management framework) to keep the undesired plant community moving forward to ultimately achieve the desired plant community to meet land management goals and objectives. The desired plant community will replace the weed infested plant community and be resistant to re-invasion by the same weed or suite of weeds and resistant to replacement by other more aggressive weed species. Successional weed management is a very comprehensive approach and typically involves:

a. Suppression or control (*designed disturbance*) of the weed or suite of weeds that currently occupies the plant community;
b. Ameliorating any soil conditions (*controlled species performance*) that would prohibit successful establishment of a desired plant community;
c. Seeding and/or transplanting propagules or whole plants (*controlled colonization*) of the desired plant community;
d. Continued weed suppression/control and soil amendments where and when necessary.

Table 1. Successional weed management treatments for mine sites.

Designed Disturbance	Controlled Colonization	Controlled Species Performance
Tillage	Seed bed preparation	Irrigation
Herbicide; Plateau Matrix Roundup Journey Landmark XP Oust	Seeding Drill Broadcast Hydroseed Transplanting Herbicide	Soil amendments Micronutrients Macronutrients Herbicide
	Mulching	Mulching
		AMF inoculation Transplant native plants

A comprehensive weed management plan

Weed management, especially successional weed management, is complex and it is essential to become organized to achieve a desirable outcome. Reclamation of the mined site is the goal and a successional weed management plan will help to achieve the reclamation goal. A successional weed management approach, however, is a component of a comprehensive weed management plan and this plan becomes a component of the reclamation process. There are several key elements to a comprehensive weed management plan including mapping, developing a successional weed management approach, being systematic about implementing the plan, monitoring and evaluating results, and detailed record keeping.

Mapping

Map the mine site first to become organized. Downy brome or Japanese brome growing anywhere on the site is a source of seed to spread elsewhere within or off the site. Stored soils should be mapped and continuously monitored to determine the presence and location of downy brome or Japanese brome. The same should be done for other noxious weeds on the mine site. Areas being reclaimed also should be mapped not only to show the location of downy brome, Japanese brome, or other noxious and common weeds, the map should identify desirable species that were planted and any variation in how stored soils are replaced at the beginning of reclamation. Size, location, and type of weed infestation are important to include on a map. Size is important to know where eradication may be possible and type refers to essentially to the stage of development of a weed infestation and characterization of type generates an idea as to the level of success that could be achieved. Location refers primarily to proximity of an individual patch to the core infestation – is it part of the core or is it on the perimeter? The latter often are overlooked and serve as sources of propagules to prolong the weed infestation. For example, small infestations (e.g. 500

to 1000 ft^2 or less) that can be easily controlled or eradicated with one or two attempts; a moderate infestation is larger (but once the weed populations are controlled (their populations are sufficiently decreased), seeding desirable species should keep reinvasion from occurring; a large infestation can be controlled but multiple control treatments will have to be used and seeding will keep reinvasion in check but would have to be accompanied by aggressive control treatments. Each of these examples has an accompanied probability for success that can be envisioned and will help guide where to begin weed management efforts and how to progress across the mapped area. This map becomes a reference for evaluating success of the weed management and reclamation process as the project is developing and especially at its termination. Roads and other vectors for weed spread, buildings, presence of and proximity to water, reference areas, other undisturbed areas and associated vegetation also should be identified on the map. Generally, a map should be sufficiently detailed so it can serve as an appropriate reference to evaluate progress at any moment during reclamation – more information usually is best!

<u>Develop a successional weed management approach</u>

Using the map as a reference, develop a successional weed management approach that dovetails into the reclamation plan for the mined site. Tool choices for decreasing (controlling) downy brome or Japanese brome infestations are somewhat limited at this time and reliance upon developing a desirable plant community is of paramount importance to preventing reinvasion and successfully reclaiming the mined site.

<u>Implement the approach systematically</u>

The map again serves as a reference to help guide where to begin the weed management effort. Vectors such as roads, creeks, wildlife corridors, and such were identified as well as small, moderate, or large weed infestations. Vectors must be monitored regularly and downy brome and Japanese brome controlled as needed to avoid spread around the mine site or off the site. Start controlling the small infestations first along vectors and perimeters and then move to small infestations elsewhere on the site. Small infestations are easiest to control and often excellent control ensues because of limited patch size and a small soil seed reserve. Controlling small patches along vectors or near perimeters prevents them from moving rapidly within or off the site. Controlling small infestations prevents them from becoming large infestations – the latter is inevitable with noxious weeds and especially so with downy brome and Japanese brome. After small infestations are controlled move to the moderate infestations and then to the large core infestation. Knowing where to exert control efforts in a logical and systematic way will help foster success.

Monitor and evaluate progress keeping detailed records

It is imperative to regularly monitor the progress being made – whether weeds remain controlled or not, whether new weeds arrive, whether seeded/transplanted species are establishing, and similar responses – to determine whether to adhere to or alter the current plan. A good, detailed record of events that includes all actions and evaluations also is imperative so successful components of the plan can be repeated and unsuccessful ones can be altered.

SPECIFIC RECOMMENDATIONS FOR DOWNY BROME AND JAPANESE BROME

The key to effectively managing downy brome or Japanese brome is to prevent seed formation. Both are annual species that reproduce only from seed and have short soil seed longevities – about 5 years for downy brome and possibly less for Japanese brome. Effective management of either species will target depleting the soil seed reserve to zero such that their presence is no longer at a particular site; i.e., eradication on a localized scale is possible given either plant's biology – it is not unrealistic to set such a goal but the practicality is very questionable. Vigilance would be absolutely necessary if such success occurs to prevent re-invasion should it be re-introduced to the cleared location. Eradication, however, should not be the goal on a large scale because of the current breadth of downy brome in the western U.S. or Japanese brome. In most situations and locations, eliminating the soil seed reserve may not be possible or practical because of neighboring infestations that are a constant source of propagules. The best defense to avoid re-invasion would be to establish a robust desirable plant community that outcompetes downy brome and Japanese brome and keeps their populations from surging and dominating.

Control tools and methods

Mechanical/physical

Tillage will control downy brome or Japanese brome because both are annual species with simple root systems. Tillage should be used to create a designed disturbance as part of a successional weed management approach. Seeding/transplanting with desirable species should follow to create a plant community that optimizes land use goals will keep the site from being reinvaded. Downy brome will not emerge from deep in the soil and most likely Japanese brome is similar. A moldboard plow will kill emerged downy brome or Japanese brome by burying them about 6 inches deep and downy brome seeds will not successfully emerge from that depth. This was readily obvious with the onset of no-tillage cropping systems where downy brome was a problem (i.e., winter wheat-fallow production systems). Downy brome thrived under no-tillage conditions because its seeds are adapted to germinate and emerge on the soil surface protected only by plant litter, but when conventional tillage was re-introduced into a particular field, most downy brome (well over 90%) was controlled and the problem was drastically reduced until rotating back to a no-tillage system. Use of a moldboard plow to bury annual brome weed seeds such that emergence success is decreased may not be practical at mine sites, but tillage to create a suitable seedbed should be strongly considered (as opposed to no-tillage methods) because tillage will control downy brome and Japanese brome. No-tillage methods would be appropriate to use if the annual brome soil seed bank is known to be exhausted. Hand-operated methods such as handpulling, hoeing, or digging will control annual bromes but lack practical application on most mined sites because of scale.

Fire to control downy brome and Japanese brome

Controlled burning will control downy brome or Japanese brome by eliminating litter that acts as mulch and protects seedlings from desiccation (Evans 1988; Evans and Young 1987a; Rasmussen 1994; Stewart and Hull 1949). However, the risk of controlled fires escaping and becoming wildfires is excessive and burning is not a method that should be used to control either weed species on mined sites. Nonetheless, fire can be a good method to manage downy brome and Japanese brome in the appropriate situations. While fire is effective at killing most annual brome plants and seeds, their presence generally is decreased for only one season leaving a small window of opportunity to reclaim the controlled area (Evans and Young 1978; Young and Evans 1978; Young 2000). If reclamation is not practiced, burned sites previously infested with downy brome often recover to pre-fire population levels within 3 years. Without management input (reclamation), downy brome populations at sites that were dominated by it before fire usually recover sufficiently during the 2nd or 3rd years after fire to preclude perennial grass establishment (Peters and Bunting 1994; Young and Evans 1978; Young 1994). Late spring or early summer burns usually are most effective (Mueggler 1976; Rasmussen 1994). Whenever fire is used in a successional weed management context, it should be used as a designed disturbance, followed by seeding to control colonization of the recovering site and create conditions that repel re-invasion by downy brome.

Whisenant (1990b) evaluated fire to control Japanese brome. He found that mature plant cover was decreased 62 to 99%1 year after the burn. Seed production was decreased 45 to 99% for 3 years following the burn with the greatest effect occurring the year following fire. The effect of fire was attributed to eliminating or reducing litter that provides protection for Japanese brome seedlings. Similar to downy brome, reclamation following fire is necessary to prevent re-invasion by Japanese brome.

Using fire as a designed disturbance combined with a herbicide used to control colonization of annual bromes can not only enhance control of the weed, it can improve establishment of seeded species. Haferkamp et al. (1987) used a controlled burn in summer to kill downy brome seeds, followed by a fall-applied herbicide to control the next generation of downy brome from the soil seed reserve, which aided the establishment of a suite of seeded species.

Cultural

Cultural control for the annual bromes will be primarily comprised of seeding competitive species on stored soils to deter the weeds and seeding or transplanting desirable species during final reclamation of the site. Irrigation or fertilizer amendments – that latter need(s) determined by representative soil analysis – might be used, and the irrigation in particular can significantly aid establishment in semiarid locations such as Colorado. Plant species for planting should be carefully selected and matched to the site being reclaimed. USDA-Natural Resource Conservation Service is an outstanding source of information for what plant species are most suitable for reclamation or restoration throughout Colorado. A neighboring undisturbed reference area that is representative of the region's natural history also could be an excellent source of information of appropriate species to use for reclamation.

Biological

There currently are no classical biocontrol agents available for either downy brome or Japanese brome. Some attempts were pursued to develop use of a bacterium that grew along the roots of wheat and downy brome but the organism was only toxic to the weed. However, it was never developed because the bacteria could not be successfully mass-produced. Livestock can be used to manage downy brome but a recommended system of management to successfully decrease its populations has not been developed.

Chemical

There are several herbicides registered to use in non-crop areas, natural areas, and rangeland that will control downy brome and Japanese brome. Herbicides should be used in a successional weed management approach as a designed disturbance when reclamation is being executed or to control colonization of brome species during mining operations to keep the site as free of downy brome or Japanese brome as is possible. Herbicides can also be used to control colonization of the target weed or to control species performance; this use primarily would be after seeding/transplanting desirable species to keep downy brome and Japanese brome from producing seed or to negatively influence its performance by killing the targets or suppressing their growth such that desirable plant growth is favored. Annual bromes should be aggressively managed on stored soils. Using herbicides on stored soils to control downy brome or Japanese brome populations such that they do not infest soil that later will be placed on the mined sites to support desirable plants will be extremely helpful during the reclamation process because fewer of their seeds will be available in the soil to allow brome re-invasion and dominance. Caution should be exercised, however, to allow enough time to pass to allow herbicides to break down and dissipate so as not to injure sensitive, desirable species that will be sown or transplanted. Most herbicide labels provide adequate information concerning appropriate time intervals from treating to planting but intervals are highly dependent upon the species planned to be sown.

During reclamation, herbicides should be used as a designed disturbance before seeding to allow seeded species to establish. Some annual brome herbicides can be applied to young desirable plants that are establishing without causing excessive injury. During this desirable plant establishment period, herbicides can be used to control colonization (seed production by either weed species) or species performance and further aid desirable plant establishment. All the herbicides that are registered to control annual bromes in mined sites inhibit protein synthesis and may decrease viable seed formation by these weeds although this has not been demonstrated for the downy brome or Japanese brome. Carefully using appropriate brome herbicides during the desirable plant establishment phase of reclamation will impact their growth (species performance) and allow precious soil moisture to be allocated to planted species rather than used by either weed species.

Herbicides should be used to aggressively manage annual bromes along roads, conveyances, and similar corridors that are vectors for weed movement. This will decrease downy brome and Japanese brome propagule levels that otherwise would be available to infest reclaimed areas at the mined site.

Plateau

Plateau is an imidazolinone herbicide manufactured by BASF and is registered to use on pastures, rangeland, non-crop areas, and natural areas. Plateau and other imidazolinone herbicides inhibit acetohydroxyacid synthase (AHAS), which catalyzes the biosynthesis of three amino acids, valine, leucine, and isoleucine (Shaner et al. 1984). Protein synthesis in susceptible plant species is incomplete and they perish over time. Plateau can be used to control downy brome at any location at a mined site – along roads, around buildings and conveyances, on stored soils, and during reclamation. While Japanese brome is not listed under the weeds controlled section of the Plateau label, it can be used for that purpose at a mine site because it is registered to use on that site.

Fall applications of Plateau (imazapic) readily control downy brome and Japanese brome when applied at the appropriate growth stage. All the imidazolinone herbicides, such as Plateau, have a similar mechanism of action (the biochemical process in plants that is disrupted by the herbicide) and inhibit an enzyme that catalyzes the biosynthesis of three amino acids thus, inhibiting protein synthesis and susceptible plants die over time. Plateau should be applied preemergence to either annual brome species or very early postemergence when the weeds have three or fewer leaves. Plateau will not break down if applied onto the soil surface in mid-summer and will be available to control germinating seedlings in late summer, fall, and through the winter. This herbicide requires water to breakdown and will remain stable on the soil surface in sunlight (it breaks down quickly in water exposed to sunlight). Precipitation (or irrigation where possible and appropriate) will move Plateau from the soil surface into the soil where it remains in the soil solution and is absorbed by seedling downy brome and Japanese brome and subsequently, they perish. Plateau can be applied from 2 to 12 fl oz/A; 2 fl oz/A usually is insufficient and while 12 fl oz/A controls annual bromes very well for a long period, this rate is most injurious to cool season perennial grasses (Grass, forbs, shrubs, and tree species sensitivity to Plateau information can be found on the Plateau label). Typical use rates are from 6 to 8 fl oz/A plus 1 pt/A of a methylated seed oil (MSO) especially when applied postemergence. Including a methylated seed soil with Plateau as part of the spray solution is of paramount importance to effect desirable weed control! Downy brome and Japanese brome establishment is favored by litter that acts as a mulch to protect seedlings from desiccation and litter interferes with herbicide performance. Higher rates overcome the negative effect on herbicide performance but caution should be exercised concerning injury to cool season perennial grass species. On stored soil where downy brome is established and a thick litter layer exists, for example, 10 to 12 fl oz/A could be used initially to control annual bromes then repeat treatments could be made at the 6 to 8 fl oz/A rate in subsequent years. Plateau often controls annual bromes for 2 years, especially when applied at 8 or more fl oz/A, but a repeat treatment(s) will have to be made to control those seedlings that emerge from longer lived seed in the soil or those that escaped the initial control attempt.

Research by Colorado State University Weed Science showed that when Plateau was applied in early fall preemergence or early postemergence (three or fewer leaves present), downy brome control ranged from 70 to 100% late the following spring and most often 90 to 100% was controlled. Variation in control was most often related to herbicide rate and size of weeds at application. Large downy brome is much more difficult to control with Plateau than small downy brome; when it was 1 to 3 inches tall and had from 3 to 6 tillers at application in fall, control the following spring ranged from 6 to 30% from rates ranging from 2 to 12 fl oz/A plus MSO. Plateau only should be applied in fall. CSU research also showed that when Plateau is applied in spring, downy brome control ranged from 14 to 30% at rates ranging from 2 to 12 fl oz/A and cool season perennial grass injury was excessive. Washington State University research showed that fall applications of Plateau at 4 or 8 fl oz/A plus MSO controlled 65 and 95% of Japanese brome the following spring.

Roundup and other glyphosate products

Glyphosate (Roundup and numerous generic products) also readily controls downy brome. Roundup is manufactured by Monsanto and most glyphosate products can be applied on pastures, rangeland, non-crop areas, and natural areas where restoration or reclamation is planned (the latter due to its non-selective nature). Roundup can be used to control downy brome and Japanese brome in any location at a mine site. Glyphosate too is a protein synthesis inhibiting herbicide but it operates on a different metabolic pathway in plants than do products like Plateau, Telar, and Oust. Glyphosate kills susceptible plants by inhibiting the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (ESPS) that catalyzes the synthesis of phenylalanine and tyrosine (Shaner 2006). Using herbicides with different mechanisms of action is crucial to avoid developing herbicide resistant weed populations.

Roundup applied at 8 to 16 fl oz/A in published CSU weed management research controlled 96 to 99% of downy brome in one experiment and 100% in another (Beck et al. 1995). Downy brome is very susceptible to glyphosate and size does not affect its performance nearly as much as Plateau. Glyphosate is non-selective and will kill most vegetation it contacts; however, application timing can be manipulated to provide selectivity. In the above experiments, applications were made in early spring (April 4, 1988 and April 11, 1990) and crested wheatgrass (*Agropyron cristatum*) was growing at application and subsequently was killed. Sand dropseed – a warm season species – by comparison was dormant at application and survived with no injury. Pubescent wheatgrass was found at one of the sites and was injured 16 to 36% (mostly cosmetic injury with minor stand loss) from Roundup applied at 8 to 16 fl oz/A when the herbicide was applied on March 25, 1988. No injury occurred, however, in a repeat experiment when Roundup was applied on March 14, 1991. If applications of glyphosate are made in late winter – no later than March 15 in most years - when cool and warm season species (grasses, forbs, and shrubs) are still dormant, injury will be minimal.

Roundup should be applied at 16 fl oz/A for downy brome or Japanese brome plants up to 6 inches tall. Rates up to 24 fl oz/A may be necessary to control larger plants that are 12 inches tall or more. CSU research found no difference between 12 and 16 fl oz/A in the experiments reported above but downy brome plants were 2 to 4 inches tall with four to five leaves and up to three tillers and Roundup was applied in early spring. Typically in Colorado, downy brome will be small enough during late winter applications of glyphosate that these lower rates can be used.

Journey

Imazapic (Plateau) + glyphosate (Roundup) is manufactured by BASF and sold as Journey and can be used on pastures, rangeland and non-crop areas. Journey can be used in any location at a mine site. It will control downy brome or Japanese brome when applied in fall or spring. Journey at 16 fl oz/A applied in late winter (applications should be made by mid-March in most years to avoid excessive cool season grass injury) will control large downy brome or Japanese brome (up to 4 inches in height). The glyphosate component will control the existing downy brome or Japanese brome and the imazapic component will remain in the soil to control the next generation of either brome species that will germinate the following fall. Journey is essentially non-selective (primarily because of the glyphosate component) and application made after mid-March may severely injure established cool season grasses and forbs.

Matrix

Matrix (rimsulfuron) is a sulfonylurea herbicide manufactured by DuPont and the supplemental label for Matrix "For selective weed control and invasive species management on non-crop sites" can be used to control downy brome and Japanese brome on non-cropland that is to be restored or reclaimed and this includes reclaiming mine sites.

All sulfonylurea herbicides have the same mechanisms of action as the imidazolinone herbicides, such as Plateau. Sulfonylurea herbicides inhibit the enzyme acetolactate synthase (ALS), which catalyzes the biosynthesis of three amino acids, valine, leucine, and isoleucine (Ray 1986). Because both herbicide families inhibit protein synthesis, it is possible that treatment at the appropriate growth stage may eliminate viable seed production but this is unknown for downy brome or Japanese brome. In another experiment on musk thistle (*Carduus nutans*), researchers found that sulfonylurea herbicides eliminated viable seed development when applied at the bolting to very early flower growth stages (Beck et al. 1990).

Matrix has excellent postemergence activity on downy brome and Japanese brome with some soil residual activity as well. Matrix will control fairly large downy brome and should be applied from 3 to 4 oz/A plus 1 qt/A of a MSO. It can be applied in fall preemergence to annual bromes or postemergence in fall or spring. If applying preemergence to the bromes, precipitation must follow to move the herbicide into the soil where it can be absorbed by germinating downy brome or Japanese brome seedlings and cause their demise.

CSU research compared preemergence applications (September 21, 2005) of Matrix to very early postemergence applications (October 16, 2005), both at 2 oz/A, to control downy brome. There were no plants present at the September application and plants were 0.5 to 0.75 inches tall with one leaf in October. Preemergence applications controlled 100% of downy brome in April, 2006 while postemergence applications controlled 76%. Both application timings provided about 50% residual control of the next generation of downy brome that germinated in fall 2006 and 25% residual control in fall 2007.

In another CSU experiment, Matrix was applied in fall (November 19, 2007) and compared to a spring application (March 26, 2008). Downy brome was large at application - 2 to 3 inches tall with 2 to 5 tillers at both dates. The fall application of Matrix at 2 oz/A controlled 60% of downy brome by the end of its life cycle in early summer while the 4 oz/A rate controlled 83%. The 2 oz/A rate applied in spring controlled 15% of downy brome by early summer while the 4 oz/A rate controlled 70% of downy brome. The highest use rate must be applied when making spring applications or control will be unacceptable. The 4 oz/A rate in the above experiment also provided residual downy brome control in fall 2008 by decreasing populations by 60 and 40% from fall and spring applications, respectively.

Matrix provides a longer window of opportunity to control downy brome or Japanese brome than Plateau and may control larger plants. Matrix selectivity for desirable grasses, forbs, and shrubs still must be determined, however, while much of that is known for Plateau and expressed on the label. There are planting intervals on the Matrix label for eight desirable grass species.

Landmark XP

A mixture of sulfometuron (Oust) and chlorsulfuron (Telar) is manufactured by DuPont and sold as Landmark XP. Sulfometuron and chlorsulfuron are sulfonylurea herbicides. It is registered to use in non-crop areas such as along roadsides, around buildings, and for non-crop site restoration/reclamation and a supplemental label allows Landmark XP to be used to restore or reclaim degraded rangeland. Landmark XP can be used at any location at a mine site including during reclamation. Caution should be exercised when treating stored soils or during reclamation to be certain that enough time has passed (planting intervals) for the to break down and not injure planted desirable species. Planting interval information is on the Landmark XP label and the supplemental label.

Landmark XP can be used to control downy brome or Japanese brome although, a higher rate must be used to control the latter. Landmark XP is very active on large downy brome. This herbicide can be applied in fall (preemergence or postemergence) or spring to control either species and 0.75 oz/A will control downy brome while 1.5 oz/A will control Japanese brome. A non-ionic surfactant at 0.25% v/v (equivalent to 1 qt of surfactant per 100 gallons of spray solution) must be added or control will be dramatically decreased from postemergence applications. The Oust and Telar components of Landmark XP have the same mechanism of action to control susceptible weeds as Plateau and Matrix. The major advantage of Landmark XP is its activity on large weeds compared to Plateau in particular. It is, however, not as selective primarily due to the Oust component.

CSU research compared Landmark XP applied preemergence to downy brome in fall 2005 to postemergence applications shortly thereafter when emerged plants were

0.5 to 0.75 inches tall with one leaf. Landmark XP at 0.75, 1.0, and 1.5 oz/A controlled 100% of downy brome the following spring (April, 2006). Residual control also was evident where the 0.75 oz/A rate controlled 55% of the fall 2006 generation while the 1 oz and 1.5 oz/A rates controlled 75 and 86% of downy brome, respectively (all data collected at the end of their life cycles in early summer 2007).

Residual control from Landmark XP is another advantage of using this herbicide. It is important, however, to keep in mind that applications of Landmark XP (especially preemergence applications) must be followed by precipitation to move the herbicide from the soil surface into the soil where it can be absorbed by roots (Landmark XP also is absorbed by foliage during postemergence applications). This also decreases off-site movement of the herbicide caused by wind moving soil with the herbicide attached (primarily the Oust component), which can injure recipient plant communities that contain susceptible species. This has been a significant issue with Oust in particular.

Oust

Sulfometuron is Oust and is manufactured by DuPont. It is a sulfonylurea herbicide with the same mechanism of action as Matrix, Landmark XP, and Plateau. Oust is registered to be used on non-crop sites and can be used along roadsides, around buildings and conveyances, and similar areas. It should not be used during the reclamation process.

Oust controls downy brome and Japanese brome very well. Oust should be applied from 0.75 to 1.5 oz/A plus 0.25% v/v of a non-ionic surfactant in fall or in spring either premergence or postemergence. Oust has excellent activity on large downy brome and will control plants up to 12 inches tall.

In the same experiment reported above for Landmark XP, Oust at 1 oz/A applied preemergence in fall controlled 100% of downy brome the following spring and residually controlled 83% of the next generation. Oust has very effectively and consistently controlled downy brome in CSU research projects and the residual control it offers is very advantageous. There is a risk, however, of off-site movement after an Oust application on wind-blown dust and this is especially the case when soils are very dry. Precipitation shortly after application will move Oust from the soil surface into the soil - where it still can be absorbed by downy brome roots – and this decreases the risk associated with off-site movement from wind-blown soil.

Herbicide resistance management

Repeated use of highly effective herbicides, such as the sulfonylureas and imidazolinones, can select for individual weeds that are resistant to the herbicide and will not be controlled regardless of rate. This has been observed to date with both these herbicide classes. Imidazolinone and sulfonylurea herbicides place a tremendous selection pressure for resistant members of weed populations because they are the only ones to survive treatment or a series of treatments. Several weed species have displayed populations resistant to these two classes of herbicides (Holt and LeBaron 1990). The resistant individuals quickly increase in population and render the use of these herbicides as ineffective in a short time unless steps are taken to avoid such development.

Downy brome resistance to sulfonylurea herbicides was found in Oregon under intense crop production (Ball and Mallory-Smith 2000; Park and Mallory-Smith 2004). These researchers confirmed that resistance was conferred by an altered structure of ALS such that sulfonylurea herbicides would not bind to the altered enzyme and inhibit the synthesis of valine, leucine, and isoleucine. The relative ecological fitness of the susceptible and resistant downy brome biotypes was assessed and no difference in growth rate or competitive ability was detected (Park et al. 2004).

Therefore, care must be exercised in Colorado (and elsewhere) to manage against development of a population of resistant downy brome. Rotation over time among herbicides with different mechanisms of action will help thwart such development. This should not be a significant issue for mine sites in Colorado but caution nonetheless should be exercised. Using ALS or AHAS inhibiting herbicides for 2 to 3 years will most likely not select quickly for resistant members of the downy brome population but such use poses some risk. It would be worthwhile to rotate to a glyphosate herbicide or tank mix of ALS/AHAS inhibiting herbicides plus glyphosate because the latter has a different mechanism of action and will control the ALS/AHAS resistant members, which would thwart or at least dramatically delay development of resistance. The rate of resistance development in a rangeland or non-crop setting has not been determined nor observed to date but caution should be exercised and land managers should be aware of this risk and monitor results of using any herbicide.

Other cultural considerations

Downy brome responds positively to increased available nitrogen in the soil (Dakheel et al. 1993; Harris 1967; Harris and Goebel 1976; Lowe et al. 2002). This favors its germination, establishment, and dominance on sites. Research has shown that decreasing the amount of available nitrogen (by increasing soil carbon) disfavors downy brome (McClendon and Redente 1991; Paschke et al. 2000). There currently are no practical methods commercially available to increase soil carbon thus, decrease available nitrogen. Some mines in Colorado, however, have experimented with placing the B-horizon stored soil on top during reclamation and experienced enhanced desirable plant establishment. It is unknown, however, whether the enhanced establishment was due to increased water holding capacity of the finer-textured soil particles found in B-horizon compared to A-horizon soils or whether it was related to decreased available nitrogen that may have disfavored downy brome and aided desirable plants. Research must be conducted to verify whether either one of these hypothesized effects are involved with the field observations before such could be recommended as a common practice.

Another consideration to improve downy brome and Japanese brome control and enhance reclamation involves arbuscular mycorrhizal fungi (AMF), which significantly aid the growth and development of mycorrhizal plants (Allen and Allen 1984; 1986; Killham 1985; Read et al. 1985; Smith et al. 1986; Trappe 1981). Downy brome is a facultative mycorrhizal plant and does not have to develop such an association to survive or even dominate a site (Pendleton and Smith 1983; Trappe 1981). Desirable native plants, however, typically are very dependent on AMF for their establishment and survival. Inoculating a site with AMF may be very beneficial to desirable species that are being used to reclaim a mine site and a healthy, vigorous plant community is the most important aspect to resist invasion by weeds, including downy brome and Japanese brome. The best source of AMF for a mine site would be from the adjacent reference area and typically small individuals of desirable species that are being used to reclaim the mine site can be transplanted and the associated AMF will be moved with them. Commercial inocula have not been as successful as using AMF from references areas.

SUGGESTED RESEARCH

- Determine whether applications of Plateau, Matrix, or Oust eliminate viable downy brome and Japanese brome seed development.
- Determine what mechanism is operable when A-horizon and B-horizon soils are inverted during reclamation;
    - Is available nitrogen decreased in B-horizon soils thus altering the C:N that favors late seral plant communities?
    - Is water holding capacity increased in B-horizon soils compared to A-horizon soils?
- What is the water holding capacity of A-horizon soils that have been replaced in their original locations during reclamation?
    - How long does it take for porosity to become similar to A-horizon soils in the local reference area?
        - What is the water infiltration rate of replaced A-horizon soils?
- Is there an advantage to inoculating soils being reclaimed with AMF from surrounding references areas?

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