Monitoring the recovery of Dalmatian Toadflax (*Linaria dalmatica*) and native grasses on north- and south-facing slopes at the National Bison Range after the application of Tordon (picloram) in 1998 & 2001

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Abstract: Invasive weeds lower yield and quality of forage, interfere with grazing, poison animals, increase costs of managing and producing livestock, and reduce land value. These undesirable dicots also impact wildlife habitat and forage, deplete soil and water resources, and reduce plant and animal diversity. There are more than 300 rangeland weeds in the United States of which one species, Dalmatian toadflax, has become a species of concern on the 18,500-acre National Bison Range. Dalmatian toadflax (*Linaria dalmatica*) is an erect, short-lived perennial herb. Because of its competitive ability, Dalmatian toadflax is a concern in pasture and rangelands, as well as in natural areas, where it may out-compete more desirable, native species. Currently, the National Bison Range controls Dalmatian Toadflax with Tordon at 2 pt/A which is aerially sprayed in targeted areas on or around June 14 yearly.

This study found strong evidence that south-facing slopes had a greater mean number of plants per site than north-facing slopes which may indicate that toadflax recovered more quickly on south-facing slopes than north-facing slopes. This may be due to the greater exposure to UV radiation on south-facing slopes than on north-facing slopes, which allowed for quicker degradation of the herbicide. There is also moderate evidence that areas treated in 1998 with Tordon had a greater mean number of plants per site than those areas treated in 2001. Given the timeframe, this suggests that Dalmatian toadflax is able to quickly reestablish itself after disturbance. Further evidence suggests that the health of the native plant population is likely reduced by the toadflax invasion and further disturbance (i.e. herbicidal application) may allow for the invasion of other non-desirable, opportunistic species. Thus, developing and implementing an integrative invasive weed management strategy may be the best solution for addressing a noxious weed problem on the National Bison Range.

Key words: Dalmatian toadflax, control and management, picloram, integrative weed management, National Bison Range.

Introduction

Rangelands and pastures comprise about 42% of the total land area of the United States, or roughly 400 million acres (Bovey 1987). Many of these rangelands have been overgrazed in the last 100 years and, as a result, changed the plant composition from the original ecosystem. Western rangelands previously dominated by perennial bunchgrasses have been converted – generally though overgrazing – to annual grasslands that are susceptible to invasion by introduced dicots. Introduced, non-native weeds cause an estimated economic loss of $2 billion annually in the United States, which is more than all other pests combined (Bovey 1987; Quimby et al. 1991). Furthermore, they impact the livestock industry by lowering yield and quality of forage, interfering with grazing, poisoning animals, increasing costs of managing and producing livestock, and reducing land value. These undesirable dicots also impact wildlife habitat and forage, deplete soil and water resources, and reduce plant and animal diversity (DiTomaso 2000). Today there are more than 300 rangeland weeds in the United States of which one species, Dalmatian toadflax (*Linaria dalmatica*), has become a species of concern on the 18,500-acre National Bison Range.

Dalmatian toadflax is an erect, short-lived perennial herb, 0.8 to 1.5 m tall. The plant is hairless and glaucous, growing from a woody, branching base. The light green, waxy, alternate leaves are heart-shaped and clasp the stem. The flowers are bright yellow, tinged with orange, and resemble snapdragon flowers. The petals have two lips; the upper lip is two-lobed while the lower one is three-lobed. Individual flowers are nearly sessile, occurring in long, terminal racemes (USDA-ARS 1971; Morishita 1991).

Dalmatian toadflax seedlings generally germinate in the spring. After germination, a primary stem emerges, which may be joined by one to three adventitious stems that develop from the hypocotyl of the seedling; both types of stems can produce flowers. Prostrate vegetative stems also develop adventitiously from the crown and roots of the seedling. The prostrate stems persist over winter and then die when the floral stems begin to develop. Plants produce one to 25 floral stems in the spring, flowering in May. Dalmatian toadflax spreads by horizontal or creeping rootstocks and by seed.

The average life span of a Dalmatian toadflax plant is three years, during which time the plant may produce half a million seeds (Robocker 1974) which are primarily dispersed by wind. The seeds may live up to ten years in the soil (Robocker 1974; Morishita 1991). Most seedlings emerge in the spring when soil temperature reaches 8°C at 2.5 cm. Germination in the fall is probably limited by soil water content, as well as possibly seed dormancy (Robocker 1974).

In its native habitat, Dalmatian toadflax occurs from the Dalmatian coast of the former Yugoslavia to Romania, Bulgaria, Albania, Greece, Crete, Turkey, Azerbaijan, Syria, Iran, and Iraq. Its Old World latitudinal range is roughly 35° N to 47° N. In North America, the species is known from at least 15 states and six Canadian provinces, with a latitudinal range of 35° N to 56° N (Alex 1962). Dalmatian toadflax occurs in a variety of habitats, including: roadsides, pastures, rangelands, and waste areas. It has spread most extensively west of the 100th meridian, occurring primarily on coarse-textured soils, ranging from sandy loams to coarse gravels (Alex 1962).

Because of its showy flowers, Dalmatian toadflax has been cultivated since the 16th century and has subsequently become widely distributed throughout the world. Dalmatian toadflax was probably introduced to North America in the late 1800's as an ornamental. Mature Dalmatian toadflax plants are strongly competitive. Mature plants are especially competitive with shallow-rooted perennials and winter annuals. Because of its competitive ability, Dalmatian toadflax is a concern in pasture and rangelands, as well as in natural areas, where it may out-compete more desirable, native species.

Studies conducted by Sutton and Beck (2000, 2002) found that yellow toadflax (*Linaria vulgaris*) is most often found in open areas with high species diversity and moist soils. This implies that these areas have greater resources than plant communities can use and gives toadflax a greater opportunity to establish. Although other site characteristics including slope, aspect, elevation, soil texture, and the carbon to nitrogen ratio were studied by Sutton and Beck, no correlations between site conditions and yellow toadflax establishment existed. Although Robocker (1974) indicates that plots without Dalmatian toadflax may produce two and a half times as much grass as plots with toadflax.

Chemical Control & Management of Dalmatian Toadflax

Herbicides are the primary method of weed control in most rangeland systems and can be applied by a number of methods including fixed-wing aircraft, helicopters, ground applicators, backpack sprayers, and rope wick applicators. Herbicides commonly

Table 1. Herbicide options for management of Dalmatian toadflax

Herbicide	Active Ingredient	Rate of Herbicide	Timing of application	Comments
Tordon 22K	picloram	1-2 qt/A	Flowering or in the fall; especially effective after first hard frost	• Residual herbicide • Selective • Retreatment for several years may be required. • Best control occurs when area re-seeded with competitive grasses
Telar	chlorsulfuron	2-3 oz/A + 0.25% (v/v) non-ionic surfactant	Flowering to fall	• Residual herbicide • Selective • Persistent in high pH soils • Retreatment for several years may be required.
Many compounds	Glyphosate*	3-4 lbs ai/acre	Early bloom	• Nonselective • Will suppress in current year, but abundant regrowth will occur the following year.
Banvel, Clarity, Vanquish	dicamba	2-4 qt/acre	Pre-bloom to flowering stage	• Residual herbicide • Selective • Retreatment for several years may be required

*Many products containing this active ingredient are available.

(Erskine-Ogden & Mark J. Renz, 2005)

used in rangelands of the western United States include dicamba, glyphosate, imazapyr, picloram, triclopyer, and several others. Of these, the auxin or growth regulator herbicides have played the most important role in rangeland weed control (DiTomaso 2000).

Dalmatian toadflax may be controlled with Tordon 22K at 2 pt/A sprayed at flowering or in fall. In a Colorado study, rates of 2, 4, and 8 pt/A of Tordon were compared and control longevity was greatest from the 2 pt rate, apparently because competition from crested wheatgrass was maintained (Beck 2001). Similarly, researchers in Wyoming treated Dalmatian toadflax in early September of 1994 with Tordon at 2 pt/A, then seeded the following year in April or August with 'Hycrest' crested wheatgrass, 'Luna' pubescent wheatgrass, 'Critana' thickspike wheatgrass, 'Bozoisky' Russian wildrye, or 'Sodar' streambank wheatgrass. The combination of spraying and seeding competitive grasses controlled Dalmatian toadflax better than spraying alone. Three years after treatments were started, control of Dalmatian toadflax ranged from 61 percent to 86 percent where grasses were seeded in April and from 76 percent to 95 percent from the August seeding, compared to no control from spraying alone (Beck 2001). Currently, the National Bison Range (NBR) controls Dalmatian Toadflax with Tordon at 2 pt/A which is aerially sprayed yearly in targeted areas on or around June 14.

Tordon (picloram): management considerations

Picloram - the active ingredient in Tordon - is a dicot-selective, persistent herbicide used to control a variety of annual and perennial broadleaved herbs and woody species. It acts as an "auxin mimic" or synthetic growth hormone that causes uncontrolled and disorganized growth in susceptible plants. Picloram does not bind strongly with soil particles and is not degraded rapidly in the soil, allowing it to be highly mobile and persistent (half-life of picloram in soils can range from one month to several years). Picloram does not volatize readily when applied in the field. The potential to volatize, however, increases with increasing temperature, increasing soil moisture, and decreasing clay and organic matter content (Helling et al. 1971).

Although microbial degradation of picloram is generally slow, it is believed to be the major pathway of picloram degradation in soils (Spiridonov et al. 1987; WSSA 1994). The primary metabolites produced during microbial degradation are degraded through microbial metabolism more rapidly than the parent compound (WSSA 1994). Conditions that favor microbial activity such as high soil moisture and temperature can increase the rate of microbial degradation of picloram (Merkle et al. 1967; Phillips & Feltner 1972, Michael et al. 1989; Watson et al. 1989).

Picloram also has a very low adsorption capacity in most soil types (K_{oc}=16 mL/g). High organic content, heavy soil texture, low pH, high hydrated iron and aluminum oxide contents, and low soil temperature can increase the adsorption capacity (Merkle et al. 1967; Farmer & Aochi 1974; Neary et al. 1985; Liu et al. 1997). Rates of adsorption also increased with time (McCall & Agin 1985). Unlike many other herbicides, however, clay content does not affect the adsorption capacity of picloram (Grover 1971; Farmer & Aochi 1974).

Picloram is readily degraded when exposed to sunlight in water or on the surface of plant foliage and soils (Merkle et al. 1967; Johnsen & Martin 1983; Cessna et al. 1989; Woodburn et al.1989). Photodegradation will occur most rapidly in clear, moving water (WSSA 1994), and slowly when exposed on the soil surface. Merkle et al. (1967)

reported 15% degradation of picloram after one-week exposure on soil, compared to 65% from exposure in an aqueous solution. There is some evidence that photodegradation occurs more rapidly at higher elevations (Johnsen & Martin 1983) possibly due to increased UV radiation (Merkle et al. 1967).

In non-susceptible species such as grasses, picloram is metabolized rapidly, while in susceptible species, picloram can remain intact for extended periods (WSSA 1994). When applied to soil, picloram is readily absorbed by plant roots. When applied to foliage, the majority of picloram (70-90%) remains in the leaves and only a small percentage is conducted to stems and roots (Meikle et al. 1966; Cessna et al. 1989; Hickman et al. 1990). Unabsorbed picloram remaining on leaf surfaces may photodegrade in sunlight or be washed off with rainfall or irrigation. Picloram absorbed by plants can be released into the soil by passive transport through the roots and then taken up by roots of other nearby plants (Hickman et al. 1990). Therefore, even selective application of picloram to specific target plants could potentially harm nearby desirable plants.

Since picloram is not readily degraded in soils, it can be persistent and mobile. Estimates of the persistence of potentially toxic concentrations vary from a few months to three years, depending on soil and environmental conditions (Scrifres et al. 1972; Fryer et al. 1979; Johnsen 1980; Norris et al. 1982; Neary et al. 1985; Smith et al. 1988; Bovey & Richardson 1991; Close et al.1998). In soils where picloram persists for long periods of time, it has high potential to move vertically and horizontally, which can lead to contamination of water sources and non-target (terrestrial and aquatic) sites. Smith et al.

(1988) reported that one and two years after treating a site with 3.38 kg/ha of picloram, residues were found in the soils and groundwater of an untreated site one km away.

Picloram is not highly toxic to birds, mammals, and aquatic species. Because of the persistence of picloram in the environment, chronic exposure to wildlife is a concern, and studies have found weight loss and liver damage in mammals following long term exposure to high concentrations (EXTOXNET 1996).

Hypotheses

Hypothesis 1: Despite the study by Sutton and Beck (2000) who found no correlation between aspect and toadflax, I predict that there will be a difference between north-facing and south-facing slopes after herbicidal application because south-facing slopes have greater exposure to UV radiation than north-facing slopes and picloram is readily degraded on the surface of plant foliage and soils. Therefore, Dalmatian toadflax will be more prevalent on south-facing slopes than north-facing slopes.

Hypothesis 2: Given the reproductive vigor and competitive ability of Dalmatian toadflax, I predict that Dalmatian toadflax will recover or reestablish itself more quickly in areas treated with Tordon in 1998 than in areas treated with Tordon in 2001.

Hypothesis 3: Due to the disturbance created by both grazing and herbicidal application, I predict there will be a considerable invasion of other non-native species (such as St. Johns' Wort, spotted knapweed, etc.) in addition to a high recovery or reestablishment of Dalmatian toadflax.

Methods

For this experiment, a systematic sampling method based on the Modified-Whittaker plot (*see* Stohlgren et al. 1998) was used at two different areas on the National Bison Range which had been sprayed in 1998 and 2001. These areas included: Elk Ridge (sprayed in 1998) and Wild Horse Mountain/Tower Two Road (sprayed in 2001). A 20m X 50m plot was established on both a north-facing and a south-facing slope in the selected areas to ensure the greatest possible coverage and variation among vegetation types. A third, or control, plot was established adjacent to the sprayed areas. Each plot was used to: (1) calculate the ratio of Dalmatian toadflax to native grasses and forbs; (2) detect other non-native species; (3) calculate the ratio of other non-native species to native vegetation and forbs; and (4) determine if slope aspect influences the effectiveness of Tordon.

As previously indicated, the Modified-Whittaker plot was altered to accommodate the restriction and availability of resources for this project. Specifically, cumulative plant species was not counted in the 1000m^2 plot or the 100m^2 subplot. Instead, the 100m^2 plot was replaced by two (2) additional 10m^2 plots in which cumulative plant species was counted. In addition, only invasive species found within the 1000m^2 plot was recorded and the height of individual plants was not recorded in the 1m^2 subplots or biomass determined.

During field sampling, five soil samples were taken in the corners and the center of each plot with a 2.5 cm diameter soil increment core to depths of 15 cm. If, due to rocks or other site characteristics, the core was unable to reach an approximate depth of 15 cm, two cores at depths averaging 7 cm were taken to ensure adequate volumes of soil. These samples were used to characterize and differentiate soil and stratigraphic units which may influence absorption and mobility of picloram. Soil temperature and moisture content were also noted.

Results

A Welch's t-test was used to determine if there was a difference among the plant communities found on north-facing and south-facing slopes in the treatment areas, as well as to establish if toadflax recovered more quickly in the area treated with Tordon in 1998 than in the area treated in 2001. Secondly, a one-way analysis of variance (ANOVA) was used to test for method effects on the total number of native species, Dalmatian toadflax, and other non-native species. Whenever ANOVA results showed a significant effect ($P < 0.05$), a Tukey's HSD test was used to determine significant differences among means. Finally, a multivariate analysis (MANOVA) was also used to determine if a correlation existed between site conditions and native species or, more importantly, Dalmatian toadflax.

The difference between the average number of toadflax plants per study site on north-facing and south-facing is 23.4 plants with a standard error of 8.5 plants (equal variances not assumed). Welch's t-test gives a test statistic of $t=2.77$ and a P-value of .008. Thus, there is strong evidence that south-facing slopes had a greater mean number of plants per site than north-facing slopes which may indicate that toadflax recovered more quickly on south-facing slopes than north-facing slopes. This may be due to the greater exposure to UV radiation on south-facing slopes than on north-facing slopes, which allowed for quicker degradation of the herbicide. However, more data is needed to determine the actual cause of this relationship.

Similarly, the difference between the average number of toadflax plants per study site in areas treated with Tordon in 1998 versus those areas treated in 2001 is 22.5 plants with a standard error of 10.4 plants (equal variances not assumed). Welch's t-test gives a test statistic of t=2.17 and a P-value of .035. Thus, there is moderate evidence that areas treated in 1998 with Tordon had a greater mean number of plants per site than those areas treated in 2001. Given the timeframe, this may be expected given the reproductive vigor and competitiveness of toadflax which enables itself to quickly reestablish after disturbance. As found in one research area in Colorado, Dalmatian toadflax increased 1,200 percent over a six year period (Beck 2001).

An one-way ANOVA provides further evidence that mean Dalmatian toadflax plants varied among north-facing, south-facing, and control plots with a P-value of <0.0001 (d.f.= 2, F= 9.09). The ANOVA test indicates no evidence that the mean native grasses (P= .33) and native forbs (P= .065) are different among the plots. However, there is strong evidence that the mean number of other invasive plants is different among the plots (P= .013). A Tukey's HSD was used to test if mean difference is significant at the .05 level. The Tukey's HSD revealed the mean difference of other invasive plants was moderately significant between north-facing and southing-facing plots (P= .04) as well as between the control and south-facing plots (P= .02). This correlation is expected given that the health of the native plant population is likely reduced by the toadflax invasion and further disturbance (i.e. herbicidal application) may allow for the invasion of other non-desirable, opportunistic species.

Finally, a MANOVA test indicated there was no evidence that site conditions (temperature, soil type, soil density, and moisture content) influenced the growth or establishment of native plant species, Dalmatian toadflax, or other invasive species except for soil temperature. The MANOVA test indicates a strong relationship between soil temperature and the presence of Dalmatian toadflax (P= .007, d.f.= 8, F= 1.2). The highest percentage of toadflax grew in areas where the soil temperature ranged between 22° and 23° Celsius, which may indicate optimal growing conditions. However, it may also be an artifact of a small sample size and simply indicative of slope aspect. Additional data is thus needed to determine if an actual correlation between temperature and the presence of Dalmatian toadflax exists.

Discussion

Land management agency vegetative goals for rangelands should call for a wide variety of healthy native plants because native plants form the basic biological matrix of all communities (Krebs 1994). The growth forms of plants are also an important component of community structure as many invasive plants form broad-leaved rosettes or in some other way shade out neighbors (Huenneke 1996). Thus, weeds often completely alter community structure when near monocultures of one invasive plant are formed by displacing native plant species through crowding, competition for resources, or by other mechanisms (Cheater 1992). As weeds displace native plants, the land manager's ability to meet land health goals is diminished.

When weed infestations become severe and widespread, especially in rugged and rocky terrain, range restoration often becomes either impractical or impossible with today's technology and economics because invasions are only recognized after it has entered an explosive phase. Unfortunately, by this stage, it is difficult or impossibly expensive to control the increase of the invader (Huenneke 1996). When a weed infestation, like other disturbances, goes beyond a certain threshold, it becomes impossible to restore a site to the before infestation condition because of changes in structure and function in the plant community (DiTomaso 2000).

Well-managed land is the best defense against the spread of weeds as invasive plants often prefer disturbed areas. However, evidence suggests that weeds also commonly invade relatively undisturbed communities. Bedunah (1992) indicates that exotic weeds will invade undisturbed climax communities and can become significant components of a community. Several exotic noxious perennial weeds including spotted, diffuse and Russian knapweeds, leafy spurge, and yellow starthistle are moving into excellent condition stands of native vegetation (Harris 1991). Tyser and Key (1988) reported that spotted knapweed invaded and reproduced in rough fescue communities in Glacier National Park. Porcella and Harvey (1983) also documented Eurasian weeds dominating relatively undisturbed grasslands in Montana. Hence, developing and implementing an integrative invasive weed management strategy may be the best solution for addressing a noxious weed problem.

Developing and implementing an integrative management strategy for noxious weeds

Once a weed is established, it is unlikely that eradicating can be accomplished without extremely high financial and labor inputs. The definitive objective under these circumstances is to manage the infested area and contain the large-scale infestation. However, the goal of any management plan should not simply to control the noxious weeds, but improvement of the degraded rangeland community, enhanced utility of the ecosystem, and prevention of reinvasion by other noxious weed species (DiTomaso 2000). When rangeland deterioration is severe and desirable species are either absent or scarce, reclaiming the productive potential of degraded rangeland through the reintroduction of desirable plan mixtures is necessary (Masters & Nissen 1998).

While herbicides may effectively control noxious weeds, they seldom provide long-term control of weeds when used alone (Bussan & Dyer 1999). In the absence of a healthy plant community composed of desirable species, one noxious weed may be replaced by another of equally undesirable species insensitive to the herbicide treatment. In addition, continuous use of a single herbicide can select for resistance in the target weed species (DiTomaso 2000). Population shifts through repeated use of a single herbicide may also reduce the plant diversity and cause nutrient changes that decrease the total vigor of the range. Thus, herbicide use in rangelands should be one part of a multi-part integrated weed management system.

Since a single method is not effective to achieve sustainable control of range weeds, a successful long-term management program should be designed to include prevention, eradication, and/or some combinations of mechanical, biological, and chemical control techniques in the event of a large-scale invasion. The major elements of a prevention program are to stop introduction of noxious weed seeds or vegetative reproductive fragments, reduce the susceptibility of the ecosystem to invasive weed establishment, develop effective education materials and activities, and establish a program for early detection and monitoring (DiTomaso 2000). Eradication, similar to prevention, requires early detection and rapid response to prevent reproduction and development of a seedbank. The goal of eradication is to completely eliminate the problem species from the site though a combination of mechanical removal and herbicidal application. It should be noted, however, that eradication is not complete until all viable propagules are removed from the soil (Zamora & Thill 1999). Finally, use of multiple control methods, such as combination of spraying with herbicide and seeding with competitive grasses or spraying and mowing the target species, may be the best management solution for the control of Dalmatian toadflax in heavily infested areas.

Given the large number of invasive plants currently found on the National Bison Range including Dalmatian toadflax, St. Johns' Wort, spotted knapweed, cheatgrass, and others, the management agency (i.e. US Fish and Wildlife Service) of the National Bison Range must address the problem to protect the forage and habitat quality of the native vegetation. Current attempts to manage Dalmatian toadflax and other invasive species are likely inadequate and should be enhanced to achieve the management goals of the agency and the refuge. This would require a more progressive approach to invasive species managements such as those discussed herein. Failure to do so may jeopardize the carrying capacity of the Bison Range in the long-term and result in the loss of a national treasure.

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