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## LONG-TERM EFFECTS OF TEBUTHIURON ON *BROMUS TECTORUM*

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**ABSTRACT.**—Use of herbicides to thin dense stands of *Artemisia* spp. (sagebrush) can free up resources for herbaceous plants and increase forage production, but may also facilitate weed invasion. We revisited a sagebrush thinning experiment in a north central Wyoming big sagebrush–grassland 11 years after application of tebuthiuron (N-[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-N'-dimethylurea) to determine the long-term responses of shrubs, available soil resources, perennial grasses, and *Bromus tectorum* L. (downy brome). Tebuthiuron reduced shrub cover by more than half, from 31% in untreated plots to 15% in treated plots ( $P = 0.002$ ), and increased downy brome cover approximately 4-fold, from 0.9% in untreated plots to 3.5% in treated plots ( $P = 0.02$ ). Treatment with tebuthiuron also resulted in marginally significant increases in cover of perennial grasses (from 9% to 12.3%;  $P = 0.07$ ) and bare ground (from 39.1% to 43.9%;  $P = 0.08$ ). In comparisons of resource availability among microsites, available  $\text{NO}_3$  was higher under dead sagebrush than under live sagebrush ( $P = 0.03$ ). No significant differences in soil water content were detected. The relatively recent expansion of downy brome populations at this site and the high  $\text{NO}_3$ -N levels observed under dead sagebrush suggest that conditions facilitating downy brome invasion may persist for many years following sagebrush thinning. We demonstrate that sagebrush thinning can cause increases in downy brome populations years after initial treatment and suggest that managers should use caution when considering thinning sagebrush if downy brome is present, even if initial populations are small.

*Keywords:* bare ground, cheatgrass, downy brome, invasion, land management, nitrogen,  $\text{NO}_3$ , resources, sagebrush thinning, water, weed.

Thinning dense stands of sagebrush with herbicides can increase forage production while causing less disturbance than mechanical techniques and fire (Hull et al. 1952, Hyder and Sneva 1956, Hedrick et al. 1966, Miller et al. 1980). Thinning influences forage production by making resources previously used by sagebrush available to herbaceous plants. Depending on site characteristics and post-thinning management, increases in forage production may be sustained for several to 35 years (Harniss and Murray 1973, Bartolome and Heady 1978, Sturges 1993, Olson and Whitson 2002, McDaniel et al. 2005). Unfortunately, increases in resource availability with sagebrush thinning may also encourage weed establishment. If established herbaceous perennials are sufficiently common, they can take up newly available nutrients (Burke et al. 1987) and water, particularly water within the upper soil profile (Hyder and Sneva 1956, Sturges 1993). If resources are not quickly preempted by desired species, however, invasive species may benefit. Many invasive plant species grow rapidly, have short generation times, and allo-

cate a high percentage of resources to reproduction and dispersal. These life history characteristics provide a competitive advantage in environments with abundant available resources (Baker 1965, Chapin 1980). *Bromus tectorum* (downy brome) is a prime example, reaching reproductive maturity in as little as 6–8 weeks, and producing tens of thousands of seeds per  $\text{m}^2$  (Hulbert 1955, Mack and Pyke 1983). It is also the most abundant invader of sagebrush ecosystems, infesting more than 40 million ha in the United States (DiTomaso 2000).

Concerns about the response of downy brome to sagebrush removal are not new. Piemeisel (1951) detailed a successional trajectory following mechanical removal of sagebrush that passes from *Salsola kali* var. *tenuifolia* Tausch (Russian thistle) through *Decurainia sophia* (L.) Webb (flixweed) and *Sisymbrium altissimum* L. (tumble mustard) to downy brome, and eventually to native perennial species. Chemical control of sagebrush avoids soil disturbance but also stimulates weed invasion. For example, Hedrick et al. (1966) found that downy brome dominated chemically treated

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rangeland in poor condition for up to 7 years. More recently, tebuthiuron (N-[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-N-N'-dimethylurea) has been recommended for its ability to control sagebrush while leaving forbs in place, thereby minimizing adverse effects on plant and animal diversity (Johnson et al. 1996, Olson and Whitson 2002). Shrub control and herbaceous biomass production increase in proportion to the tebuthiuron application rate (Whitson and Alley 1984, Whitson et al. 1988, McDaniel et al. 2005). At several sites, however, trends were observed towards higher biomass of downy brome in treated plots (Olson and Whitson 2002), and at 1 site downy brome dominated treated plots 7 years after tebuthiuron application (Whitson et al. 1988).

Although the potential for short-term increases in downy brome abundance following sagebrush control has been well documented, there are few long-term studies of the effect of sagebrush thinning on brome invasion. Given the emergence of downy brome as one of the most problematic rangeland weeds in North America (Young and Allen 1997), an important priority is to determine whether increases following sagebrush thinning represent temporary successional trends or longer-term changes in plant community composition. In this study we revisited an experimental site that was treated with tebuthiuron in 1993 and did not show an increase in downy brome abundance with tebuthiuron application 2 or 4 years after treatment (Olson and Whitson 2002). Our objective was to determine the long-term effects of tebuthiuron on downy brome invasion and on soil resources that may influence downy brome invasion.

## METHODS

### Study Site and Experimental Design

The study site was located in a sagebrush-grassland ecosystem dominated by *Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young (Wyoming big sagebrush), on the Tim McKinney ranch (42°42'28"N, 108°36'21"W), approximately 22 km southeast of Lander, Wyoming (Olson and Whitson 2002). The elevation was 1696 m. Over the 10 years between tebuthiuron application and this study, annual precipitation in Lander averaged 95% of the

340-mm mean. Annual precipitation was considerably lower than average during the 3 years immediately preceding this study: 218 mm in 2000, 137 mm in 2001, and 205 mm in 2002. Annual precipitation and June–September precipitation were 261 mm and 100 mm in 2003, and 368 mm and 174 mm in 2004 (Western Regional Climate Center). The site was grazed annually at a moderate stocking rate throughout the study. Spring and fall grazing occurred in alternate years, and the site was grazed prior to vegetation sampling in 2004.

In the original study a randomized complete block design was used, with 3 replications of 4 herbicide treatments: 0 (Control), 0.1, 0.2, or 0.4 kg ai · ha<sup>-1</sup> tebuthiuron (Olson and Whitson 2002). Individual plots were 402 m × 102 m and separated by 25-m buffers. The principle native species, besides Wyoming big sagebrush, were *Chrysothamnus viscidiflorus* Nutt. (rabbitbrush), *Pascopyrum smithii* [(Rydb.) A. Löve] (western wheatgrass), *Koeleria macrantha* (Ledeb.) J.A. Schultes (June grass), *Phlox hoodii* Richards. (phlox), and *Astragalus bisulcatus* (Hook.) Gray (two-grooved milkvetch; Olson and Whitson 2002). Downy brome was the most prevalent invasive weed. Although differences were not statistically significant, in 1995 and 1997 more downy brome was found in untreated than treated plots (Olson and Whitson 2002). Thus, tebuthiuron did not increase downy brome during the first 4 years of this study.

In summer 2004, eleven years after herbicide treatment, we measured canopy cover of downy brome, perennial grasses, and shrubs, and cover of bare ground in control plots and plots treated with the highest level of tebuthiuron (0.4 kg ai · ha<sup>-1</sup>). We also measured the effect of sagebrush death on soil resources in 2003, comparing soil water, total organic C and N, and mineral N (NO<sub>3</sub>-N and NH<sub>4</sub>-N) among 3 surface microsites: live sagebrush, dead sagebrush, and sagebrush interspaces.

### Vegetation Sampling

Because the experiment had limited replication and patchy distribution of vegetation types within plots, we attempted to maximize the area sampled within each plot. This required sampling methods that were different from those used in 1994 and 1997. We estimated canopy cover of shrubs, perennial grasses, and downy brome, and cover of bare

ground using Daubenmire cover classes (Daubenmire 1959) in a total of 2088 subplots (1 m  $\times$  0.5 m) in August 2004. Subplots were placed at 5 m intervals along nine 200-m transects (41 subplots  $\cdot$  transect<sup>-1</sup>) in each plot, for a maximum of 369 subplots per plot. Transects were located in the center of plots and separated by 10 m. Subplots within 10 m of atypical landscape features, including roads, ditches, streams, and wetland areas, were not measured. Therefore, to ensure a minimum of 300 subplots in each whole plot, additional transects were randomly assigned to locations between the original transects where necessary. Cover classes were converted to the median of each cover range for data analysis.

#### Soil Resource Sampling

Given the small number of replications and the high variability among soil samples in preliminary tests, we did not attempt to measure differences in soil resources among herbicide treatments. Instead, we examined the effect of tebuthiuron on soil resources indirectly by measuring the effects of Wyoming big sagebrush death on soil resources. Effects of sagebrush death on soil resources were determined by comparing resource measurements taken from under dead sagebrush, under live sagebrush, and in sagebrush interspaces. Because dead sagebrush plants were rare in untreated plots, these comparisons were conducted only in areas treated with the highest level of tebuthiuron (0.4 kg ai  $\cdot$  ha<sup>-1</sup>). Soil samples were collected from randomly selected locations within 6 (for mineral N and soil water) or 9 (for total C and N) blocks, each comprised of a randomly selected dead sagebrush plant paired with the nearest live sagebrush plant and sagebrush interspace.

For mineral N and water, soil samples were collected at 19 dates between May 2003 and November 2003 (approximately 10-day intervals). Three 1.9-cm-diameter  $\times$  10-cm cores were pooled from each microsite type—live sagebrush canopy, dead sagebrush canopy, and sagebrush interspace—using a soil step-probe. Soil samples from underneath live and dead sagebrush canopies were obtained approximately 15 cm away from the shrub main stem. Soil cores were bagged, stored on ice, and transported to the laboratory for immediate extraction in 1 M KCl. Extractable mineral N was determined on a 1 M KCl extract using a

continuous flow colorimetric procedure (Lachat Instruments, Hach Company, Loveland, CO); NH<sub>4</sub>-N was determined with a sodium salicylate-based method, and NO<sub>3</sub>-N with a cadmium reduction method. To measure effects of microsite on gravimetric water content deeper in the soil profile, one 2.2-cm-diameter  $\times$  50-cm-deep soil core was taken from each microsite-block combination in June, July, August, and September 2003. Soil moisture was determined gravimetrically by drying samples to a constant weight at 105°C. To obtain total C and N, one 5-cm-diameter  $\times$  15-cm core was collected from each microsite-block combination in May 2003. Following removal of all visible roots, soil was passed through a 2-mm sieve, air-dried, and ground with a powder roller. Total C and N were determined with a Carlo Erba NA 1500 automatic carbon-nitrogen analyzer (Haake Buckler Instruments Inc., Saddle Brook, NJ). Inorganic C was measured with a modified pressure-calimeter method (Sherrod et al. 2002). Organic C was calculated by subtracting inorganic C from total C.

#### Data Analysis

All data analyses were conducted using JMP version 5 (SAS Institute 2002). Percent covers of shrubs, bare ground, downy brome, and perennial grasses were compared between herbicide treatments with ANOVA models containing the terms block (random effect), herbicide (fixed effect), herbicide  $\times$  block (random effect), and subplot (fixed effect). Differences in methods precluded statistical comparisons between data from 2004 and data from 1995 or 1997. Therefore, we limit discussion of changes over time to qualitative differences in observed patterns of downy brome invasion. Mineral N and soil water were compared among microsites with ANOVAs containing the terms block (random effect), microsite (fixed effect), microsite  $\times$  block (random effect), and date (fixed effect). Total organic C and N, measured on only 1 date, were compared among microsites with ANOVAs containing the terms block (random effect) and microsite (fixed effect). Effects of herbicide were tested against the herbicide  $\times$  block interaction in all analyses. For all variables compared among microsites, preplanned contrasts were used to determine whether dead sagebrush differed from live sagebrush. Response variables were natural log-transformed as

necessary to correct for heteroscedasticity. For clarity, figures are presented on nontransformed axes.

## RESULTS

### Vegetation

Eleven years following application, tebuthiuron treatment ( $0.4 \text{ kg ai} \cdot \text{ha}^{-1}$ ) had reduced shrub cover by 52% (Fig. 1). Downy brome was common but patchily distributed, occurring in 48% of subplots. Tebuthiuron application increased downy brome cover approximately 4-fold, from 0.9% in untreated plots to 3.5% in treated plots (Fig. 1). Perennial grasses occurred in 99.8% of subplots and also appeared to increase (from 9% to 12.3%) with tebuthiuron application, although this trend was only marginally significant ( $F = 12.9$ ,  $P = 0.07$ ; Fig. 1). Even though downy brome showed a much larger proportional increase in cover than did perennial grasses, their absolute increases in cover were similar. Due to the late-summer sampling date, cover values probably underestimate the maximum seasonal cover for both downy brome and perennial grasses. Percent bare ground also showed a marginally significant increase (from 39.1% to 43.9%) with tebuthiuron application ( $F = 11.6$ ,  $P = 0.08$ ; Fig. 1).

### C, N, and Water Content of Soils

Repeated measures analysis revealed that  $\text{NO}_3\text{-N}$  concentration was significantly affected by both microsite (Fig. 2) and date ( $F = 7.27$ ,  $P < 0.0001$ ), but not by their interaction. Soil organic C and N were also significantly different among microsites (Fig. 2). Preplanned contrasts demonstrated that  $\text{NO}_3\text{-N}$  concentration was higher under dead sagebrush than live sagebrush, but organic C and N did not differ between dead and live sagebrush (Fig. 2).  $\text{NH}_4\text{-N}$  concentrations and soil water content were not influenced by microsite or date (data not shown).

## DISCUSSION

A decade after treatment with tebuthiuron, the herbaceous plant community has expanded, leading to little net change in bare ground, but the proportional increase of downy brome has been much larger than that of perennial grasses

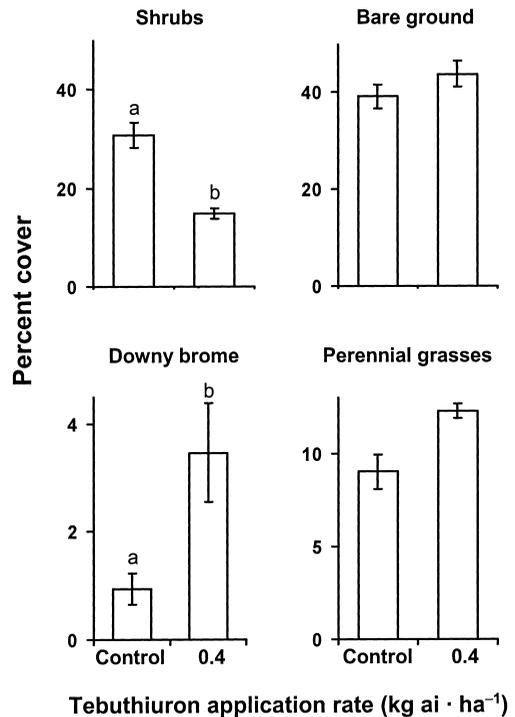


Fig. 1. Percent cover ( $\pm 1 \text{ s.e.}$ ) of vegetation and bare ground in control and herbicide-treated plots 11 years after treatment with tebuthiuron. Note the differences in scale among y-axes. Bars with different letters are significantly different (shrubs:  $F_{1,2} = 609$ ,  $P = 0.002$ ; downy brome:  $F_{1,2} = 52.9$ ,  $P = 0.02$ ) based on split-plot ANOVAs conducted on natural log-transformed data. Herbicide was tested against the herbicide  $\times$  block interaction.

(Fig. 1). This occurred even though downy brome was more patchily distributed (present in 48% of plots) than perennial grasses (present in 99% of plots) and therefore less likely to be exposed to increases in resources made available by shrub death. Although downy brome was locally abundant, its average cover was quite low, demonstrating that tebuthiuron has not yet led to a serious weed problem at this site. Nevertheless, the large proportional increase in downy brome cover suggests that tebuthiuron may have the potential to cause more serious infestations in future years or at other locations. Furthermore, our late-season measurements probably underestimate the contribution of both downy brome and perennial grasses to cover during peak season.

Multiple processes may have contributed to the relatively small proportional responses of perennial grasses relative to downy brome

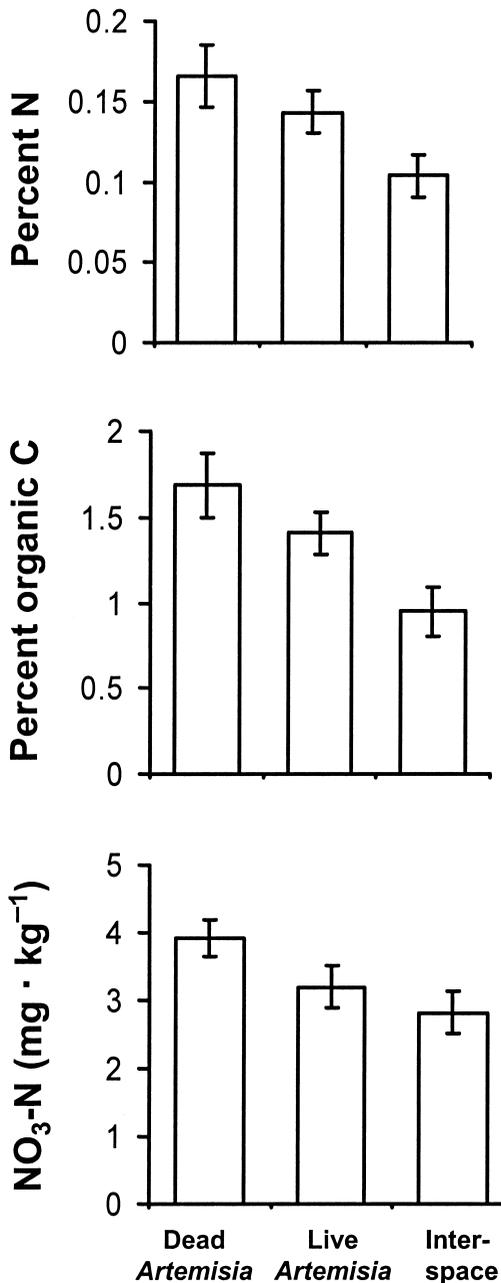


Fig. 2. The effect of microsite type on total organic C (0–15 cm), total N (0–15 cm), and NO<sub>3</sub> (0–15 cm) concentration ( $\pm 1$  s<sub>e</sub>). Effects of microsite were significant for C ( $F_{2,16} = 11.3$ ,  $P < 0.001$ ), N ( $F_{2,16} = 8.92$ ,  $P = 0.003$ ), and NO<sub>3</sub> ( $F_{2,10} = 7.87$ ,  $P = 0.009$ ), based on a split-plot ANOVA in which microsite was tested against the block  $\times$  microsite interaction. Preplanned contrasts demonstrated that NO<sub>3</sub> concentrations were significantly higher under dead sagebrush than live sagebrush ( $F_{1,10} = 6.67$ ,  $P = 0.03$ ), but percent C ( $F_{1,16} = 3.09$ ,  $P = 0.1$ ) and percent N ( $F_{1,16} = 2.21$ ,  $P = 0.2$ ) did not differ among the 2 microsites.

at this site. Because of its rapid growth and high allocation of resources to dispersal, downy brome may have greater ability than perennial grasses to take advantage of newly available resources. In addition, annual grazing of the site may have limited perennial grass response to increased resource availability. It is also possible that the drought immediately preceding this sampling interacted with tebuthiuron, potentially increasing or decreasing the success of downy brome relative to that of perennial grasses.

While this is the longest running study to show a significant difference in downy brome cover between sagebrush thinning treatments, it is in accord with other studies in which downy brome was present prior to herbicide application (Piemeisel 1951, Hedrick et al. 1966, Olson and Whitson 2002). In addition to the 11 years since treatment, 2 lines of evidence suggest that the observed pattern of downy brome abundance may represent a relatively long-term change in the plant community. Four years after treatment this site showed a (nonsignificant) trend in the opposite direction, with more downy brome in control plots than in herbicide-treated plots (Olson and Whitson 2002). This suggests that the differences we measured developed between 4 and 11 years after treatment. Soil resource availability also differed more than 10 years after treatment, with higher NO<sub>3</sub>-N beneath dead sagebrush than beneath live sagebrush (Fig. 2). This may be the direct result of sagebrush death due to decreased uptake or increased decomposition and mineralization of dead sagebrush. Alternatively, higher NO<sub>3</sub>-N could result from downy brome invasion, as downy brome can influence N availability (Evans et al. 2001, Svejcar and Sheley 2001, Booth et al. 2003). Because high levels of available NO<sub>3</sub> are also known to facilitate downy brome invasion and persistence (Paschke et al. 2000, Lowe et al. 2003), conditions may be favorable for continued expansion of downy brome at this site.

#### CONCLUSIONS

At this study site, downy brome invaded following sagebrush thinning despite patchy distribution of downy brome relative to that of perennial grasses. The slow expansion of perennial grasses relative to downy brome (Fig. 1)

and the pattern of higher NO<sub>3</sub>-N availability under dead than live sagebrush plants (Fig. 2) suggest that dispersal and establishment of perennial grasses can be insufficient to monopolize newly available resources. The primary implication of these results for management is that even small populations of downy brome may have sufficient opportunity to find and exploit resources made available by shrub thinning.

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