Environmental Management (2011) 48:539–546
DOI 10.1007/s00267-011-9715-3

#705

Are There Benefits to Mowing Wyoming Big Sagebrush Plant Communities? An Evaluation in Southeastern Oregon

Kirk W. Davies · Jon D. Bates · Aleta M. Nafus

Received: 15 September 2010 / Accepted: 21 June 2011 / Published online: 14 July 2011

Abstract Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle & Young) communities frequently are mowed in an attempt to increase perennial herbaceous vegetation. However, there is limited information as to whether expected benefits of mowing are realized when applied to Wyoming big sagebrush communities with intact understory vegetation. We compared vegetation and soil nutrient concentrations in mowed and undisturbed reference plots in Wyoming big sagebrush plant communities at eight sites for three years post-treatment. Mowing generally did not increase perennial herbaceous vegetation cover, density, or biomass production ($P > 0.05$). Annual forbs and exotic annual grasses were generally greater in the mowed compared to the reference treatment ($P < 0.05$). By the third year post-treatment annual forb and annual grass biomass production was more than nine and sevenfold higher in the mowed than reference treatment, respectively. Our results imply that the application of mowing treatments in Wyoming big sagebrush plant communities does not increase perennial herbaceous vegetation, but may increase the risk that exotic annual grasses will dominate the herbaceous vegetation. We suggest that mowing Wyoming big sagebrush communities with intact understories does not produce the expected benefits. However, the applicability of our results to Wyoming big sagebrush communities with greater sagebrush cover and/or degraded understories needs to be evaluated.

Keywords Annual grass · *Artemisia tridentata* · *Bromus tectorum* · Brush control · Brush management · Sage-grouse

Introduction

Sagebrush (*Artemisia* L.) plant communities occupy approximately 62 million hectares in the western United States (Küchler 1970; Miller and others 1994; West and Young 2000). With European settlement, fire return intervals in some sagebrush plant communities were lengthened and sagebrush dominance increased, which reduced the herbaceous component (West 1983; Miller and Rose 1999). Consequently, there is a desire to increase understory herbaceous production and diversity of stand characteristics across sagebrush landscapes to provide a mosaic of habitats (Connelly and others 2000; Olson and Whitson 2002; Crawford and others 2004; Beck and others 2009). Thus, sagebrush control treatments have been applied across a variety of sagebrush plant communities with degraded to relatively intact herbaceous understories (dominated by native perennial bunchgrasses and forbs). However, limited information is available to evaluate the effects of applying mowing treatments in Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle & Young) plant communities with relatively intact herbaceous understories.

Sagebrush control, using a variety of methods, has been reported to generate two to threefold increases in herbaceous vegetation (Davies and others 2007a; Harniss and Murray 1973; Hedrick and others 1966; McDaniel and

Mention of a proprietary product does not constitute a guarantee or warranty of the product by USDA, Oregon State University, or the authors and does not imply its approval to the exclusion of other products.

K. W. Davies (✉) · J. D. Bates · A. M. Nafus
Agricultural Research Service, Eastern Oregon Agricultural Research Center, United States Department of Agriculture, 67826-A Hwy 205, Burns, OR 97720, USA
e-mail: kirk.davies@oregonstate.edu

others 1991; Mueggler and Blaisdell 1958; Sneva 1972; Sturges 1983, 1993; Uresk and others 1976; Wambolt and Payne 1986). However, herbaceous vegetation does not always increase following sagebrush control (Blaisdell 1953; Peek and others 1979; Sturges 1986). There is also a risk that the increase in herbaceous vegetation will be exotic annual grasses. Exotic annual grass invasion has been documented to occur following disturbances that reduce sagebrush in Wyoming big sagebrush plant communities (Davies and others 2009b; Stewart and Hull 1949; Young and Allen 1997).

Sagebrush control treatments may improve habitat for some wildlife species by increasing perennial forbs and grasses, especially when sagebrush cover is high (Beck and Mitchell 2000; Crawford and others 2004; Dahlgren and others 2006). However, recent work suggested that this may not always apply to Wyoming big sagebrush plant communities (Beck and others 2009; Rhodes and others 2010). Beck and others (2009) and Rhodes and others (2010) reported that burning Wyoming big sagebrush plant communities did not improve sage-grouse (*Centrocercus urophasianus*) habitat. Davies and others (2009a) cautioned against mowing Wyoming big sagebrush in winter habitat for sagebrush facultative and obligate wildlife because of the cover and forage benefits provided by sagebrush; however, they did not evaluate herbaceous response to mowing.

Much of the research demonstrating positive vegetation responses to mowing and other mechanical sagebrush control has occurred in dense mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana* (Rydb.) Beetle) plant communities (e.g., Dahlgren and others 2006), thus limiting the inferences that can be made in Wyoming big sagebrush plant communities. In the northern Great Basin, Wyoming big sagebrush plant communities are less diverse, produce less herbaceous vegetation, and generally have less than half as much sagebrush cover as mountain big sagebrush plant communities (Davies and Bates 2010a, b). Thus, extrapolating results from mountain big sagebrush plant communities to Wyoming big sagebrush plant communities is not prudent. Understanding the impacts of mowing Wyoming big sagebrush plant communities is critical because these plant communities are widely distributed across western North America and provide valuable wildlife habitat (Connelly and others 2000; Shipley and others 2006; Wallestad and others 1975) and an important forage base for livestock operations (Davies and others 2006).

The objective of this study was to evaluate the response of relatively intact Wyoming big sagebrush plant communities to mowing. We hypothesized that mowing would: (1) increase perennial forbs and perennial grasses, (2) decrease sagebrush cover and density, and (3) increase annual forbs and annual grasses in the first post-treatment year, but they would rapidly (in the 2nd or 3rd year post-treatment) decline to levels comparable to the non-treated controls as perennial grasses and perennial forbs increased.

Methods

Study Area

The study occurred on eight sites in the middle of the High Desert Ecological Province (Anderson and others 1998) in southeastern Oregon between Wagontire, OR and Diamond, OR. Climate across the study area is characteristic of the northern Great Basin with cool, wet winters and springs, and hot, dry summers. Regional precipitation during 2007, 2008, and 2009 was approximately 80, 66, and 88% of the 40-year long-term average precipitation, respectively. Average annual precipitation ranges between 250 and 275 mm across the study area (Oregon Climatic Service 2009). The dominant shrub at all sites was Wyoming big sagebrush. Sites selected for inclusion in the experiment were considered Wyoming big sagebrush plant communities with relatively intact, native herbaceous understories based on vegetation characteristics described in Davies and others (2006). Prior to treatment the herbaceous understory was dominated by native perennial bunchgrasses and forbs. Native perennial bunchgrass and forb cover averaged 8 and 2%, respectively. Exotic annual grass cover was <0.5% in all sites prior to treatment. Sagebrush cover averaged 14% and ranged from 9 to 17%, depending on site, prior to treatment. These herbaceous and sagebrush cover values were within the range reported by Davies and others (2006) for undisturbed, intact Wyoming big sagebrush plant communities. Common perennial grasses included bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Löve), Thurber's needlegrass (*Achnatherum thurberianum* (Piper) Barkworth), squirreltail (*Elymus elymoides* (Raf.) Swezey), and Sandberg bluegrass (*Poa secunda* J. Presl). Dominant perennial bunchgrass species varied among the sites. Common perennial forbs included hawksbeard (*Crepis* L. species), biscuitroot (*Lomatium* Raf. species), and milkvetch (*Astragalus* L. species). Livestock were excluded from the study sites for the duration of the experiment. Elevation of the study sites ranged from 1450 to 1530 m above sea level. Slopes ranged from flat (0–2%) to approximately 8% across the eight sites.

Experimental Design and Measurements

A randomized block design was used to evaluate the vegetation response to mowing. Eight sites (blocks) were selected for inclusion in the study. Blocks were on three different Ecological Sites and varied in topography, herbaceous vegetation, and stand structure. Ecological Sites were Clayey 10-12 PZ-Wyoming big sagebrush/Thurber needlegrass, Loamy 10-12 PZ-Wyoming big sagebrush/ bluebunch wheatgrass, and South Slopes 8-12 PZ-Wyoming big sagebrush/bluebunch wheatgrass (NRCS 2010). Three blocks were located on each Ecological Site, except only two blocks were on the South Slopes 8-12 PZ-Wyoming big sagebrush/bluebunch wheatgrass Ecological Site. Each block consisted of two, 25 × 120-m plots and treatments were randomly assigned to one of the plots. Both plots within a block had uniform vegetation characteristics, topography, and soils. Treatments were either: (1) mowed or (2) an undisturbed reference site (reference). Mowing treatments were implemented with a John Deere 1418 rotary cutter (Deer and Company, Moline, IL, USA) in the fall of 2006. Sagebrush was mowed at 20 cm height above the soil surface. Response variables were herbaceous vegetation cover, density, and biomass production, shrub cover and density, litter and moss cover, and soil nutrient concentrations.

Vegetation response variables at each plot were measured using two, parallel 100-m transects, spaced 10 m apart and 7.5 m from the treatment edges. Vegetation characteristics were sampled in mid-June in 2007, 2008, and 2009. Shrub canopy cover by species was measured using the line intercept method (Canfield 1941) on each of the 100-m transects. Canopy gaps less than 15 cm were included in the shrub canopy cover measurements. Shrub density was measured by species by counting all plants rooted inside two, 2 × 100-m belt transects. The belt transects were placed along each of the two, 100-m transects spaced 10-m apart. Wyoming big sagebrush density was separated into mature and juvenile sagebrush classes. Sagebrush plants were classified as juvenile if they were less than 20 cm tall, had not been mowed, and did not have reproductive structures. Herbaceous canopy cover was visually estimated by species to the nearest 1% inside 40 × 50-cm quadrats (0.2 m^2) located at 3-m intervals on each 100-m transect (starting at 3 m and ending at 90 m), resulting in 30 quadrats per transect and 60 quadrats per plot. Litter and moss ground cover were also visually estimated inside 0.2-m^2 quadrats. Moss was not identified to genera or species level. Herbaceous vegetation density was measured by counting individuals by species inside each 0.2-m^2 quadrat. Herbaceous biomass production (above-ground) was determined by plant functional group by clipping to 3-cm height, oven drying at 50°C until reaching a consistent weight, separating current year's growth from previous years' growth, and then weighing, to the nearest 0.1 g, the current year's growth from 15 randomly located 1-m^2 quadrats per plot.

Nutrient supply rates of potassium, phosphorus, and inorganic nitrogen (nitrate and ammonium) were estimated using four anion and four cation PRS™-probes (Western Ag Innovations, Saskatoon, Saskatchewan, Canada) randomly placed in each treatment plot in each site. The PRS™-probe pairs were buried directly into the soil to estimate the availability of soil nutrients to plants in each treatment plot (Jowkin and Schoenau 1998). PRS™-probes attract and adsorb ions through electrostatic attraction on an ion-exchange membrane. PRS™-probes were placed vertically in the upper 20 cm of the soil profile to estimate nutrient supply rates from 15 April until 1 July in 2007, 2008, and 2009. PRS™-probes were returned to Western Ag Innovations for analysis. The probes were extracted with 0.5 N HCl and analyzed colourimetrically with an autoanalyzer to determine nutrient supply.

Statistical Analyses

We used repeated measures analysis of variance (ANOVA) using the mixed models procedure (Proc Mix) in SAS v.9.1 (SAS Institute Inc., Cary, NC) to determine the influence of mowing on vegetation characteristics and soil nutrient supply rates. Fixed variables were treatment and time since treatment (year) and their interactions. Random variables were sites and site by treatment interactions. Covariance structures used in the ANOVA's were determined using the Akaike's Information Criterion (Littell and others 1996). When there was an interaction between year and treatment, treatment effects were also evaluated in each year of the study. Fisher's protected LSD was used to test for differences between treatment means. Data were tested for normality using the univariate procedure in SAS v.9.1 (Littell and others 1996). Data that violated assumptions of normality were log-transformed. Data plotted in graphs were original data (i.e., non-transformed). Response variable means were reported with standard errors. Differences between means were considered significant at $P \leq 0.05$. For analyses, herbaceous cover, density, and biomass production were grouped into five functional groups: Sandberg bluegrass, large perennial grass, annual grass (cheatgrass was only annual grass detected), perennial forbs, and annual forbs. Sandberg bluegrass was treated as a separate functional group from the other (large) perennial grasses because it is smaller in size and its phenological development occurs earlier than other perennial grasses in these plant communities (Davies 2008; James and others 2008). Annual forb functional group included both native and introduced annual forbs; however, this functional group was dominated by natives.

Results

Large perennial grass and sagebrush canopy cover were greater in the reference than mowed treatment (Fig. 1;

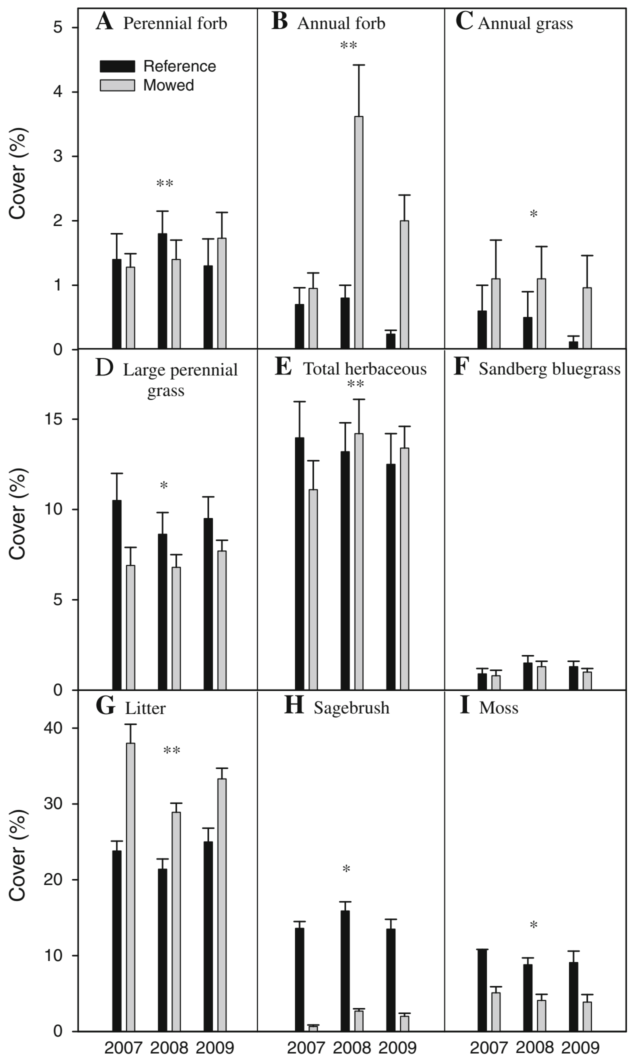

Fig. 1 Functional group canopy cover, and litter and moss ground cover values (mean + S.E.) of the mowed and reference treatments in Wyoming big sagebrush plant communities in 2007, 2008, and 2009. A single asterisk (*) indicates significant ($P \leq 0.05$) treatment differences and a double asterisk (**) indicates significant ($P \leq 0.05$) treatment × year interaction

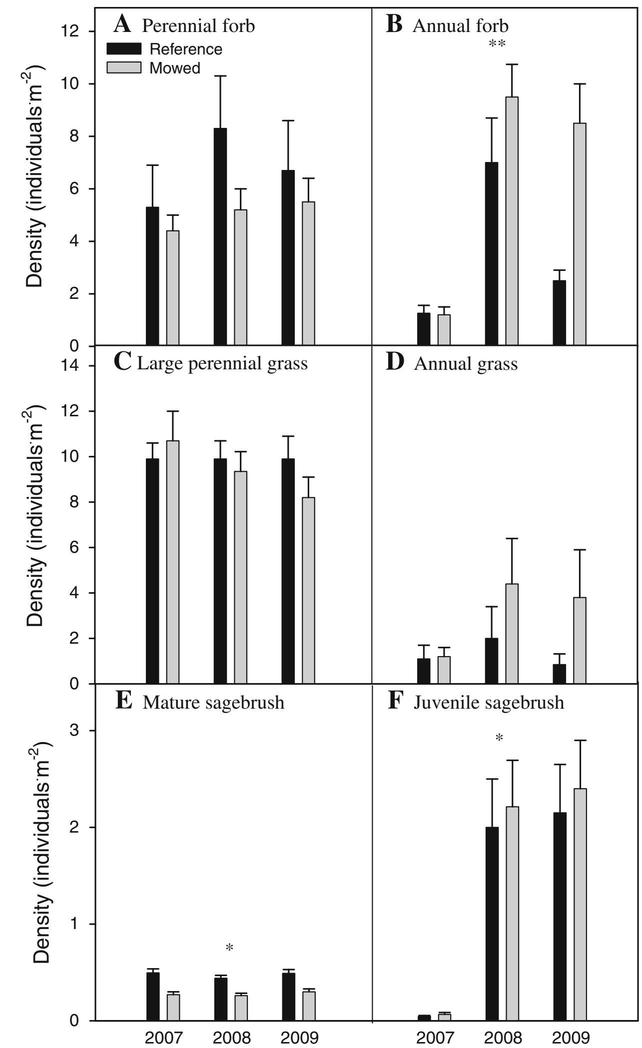

Fig. 2 Functional group density values (mean + S.E.) of the mowed and reference treatments in Wyoming big sagebrush plant communities in 2007, 2008, and 2009. A single asterisk (*) indicates significant ($P \leq 0.05$) treatment differences and a double asterisk (**) indicates significant ($P \leq 0.05$) treatment × year interaction

$P = 0.02$ and <0.01, respectively). Annual grass canopy cover was greater in the mowed than reference treatment ($P = 0.05$). Perennial forb, annual forb, total herbaceous, and litter cover were influenced by the interaction between treatment and year ($P = 0.03$, <0.01, 0.01, and <0.01, respectively). In 2007 and 2009, perennial forb canopy cover was not different between treatments ($P > 0.05$), but in 2008 it was greater in the reference treatment ($P < 0.01$). Annual forb canopy cover was not different between treatments in 2007 ($P = 0.11$), but in 2008 and 2009 annual forb cover was greater in the mowed compared to the reference treatment ($P < 0.01$). Total herbaceous canopy cover was greater in the reference in 2007 ($P < 0.01$), but no difference was detected in 2008 and 2009 ($P > 0.10$). Litter ground cover was less in the reference than mowed treatment in all years ($P < 0.01$). Moss ground cover was twofold greater in the reference than mowed treatment ($P < 0.01$). Sandberg bluegrass and green rabbitbrush (*Chrysothamnus viscidiflorus* (Hook.) Nutt.) canopy cover were not influenced by treatment ($P > 0.10$).

Annual forb density was influenced by the interaction between treatment and year (Fig. 2; $P = 0.01$). Annual forb density did not differ between treatments in 2007 and 2008 ($P > 0.10$); however, annual forb density was almost fourfold greater in the mowed compared to the reference in 2009 ($P < 0.01$). Mature Wyoming sagebrush density was generally more than twofold higher in the reference than the mowed treatment ($P < 0.01$). Juvenile sagebrush

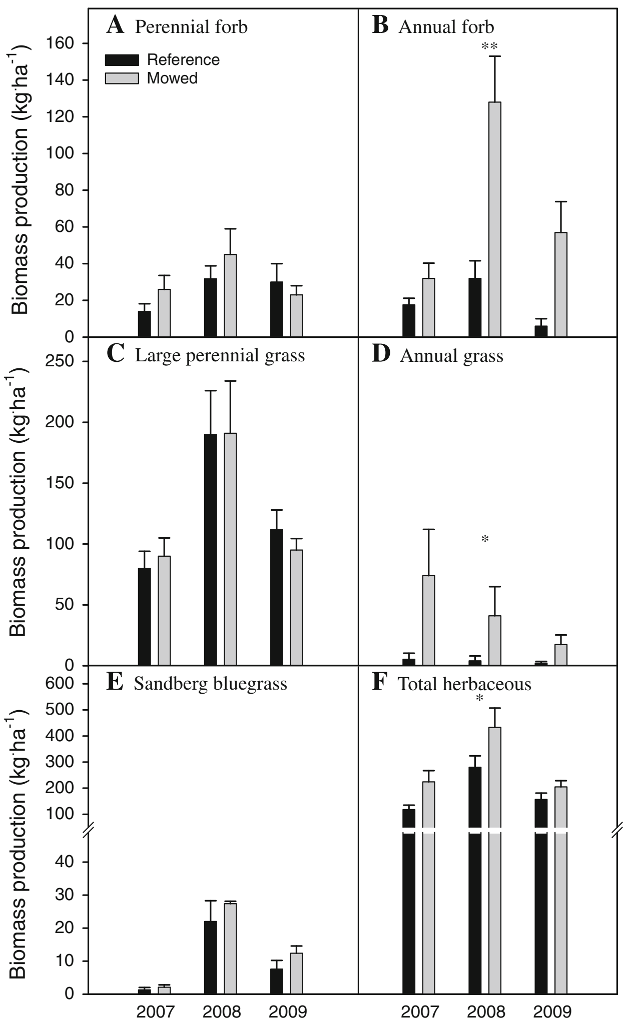

Fig. 3 Functional group biomass production (above-ground) (mean + S.E.) of the mowed and reference treatments in Wyoming big sagebrush plant communities in 2007, 2008, and 2009. A single asterisk (*) indicates significant ($P \leq 0.05$) treatment differences and a double asterisk (**) indicates significant ($P \leq 0.05$) treatment × year interaction

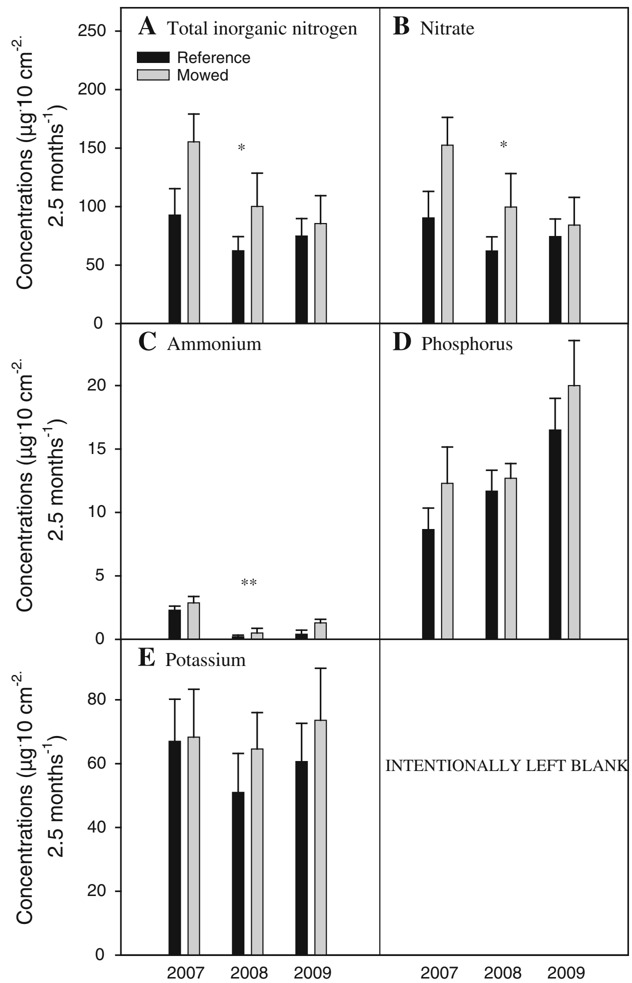

Fig. 4 Soil nutrient concentrations (mean + S.E.) of the mowed and reference treatments in Wyoming big sagebrush plant communities in 2007, 2008, and 2009. A single asterisk (*) indicates significant ($P \leq 0.05$) treatment differences and a double asterisk (**) indicates significant ($P \leq 0.05$) treatment × year interaction

density was approximately 1.1-fold greater in the mowed compared to the reference treatment ($P < 0.01$). Sandberg bluegrass (data not shown), large perennial grass, annual grass, perennial forb, and green rabbitbrush density did not vary by treatment ($P > 0.10$).

Annual forb biomass production was influenced by the interaction between treatment and year (Fig. 3; $P = 0.02$). Annual forb biomass production was greater in the mowed compared to the reference treatment in 2008 and 2009 ($P < 0.01$). Annual grass biomass production was 14-, 10- and 7-fold greater in the mowed compared to the reference treatment in 2007, 2008, and 2009, respectively ($P < 0.01$). Total herbaceous biomass production was between 1.3- and 1.9-fold greater in the mowed than the reference treatment ($P < 0.01$). Sandberg bluegrass, large perennial grass, and perennial forb biomass production did not differ between treatments ($P = 0.11$, 0.90, and 0.41, respectively).

Total inorganic N and nitrate supply rates were 1.1 to 1.7-fold higher in the mowed than reference treatment (Fig. 4; $P = 0.04$ and 0.04, respectively). Ammonium soil supply rates varied by the interaction between treatment and year ($P < 0.01$). Ammonium soil supply rates did not differ between treatments in 2007 and 2008 ($P = 0.34$ and 0.11, respectively), but were greater in the mowed than reference treatment in 2009 ($P < 0.01$). Potassium and phosphorus soil supply rates did not vary by treatment ($P = 0.32$ and 0.14, respectively).

Discussion

Our results question the appropriateness of applying mowing treatments in relatively intact Wyoming big sagebrush plant communities to increase native perennial herbaceous vegetation. The lack of increase in perennial grasses and perennial forbs suggests that mowing Wyoming big sagebrush does not have a desirable impact. Though total herbaceous production was greater with mowing, it was mainly due to greater amounts of annual forbs and exotic annual grasses in the mowed than reference treatment (Fig. 3). The dissimilarity between our results and others (e.g., Dahlgren and others 2006; Hedrick and others 1966; Mueggler and Blaisdell 1958; Wambolt and Payne 1986) is probably due to variation among different sagebrush plant communities. For example, Wyoming big sagebrush plant communities produce about half the herbaceous production and plant diversity as mountain big sagebrush plant communities (Davies and Bates 2010a). Thus, differing responses to a management action between Wyoming and mountain big sagebrush plant communities is not surprising. However, Wyoming big sagebrush plant communities with greater sagebrush cover than our study sites may have responded differently. Herbaceous understories at our study sites were not suppressed by a dense sagebrush stand, thus reducing sagebrush may not have greatly increased resource availability to perennial herbaceous vegetation. In addition, the three post-treatment years were also drier than the long-term average and this may have limited perennial herbaceous vegetation response. Thus, longer term evaluation is needed to determine if there may be a lagged perennial herbaceous vegetation response to mowing.

The small increase in exotic annual grass after mowing is a concern. Exotic annual grass invasion can reduce the quality and/or quantity of livestock forage, degrade wildlife habitat, decrease biodiversity, increase fire frequency, and alter ecological processes (Dahl and Tisdale 1975; Davies and Svejcar 2008; Hironaka 1961; Mack 1981; Young 1992). However, exotic annual grass was not a major component of either the mowed or undisturbed Wyoming big sagebrush plant communities and thus, its increase may be biologically insignificant. Nevertheless, its increased presence may elevate the risk of conversion to exotic annual grass dominant plant communities, especially if subsequent disturbances occur. Exotic annual grass may also have been a more serious problem if it had been a larger component of theses plant communities prior to mowing.

The increased concentrations of soil inorganic N following mowing treatments may have facilitated the exotic annual grass increase. Excess resources increase the success of exotic plant invasions (Burke and Grime 1996; Davis and others 2000; Huenneke and others 1990). Exotic annual grasses become more competitive with native plants with increasing soil resource concentrations (Vasquez and others 2008; Young and Allen 1997). Exotic annual grasses also are more effective at exploiting pulses of resources than native perennial vegetation (James and others 2006; Norton and others 2007). Because of the increase in exotic annual grass production, elevated soil inorganic N, and lack of perennial herbaceous vegetation response observed in this study following mowing, practitioners should be cognitive of the increased risk of exotic annual dominance post-mowing.

Lower moss cover in the mowed compared to the reference treatment is also concerning, because moss, a major component of biological soil crusts, is an essential component of desert ecosystems (Belnap and others 2006). Less moss cover with mowing is probably the result of increased soil surface disturbance (i.e., soil disturbance from tractor tires and propelled sagebrush twigs) and decreased sagebrush cover. Soil surface disturbances have been repeatedly demonstrated to reduce moss abundance (Warren and Eldridge 2003). The recovery of surface mosses from disturbances in sagebrush plant communities is also slow (Hilty and others 2004). Decreased sagebrush cover may have also negatively impacted moss cover, because moss cover is more than twofold greater under sagebrush canopies than in the interspace between canopies (Davies and others 2007b). Thus, mowing may have some long-term negative impacts on biological soil crusts.

Less sagebrush cover and fewer mature sagebrush plants in the mowed treatment have substantial implications to wildlife species that rely heavily on sagebrush. Sage-grouse and pygmy rabbit (*Brachylagus idahoensis*) diets are high in sagebrush leaves and at times sagebrush is almost their sole food source (Green and Flinders 1980; Shipley and others 2006; Wallestad and others 1975). Other wildlife species also consume large quantities of big sagebrush. Pronghorn (*Antilocapra americana*) diets contained about 61% sagebrush in Oregon (Mason 1952) and sagebrush can comprise more than 50% of mule deer diets in January and February (Austin and Urness 1983). Greater density of juvenile sagebrush plants in the mowed compared to the reference treatment suggests that sagebrush will recover. However, sagebrush density and cover are estimated to be depressed approximately 10 and 19 years post-mowing, respectively (Davies and others 2009a).

Our study does not provide evidence of a benefit from mowing Wyoming big sagebrush plant communities with relatively intact herbaceous understories. We did not, however, evaluate the potential response of Wyoming big sagebrush plant communities with a depleted herbaceous understory. Degraded understories may need sagebrush dominance to be reduced to recover (Olson and Whitson 2002; West 2000). However, our study implies that exotic annual grasses could be a potential problem with mowing degraded Wyoming big sagebrush plant communities.

Conclusions

Our study suggests that the presumed benefits of mowing relatively intact Wyoming big sagebrush plant communities in the northern Great Basin may be unrealized. The positive effects of mechanically treating mountain big sagebrush plant communities (Dahlgren and others 2006) does not appear to apply to relatively intact Wyoming big sagebrush plant communities. The elevated risk of exotic annual grass dominance post-mowing provides evidence that questions the wisdom of applying this treatment. However, we suggest that longer term evaluations of mowing intact Wyoming big sagebrush plant communities are needed to determine if there is a lagged perennial herbaceous vegetation response. The effects of mowing Wyoming big sagebrush plant communities with degraded understories and/or higher sagebrush cover also needs to be evaluated. Thus, we caution against mowing relatively intact Wyoming big sagebrush plant communities, especially considering the decline of sagebrush across the western United States.

Acknowledgments The authors thank summer students for their assistance in implementing and collecting data for this experiment. The authors also thank Burns-District Bureau of Land Management for providing land for this research project and applying the treatments. The USDA – Agricultural Research Service provided all additional funds to conduct this research.

References

Anderson EW, Borman MM, Krueger WC (1998) The ecological provinces of Oregon: a treatise on the basic ecological geography of the state. Oregon Agricultural Experiment Station, Corvallis

Austin DD, Urness PJ (1983) Overwinter forage selection by mule deer on seeded big sagebrush-grass range. Journal of Wildlife Management 47:1203–1207

Beck JL, Mitchell DL (2000) Influences of livestock grazing on sage grouse habitat. Wildlife Society Bulletin 28:993–1002

Beck JL, Connelly JW, Reese KP (2009) Recovery of greater sage-grouse habitat features in Wyoming big sagebrush following prescribed fire. Restoration Ecology 17:393–403

Belnap J, Phillips SL, Troxler T (2006) Soil lichen and moss cover and species richness can be highly dynamic: The effects of invasion by the annual exotic grass *Bromus tectorum*, precipitation, and temperature on biological soil crusts in SE Utah. Applied Soil Ecology 32:63–76

Blaisdell JP (1953) Ecological effects of planned burning of sagebrush-grass range on the upper Snake River Plains. USDA Technical Bulletin No. 1075, Washington

Burke MJW, Grime JP (1996) An experimental study of plant community invasibility. Ecology 77:776–790

Canfield RH (1941) Application of the line interception method in sampling range vegetation. Journal of Forestry 39:388–394

Connelly JW, Schroeder MA, Sands AR, Braun CE (2000) Guidelines to manage sage grouse populations and their habitats. Wildlife Society Bulletin 28:967–985

Crawford JA, Olson RA, West NE, Mosley JC, Schroeder MA, Whitson TD, Miller RF, Gregg MA, Boyd CS (2004) Ecology and management of sage-grouse and sage-grouse habitat. Journal of Range Management 57:2–19

Dahl BE, Tisdale EW (1975) Environmental factors related to medusahead distribution. Journal of Range Management 28:463–468

Dahlgren DK, Chi R, Messmer TA (2006) Greater sage-grouse response to sagebrush management in Utah. Wildlife Society Bulletin 34:975–985

Davies KW (2008) Medusahead dispersal and establishment in sagebrush steppe plant communities. Rangeland Ecology and Management 61:110–115

Davies KW, Bates JD (2010a) Vegetation characteristics of mountain and Wyoming big sagebrush plant communities in the northern Great Basin. Rangeland Ecology and Management 63:461–466

Davies KW, Bates JD (2010b) Native perennial forb variation between mountain big sagebrush and Wyoming big sagebrush plant communities. Environmental Management 46:452–458

Davies KW, Svejcar TJ (2008) Comparison of medusahead-invaded and noninvaded Wyoming big sagebrush steppe in southeastern Oregon. Rangeland Ecology and Management 61:623–629

Davies KW, Bates JD, Miller RF (2006) Vegetation characteristics across part of the Wyoming big sagebrush alliance. Rangeland Ecology and Management 59:567–575

Davies KW, Bates JD, Miller RF (2007a) Short-term effects of burning Wyoming big sagebrush steppe in southeastern Oregon. Rangeland Ecology and Management 60:515–522

Davies KW, Bates JD, Miller RF (2007b) The influence of *Artemisia tridentata* ssp. *wyomingensis* on microsite and herbaceous vegetation heterogeneity. Journal of Arid Environments 69: 441–457

Davies KW, Bates JD, Johnson DD, Nafus AM (2009a) Influence of mowing *Artemisia tridentata* ssp. *wyomingensis* on winter habitat for wildlife. Environmental Management 44:84–92

Davies KW, Svejcar TJ, Bates JD (2009b) Interaction of historical and nonhistorical disturbances maintains native plant communities. Ecological Applications 19:1536–1545

Davis MA, Grime JP, Thompson K (2000) Fluctuating resources in plant communities: a general theory of invasibility. Journal of Ecology 88:528–534

Green JS, Flinders JT (1980) Habitat and dietary relationships of the pygmy rabbit. Journal of Range Management 33:136–142

Harniss RO, Murray RB (1973) 30 years of vegetal change following burning of sagebrush-grass range. Journal of Range Management 26:322–325

Hedrick DW, Hyder DN, Sneva FA, Poulton CE (1966) Ecological response of sagebrush-grass range in Central Oregon to mechanical and chemical removal of *Artemisia*. Ecology 47:432–439

Hilty JH, Eldridge DJ, Rosentreter R, Wicklow-Howard MC, Pellant M (2004) Recovery of biological soil crusts following wildfire in Idaho. Journal of Range Management 57:89–96

Hironaka M (1961) The relative rate of root development of cheatgrass and medusahead. Journal of Range Management 14:263–267

Huenneke LF, Hamburg SP, Koide R, Mooney HA, Vitousek PM (1990) Effects of soil resources on plant invasion and community structure in Californian serpentine grasslands. Ecology 71:478–491

James JJ, Caird MA, Drenovsky RE, Sheley RL (2006) Influence of resource pulses and perennial neighbors on the establishment of an invasive annual grass in the Mojave Desert. Journal of Arid Environments 67:528–534

James JJ, Davies KW, Sheley RL, Aanderud ZT (2008) Linking nitrogen partitioning and species abundance to invasion resistance in the Great Basin. Oecologia 156:637–648

Jowkin V, Schoenau JJ (1998) Impact of tillage and landscape position on nitrogen availability and yield of spring wheat in the brown soil zone in southwestern Saskatchewan. Canadian Journal of Soil Science 78:563–572

Küchler AW (1970) Potential natural vegetation. The national atlas of U.S.A. In: Gerlach AC (ed) The national atlas of U.S.A. US Government Printing Office, Washington, pp 90–91

Littell RC, Milliken GA, Stroup WW, Wolfinger RD (1996) SAS System for mixed models. SAS Institute Inc., Cary

Mack RN (1981) Invasion of *Bromus tectorum* L. into western North America: an ecological chronicle. Agro-ecosystems 7:145–165

Mason E (1952) Food habits and measurements of Hart Mountain antelope. Journal of Wildlife Management 16:387–389

McDaniel KC, Anderson DL, Balliette JF (1991) Wyoming big sagebrush control with metsulfuron and 2,4-D in northern New Mexico. Journal of Range Management 44:623–627

Miller RF, Rose JA (1999) Fire history and western juniper encroachment in sagebrush steppe. Journal of Range Management 52:550–559

Miller RF, Svejcar TJ, West NE (1994) Implications of livestock grazing in the intermountain sagebrush region: plant composition. In: Vavra M, Laycock WA, Pieper RD (eds) Ecological implications of livestock herbivory in the West. Society for Range Management, Denver, pp 101–146

Mueggler WF, Blaisdell JP (1958) Effects on associated species of burning, rotobeating, spraying, and railing sagebrush. Journal of Range Management 11:61–66

Norton JB, Monaco TA, Norton U (2007) Mediterranean annual grasses in western North America: kids in a candy store. Plant and Soil 298:1–5

NRCS (2010) Soil Survey. http://websoilsurvey.nrcs.usda.gov/. Accessed 5 Jan 2010

Olson RA, Whitson TD (2002) Restoring structure in late-successional sagebrush communities by thinning with tebuthiuron. Restoration Ecology 10:146–155

Oregon Climatic Service (2009) http://www.ocs.oregonstate.edu/index.html. Accessed 1 Sep 2009

Peek JM, Riggs RA, Lauer JL (1979) Evaluation of fall burning on bighorn sheep winter range. Journal of Range Management 32:430–432

Rhodes EC, Bates JD, Sharp RN, Davies KW (2010) Fire effects on cover and dietary resources of sage-grouse habitat. Journal of Wildlife Management 74:755–764

Shipley LA, Davila TB, Thines NJ, Elias BA (2006) Nutritional requirements and diet choices of pygmy rabbit (*Brachylagus idahoensis*): a sagebrush specialist. Journal of Chemical Ecology 32:2455–2474

Sneva FA (1972) Grazing return following sagebrush control in eastern Oregon. Journal of Range Management 25:174–178

Stewart G, Hull AC (1949) Cheatgrass (*Bromus tectorum* L.)—an ecologic intruder in southern Idaho. Ecology 30:58–74

Sturges DL (1983) Long-term effects of big sagebrush control on vegetation and soil water. Journal of Range Management 36:760–765

Sturges DL (1986) Response of vegetation and ground cover to spraying a high elevation, big sagebrush watershed with 2,4-D. Journal of Range Management 39:141–146

Sturges DL (1993) Soil-water and vegetation dynamics through 20 years after big sagebrush control. Journal of Range Management 46:161–169

Uresk DW, Cline JF, Rickard WH (1976) Impacts of wildfire on three perennial grasses in south-central Washington. Journal of Range Management 29:309–310

Vasquez E, Sheley R, Svejcar T (2008) Nitrogen enhances the competitive ability of cheatgrass (*Bromus tectorum*) relative to native grasses. Invasive Plant Science and Management 1:287–295

Wallestad R, Peterson JG, Eng RL (1975) Foods of adult sage grouse in central Montana. Journal of Wildlife Management 39:628–630

Wambolt CL, Payne GF (1986) An 18-year comparison of control methods for Wyoming big sagebrush in southwestern Montana. Journal of Range Management 39:314–319

Warren SD, Eldridge DJ (2003) Biological soil crusts and livestock in arid ecosystems: are they compatible? In: Belnap J, Lange O (eds) Biological soil crusts: structure, function, and management. Springer, Berlin, pp 401–415

West NE (1983) Western Intermountain sagebrush steppe. In: West NE (ed) Ecosystems of the world: temperate deserts and semideserts. Elsevier Scientific Publishing Company, Amsterdam, pp 351–374

West NE (2000) Synecology and disturbance regimes of sagebrush steppe ecosystems. In: Entwistle PG, DeBolt AM, Kaltenecker JH, Steenhof K (eds) Sagebrush steppe ecosystem symposium. Bureau of Land Management, Boise, pp 15–26

West NE, Young JA (2000) Intermountain valleys and lower mountain slopes. In: Barbour MG, Billing WD (eds) North American terrestrial vegetation. Cambridge University Press, Cambridge, pp 255–284

Young JA (1992) Ecology and management of medusahead (*Taeniatherum caput-medusa* spp. *asperum* [SIMK] Melderis). Great Basin Naturalist 52:245–252

Young JA, Allen FL (1997) Cheatgrass and range science: 1930–1950. Journal of Range Management 50:530–535