FORAGE RESPONSE TO SIMULATED SHEEP GRAZING OF LEAFY SPURGE

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Animal and Range Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

January 2008

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Benjamin John Hileman

January 2008

ACKNOWLEDGEMENTS

I would like to thank the people who made this project possible. Thank you to my graduate committee, Bret Olson, Matt Rinella, and Jim Robison-Cox, for sound academic advice, valuable thesis feedback, and statistical guidance. I am especially grateful to Matt for developing, securing funding, and allowing me to be part of this project.

Thank you to the Montana Department of Agriculture-Noxious Weed Trust Fund, the USDA-Agricultural Research Service, and the MSU-Montana Agricultural Experiment Station for funding this research. Also, thank you to Jim Phalen and Christine Keltner for the use of your properties as study sites.

Thank you to Kaci Woods, Joe Herzog, Prairie Hight, Danny Pratt, Garrett Larson, and Christine Corbin. This project would not have been possible without your help with field work. Thank you also to Nina Lynch for starting field work on this project and for loaning me your basement during the summers I spent in Miles City.

Thank you to Kenny Strobel, Phil Smith, Eddie Arnoldt, and Lee Hendry, for fixing tires, welding plot frames, changing oil, and much more. Thank you to Diona Austill and Sue Miles for helping with graphs, and everyone at Fort Keogh for your friendship and willingness to help whenever possible.

Thank you to all of the graduate students who call the basement of Linfield Hall home. Your friendship and encouragement will not be forgotten. And last, but certainly not least, I would like to thank my wife, Christin, and the rest of my family for your love and support throughout the last two years. I could not have done this without all of you.

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ABSTRACT

Sheep grazing can lower leafy spurge biomass production; however, forage available for other domestic livestock or wildlife after sheep grazing is unknown. Our objective was to determine how forage biomass was affected by different sheep grazing patterns to answer the following questions: 1) will forage consumed by sheep while grazing leafy spurge be mitigated by higher forage biomass production resulting from lowering leafy spurge biomass production, 2) what timing and intensity of grazing maximizes forage biomass production and minimizes leafy spurge biomass production, 3) will defoliating leafy spurge result in higher forage biomass production by the end of the first grazing season, and 4) does the density of leafy spurge affect the response of forage biomass production. Three leafy spurge-infested sites in southeastern Montana were mechanically defoliated each summer for two or three years in a manner which mimicked sheep grazing. Plots were defoliated once or twice per growing season at pre-flowering, flowering, seed production, or pre-flowering and seed producing phenological stages of leafy spurge. Grasses, forbs, and leafy spurge were defoliated at two different intensities in irrigated and non-irrigated plots. High intensity defoliation of only forage species at flowering tended to result in lower forage biomass and higher leafy spurge biomass. On average, three years of high intensity defoliation of forage species at pre-flowering resulted in forage biomass sufficient to replace forage removed by sheep; three years of low intensity defoliation of forage species at pre-flowering and seed production resulted in forage biomass higher than baseline at all sites, but forage biomass production was not sufficient to replace all forage removed by sheep. These same treatments lowered the amount of leafy spurge biomass produced. High intensity defoliation of forage species and leafy spurge at pre-flowering, and at pre-flowering and seed production resulted in higher forage biomass at the end of the first grazing season at only one site. Leafy spurge density did not affect treatments. Therefore, sheep grazing at the proper timing and intensity can lower leafy spurge biomass and result in higher forage biomass production. However, care must be taken to avoid overgrazing desirable species after pre-flowering.

CHAPTER 1

INTRODUCTION

Invasive weeds continue to spread on rangelands throughout the western United States. Using chemicals, mechanical treatments, or fire to control these weeds is often ineffective, impractical, or both. This has led to interest in targeted grazing as a method to reduce invasive weeds and enhance desired native vegetation. Sheep (*Ovus* spp.) are being used to control invasive weeds like spotted knapweed (*Centaurea stoebe* L.; (Olson et al. 1997), tansy ragwort (*Senecio jacobaea* L.; (Sharrow and Mosher 1982), and leafy spurge (*Euphorbia esula* L.; (Bowes and Thomas 1978; Dahl et al. 2001). This study focuses on simulated sheep grazing of leafy spurge.

Leafy spurge is a perennial invasive weed introduced into the U.S. from Eurasia in the early 19th century (Bakke 1936; Selleck et al. 1962; Messersmith et al. 1985) and currently infests nearly 2 million hectares in the 17 western United States (Duncan et al. 2004). Spread of leafy spurge lowers land values (Leitch et al. 1994; Duncan et al. 2004), reduces forage for livestock and wildlife (Lym and Kirby 1987; Olson 1999), and lowers biodiversity (Belcher and Wilson 1989; Butler and Cogan 2004).

The rapid spread of leafy spurge may be partially explained by the predominance of cattle on Western rangelands. Cattle (*Bos* spp.) avoid leafy spurge (Lym and Kirby 1987; Kronberg et al. 1993) while selectively grazing associated grasses. Avoiding leafy spurge while repeatedly grazing preferred grasses may result in a competitive advantage for weedy forbs and shrubs. Sheep and goats (*Capra* spp.) prefer forbs and shrubs, however, which may shift the competitive advantage back to grasses (Olson 1999).

Sheep readily graze leafy spurge (Johnston and Peake 1960), and it can comprise up to 50% of their diet (Landgraf 1982; Landgraf et al. 1984; Olson et al. 1996). Sheep grazing will not eradicate leafy spurge, but long-term sheep grazing has provided effective control (Johnston and Peake 1960; Bowes and Thomas 1978). Sheep grazing can be an economical and practical choice for controlling leafy spurge compared with repeatedly applying herbicides or not treating infestations (Williams et al. 1996; Bagsund et al. 2001).

Targeted grazing by sheep has been used to control leafy spurge. Four years of season-long sheep grazing reduced the basal density of leafy spurge 98% (Johnston and Peake 1960). Season-long sheep grazing reduced leafy spurge stem densities 60%; and twice-over rotation grazing reduced leafy spurge stem densities 32% after four years (Dahl et al. 2001). Three years of season-long rotational sheep grazing reduced stem heights, number of seeds, and number of viable seeds in the seedbank, but did not reduce densities of mature leafy spurge stems (Olson and Wallander 1998).

Grass response was measured in a study using sheep to control leafy spurge. Sheep grazing leafy spurge in an Idaho fescue (*Festuca idahoensis* Elmer) community in southwestern Montana increased the density of Idaho fescue but reduced density of bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Löve) after three years (Olson and Wallander 1998). Grazing increased the frequency of Kentucky bluegrass (*Poa pratensis* L.), Sandberg bluegrass (*Poa secunda* J. Presl), annual bromes, and sedges.

Goat grazing has also been used to control leafy spurge. Season-long Angora goat grazing decreased leafy spurge densities 44% after two years (Sedivec and Maine

1993). Clipping twice per season in a manner that mimicked goat grazing reduced the density of leafy spurge 55% after five years (Kirby et al. 1997). Four years of intensive season-long Angora goat grazing reduced the density of leafy spurge stems 40% after two years and 84% after four years (Sedivec et al. 1995).

The response of grass species was measured in various studies using goats to control leafy spurge. Clipping twice per season in a manner that mimicked goat grazing increased grass production an average of 185% after five years; however, grasses and forbs were not defoliated in this study (Kirby et al. 1997). Four years of intensive season-long angora goat grazing increased grass production by 17% (Sedivec et al. 1995). Two years of season-long Angora goat grazing increased grass density by 57% (Sedivec and Maine 1993).

Sheep and goat grazing can reduce leafy spurge (Johnston and Peake 1960; Sedivec et al. 1995; Dahl et al. 2001). However, many land managers do not use sheep because they believe sheep will consume desirable forage while grazing leafy spurge. The number of seasons needed for sheep grazing to enhance biomass production of desirable species, the timing and/or intensity of grazing that provides the greatest effect, and whether leafy spurge density affects these responses, is largely unknown.

This study addressed these questions using four timings and two defoliation levels for leafy spurge, and associated grasses and forbs (forage species) at three different locations in southeast Montana. Leafy spurge densities differed at all three locations at the beginning of the study. We monitored grass, forb, and leafy spurge biomass production in irrigated and non-irrigated plots at the end of each growing season. Our objective was to determine how forage biomass was affected with different timing and

defoliation patterns of simulated sheep grazing. We hypothesized that additional forage would be available for livestock or wildlife after sheep grazing, even though sheep consume some forage while grazing.

CHAPTER 2

MATERIALS AND METHODS

Study Site Descriptions

Study sites were located in pastures of three different cattle operations in southeastern Montana. Sites were fenced to exclude livestock grazing. Different densities of leafy spurge were present at each of the three sites at the beginning of the study. Precipitation and temperature data were collected from the closest National Oceanic and Atmospheric Association (NOAA) weather stations. Weather stations for the Phalen Ranch (Site 1), Keltner Ranch (Site 2), and Sadie Bottom Pasture (Site 3), were Mizpah 4 NNW (15.3 km away), Carlyle 13 NW (19.2 km away), and Miles City F Wiley Field (9.6 km away), respectively.

Site 1 is located on the floodplain of Sheep Creek about 16 km south of Locate, Montana (lat 46°16'38"N, long 105°08'56"W). Annual precipitation averages 328.4 mm with 63.3% received during March through July. Maximum temperature averages 15.4°C, and minimum temperature averages -0.8°C. Dominant grasses are western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve), Kentucky bluegrass (*Poa pratensis* L.), and buffalograss (*Bouteloua dactyloides* (Nutt.) J.T. Columbus). Forbs at this site included common dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers), prickly lettuce (*Lactuca serriola* L.), alfalfa (*Medicago sativa* L.), yellow salsify (*Tragopogon dubius* Scop.), and blue lettuce (*Lactuca tatarica* (L.) C.A. Mey. var. *pulchella* (Pursh) Breitung). Leafy spurge density was initially medium at this site (50-100 stems m^{-2}).

Soil is a Havre-Harlake complex (Havre = Fine-loamy, mixed, superactive, calcareous, frigid Aridic Ustifluvents; Harlake = Fine, smectitic, calcareous, frigid Aridic Ustifluvents; with less than 2% slope). This site has been grazed by cattle for more than 60 years and by cattle and sheep for the past 11 years.

Site 2 is located on the floodplain of Cabin Creek, about 50 km southeast of Fallon, Montana (lat 46°41'49"N, long 104°39'48"W). Annual precipitation averages 400.8 mm with 59.9% received during March through July. Maximum temperature averages 13.1°C, and minimum temperature averages -0.2°C. The dominant grass is smooth brome (*Bromus inermis* Leyss.). Forbs at this site included alfalfa, American vetch (*Vicia americana* Muhl. ex Willd.), common dandelion, yellow salsify, yellow sweetclover (*Melilotus officinalis* (L.) Lam.), white sweetclover (*Melilotus albus* Medik.), and blue lettuce. Leafy spurge density was initially low at this site (10-20 stems m^{-2}). Soil is a Glendive loam (Glendive = Coarse-loamy, mixed, superactive, calcareous, frigid Aridic Ustifluvents; with less than 2% slope). This area was seeded to smooth brome in the early 1960s and has been grazed intermittently by cattle for at least 95 years.

Site 3 is located about 8 km west of Miles City, Montana, on United States Department of Agriculture-Agricultural Research Service (USDA-ARS) Fort Keogh property (lat 46°20'50"N, long 105°59'11"W). Plots were located on the floodplain of the Yellowstone River. Annual precipitation averages 340.1 mm with 63.1% received during March through July. Maximum temperature averages 14.6°C, and minimum temperature averages 1°C. Dominant grasses are Japanese brome (*Bromus arvensis* L.), cheatgrass (*Bromus tectorum* L.), and western wheatgrass. Forbs at this site included common dandelion, American licorice (*Glycyrrhiza lepidota* Pursh), pepperweed

(*Lepidium densiflorum* Schrad.), and yellow salsify. Leafy spurge density was initially high at this site (150-300 stems m^{-2}). Soil is a Glendive-Havre complex. Cattle have grazed this site since the early 1920s.

Experimental Design and Procedures

The timing of clipping was the same for all sites and coincided with particular phenological stages of leafy spurge. Plants were clipped at pre-flowering, or flowering, or seed production, or at pre-flowering and seed production stages.

Some treatments were designed to represent common grazing practices on rangelands. First, the low intensity-grass/forb only (leafy spurge was not clipped) (LG) treatment represents a typical "take half-leave half" cattle grazing prescription. Second, the low intensity grass/forb-low intensity leafy spurge (LGLS) and low intensity grass/forb-high intensity leafy spurge (LGHS) treatments represent grazing by sheep (Olson et al. 1996). Third, the high intensity grass/forb-high intensity leafy spurge (HGHS) and high intensity grass/forb-low intensity leafy spurge (HGLS) treatments were designed to characterize possible outcomes with more intense sheep grazing. Fourth, the high intensity-grass/forb only (leafy spurge was not clipped) (HG) represents intensive cattle grazing. Finally, the not treated (NT) represents ungrazed infestations.

Our leafy spurge defoliation treatments (number of stems clipped and height removed from each stem) were based on an unpublished pilot grazing study from 2005 where USDA-ARS measured utilization of leafy spurge by sheep at different phenological stages. The high intensity leafy spurge treatment consisted of clipping 100% of the leafy spurge stems: 1) at ground level at the pre-flowering timing, 2)

removing the top 20% of stem height at the flowering timing, or 3) removing the top 30% of stem height at the seed production timing. The low intensity leafy spurge treatment used the same defoliation levels but was applied to 80% of the leafy spurge stems at flowering and seed production timings. The HG treatment consisted of clipping grasses and forbs to 1.9 cm. The LG treatment consisted of removing 50% of grass and forb biomass.

Site 1 (n=64) and Site 2 (n=64) had defoliation treatments applied to leafy spurge and/or grass in 1.25 m^2 plots. Biomass was only collected from the 1 m^2 center of each plot. Defoliation treatments at Sites 1 and 2 were NT, HGHS, HGLS, LGHS, LGLS, LG, and HG. A factorial combination of irrigation treatments was added to determine if effects were constant for wet or droughty years. Irrigated plots received the 30-year monthly average precipitation for May (53.8 mm) and June (60.6 mm) in addition to ambient precipitation. Water was applied in two equal irrigation treatments each month. Plots were irrigated overhead with a handheld sprinkler. Irrigation rates were measured using a totalizing water meter (Model MT-C-1, Hays Fluid Controls, Dallas, NC). Treatments were replicated two times in a randomized block design where soils, species, and aspect were similar within blocks. Pre-treatment data were collected in 2004 and treatments were applied annually for three consecutive years beginning in 2005. Pretreatment data included grass, forb, and leafy spurge biomass and were used to account for intrinsic differences in composition among plots.

Site 3 had only three of the seven defoliation treatments, but plot size was the same as the other sites. There were no irrigated plots at Site 3. Defoliation treatments at Site 3 were NT, HGHS, and LGHS. Treatments were replicated three times in a split-plot

design where the main plot was timing, and the subplot was defoliation treatment. Pre-treatment data were collected in 2005 and treatments were applied annually for two consecutive years beginning in 2006. Pretreatment data included grass, forb, and leafy spurge biomass and were used to account for intrinsic differences in composition among plots.

Grasses and forbs were collected separately from leafy spurge while clipping. Clipped material was dried at 60°C for 48 hours. Grasses and forbs were clipped to the soil level at the end of the growing season in three randomly located 100 cm^2 frames in 2005, and two randomly located 400 cm^2 frames in 2006, within each plot. These materials were used to estimate biomass remaining in plots at the end of the growing season in 2005 and 2006. These biomass estimates were added to grass and forb biomass clipped earlier in the season, resulting in total grass and forb biomass estimates within a plot for an entire season. In 2007, all grasses and forbs in each plot were clipped to the soil level at the end of the growing season, dried at 60°C for 48 hours, and weighed. Because forbs comprised a small fraction of the biomass (6.9, 7.7, and 1.6% at Site 1, Site 2, and Site 3, respectively), grasses and forbs were grouped for analysis.

Clipping current year's leafy spurge to soil level at the end of the season would influence subsequent year's biomass. Therefore, heights of every leafy spurge stem were measured at the end of the season, and regression was used to estimate leafy spurge biomass remaining in the plot after clipping. To develop the regression, random stems were clipped at each site (outside plot areas), measured (cm), dried at 60°C for 48 hours, and weighed. Weight was regressed on height for each site. Regression estimates were added to leafy spurge biomass clipped earlier in the season, resulting in total leafy spurge

biomass estimates within a plot for an entire season. In 2007, all leafy spurge stems within a plot were clipped to soil level at the end of the growing season, dried at 60°C for 48 hours, and weighed.

Percent of current year's grass and forb biomass in the bulk samples was estimated visually. Bulk samples consisted of live grasses, live forbs, and dead material from previous seasons from an entire plot. At each phenological stage of treatment, grasses and forbs were clipped to treatment height in three randomly located 100 cm^2 frames in 2005, and two randomly located 400 cm^2 frames in 2006 within each plot. These samples were separated by live and dead material in the lab. Weights were recorded for live and dead material, and live and dead material was remixed. Visual estimates of live material for 100 of these samples were regressed on actual live material in each sample (R^2=0.95). To estimate live biomass for clipped grasses and forbs, we visually estimated live material in bulk samples and applied our regression to these visual estimates.

Statistical Analysis

The experimental unit for this study was plot (n = 64, 64, and 36 for Sites 1, 2, and 3, respectively). We used the following model to quantify treatment effects on biomass production at each site:

$$\ln(Y_{ij}) \sim N(\mu + t_j + w_i + \beta_j s_i + d_{jk} + p_i, \sigma_j^{\,2}) \qquad (1)$$

where $\ln(Y_{ij})$ is natural-log transformed grass and forb or leafy spurge biomass for plot i year j, μ is the mean grass and forb or leafy spurge biomass for all plots, t_j is a year

effect, w_i is the effect of irrigation, s_i is plot-specific pretreatment biomass, β_j is the year-specific effect of the pretreatment biomass, d_{jk} is a year-specific defoliation treatment, p_i is a plot effect, and σ_j^2 is a year-specific error term. Because different methods were used to estimate or collect the response variables (grass and forb biomass, and leafy spurge biomass) in different years, our error variances were allowed to differ by year in our analysis. All regression coefficients were fixed except for plot and subplot (Site 3 only) which were random effects. To meet normality and equal variance assumptions for linear regression, grass and forb, and leafy spurge data were natural log-transformed; however, our results are presented in back-transformed units relative to our baseline treatment. A Bayesian analysis with non-informative priors was used to analyze the data (Gelman et al. 2004); See Appendix 1 for details).

We used Gibbs sampling to simulate the joint posterior distribution of the model parameters (Gelman et al 2004). Graphical posterior predictive checks indicated that Equation (1) accurately described the data. We based our results on comparing 95% central posterior intervals for treatments with the baseline treatment. If intervals did not overlap the 0 line (baseline treatment) the posterior distribution supported the conclusion that the treatment of interest and baseline treatment differed.

Based on graphical posterior predictive checks, LG and NT treatments did not differ. Therefore, LG and NT treatments were grouped as the baseline treatment for analysis Sites 1 and 2. Site 3 did not have the LG treatment, and therefore, the baseline treatment was based on NT plots only. Similarly, including separate regression coefficients for low and high intensity leafy spurge defoliation did not improve the

model. Therefore, the effects of low and high intensity leafy spurge defoliation were described with a single regression coefficient.

Combining the response to LG and NT into one coefficient made biological sense. Responsible grazing that does not harm grasses should not give leafy spurge a competitive advantage. Combining the response to high and low intensity leafy spurge defoliation into one coefficient made sense because the leafy spurge biomass removed differed little between the high and low intensity treatments. The average biomass removed among 80 and 100% treatments at Sites 1 and 2 for 2007 differed by less than two grams. Therefore, all results referring to the intensity of defoliation refer to grass and forb defoliation.

Because Site 3 was established a year later than Sites 1 and 2, all results refer to the second (Site 3) or third (Sites 1 and 2) year of treatment unless otherwise noted. To help interpret treatment effects, mean annual production for not-treated plots at each site and year of treatment are presented in Table 1.

Table 1. Mean annual production (g m^{-2}) for not-treated plots at each study site.

	2005		2006		2007	
Site	Grass/Forbs	Leafy spurge	Grass/Forbs	Leafy spurge	Grass/Forbs	Leafy spurge
	---------- g m^{-2} ----------					
1	255.9	130.2	216.5	122.8	256.0	154.6
2	197.3	161.5	158.4	112.7	293.0	176.9
3	-	-	48.7	111.6	130.6	216.0

CHAPTER 3

RESULTS

Grass and forb biomass from clipped plots was greater at the end of the first growing season only at Site 3. This response was evident only for plants defoliated at high intensity at pre-flowering, and at the pre-flowering and seed production stages. In general, when leafy spurge biomass was lowered by defoliation, forage biomass was higher; if forage biomass was lowered by defoliation, then leafy spurge biomass was higher. Changes in grass and forb or leafy spurge biomass were more apparent after two or three years of defoliation, as described in the following sections.

Pre-flowering

Low intensity defoliation of grasses and forbs at pre-flowering resulted in higher grass and forb biomass only at Site 1, although grass and forb biomass was slightly higher than baseline at Sites 2 and 3 after the second year of clipping. Grass and forb biomass was between 9.4 (2.5^{th} posterior percentile) and 169.0 g m^{-2} (97.5^{th} posterior percentile) higher than baseline at Site 1. Low intensity defoliation at pre-flowering tended to lower leafy spurge biomass. Leafy spurge biomass was between 114.3 g m^{-2} lower and 11.8 g m^{-2} higher than baseline at Site 1, between 92.3 and 6.6 g m^{-2} lower than baseline at Site 2, and between 152.5 and 17.1 g m^{-2} lower than baseline at Site 3 (Figure 1).

High intensity defoliation of grasses and forbs at pre-flowing tended to result in higher grass and forb biomass and lower leafy spurge biomass. High intensity defoliation

resulted in grass and forb biomass between 64.5 and 194.4 g m^{-2} higher than baseline at Site 1, between 4.1 and 143.7 g m^{-2} higher than baseline at Site 2, and between 9.1 g m^{-2} lower and 187.6 g m^{-2} higher than baseline at Site 3. High intensity defoliation resulted in leafy spurge biomass between 86.4 g m^{-2} lower and 23.7 g m^{-2} higher than baseline at Site 1, between 71.5 g m^{-2} lower and 1.2 g m^{-2} higher than baseline at Site 2, and between 179.1 and 61.9 g m^{-2} lower than baseline at Site 3 (Figure 1).

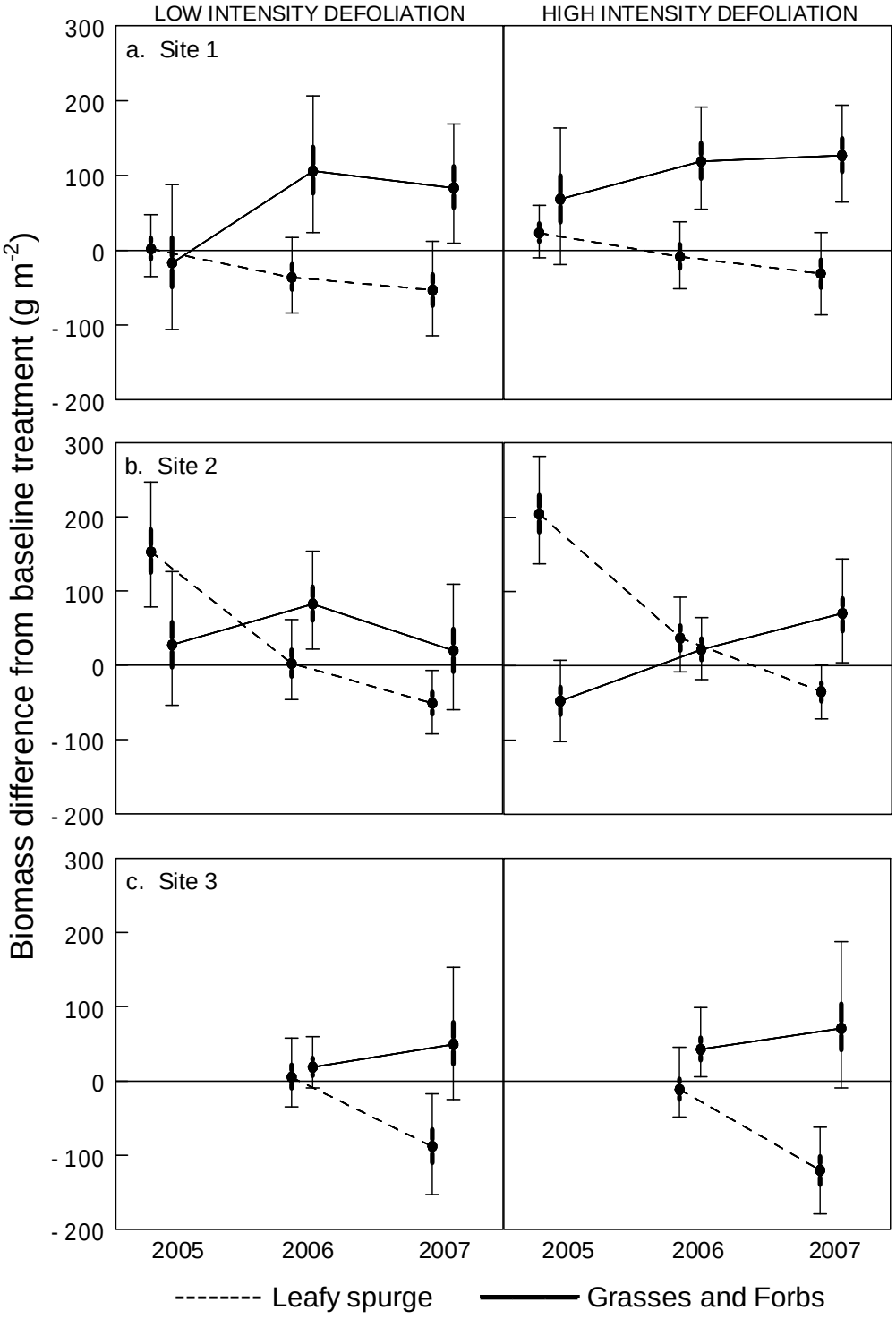

Figure 1. Biomass difference from baseline treatment (g m^{-2}) for grasses and forbs defoliated at high- and low-intensity (80 or 100% of leafy spurge stems were clipped) at the pre-flowering stage of leafy spurge growth for Sites 1, 2, and 3 (a-c) during 2005, 2006, and 2007. Mean (•), 50% (**—**), and 95% (—) central posterior intervals.

Flowering

Low intensity defoliation of grasses and forbs at flowering may result in higher grass and forb biomass. Grass and forb biomass was between 5.5 and 161.4 g m^{-2} higher than baseline at Site 1, between 49.5 g m^{-2} lower and 121.2 g m^{-2} higher than baseline at Site 2, and between 49.2 g m^{-2} lower and 99.7 g m^{-2} higher than baseline at Site 3. Low intensity grazing lowered leafy spurge biomass only at Site 2 (Figure 2).

High intensity defoliation of grasses and forbs at flowering did not substantially change grass and forb or leafy spurge biomass. Grass and forb biomass was slightly lower and leafy spurge production was slightly higher at all three sites by the second or third year of clipping (Figure 2).

High intensity defoliation of only grasses and forbs at flowering tended to result in lower grass and forb biomass and higher leafy spurge biomass. Grass and forb biomass was between 81.2 g m^{-2} lower and 0.3 g m^{-2} higher than baseline at Site 1, and between 132.1 g m^{-2} lower and 2.3 g m^{-2} higher than baseline at Site 2. Leafy spurge biomass was between 32.6 g m^{-2} lower and 165.8 g m^{-2} higher than baseline at Site 1, and between 14.2 g m^{-2} lower and 113.0 g m^{-2} higher than baseline at Site 2 (Figure 3).

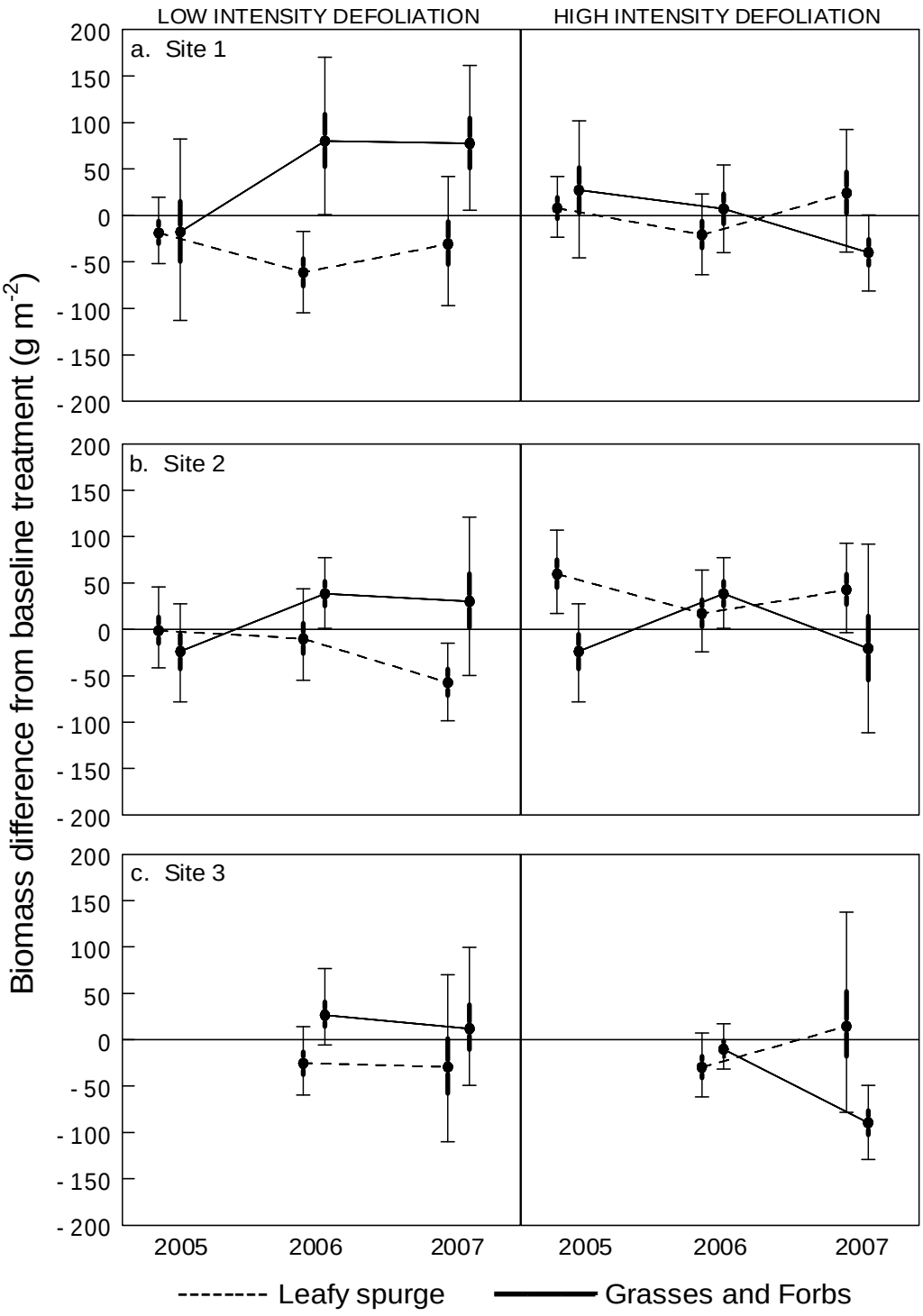

Figure 2. Biomass difference from baseline treatment (g m^{-2}) for grasses and forbs defoliated at high- and low-intensity (80 or 100% of leafy spurge stems were clipped) at the flowering stage of leafy spurge growth for Sites 1-3 (a-c) during 2005, 2006, and 2007. Mean (•), 50% (▬), and 95% (—) central posterior intervals.

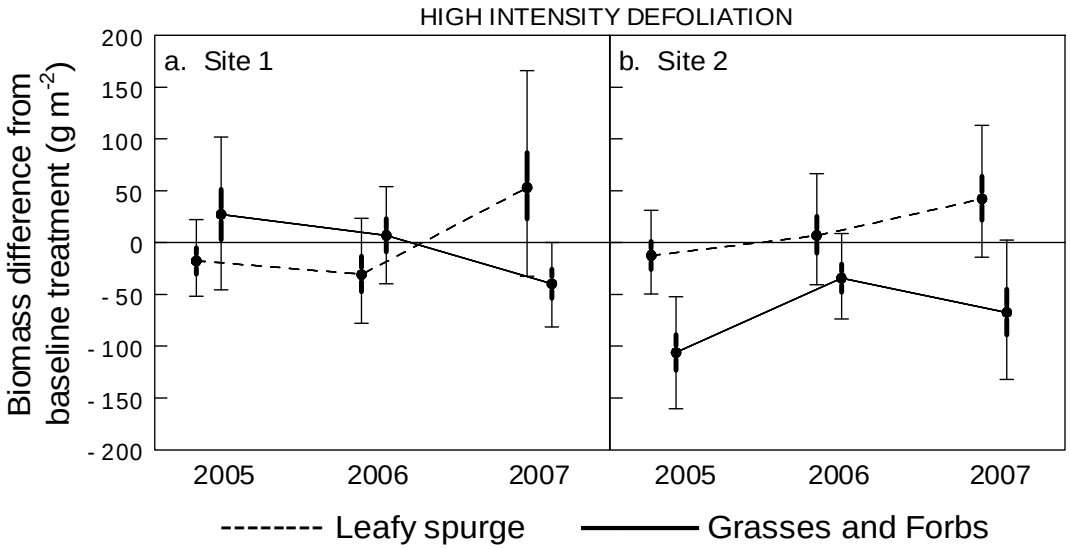

Figure 3. Biomass difference from baseline treatment (g m^{-2}) where only grasses and forbs were defoliated at high intensity (leafy spurge was not clipped) at the flowering stage of leafy spurge growth for Sites 1-2 (a-b) during 2005, 2006, and 2007. Mean (•), 50% (**—**), and 95% (—) central posterior intervals.

Seed Production

At Sites 1 and 2, low intensity defoliation of grasses and forbs when leafy spurge was producing seed did not substantially change grass and forb or leafy spurge biomass. At Site 3, grass and forb biomass was between 107.9 and 18.5 g m^{-2} lower than baseline (Figure 4).

High intensity defoliation of grasses and forbs when leafy spurge was producing seed tended to lower grass and forb biomass, but changes in leafy spurge biomass varied among sites. Grass and forb biomass was between 148.0 and 68.4 g m^{-2} lower than baseline at Site 1, between 111.4 g m^{-2} lower and 0.1 g m^{-2} higher than baseline at Site 2, and between 128.6 and 49.6 g m^{-2} lower than baseline at Site 3 (Figure 4).

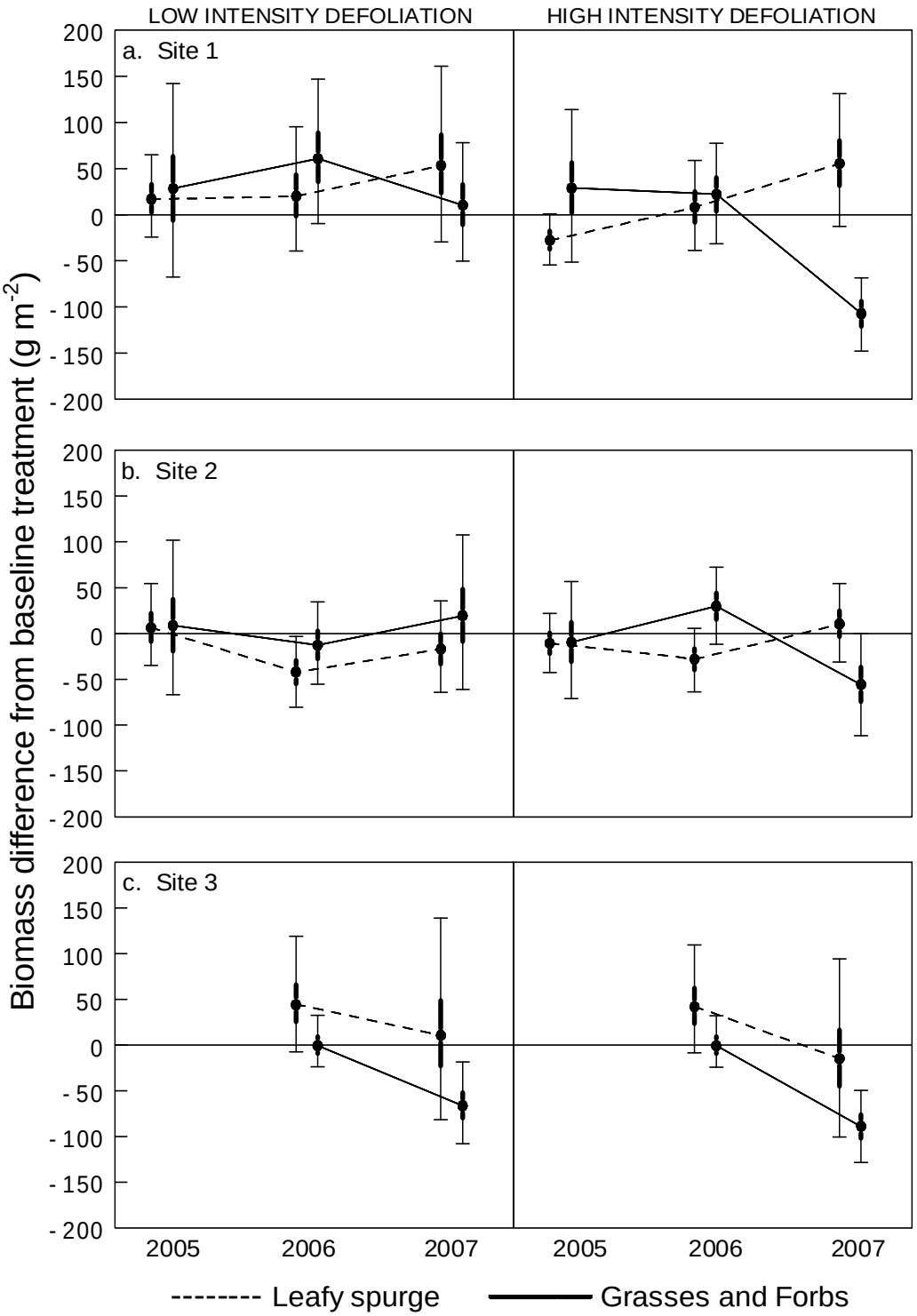

Figure 4. Biomass difference from baseline treatment (g m^{-2}) for grasses and forbs defoliated at high- and low-intensity (80 or 100% of leafy spurge stems were clipped) at the seed producing stage of leafy spurge growth for Sites 1-3 (a-c) during 2005, 2006, and 2007. Mean (•), 50% (▬), and 95% (—) central posterior intervals.

Pre-flowering and Seed Production

Low intensity defoliation of grasses and forbs at pre-flowering and when leafy spurge was producing seed tended to result in higher grass and forb biomass and lower leafy spurge biomass. Grass and forb biomass was between 6.8 and 158.4 g m^{-2} higher than baseline at Site 1, between 44.2 g m^{-2} lower and 132.1 g m^{-2} higher than baseline at Site 2, and between 58.1 and 415.1 g m^{-2} higher than baseline at Site 3. Leafy spurge biomass was between 144.0 and 39.4 g m^{-2} lower than baseline at Site 1, between 106.4 and 26.3 g m^{-2} lower than baseline at Site 2, and between 139.8 g m^{-2} lower and 12.3 g m^{-2} higher than baseline at Site 3 (Figure 5).

High intensity defoliation of grasses and forbs at pre-flowering and when leafy spurge was producing seed tended to lower grass and forb biomass, but leafy spurge biomass varied among sites. Grass and forb biomass was between 115.9 and 32.4 g m^{-2} lower than baseline at Site 1, between 46.9 and 148.5 g m^{-2} lower than baseline at Site 2, and between 56.6 g m^{-2} lower and 85.3 g m^{-2} higher than baseline at Site 3 (Figure 5).

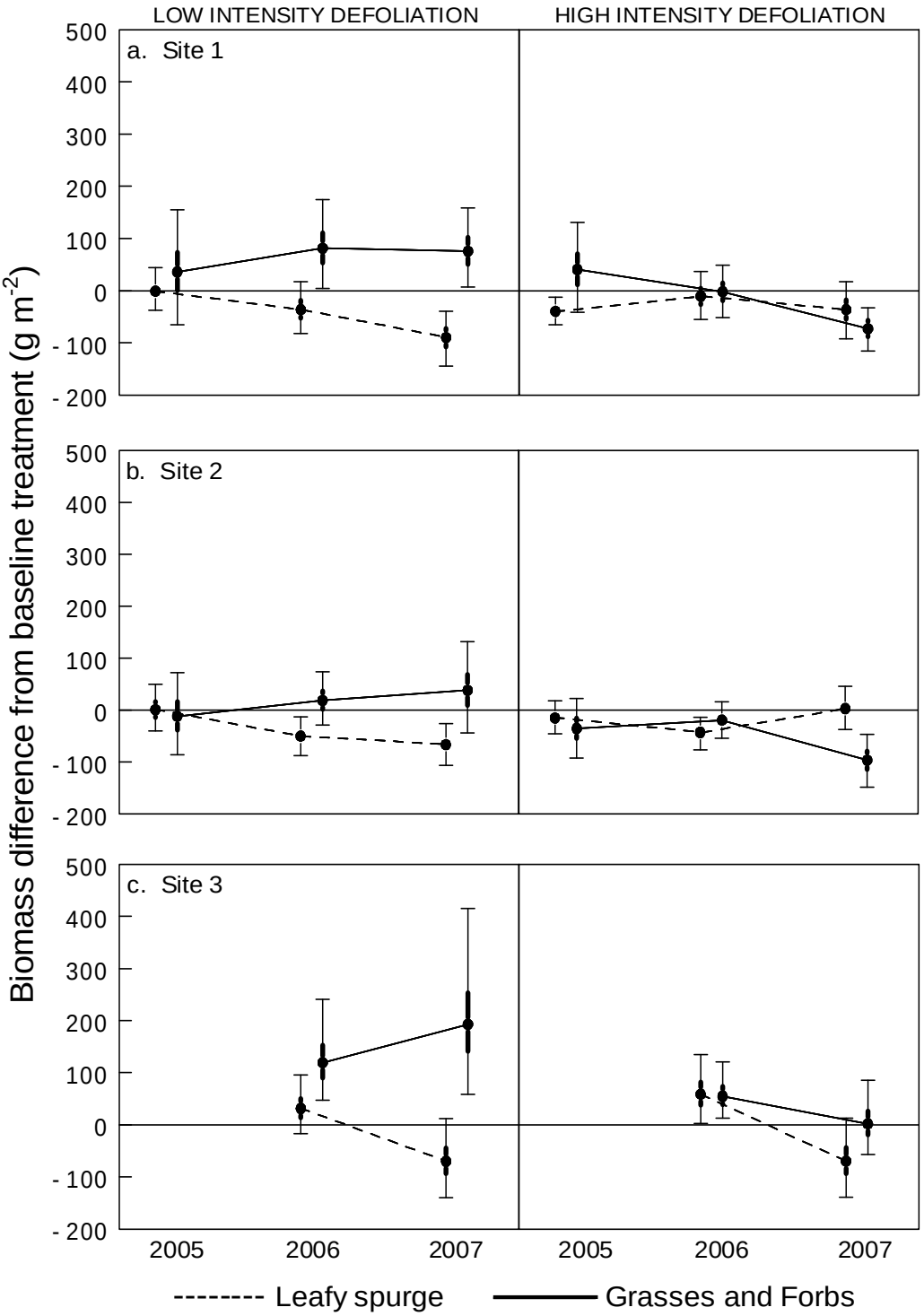

Figure 5. Biomass difference from baseline treatment (g m^{-2}) for grasses and forbs defoliated at high- and low-intensity (80 or 100% of leafy spurge stems were clipped) at the pre-flowering and seed producing stages of leafy spurge growth for Sites 1-3 (a-c) during 2005, 2006, and 2007. Mean (•), 50% (▬), and 95% (—) central posterior intervals.

CHAPTER 4

DISCUSSION

Using sheep to control leafy spurge, or increase forage biomass by reducing leafy spurge is a long term commitment. Three or more years of defoliation are often needed to reduce leafy spurge density (Johnston and Peake 1960; Selleck et al. 1962; Olson and Wallander 1998). Therefore, we did not expect leafy spurge biomass to be substantially lower in the first or second year of this study. In fact, leafy spurge biomass was sometimes higher in clipped plots than in not-treated plots during the first year of clipping. Similarly, leafy spurge stem density may increase after a single year of grazing (Bowes and Thomas 1978), herbicide treatment (Hanson and Rudd 1933), or tillage (Hanson and Rudd 1933; Selleck et al. 1962), presumably because killing top growth removes apical dominance and stimulates root bud growth (Selleck et al. 1962). However, even though leafy spurge density may remain the same or increase after a single year of grazing, its density is lowered with multiple years of defoliation (Johnston and Peake 1960; Bowes and Thomas 1978; Dahl et al. 2001).

High intensity defoliation of leafy spurge at pre-flowering and at pre-flowering and seed production resulted in grass and forb biomass higher than baseline at the end of the first grazing season at Site 3. In resource-limited areas, removing competitors increases the availability of resources to remaining vegetation (Wilson and Tilman 1993). However, during the first season of clipping some nutrients may have already been immobilized in roots and shoots of leafy spurge, or used for regrowth. These nutrients

would not have been available to adjacent grasses and forbs. As leafy spurge biomass was lowered with successive years of grazing, nutrients previously used by leafy spurge presumably were made available for adjacent grasses and forbs resulting in higher grass and forb biomass production. Site 3 was dominated by annual grasses which may explain the higher grass and forb biomass after the first grazing season. Clipping the first cohort of these grasses may have allowed a second cohort of these annuals to germinate and reach maturity, resulting in more grass and forb biomass produced at this site.

Repeated or season-long sheep or goat grazing is often used to reduce leafy spurge densities (Sedivec et al. 1995; Olson and Wallander 1998; Dahl et al. 2001). Our low intensity defoliation at pre-flowering and seed production reduced leafy spurge biomass after 3 years which supports previous clipping and grazing studies (Kirby et al. 1997; Lym et al. 1997).

A single defoliation each year for several years may also lower leafy spurge biomass in some situations. Our high intensity defoliation at pre-flowering lowered leafy spurge biomass at 2 of 3 sites. Similarly, leafy spurge density was lowered with clipping once per season in North Dakota, but the change was not statistically significant (Kirby et al. 1997).

Lower leafy spurge biomass in our study may be the result of clipping leafy spurge stems at ground level at pre-flowering, whereas defoliation may have been more moderate in other studies. For example, in North Dakota the target utilization of leafy spurge infested pastures was 50-60% overall pasture utilization (Dahl et al. 2001). In another study, only the top 5 cm of leafy spurge stems was removed (Kirby et al. 1997).

Moderate livestock grazing intensity is often recommended to maintain or improve range condition (Olson et al. 1985; Biondini et al. 1998). However, high intensity clipping of grasses and forbs at pre-flowering resulted in higher grass and forb biomass after three years in our study. Similarly, mowing tallgrass prairie six times at ground level resulted in higher grass biomass compared with mowing eight times at 5 cm (Turner et al. 1993). The difference was attributed to the greater length of recovery time with ground level mowing (25 days for ground level mowing compared with 12 days for 5 cm mowing) during the first half of the growing season when growing conditions were favorable.

Water was not limiting at pre-flowering during any year of treatment in our study; precipitation received March through June was between 100 and 155% of the 30-year average at all three sites. Plants defoliated at pre-flowering also had the longest recovery time before biomass was collected at the end of the season. This may partially explain the higher biomass produced with high intensity clipping at this time.

Overcompensation is when the total dry weight, including removed material, of defoliated plants is greater than the total dry weight of undefoliated plants (Belsky 1986). Grazed plant material may compensate or be stimulated by: 1) increased photosynthetic rates in ungrazed plant material, 2) reallocation of substrates from other plant parts for new tissue growth, 3) removal of older, less efficient photosynthetic material resulting in the growth of new efficient photosynthetic material, 4) increased light penetration to younger photosynthetic material resulting from removal of older upper canopy leaves, and 5) changes in hormonal concentrations which promote rapid growth and tillering (McNaughton 1976). These plant responses may explain why high intensity clipping at

pre-flowering resulted in higher grass and forb biomass in our study. However, overcompensation has only been observed in limited situations (McNaughton 1979; Williamson et al. 1989; De Mazancourt et al. 1998; Leriche et al. 2003) and with few species (McNaughton 1983; Wallace et al. 1985; Georgiadis et al. 1989).

Competing vegetation can greatly influence plant biomass production after being defoliated. Bluebunch wheatgrass, a grazing intolerant species, produces more biomass and flowering stalks when defoliated in the absence of competing vegetation, than when left intact in the presence of competition (Mueggler 1972). The root system of leafy spurge, a grazing tolerant species, can support the demand for carbon in defoliated shoots, even when 75% of the shoot biomass is removed (Olson and Wallander 1999), which may explain why most of the sites did not produce more grass and forb biomass by the end of the first clipping season. However, repeatedly defoliating leafy spurge for three years apparently reduced its competitive ability, giving neighboring plants an advantage, resulting in higher grass and forb biomass such as we observed.

Collecting biomass multiple times during the growing season usually results in higher biomass estimates compared with biomass estimates from peak standing crop (Scurlock et al. 2002). Measuring at peak standing crop underestimates biomass because this approach typically ignores within-season turnover, herbivory, and plants reaching peak biomass at different times. Grass biomass estimates were 2.5 times higher than estimates from peak standing crop when biomass was collected numerous times per year (Wiegert and Evans 1964). Possibly, pre-flowering high intensity defoliation had slightly higher grass and forb biomass estimates because we collected biomass twice during the growing season compared with once at peak standing crop with baseline treatments, or

because clipping at that stage enhanced growth, or most likely both. However, biomass collected multiple times in other treatments resulted in grass and forb biomass estimates lower than baseline, indicating the negative effect of clipping exceeded the potential greater amounts of biomass harvested with multiple clippings during the season.

Timing of defoliation can affect plant response. High intensity defoliation after pre-flowering tended to lower grasses and forb biomass after three years, presumably giving leafy spurge a competitive advantage. Approximately 69% of aboveground biomass is produced by June 1 in cool-season dominated communities in Montana (Heitschmidt and Vermeire 2005). Thus, our defoliated grasses and forbs may have produced less biomass than the baseline treatment because water or nutrients limited regrowth after pre-flowering. Besides the potential for water and nutrients to limit regrowth when plants were defoliated after pre-flowering, the lower grass and forb biomass may reflect that more leaf area had been produced above the 1.9 cm clipping height, and thus was subject to removal, at these later phenological stages.

High intensity grazing after pre-flowering did not greatly affect grass and forb biomass by the end of the first or second year of clipping, although grass and forb biomass was usually lower than baseline by the end of the third year. This indicates that the effects of high intensity grazing are cumulative.

Sheep will consume up to 50% leafy spurge in their diet (Landgraf et al. 1984; Bartz et al. 1985; Olson et al. 1996). Our treatments removed more grass and forb biomass than sheep would have consumed according to these studies. Because our main focus for this study was to determine forage biomass response, clipping treatments were designed to characterize the response of forage species over a wide range of defoliation

patterns at different phenological stages. On average, leafy spurge comprised 31, 14, and 53% of material collected from clipping at Sites 1, 2, and 3, respectively. Differences in leafy spurge composition of clipped material for each site reflect different densities of leafy spurge at each site. Most likely, utilization of grasses and non-leafy spurge forbs by sheep will be lower in actual grazing situations (Landgraf et al. 1984; Bartz et al. 1985; Olson et al. 1996) which could result in higher grass and forb biomass production than we observed.

Leafy spurge is a clonal species with an extensive root system (Selleck et al. 1962; Messersmith et al. 1985), therefore plot size should be considered when studying leafy spurge. Whether a plot encompasses one plant or many is difficult to assess. Further, the effect of clipping may be mitigated by lateral roots outside the plot transferring nutrients to clipped stems. We treated plots that were 1.25 m^2, but only collected biomass from the center 1 m^2 in an attempt to minimize this issue. In addition, translocation of nutrients may not be required because the root system of leafy spurge is able to supply shoots with sufficient carbon for regrowth after defoliation (Olson and Wallander 1999). In our study, leafy spurge biomass changed substantially after 3 years, similar to studies with larger plots or entire pastures (Kirby et al. 1997; Dahl et al. 2001). This indicates that nutrients from lateral roots outside the treatment area were not translocated to plants in our plots.

The results of this study are based on clipping. Clipping allows us to carefully apply treatments and collect data, but it does not represent the selectivity of grazing animals (Heady 1961, 1975). Animals graze plants based on preference, palatability, and availability. Clipping all grasses and forbs within a plot to a uniform height does not

represent an actual grazing situation, except perhaps under very heavy utilization (Heady 1975). However, because each of our sites was dominated by one or two main grasses, animals could not have been very selective at our sites. Further, many of our results are similar to those from other sheep and goat grazing studies (Sedivec et al. 1995; Lym et al. 1997; Dahl et al. 2001), indicating the amount of biomass produced and removed is the major factor that contributes to changes in plant community composition, and not the species removed or method of removal.

Previous research has not been able to answer the questions we asked. Studies reporting to have increased grass or grass-like production while grazing leafy spurge have used paired plots or other measurements which rely on production data from the year after treatment ended (Sedivec et al. 1995; Dahl et al. 2001). Leafy spurge begins to increase in density as soon as grazing is discontinued (Bowes and Thomas 1978). Therefore, using paired plots or determining biomass the year after grazing cannot assess whether sheep grazing results in higher forage biomass by the end of a specific grazing season. Forage species may be suppressed by leafy spurge by the time biomass is measured the following year.

Conversely, our results accurately represent the response of forage species biomass by the end of the season in which leafy spurge was defoliated. In North Dakota, adjacent grasses or forbs were never defoliated during a five-year clipping study of leafy spurge (Kirby et al. 1997), which would likely give grasses and forbs a competitive advantage. Their estimates of increased forage production would be unrealistic compared with an actual grazing situation because goats and especially sheep will consume some grasses and forbs while grazing leafy spurge. Conversely, our study kept track of all

biomass removed from each plot, and estimated any biomass that could not be removed from plots for biological reasons. Therefore, our study determined how defoliation of grasses, forbs, and leafy spurge affects forage and leafy spurge biomass production.

On average, three years of high intensity clipping of grasses and forbs at pre-flowering resulted in grass and forb biomass production high enough to replace grass and forb biomass removed by clipping, i.e. sheep, by the end of the third season. Low intensity clipping of grasses and forbs at pre-flowering and seed production resulted in forage biomass higher than baseline treatments at all sites, but biomass production was only high enough to replace grass and forb biomass removed by clipping, i.e. sheep, at only one site by the end of the third season. These same treatments lowered leafy spurge biomass. High intensity clipping of only grasses and forbs, i.e. cattle, at the flowering timing tended to result in lower forage biomass and higher leafy spurge biomass. High intensity clipping of leafy spurge at pre-flowering and at pre-flowering and seed production resulted in higher grass and forb biomass by the end of the first growing season only at Site 3, which was dominated by annual grasses. Leafy spurge density did not affect treatments.

Finally, these results, based on different combinations of timing and grazing intensity, identify the best grazing patterns to control leafy spurge and maximize forage biomass. Further, using sheep to reduce leafy spurge and/or to enhance forage biomass is at least a three year commitment, and leafy spurge will increase in density when grazing is discontinued (Bowes and Thomas 1978). The effects of defoliating leafy spurge are cumulative and leafy spurge biomass is lowered with each successive year of grazing. The result is a competitive advantage for forage species. Most likely, our treatments

would have resulted in lower leafy spurge biomass or greater grass and non-leafy spurge forb biomass had we continued to defoliate plots for additional seasons.

CHAPTER 5

MANAGEMENT IMPLICATIONS

High intensity clipping at the pre-flowering resulted in estimated forage biomass production between 1.4 and 4.3 animal unit months (AUMs)·ha^{-1} higher than baseline at Site 1, between 0.1 and 3.2 AUMs·ha^{-1} higher than baseline at Site 2, and between 0.2 AUMs·ha^{-1} lower and 4.1 AUMs·ha^{-1} higher than baseline at Site 3. Changes in biomass at Site 3 were not statistically significant. Low intensity clipping at pre-flowering and seed production resulted in estimated forage biomass production between 0.2 and 3.5 AUMs·ha^{-1} higher than baseline at Site 1, between 1.0 AUMs·ha^{-1} lower and 2.9 AUMs·ha^{-1} higher than baseline at Site 2, and between 1.3 and 9.1 AUMs·ha^{-1} higher than baseline at Site 3. Changes in biomass at Site 2 were not statistically significant. High intensity clipping of only grasses and forbs, i.e. cattle, at flowering resulted in estimated forage biomass production between 1.8 AUMs·ha^{-1} lower and 0.1 AUMs·ha^{-1} higher than baseline at Site 1, and between 2.9 AUMs·ha^{-1} lower and 0.1 AUMs·ha^{-1} higher than baseline at Site 2, although these changes were not statistically significant.

Therefore, sheep grazing at the proper time and intensity can lower leafy spurge biomass and result in higher grass and forb biomass production. However, to avoid lower forage biomass and higher leafy spurge biomass, careful management is required to ensure that grasses and forbs are not over grazed after pre-flowering.

APPENDICES

APPENDIX A

STATISTICAL PROCEDURES

Bayesian methods were used to fit our models to the data which require prior distributions be assigned to regression coefficients (β), data variances (σ^2), population means (μ), and variances (τ^2) of those effects considered random in the models. We did a sensitivity analysis using two non-informative prior distributions assigned to regression coefficients to ensure that the choice of prior did not affect our results. The prior distributions used for this analysis were $p(\beta) \sim N(0, \sigma^2 = 100{,}000$ and $p(\beta) \sim N(0, \sigma^2 = 1{,}000{,}000$. Because both priors provided similar parameter estimates we used the first prior listed. The prior distribution for data variances was $p(\sigma^2) \propto \frac{1}{\sigma^2}$. The prior distributions for the population parameters were uniform over the whole real line for μ and $p(\tau^2) \propto 1$. Given these priors, all marginal posterior distributions were in closed form with the variances being scaled inverse chi-square, and all other parameters being normally distributed (Gelman et al. 2004).

Markov Chain Monte Carlo integration (i.e., Gibbs sampler) was used to simulate posterior distributions (Gelman et al. 2004). To ensure convergence we constructed 10 Markov chains and monitored the between- and within-chain variances (Gelman and Rubin 1992). This process involved obtaining dispersed starting points for the 10 chains. Multiple linear regression gave us a crude approximation of the posterior distribution, and the 10 starting locations were drawn from this distribution.

The number of simulations to be discarded as burnin was determined dynamically. All 10 chains were grown for 2500 iterations, and then convergence statistics were calculated (Gelman and Rubin 1992). If convergence was not achieved,

all simulations were discarded and 2500 new links were added to each chain using the last iterations of the initial 2500 simulations as the new starting values. This process was continued until convergence was achieved. Upon convergence, the first half of each chain was discarded as burnin, and inferences were based on the remaining 10*1250 simulations.

Finally, we ran the entire program again to ensure that parameter estimates from the first run matched estimates obtained from the second run. The program used for simulating the posterior distribution was written in Intel FORTRAN 10.1 (Corporation 2003). Some subroutines were written by Dr. Matthew Rinella (i.e. subroutines for constructing the Markov chains), and other subroutines such as matrix inversion, Cholesky decomposition, and random number generation were written by Visual Numerics (1997).

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