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Targeted Grazing of White Locoweed: Short-Term Effects of Herbivory Regime on Vegetation and Sheep

Laura E. Goodman, André F. Cibils, Stephanie C. Lopez, Robert L. Steiner, John D. Graham, Kirk C. McDaniel, Laurie B. Abbott, Bryan L. Stegelmeier, and Dennis M. Hallford

Abstract

White locoweed (Oxytropis sericea Nuttall) and nontarget vegetation response to 2 yr of targeted grazing by sheep, one treatment of picloram plus 2, 4-D (HER) or no treatment (CON) were compared. Serum of sheep that grazed locoweed intermittently (IGZ, 5 d on locoweed followed by 3 d off locoweed) vs. counterparts that grazed locoweed continuously for 24 d (CGZ) was also examined. Alkaloid toxicity was inferred by serum levels of thyroxine (T4), triiodothyronine (T3), alkaline phosphatase (ALKP), aspartate aminotransferase (AST), and swainsonine, as well as behavior and body weight gains. Three sites were used in a randomized complete block design. IGZ, CGZ, and HER treatments reduced locoweed density (P < 0.01), canopy cover (P < 0.01), number of flower stalks (IGZ: P = 0.02, CGZ and HER: P = 0.01), and plant size (P < 0.01). White locoweed seed density in the soil seed bank was not reduced with grazing, and nontarget vegetation was mostly unaffected by treatments. Grass canopy cover increased in grazed and herbicide plots throughout the study (IGZ: P = 0.03, CGZ and HER: P < 0.01). Percentage bare ground was unchanged (IGZ: P = 0.46, CGZ: P = 0.44) in grazed plots but decreased (P = 0.03) in HER plots. After 24 d, ewes in the IGZ treatment had lower levels of serum ALKP (P < 0.01) and AST (P = 0.02) and marginally lower swainsonine levels (P < 0.07) than CGZ ewes that tended to exhibit lower serum T3 (P < 0.07) and similar serum T4 (P = 0.25) levels. Time spent feeding on locoweed tended to differ (P = 0.06) between treatments. Body weight gain was the same (P = 0.19) regardless of treatment. IGZ of locoweed-infested rangeland with sheep may be a viable short-term means of reducing locoweed density without detrimentally affecting animal health.

Key Words: biological control, prescribed grazing, seed bank, swainsonine, toxic plants

INTRODUCTION

Targeted grazing (TG), defined as the “application of a specific kind of livestock at a determined season, duration, and intensity to accomplish vegetation or landscape goals” (Launchbaugh and Walker 2006), has been used successfully to control a wide variety of invasive plants. Diffuse (Centaurea diffusa Lam.), Russian (Acreptilon repens [L.] DC.), and spotted (Centaurea stoebe L.) knapweed, kudzu (Pueraria montana [Lour.] Merr.), musk thistle (Carduus nutans L.), yellow starthistle (Centaurea solstitialis L.), blackberry (Rubus spp.), juniper (Juniperus spp.), and cheatgrass (Bromus tectorum L.) are a few examples (Wilson et al. 2006). Sheep (Ovis aries) are often the livestock species used in TG programs, particularly if the target plants are forbs, as their rumen to body volume ratio make forbs their most preferred plant functional group (Demment 1982; Hanley 1982). Sheep have been used successfully to decrease larkspur (Delphinium barbeyi [Huth] Huth), an alkaloid-synthesizing forb, for a season because they are more resistant to its toxins than cattle (Olsen 1978). By grazing sheep prior to cattle in larkspur-infested (D. glaucescens Wats) pastures, subsequent larkspur use by cows was reduced by 43–93% (Ralphs and Olsen 1992).

White locoweed (Oxytropis sericea Nuttall) is a common alkaloid-synthesizing toxic rangeland legume that is responsible for substantial economic losses to the livestock industry in western North America (Nielsen 1978; Torell et al. 2000). Relatively little is known about the efficacy of biological methods to suppress locoweed compared with more traditional chemical control techniques (McDaniel et al. 2007). The effectiveness of TG or severe defoliation in killing or decreasing vigor of locoweed plants is unknown. Most research has investigated methods to prevent locoweed grazing by livestock because it contains swainsonine, an indolizidine alkaloid (Molyneux and James 1982; Molyneux et al. 1999) that has negative effects on reproduction (James et al. 1967; James and Van Kampen 1971; Mcllwraith and James 1982; Panter and James 1989; Ralphs et al. 1994b; Ortiz et al. 1997), weight gains (Stegelmeier et al. 1999a; Ralphs et al. 2000), and behavior (Panter et al. 1999; Pfister et al. 2006a, 2006b) of all classes of livestock (Molyneux et al. 1985; Stegelmeier et al. 2007).
Although sheep are susceptible to alkaloid intoxication if ingestion of white locoweed occurs continuously for 30 d at levels as low as 3% of their diet (James et al. 1967; Stegelemeier et al. 1995, 1999a, 2007), little is known about how animals are affected by intermittent grazing of locoweed-infested pastures. When sheep consume levels of swainsonine known to cause lesions, the distribution and extent of lesions do not increase with a higher toxin dose, suggesting that there is a threshold response to swainsonine ingestion (Stegelmeier et al. 1999a). Rapid recovery of animals receiving high concentrations of swainsonine for short periods of time has been reported (Stegelmeier et al. 1998, 2004). Furthermore, there is anecdotal evidence (James et al. 1986) as well as research results that suggest that an intermittent grazing regime may provide a way of preventing intoxication associated with white locoweed ingestion (Pfister et al. 1996; Stegelmeier et al. 1999b; Obeidat et al. 2005; Ashley et al. 2006). Because swainsonine exhibits rapid blood clearance rates, intermittent grazing of white locoweed may be an effective means of controlling this undesired plant while avoiding the intoxication of grazers.

The main objective of this study was to evaluate the influence of 2 yr of TG by sheep on the survival and reproductive vigor of white locoweed plants. The efficacy of TG was assessed by comparing it to a proven chemical control method (positive control) and to untreated, infested rangeland (negative control). The hypotheses tested were that 1) TG with sheep for two consecutive years would reduce locoweed abundance (including seed bank abundance of locoweed seeds) and that its efficacy would be intermediate compared to untreated and chemically treated rangeland, 2) abundance of grasses and other forbs would not be negatively affected by the TG prescription, and 3) intermittent and continuous TG for two consecutive years would affect locoweed abundance similarly. A secondary objective of this study was to evaluate the influence of intermittent TG prescriptions of white locoweed on serum constituents, grazing behavior, and body weight gains of sheep. The hypotheses tested were that sheep grazing locoweed-infested plots intermittently would have 1) lower serum swainsonine concentrations, 2) lower serum alkaline phosphatase [ALKP] and aspartate aminotransferase [AST] levels, 3) higher serum triiodothyronine [T3] and thyroxine [T4] levels, 4) similar foraging behavior, and 5) similar body-weight gains as sheep that grazed locoweed-infested plots continuously.

**METHODS**

**Study Sites**

The study was conducted on three ranches in Union County, New Mexico, during May and June 2009 and 2010. Sites were selected for their similar white locoweed densities and equi-distance from water (< 0.4 km). Mean annual, spring, and summer precipitation for this area are 408, 114, and 239 mm respectively, based on approximately 12 yr of records from the National Weather Service Cooperative Observation station in Capulin, New Mexico (lat 36°44′N, long 103°59′W) ([NOAA] National Oceanic and Aeronautics Administration 2010). Spring (January through May) precipitation was 81 mm (dry) and 212 mm (wet) for 2009 and 2010, respectively, while summer (June through September) precipitation was 242 mm (average) and 167 mm (dry) for each of the two study years, respectively. The 2 yr following the study were also dry with mean annual precipitation of 345 mm (2011) and 267 mm (2012).

The first site was located on Archuleta Ranch, 1.48 km southwest of Des Moines, New Mexico (lat 36°45′12.43″N, long 103°51′00.99″W) at an elevation of 2062 m above sea level. It had a moderate slope with northern exposure and the soils consisted of cobbly loam and cobbly clay loam with basalt rock outcroppings. Basalt fragments occupy 5–35% of the surface and soil at this site ([USDA, NRCS] United States Department of Agriculture, Natural Resource Conservation Service 2007). Dominant grasses included blue grama ([Bouteloua gracilis [Willd. ex Kunth] Lag. ex Griffiths], little bluestem ([Schizachyrium scoparium [Michx.] Nash]), western wheatgrass ([Pascopyrum smithii [Rydb.] A. Löve]), sideoats grama ([B. curtipendula [Michx.] Torr.]), and hairy grama ([B. bursata Lag.]). Forbs consisted of white locoweed, globemallow ([Sphaeralcea spp.]), and dalea ([Dalea spp.]), with white locoweed being the most frequent. Fringed sagewort ([Artemisia frigida Willd.]), skunkbush sumac ([Rhus tobiolata Nutt.]), yucca ([Yucca spp.]), one-seed juniper ([Juniperus monosperma [Engelm.] Sarg.]), and pinyon pine ([Pinus edulis Engelm.]) were common woody plants, while plains pricklypear ([Opuntia polyacantha Haw.]) was the predominant cactus.

The second site was located on Mondragon Ranch, 2.18 km northwest of Des Moines, New Mexico (lat 36°46′21.18″N, long 103°51′32.13″W) at an elevation of 2042 m above sea level. This area of open grassland had loam, clay loam, and gravelly loam soils. Dominant grasses were blue grama, galleta ([Pleuraphis jamesii Torr.]), tobosa ([P. mutica Buckley]), buffalograss ([Buchloeleae dactyloides [Nutt.] J.T. Columbus]), sideoats grama, sand dropseed ([Sporobolus cryptandrus [Torr.] A. Gray]), and western wheatgrass. Here too the most prevalent forb was white locoweed. Other forbs included globemallow and sunflower ([Helianthus annuus L.]). Shrubs were rare, although winterfat ([Krascheninnikovia lanata [Pursh] A. Meeuse & Smit) and groundsel ([Senecio spp.]) were present.

The third site was at the base of Capulin Volcano (lat 36°45′22.87″N, long 103°58′24.47″W), 2.34 km northeast of Capulin, New Mexico, at an elevation of 2099 m above sea level. Blue grama, western wheatgrass, bottlebrush squirreltail ([Elymus elymoides [Raf.] Swezey]), sideoats grama, perennial threeawn ([Aristida spp.]), and buffalo grass were common grasses. Again the dominant forb was white locoweed, with western ragweed ([Ambrosia psilostachya DC.]), dotted gay-feather ([Liatris punctata Hook.]), prairie coneflower ([Ratibida columnifera [Nutt.] Woot. & Standl.]), sunflower, and globemallow also present. The only shrub present in the study plots was fringed sagewort, although skunkbush sumac, one-seed juniper, and pinyon pine were nearby.

**Experimental Protocol**

At each of the three sites four 200 m² plots (10 m × 20 m) with similar density of locoweed plants were established and randomly assigned to one of the following treatments: 1) control with no treatment [CON]; 2) herbicide as a positive control [HER]; 3) grazed for 5 d by ewes exposed to locoweed.
plots continuously [CGZ]; and 4) grazed for 5 d by ewes exposed to locoweed intermittently [IGZ]. One additional plot was used to analyze the effectiveness of a new herbicide although those results are not reported here. Two additional 200 m² plots, one locoweed free (assigned to IGZ ewes) and although those results are not reported here. Two additional

1 Pregrazing measurements were taken in June, and fall measurements were taken in September in both years.

2 Means with different letters in columns (abc) indicate detectable differences (P < 0.05) by treatment between pregrazing in 2009, fall 2010, and spring 2013 (density); means with different letters in rows (def) indicate detectable differences (P < 0.05) between treatments within dates.

3 Locoweed density SEM: pregrazing 2009 = 0.06; fall 2009 = 0.14; pregrazing 2010 = 0.12; fall 2010 = 0.06; spring 2013 = 0.01.

4 Locoweed canopy cover SEM: pregrazing 2009 = 0.18; fall 2009 = 0.27; pregrazing 2010 = 0.44; fall 2010 = 0.33.

5 Flowering stalks SEM: pregrazing 2009 = 0.14; fall 2009 = 0.16; pregrazing 2010 = 0.18; fall 2010 = 0.08.


7 Locoweed biomass SEM: pregrazing 2009 = 1.96; fall 2009 = 0.17; pregrazing 2010 = 1.27; fall 2010 = 0.35.

Table 1. Date × treatment comparisons of locoweed (Oxytropis sericea) responses to two seasons of intermittent or continuous grazing with sheep (IGZ or CGZ), one application of Grazon® P + D (HER), or no treatment (CON) at three sites in northern New Mexico. Option pdiff was used on a subset of preplanned comparisons. Values are least square means.

<table>
<thead>
<tr>
<th>Date</th>
<th>CON</th>
<th>IGZ</th>
<th>CGZ</th>
<th>HER</th>
<th>CON</th>
<th>IGZ</th>
<th>CGZ</th>
<th>HER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pregrazing 2009</td>
<td>1.17a d</td>
<td>1.45a d</td>
<td>1.56a d</td>
<td>1.59a d</td>
<td>4.39a d</td>
<td>4.56a d</td>
<td>5.48a d</td>
<td>5.66a d</td>
</tr>
<tr>
<td>Fall 2009</td>
<td>0.98</td>
<td>1.05</td>
<td>1.38</td>
<td>0.10</td>
<td>2.46</td>
<td>0.61</td>
<td>0.79</td>
<td>0.39</td>
</tr>
<tr>
<td>Pregrazing 2010</td>
<td>0.86</td>
<td>1.04</td>
<td>1.27</td>
<td>0.32</td>
<td>3.46</td>
<td>3.46</td>
<td>3.51</td>
<td>0.39</td>
</tr>
<tr>
<td>Fall 2010</td>
<td>0.78b d</td>
<td>0.44b d</td>
<td>0.69b d</td>
<td>0.32b d</td>
<td>2.63a d</td>
<td>0.09b e</td>
<td>0.39b e</td>
<td>0.75b de</td>
</tr>
<tr>
<td>Spring 2013</td>
<td>0.01c d</td>
<td>0.03c d</td>
<td>0.08c d</td>
<td>0.01b d</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

1 Pregrazing measurements were taken in June, and fall measurements were taken in September in both years.

2 Means with different letters in columns (abc) indicate detectable differences (P < 0.05) by treatment between pregrazing in 2009, fall 2010, and spring 2013 (density); means with different letters in rows (def) indicate detectable differences (P < 0.05) between treatments within dates.

3 Locoweed density SEM: pregrazing 2009 = 0.06; fall 2009 = 0.14; pregrazing 2010 = 0.12; fall 2010 = 0.06; spring 2013 = 0.01.

4 Locoweed canopy cover SEM: pregrazing 2009 = 0.18; fall 2009 = 0.27; pregrazing 2010 = 0.44; fall 2010 = 0.33.

5 Flowering stalks SEM: pregrazing 2009 = 0.14; fall 2009 = 0.16; pregrazing 2010 = 0.18; fall 2010 = 0.08.


7 Locoweed biomass SEM: pregrazing 2009 = 1.96; fall 2009 = 0.17; pregrazing 2010 = 1.27; fall 2010 = 0.35.

Electric net fencing (Kencove Supplies, Blairsville, PA) was used to contain the sheep inside plots. In 2009 forage availability in the plots provided a mean allocation of 505 g ± 89 SE of DM·ewe⁻¹·d⁻¹, an amount estimated to be approximately 50% of a ewe’s daily forage demand for a target intake of 1.8% body weight·d⁻¹ DM basis. In 2010, mean animal forage allowance was 495 g ± 143 SE of DM·ewe⁻¹·d⁻¹, which was approximately 45% of daily forage demand for the same target intake as in 2009. Alfalfa (Medicago sativa L.) hay was weighed and fed in the evening following behavior observations, to bring daily intake up to 1.8% of body weight on a DM basis. Alfalfa hay supplementation was selected since James and Van Kampen (1974) found no decreases in intoxication of ewes fed a diet of 81% alfalfa and 19% locoweed. Hay was typically fed in tubs on the last 2 d in the 5-d plots, as grazing intensity increased with time. Mean forage utilization in both IGZ and CGZ plots for 2009 and 2010 was 81% ± 1 SE and 78% ± 9 SE, respectively. To induce high levels of utilization we applied a stocking rate of 0.30 acres/AUM over 5 d, approximately an order of magnitude higher than stocking rates of 2–3 acres/AUM (USDA, NRCS 2007) recommended for continuously grazed rangeland of the area in excellent condition.
five-nozzle boom sprayer with CO2 cartridge delivering 200·L·ha−1 in June 2009. White locoweed was in the late-flowering stage at all sites when sprayed. Weather on the days that herbicides were applied averaged ambient air temperature of 22°C ± 2 SEM, soil temperature of 20°C ± 1 SEM, relative humidity of 21% ± 3 SEM, and wind speed of 3 m·sec−1 ± 0.3 SEM. Herbicide-treated plots were fenced until the following fall to prevent cattle from grazing the dead locoweed plants immediately after treatment per producers' request. Cattle grazing of plots following herbicide treatment and TG were at moderate stocking rates.

Canopy cover of white locoweed, perennial grasses, forbs, and litter in addition to bare ground cover were recorded in all plots using point intercept taken every 10 cm on four 20-m permanent transects per plot. Locoweed density was also recorded on the same transect using a 1-m² quadrat, centered at permanent transects per plot. Locoweed density was also recorded immediately after treatment per producers' request. Cattle grazing of plots following herbicide treatment and TG were at moderate stocking rates.

Table 1. Extended.

<table>
<thead>
<tr>
<th>Flowering stalks5 (no./plant)</th>
<th>Plant size6 (cm²)</th>
<th>Locoweed biomass7 (g·m−2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable2</td>
<td>Variable2</td>
<td>Variable2</td>
</tr>
<tr>
<td>CON</td>
<td>IGZ</td>
<td>CGZ</td>
</tr>
<tr>
<td>3.10a d</td>
<td>3.52a d</td>
<td>4.03a d</td>
</tr>
<tr>
<td>1.23</td>
<td>0.05</td>
<td>0.17</td>
</tr>
<tr>
<td>1.56</td>
<td>0.80</td>
<td>0.39</td>
</tr>
<tr>
<td>0.58a d</td>
<td>0.00b e</td>
<td>0.00b e</td>
</tr>
</tbody>
</table>

Locoweed plant density was used as the criterion to select the location of soil sample frame placement. Thus, frames with highest (n=6) and lowest (n=6) initial locoweed density in each of the three experiment plots at each site were sampled. Soil samples (n=108) were manually crushed and screened in the lab, and locoweed seeds were separated from rock, soil, root material, and organic matter using both a 1-mm and 0.5-mm mesh screen soil sieve. Seeds recovered from each soil sample were counted and classified into presumed recent (brown) or older (black) seed crops.

In addition to soil samples, dry sheep fecal pellets were also collected during the fall of 2010 from grazed plots. Seed removal from feces began with a 4-h soak in cold water prior to washing. Fecal pellets were washed using two mesh screen sieves (2 and 1 mm) to recover white locoweed seeds. Fecal pellets were rinsed with running water and rubbed lightly to break up the sample. The material recovered from the sieve was dried at 37°C for 24 h and then placed in cold storage in preparation for seed retrieval (Olson et al. 1997).

All white locoweed seeds were tested in the laboratory for germinability using an Intellus Environmental Controller, where temperature regulation and lighting can be controlled and monitored. Prior to germination, locoweed seeds were surface sterilized by immersion in 70% ethanol for 1 min, followed by 10% bleach solution for 2 min and rinsed in sterile deionized water for 5 min. Seeds were then placed on sterile paper towels to dry prior to mechanical scarification, which consisted of gently rubbing seeds between two pieces of sterile fine-grit sand paper (Delaney et al. 2011). After the scarification process, seeds were placed in petri dishes lined with water-moistened Whatman filter paper and placed in the germination chamber for 6 wk at 7°C for 10 h and 13°C for 14 h to simulate spring day and night soil temperatures (Ziemkiewicz and Cronin 1981).

Sheep response variables measured included blood serum constituents, behavior, and weight. Blood samples were collected from all animals via jugular venipuncture prior to locoweed grazing and upon completion of 5-d and 3-d grazing periods at each site. Blood samples were allowed to clot at room temperature for 30 min and then centrifuged at 1 700 ×g for 20 min. Serum was decanted into polypropylene tubes and stored at −10°C until subsequent analysis. Analyses included assays to detect levels of swainsonine, ALKP, AST, T3, and T4. All blood analyses were conducted on a subset of 16 ewes (4 ewes·treatment−1·year−1) consisting of the top four locoweed eaters in each treatment except in the IGZ treatment in 2009 where two pregnant ewes, which ranked first and fourth in frequency of locoweed grazing observations, were replaced by lower-ranking open peers. Pregnancy has been found to alter
serum ALKP, AST (Hallford and Gaylean 1982), T3, and T4 (Glinnoe et al. 1990; Glinnoe 1999) levels, and it was therefore judged reasonable to use pregnancy as the criterion for exclusion in this treatment group. Although pregnancy is unlikely to alter serum swainsonine concentration; blood samples from the same subset of ewes described above were analyzed to maintain consistency. Swainsonine analyses were conducted at the USDA ARS Poisonous Plant Lab in Logan, Utah, following a protocol developed by Stegelmeier et al. (1998). Levels of ALKP and AST were determined at the New Mexico State University Analytical Laboratory using protocols developed by Wells et al. (2003) and Richards et al. (1999) for T3 and T4 analyses, respectively.

Blood serum constituent data were analyzed using a mixed model using version 9.1 of SAS (SAS 2006). Response variables considered were white locoweed density (plants·m⁻²), white locoweed cover (%), number of white locoweed flowering heads, white locoweed plant canopy size (cm²), white locoweed biomass (g·m⁻²), grass biomass (g·m⁻²), grass cover (%), forb cover (%), and bare ground (%). A subset (initial and final) of selected date by treatment comparisons of interest were conducted for each response variable using least square means. Covariance structures were tested for each variable and residual plots were examined to detect outliers and violations of analysis of variance (ANOVA) assumptions. Differences were declared statistically significant at P ≤ 0.05. Treatment by date interactions with P ≤ 0.10 were further examined.

Two-way contingency analysis was conducted to determine association between experiment treatments and a) black (presumed old) vs. brown (presumed new) seed counts, b) total seed counts, and c) germination rates. A χ² test was used to determine whether association was statistically detectable. All analyses were conducted in SAS 9.1 using the FREQ procedure, and tests with P ≤ 0.01 were declared significant.

Blood serum constituent data were analyzed using a randomized complete block experimental design with year as the blocking factor and individual ewes nested within year as the experimental unit. All statistical analyses were conducted using the subset of 16 ewes (4 ewes·treatment⁻¹·yr⁻¹) mentioned above. The effect of treatment, date (blood sampled on days 1, 5, 8, 13, 16, 21, and 24 of the experiment), year, and the interaction of treatment×date on the levels of blood metabolites were analyzed as repeated measures using PROC MIXED in SAS 9.1. A first order autoregressive covariance structure was used, and residual plots were examined to detect outliers and violations of ANOVA assumptions.

The model used to analyze ewe feeding behavior determined the effect of treatment, period (days 1–8, 9–16, or 17–24), year, and the interaction of treatment×period on the frequency of locoweed grazing using a repeated measures mixed model with individual ewes nested within year as the experimental unit. The same covariance structure and diagnostic tests as those described above were used in this analysis.

### Table 2

<table>
<thead>
<tr>
<th>Date</th>
<th>CON</th>
<th>IGZ</th>
<th>CGZ</th>
<th>HER</th>
<th>Variable²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>grass biomass³ (g·m⁻²)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pregrazing 2009</td>
<td>90.46a d</td>
<td>85.26a d</td>
<td>95.76a d</td>
<td>109.20a d</td>
<td></td>
</tr>
<tr>
<td>Fall 2009</td>
<td>84.52</td>
<td>49.84</td>
<td>61.44</td>
<td>110.60</td>
<td></td>
</tr>
<tr>
<td>Pregrazing 2010</td>
<td>115.71</td>
<td>80.75</td>
<td>90.20</td>
<td>143.20</td>
<td></td>
</tr>
<tr>
<td>Fall 2010</td>
<td>85.48a d</td>
<td>45.22a e</td>
<td>44.78b e</td>
<td>93.02a d</td>
<td></td>
</tr>
<tr>
<td><strong>Grass canopy cover⁴ (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pregrazing 2009</td>
<td>73.60a d</td>
<td>71.58b d</td>
<td>69.60b d</td>
<td>70.79b d</td>
<td></td>
</tr>
<tr>
<td>Fall 2009</td>
<td>78.55</td>
<td>79.91</td>
<td>80.75</td>
<td>81.89</td>
<td></td>
</tr>
<tr>
<td>Pregrazing 2010</td>
<td>72.89</td>
<td>71.62</td>
<td>70.35</td>
<td>80.83</td>
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<tr>
<td>Fall 2010</td>
<td>76.01a e</td>
<td>78.20a de</td>
<td>79.56a de</td>
<td>84.60a d</td>
<td></td>
</tr>
</tbody>
</table>

¹Pregrazing measurements were taken in June, and fall measurements were taken in September in both years.
²Means with different letters in columns (abc) indicate detectable differences (P < 0.05) by treatment between pregrazing in 2009 and fall 2010; means with different letters in rows (def) indicate detectable differences (P < 0.05) between treatments within dates.
³Grass biomass SEM: pregrazing 2009 = 2.97; fall 2009 = 7.75; pregrazing 2010 = 8.09; fall 2010 = 7.43.
⁴Grass canopy cover SEM: pregrazing 2009 = 0.48; fall 2009 = 0.40; pregrazing 2010 = 1.36; fall 2010 = 1.05.
⁵Forb canopy cover SEM: pregrazing 2009 = 0.35; fall 2009 = 0.61; pregrazing 2010 = 0.57; fall 2010 = 0.94.
⁶Bare ground SEM: pregrazing 2009 = 0.49; fall 2009 = 0.67; pregrazing 2010 = 0.72; fall 2010 = 0.98.
Finally, the effects of treatment and year on body-weight gains were analyzed with a mixed model using individual ewes nested within year as the experimental unit and initial body-weight as a covariate. A compound symmetry covariance structure was used and residual plots were again examined to detect violations of ANOVA assumptions. Differences were declared statistically significant at $P \leq 0.05$ for blood serum constituents, feeding behavior, and body weights.

**RESULTS**

**Effects of Targeted Grazing and Herbicide on White Locoweed**

There was no detectable effect of the experiment site (block) on any of the locoweed response variables considered except for locoweed canopy cover ($P < 0.01$: Table 1) which responded differently at the Archuleta site (1). Treatment by date interactions (detailed below) were detected for locoweed density ($P < 0.01$), cover ($P = 0.10$), and plant size ($P = 0.04$).

Locoweed density was similar in all plots prior to treatment in June 2009 (Table 1) and decreased by the end of the experiment for IGZ ($P < 0.01$), CGZ ($P < 0.01$), and HER-treated ($P < 0.01$) plots, but remained the same in CON plots ($P = 0.17$). Density was lower in spring 2013 compared to fall 2010 in CON ($P < 0.01$), IGZ ($P = 0.03$), and CGZ ($P < 0.01$), but not in HER ($P = 0.09$). All plots had similar density in spring 2013 (Table 1). Mean canopy area of locoweed plants (plant size) did not differ across plots at the beginning of the experiment in 2009 and decreased in IGZ ($P < 0.01$), CGZ ($P < 0.01$), and HER ($P < 0.01$) but not in CON plots ($P = 0.38$) by fall 2010 (Table 1). IGZ plots had smaller plants than those in CON plots at the end of the study ($P = 0.05$, Table 1).

Locoweed canopy cover dynamics resembled that of density; all plots had similar cover prior to treatment in June 2009 followed by a decrease in cover in response to IGZ ($P < 0.01$), CGZ ($P < 0.01$), and HER ($P < 0.01$) treatments but not to CON ($P = 0.10$), by the end of the experiment (Table 1). In fall 2010, locoweed cover was lower in IGZ and CGZ than CON plots ($P = 0.02$, and $P = 0.03$, respectively) but was the same in CON vs. HER plots ($P = 0.07$), which had intermediate levels of locoweed cover (Table 1). Locoweed cover in HER plots in fall 2010 was not different from that of the IGZ- and CGZ-treated plots ($P = 0.51$ and 0.73, respectively).

Mean number of flower stalks on locoweed plants in CON, IGZ, CGZ, and HER plots did not differ in June 2009, prior to applying treatments. As with other response variables, the mean number of flower stalks per plant in CON plots did not change during the experiment ($P = 0.09$) but decreased in IGZ ($P = 0.02$), CGZ ($P = 0.01$), and HER ($P = 0.01$) plots from June 2009 to fall 2010 (Table 1). By the end of the study, number of flower stalks on locoweed plants in IGZ, CGZ, and HER-treated plots were similar to each other and lower than on plants in the CON plots ($P = 0.03$, $P = 0.03$, and $P = 0.03$, respectively; Table 1).

Locoweed biomass differed among plots at the onset of the experiment. HER plots had greater locoweed biomass than CON ($P = 0.03$) and IGZ ($P = 0.02$) plots in June 2009 and were the only treatment plots that showed a decrease in locoweed biomass by the end of the study in fall 2010 ($P < 0.01$; Table 1).

**Effects of Targeted Grazing and Herbicide on Nontarget Vegetation and Bare Ground**

Grass biomass ($P = 0.04$), grass cover ($P < 0.01$), and forb cover ($P = 0.02$) responded differently at different sites. Of the nontarget vegetation variables, forb cover was the only one to exhibit a marginal treatment by date interaction ($P = 0.10$).

Grass biomass was similar in all plots at the beginning of the study (Table 2) and remained similar over time in CON ($P = 0.83$), IGZ ($P = 0.09$), and HER-treated ($P = 0.49$) plots. Grass biomass in CGZ plots decreased ($P = 0.04$) from June 2009 to fall 2010, but CGZ- and IGZ-treated plots were similar ($P = 0.98$) in fall 2010. Grass biomass was lower in both grazing treatment plots than in CON and HER plots in fall 2010 (Table 2). Conversely, grass canopy cover in IGZ ($P = 0.03$), CGZ ($P < 0.01$), and HER-treated ($P < 0.01$) plots increased from June 2009 to fall 2010, and by the end of the study the HER plots had higher grass canopy cover ($P = 0.03$) than CON, while all other treatments were similar (Table 2).

Again, all plots were similar (Table 2) to each other in grass cover prior to treatment and CON plots remained constant over time ($P = 0.41$).

Forb canopy cover was similar among plots prior to treatment (Table 2), but in contrast to the other variables, forb cover in IGZ ($P = 0.45$), CGZ ($P = 0.53$), and HER-treated ($P = 0.33$) plots was similar from beginning to end, but increased in CON plots ($P = 0.02$) through time. CON plots had higher ($P = 0.01$) forb canopy cover than CGZ plots in fall 2010, but the CGZ plots did not differ from IGZ ($P = 0.27$) or HER ($P = 0.17$) plots (Table 2).
DISCUSSION

Vegetation and Soil Seed Bank
The reduction in locoweed density, canopy cover, number of flower stalks, and plant size as a result of TG supported our first hypothesis that TG with sheep for two consecutive years would temporarily decrease locoweed abundance. Furthermore, locoweed responses to TG were in some cases better than predicted when compared to untreated and chemically treated plots.
rangeland. Grazed and chemically treated plots performed in a similar manner by exhibiting similarly low values of locoweed canopy cover, number of flower stalks, and plant size. TG involved actual removal of most of the aerial plant parts (often including crowns and superficial roots) while the herbicide killed plants but left dead standing biomass intact. This may be an important difference as the toxicity of senesced white locoweed is unknown and complete removal of plant parts maybe the only safe way, when utilizing infested rangeland, to prevent grazing and subsequent intoxication.

Table 4. Least square means of blood constituents at day 24 and overall means for grazing behavior and body-weight gains of sheep that grazed locoweed (Oxytropis sericea) intermittently (IGZ) or continuously (CGZ) for 24 d.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Intermittent</th>
<th>Continuous</th>
<th>SE</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swainsonine (ng mL⁻¹)</td>
<td>11.80</td>
<td>459.14</td>
<td>228.83</td>
<td>0.07</td>
</tr>
<tr>
<td>Alkaline phosphatase (ALKP, U L⁻¹)</td>
<td>148.75</td>
<td>995.87</td>
<td>189.51</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Aspartate aminotransferase (AST, U L⁻¹)</td>
<td>211.12</td>
<td>312.25</td>
<td>44.47</td>
<td>0.04</td>
</tr>
<tr>
<td>Triiodothyronine (T3, ng mL⁻¹)</td>
<td>1.09</td>
<td>0.70</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>Thyroxine (T4, ng mL⁻¹)</td>
<td>41.71</td>
<td>26.49</td>
<td>12.70</td>
<td>0.25</td>
</tr>
<tr>
<td>Locoweed grazing frequency (%)</td>
<td>1.95</td>
<td>4.99</td>
<td>1.56</td>
<td>0.06</td>
</tr>
<tr>
<td>Initial weights (kg)</td>
<td>58.74</td>
<td>53.18</td>
<td>—</td>
<td>0.25</td>
</tr>
<tr>
<td>Weight gains (kg)</td>
<td>6.21</td>
<td>3.42</td>
<td>1.98</td>
<td>0.19</td>
</tr>
</tbody>
</table>

1Treatments diverged through time (day by treatment interaction); therefore means for last day (day 24) are shown.
2Prelocoweed exposure values for SRA: IGZ < 0.01; CGZ < 0.01, ALKP: IGZ = 109.38; CGZ = 114.38, AST: IGZ = 87.62; CGZ = 97.87, T3: IGZ = 1.04; CGZ = 1.04, T4: IGZ = 55.14; CGZ = 49.14. Preexposure levels of all blood constituents measured were similar between treatments (P > 0.05).
3Normal value ranges: ALKP < 161 U L⁻¹; AST < 93 U L⁻¹ (Stegelmeier et al. 1999a); T3 = 0.75–2.4 ng mL⁻¹ (Obiedat et al. 2005, Camacho et al. 2012); T4 = 50–85 ng mL⁻¹ (Richards et al. 1999; Camacho et al. 2012). Normal values can vary based on analytical method, and type, age, and physiological state of the animal.
4Values shown are actual means and P values for the covariate.
Our results differ from those reported by Ralphs et al. (2002) who found that clipping white locoweed plants for four consecutive years did not reduce leaf length (~plant size in this study) or increase mortality (i.e., decrease density). This apparent inconsistency may be due to known differences in plant responses to clipping vs. grazing (Weir and Torell 1959; Taylor et al. 1960; Peterson et al. 1994) and in this case differences in the severity of defoliation. In a comparison of continuous grazing, rotational grazing, and repeated clipping on Kura clover (Trifolium ambiguum M. Bieb.), Peterson et al. (1994) found that stand density, total nonstructural carbohydrates, and total below-ground mass all decreased with grazing but not with clipping. The authors speculated that this may have been due to the low stubble height left in the grazed plots. Clipping rarely disturbs the root crowns of target plants, whereas sheep in this study severely damaged root crowns and often uprooted entire plants even when other forage was abundant. James et al. (1968) observed similar behaviors and reported that sheep dug below the soil surface to eat the succulent locoweed crowns and roots. The apparent discrepancy between locoweed canopy cover and biomass results was most likely due to the large difference in sampling intensity used to estimate each of these plant attributes. Since biomass estimates involved destructive sampling (clipping), the intensity with which this attribute was measured was intentionally low. Arealwise, biomass samples totaled 1% of each plot while density samples totaled 20%. The apparent increase in locoweed biomass measured in the second season could have also been caused by a very wet spring that occurred in that year.

Our grazing results, however, do support the findings of Ralphs et al. (2002) regarding a reduction in the number of flower stalks induced by clipping. Wyka (1999) also observed that clipping treatments suppressed growth of new inflorescences of O. sericea in an alpine meadow at high elevation. The decrease in number of flower stalks observed in our study was likely not related to normal end of season senescence since numbers in the control plots remained unchanged, while treated plots exhibited a detectable decrease. Two years of drought following our experiment appeared to erase all short-term treatment effects. Locoweed populations naturally decrease during dry years (Ralphs et al. 2002, 2003); however, the effects of targeted grazing and herbicide application on postdrought population recovery are unknown.

Soil cores from control plots yielded the lowest number of locoweed seeds. We speculate that levels of seed predation by invertebrates during our study may have been highest in control plots where seed pods were allowed to complete their cycle undisturbed. Although monitoring of this phenomenon was beyond the scope of our study, heavy infestation by insect larvae were observed at one of our study sites. Recovery of a few seeds from sheep fecal pellets suggests that a degree of granivory by sheep occurred in our study. Although the number of digested seeds was too small to derive statistically valid conclusions regarding their germination rates, our results suggest that the likelihood of locoweed seed dispersal by sheep is possibly very limited. Lacey et al. (1992) reported that sheep ingestion reduced germinability and viability of leafy spurge seeds, an observation that supports our limited results. Herbicide-treated plots had twice the density of new locoweed seeds compared to targeted grazing plots, suggesting that in the absence of seed predation by invertebrates, TG may be a more effective means of controlling long-term population cycles.

The overall effects of targeted grazing with sheep on white locoweed observed in this experiment are analogous to results obtained in studies investigating effects of similar herbivory regimes on other forb species. For example, Ralphs et al. (1991) reported decreases of 14–73% of flowering heads, and 0–89% of stalks with leaves on waxy larkspur plants (another alkaloid-synthesizing forb) following sheep grazing. In the first 2 yr of that study, stem heights were reduced an average of 14 cm (Ralphs and Olson 1992). In another study, a high-intensity low-frequency system using cattle decreased density, height, and number of flowering stems of Canada thistle (Cirsium arvense [L.] Scop) (De Bruijn and Bork 2006). Plots in that study were grazed at comparable utilization levels (72%) and for similar grazing periods of 3.0–4.1 d to those used in our experiment. De Bruijn and Bork's (2006) treatment was so effective that the bud stage was only reached by three Canada thistle plants in the high-intensity low-frequency plots in the entire 3-yr study. Lacey and Shelley (1996) also reported that stem densities were reduced and stems tended to be shorter and produce fewer flowers on leafy spurge (Euphorbia esula L.) plots following sheep grazing.

Grass cover increased following both grazing treatments supporting our second hypothesis. The increase in grass canopy cover observed may have been due to increased tillering by blue grama following defoliation (Enoe et al. 2002) supported by the increased rate of nutrient cycling due to the urine and feces deposition from sheep in grazed plots (Hobbs 1996 and references therein). Forb cover in the grazed plots was more similar to the herbicide treatment than the control possibly due to the limited ability of dicotyledonous plants to recover following grazing (Archer and Tieszen 1986). Although grass canopy cover increased after treatment, grass biomass remained the same or decreased in grazed plots. Utilization in TG plots was approximately 80% in both years, and although blue grama recovers well after severe defoliation, western wheatgrass (which was abundant at all sites) does not recover as quickly since most of its tillers are produced before mid-July (Hart et al. 1993). Grass biomass in the grazed plots may have also been affected by subsequent grazing by wildlife and cattle, which prefer the succulent regrowth of previously grazed patches (Laca 2008; Goodman, unpublished data). The amount of bare ground was not affected by the TG treatments and remained unchanged throughout the 2 yr of the study, a trend which mirrored the CON plots. Bare ground decreased in the HER-treated plots, most likely due to an apparent pulse of grass growth that occurred after herbicide application from decreased competition with locoweed for nutrients (Mueggler 1972) and/or exclusion of cattle and antelope grazing during the first growing season after treatment (June–September 2009). Collectively, grass canopy cover, forb canopy cover, and bare ground results support our second hypothesis that the grazing treatments would not negatively affect nontarget vegetation.

Our third hypothesis, that intermittent and continuous TG would affect locoweed similarly, was supported by our results since no detectable difference in white locoweed responses were found between IGZ and CGZ. Selectivity may have been different for the first couple days of the experiment in each year,
but as grazing pressure increased choices became more limited. Sheep in both grazing treatments exhibited grazing behavior analogous to that reported by Ralphs et al. (1994a) who found that as grazing pressure increased because of lack of available forage, white locoweed consumption increased in the diets of cattle not predisposed to consume locoweed.

Sheep Serum, Behavior, and Weight Gains

Serum swainsonine has been used as an indicator of locoweed intoxication (Stegelmeier et al. 1995, 1999a; Taylor et al. 2000; Whittet et al. 2002), although its concentration can drop below detectable levels within days of poisoning, depending on the dose administered (Ashley et al. 2006). This is most likely due to its short half-life of 18 to 20 h (Stegelmeier et al. 1998, 1999a). Differences between treatments, in this study, may have been even greater than shown as it is likely that serum swainsonine levels dropped in both intermittent and continuous groups particularly at the third site, when ewes typically began eating locoweed earlier and consumed most of the locoweed during the first day of the 5- and 3-d periods. This would have given swainsonine more than double the time of its half-life to clear from the serum before blood was drawn, rendering it less detectable. Nevertheless, significantly lower swainsonine levels were detected in ewes in the IGZ treatment, supporting the hypothesis that sheep grazing locoweed intermittently have lower serum swainsonine concentrations than sheep allowed to graze locoweed continuously.

Serum ALKP has been found to increase in sheep and cattle consuming locoweed (Pulsipher et al. 1994; Taylor et al. 2000), a response that occurs as early as 24 h after a single locoweed gavage (Taylor and Strickland 2002). Serum levels of AST and ALKP may be not only the earliest but also the most sensitive indicators of swainsonine-induced a-mannosidase inhibition, since swainsonine doses as low as 0.05 and 0.10 mg·kg⁻¹ can alter these serum constituents (Stegelmeier et al. 1999a). Increases outside of normal ranges were found in AST and ALKP levels in sheep dosed with only 0.05 mg·kg⁻¹ for 15 d, and AST increased within the first 3 d of the animals receiving locoweed through gavage. Furthermore, these increases were seen before swainsonine was detected in the serum, while body-weight gains were still unaffected, and only minimal histological changes had occurred (Stegelmeier et al. 1999a). Serum ALKP is generally used as an index of diseased liver or bone tissue. Cellular vacuolization of the hepatocytic cells of the liver (Van Kampen and James 1969; Bachman et al. 1992; Pulsipher et al. 1994) or altered glycoprotein processing (Obeidat et al. 2005) are likely the cause of increases of ALKP with increased locoweed consumption. Increased serum AST may be caused by vacuolization of neural, hepatic, or renal tissue (Obeidat et al. 2005). Because ALKP and AST concentrations are altered by cell damage, levels remain elevated for some time. ALKP has been reported to remain high for 7 d and above normal for 14 d, following the termination of subacute locoweed exposure (Bachman et al. 1992; Pulsipher et al. 1994; Taylor et al. 2000). This suggests ewes grazing locoweed intermittently were most likely receiving low doses of swainsonine since even after a spike in ALKP following 5 d of grazing locoweed, ALKP levels dropped back down following 3 d of grazing locoweed free plots. These results support our hypothesis that ewes grazing locoweed plots, intermittently, would have lower serum ALKP and AST levels than ewes grazing locoweed continuously.

Serum T3 and T4 levels are usually depressed by locoweed consumption (Pulsipher et al. 1994; Ortiz et al. 1997; Richards et al. 1999). This effect is most likely caused by either an increase in catabolism of the hormones or by follicular cell destruction in the thyroid (Pulsipher et al. 1994). As described above, swainsonine interrupts the enzyme a-mannosidase function by preventing it from trimming sugar molecules from glycoproteins for digestion. This in turn causes oligosaccharides and glycoproteins to build up in the cell and eventually cause vacuolation, or accumulation of vacuoles (Molyneux 1999). The storage form of and precursor to the thyroid hormone, thyroglobulin, is a glycoprotein (Kaneko 1997), which may also be a reason for depressed T3 and T4 levels. Follicular cell death may decrease thyroid hormone levels because thyroglobulin is converted to T3 and T4 by using lysosomal proteases of the thyroid follicular cells. Serum T3 and T4 levels have been found to decrease within 7 d of initiating locoweed feeding (Ortiz et al. 1997; Richards et al. 1999; Obeidat et al. 2005) and were not different than the control 7 d after the completion of locoweed feeding (Ortiz et al. 1997). This would explain why T3 and T4 levels did not decrease for either treatment until after 8 d of locoweed grazing. These data support the hypothesis that ewes grazing locoweed-infested plots, intermittently, would have higher T3 and T4 levels than ewes grazing locoweed continuously.

Ewes that grazed locoweed intermittently exhibited a tendency to graze locoweed less frequently than their CGZ counterparts contradicting our prediction that both groups would exhibit similar grazing behaviors. All ewes avoided locoweed during the first days of the study and tended to spend more time feeding on locoweed as the trial progressed. This was most likely due to increasing reduction in available forage choices, although alfalfa was supplemented to maintain intake at 1.8% body weight. Hay supplementation may have altered behavior in the last 2 d of grazing at each site; however, previous studies have shown that alfalfa did not decrease intoxication of sheep that received a diet composed of 81% alfalfa hay (James and Van Kampen 1974). Locoweed consumption by intoxicated animals tends to increase with time until animal behavior is altered because of neurological damage (Pritchard et al. 1990; Ralphs et al. 1996) so increased consumption in this study is likely due to increasing levels of toxicosis although no clinical symptoms of neurological alterations were observed in ewes of either treatment. The fact that ewes in the CGZ group showed a tendency to spend more time feeding on locoweed could point to their advancing state of intoxication, although these differences were not reflected in the vegetation responses as no detectable differences were found in locoweed response variables to IGZ and CGZ.

Our last hypothesis predicted that ewe body-weight would not differ between treatments because ewes did not graze locoweed for more than the 30-d threshold (Stegelmeier et al. 1999a) needed for clinical intoxication or histological lesions to develop and consequently cause body weight to decrease. We expected to see no difference in body-weight gains between treatments based on the fact that previous studies had found that such differences were not seen until 35 d after the initiation of locoweed consumption at levels of 7%, 14%, and 21% of
diet (Ortiz et al. 1997). Differences between years in ewe body-weight gains are likely due to differences in foraging experience as 2010 ewes were pen raised. Despite this, our results suggest that there is a potential for intermittent TG of locoweed to be associated with greater body-weight gains than prescriptions that involve continuous TG of this noxious plant.

IMPLICATIONS

TG with sheep may be an effective tool to reduce small patches of locoweed, although additional research and practical experience is needed to assess its long-term effects on locoweed populations and nontarget vegetation. Large-scale application of this grazing method is not recommended due to the high-utilization levels needed to negatively impact locoweed plants. Even if TG only promoted a short-term decrease of white locoweed patches, it could allow producers to graze infested ranges, following TG with sheep, and to expect reduced levels of intoxication in cattle. Decreased livestock losses, reduction in herbicide and fencing costs may also have positive economic implications. Our study suggests that intermittent exposure of sheep to locoweed-infested rangeland appears to prevent significant cell damage induced by swainsonine ingestion. However, because our study lacked a satisfactory level of animal replication, implications of these results are mostly restricted to our research sites in northeastern New Mexico. The on-and-off grazing regime used in this study may be a way to safely graze locoweed-infested ranges although additional research with independent replications is needed to confirm these results.

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