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Original Research

Targeted Sheep Grazing to Suppress Sulfur Cinquefoil *(Potentilla recta)* on Northwestern Montana Rangeland☆

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ABSTRACT

Sulfur cinquefoil (*Potentilla recta* L.), a perennial forb native to the eastern Mediterranean region of Eurasia, is a major noxious weed on rangelands of the northwestern United States and southwestern Canada. We assessed targeted sheep grazing to suppress sulfur cinquefoil in a 2-yr rangeland field experiment in northwestern Montana. We evaluated targeted sheep grazing with and without protein-energy supplementation (37 g crude protein [CP] sheep^{-1} d^{-1} and 0.17 kg total digestible nutrients [TDN] sheep^{-1} d^{-1}) during late June (sulfur cinquefoil in early flowering stage) and mid-July (sulfur cinquefoil in late flowering — early seedset stage). Sheep readily consumed sulfur cinquefoil stems, leaves, flowers, and developing seed heads, with or without supplementation. Sulfur cinquefoil comprised the largest proportion of sheep diets during both late June and mid-July, averaging 46%, but more sulfur cinquefoil dry matter (DM) was consumed by sheep during mid-July (0.6 vs. 1.0 kg DM sheep^{-1} d^{-1} in June vs. July, respectively). Supplementation did not increase DM intake (DMI) of sulfur cinquefoil, nor did supplementation improve the nutritive quality of sheep diets. We also documented that 1) targeted sheep grazing achieved heavy utilization of sulfur cinquefoil (67%) while keeping perennial graminoid use light to moderate (18 — 41%); 2) targeted sheep grazing reduced viable seed production of sulfur cinquefoil by 97% in June-grazed paddocks and 95% in July-grazed paddocks; and 3) targeted sheep grazing reduced sulfur cinquefoil yield the next summer by 41% in June-grazed paddocks and 47% in July-grazed paddocks without decreasing yield or plant community composition of perennial graminoids. We conclude that supplemented or nonsupplemented targeted sheep grazing applied in either late June or mid-July can effectively suppress sulfur cinquefoil. Sheep nutrition and sulfur cinquefoil DMI will be optimized by targeted sheep grazing applied during mid-July.

Introduction

Sulfur cinquefoil (*Potentilla recta* L.) is a perennial forb native to the eastern Mediterranean region of Eurasia (Rice, 1999). It is a minor cropland weed in the eastern and central United States (Werner and Soule, 1976), but large infestations of this invasive plant exist on rangelands of the northwestern United States and southwestern Canada (Duncan et al., 2004; Rice, 1999). The plant also has likely avoided detection in many North American rangelands because it is similar in appearance to native, co-occurring congeners, particularly slender cinquefoil (a.k.a., Northwest cinquefoil; *Potentilla gracilis* Douglas ex Hook) (Duncan et al., 2004; Dwire et al., 2006; Rice, 1999).

Sulfur cinquefoil has broad ecological amplitude and is capable of invading conifer, grassland, shrubland, and riparian ecosystems throughout the western United States and western Canada (Rice, 1999; USDA-NRCS, 2017; Zouhar, 2003). Sulfur cinquefoil displaces indigenous plants, lowers biological diversity, and reduces desirable forage for livestock and wildlife (Rice, 1999; Sheley and Denny, 2006). Sulfur cinquefoil is especially worrisome because it can invade relatively undisturbed plant communities (Lesica and Martin, 2003; Naylor et al., 2005). In some areas, sulfur cinquefoil may outcompete other nonindigenous invasive plants such as spotted knapweed (*Centaurea stoebe* L.), yellow star-thistle (*Centaurea solstitialis* L.), and leafy spurge (*Euphorbia esula* L.) (Rice, 1999).

Few options currently exist for suppressing sulfur cinquefoil on North American rangelands. Sulfur cinquefoil is closely related to domestic strawberries and native cinquefoil plants, making it a poor candidate for biological control with phytophagous insects or plant pathogens (Duncan et al., 2004). Prescribed fire is ineffective (Lesica and Martin, 2003), and herbicides have provided only mixed results. Picloram herbicide is usually, but not always, effective (Endress et al., 2008; Lesica and Martin, 2003; Sheley et al., 2006);

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however, retreatment is necessary every 3 − 5 yr (Duncan et al., 2004; Lesica and Martin, 2003). Fortunately, our previous research demonstrated that defoliation can suppress sulfur cinquefoil yield and seed production (Frost and Mosley, 2012). Hand-clipping during flowering or the early seedset phenotypic stage suppressed the end-of-growing season standing crop of sulfur cinquefoil 78 − 89% and suppressed viable seed production of sulfur cinquefoil 99 − 100% (Frost and Mosley, 2012).

Targeted livestock grazing is a potential tool for defoliating sulfur cinquefoil on rangelands. Targeted livestock grazing is the application of the appropriate species of livestock at the appropriate timing, frequency, intensity, and duration to accomplish specific vegetation management goals (Launchbaugh and Walker, 2006). Previous research by us and others has demonstrated that targeted livestock grazing can suppress other invasive perennial forbs such as leafy spurge (Olson and Wallander, 1998) and spotted knapweed (Mosley et al., 2016; Olson et al., 1997).

The propensity of livestock to consume sulfur cinquefoil is poorly understood. In general, sulfur cinquefoil is considered unpalatable to livestock (Rice, 1999). Cattle in northeastern Oregon, however, consumed substantial amounts of sulfur cinquefoil plants, including seed heads (Parks et al., 2008), and sheep and goats have been observed consuming sulfur cinquefoil while grazing on pasture and rangeland in Montana (B. E. Olson, unpublished data; R. A. Frost, personal observations). One potential factor limiting livestock consumption of sulfur cinquefoil is its relatively low nutritive value (Frost et al., 2008). Another potential limitation is that sulfur cinquefoil contains tannins (Tomczyk et al., 2011; Werner and Soule, 1976). Tannins are phenolic compounds that can reduce plant palatability, intake, digestibility, and nutrient availability for herbivores (Frutos et al., 2004; Rogosic et al., 2008). Protein and energy supplementation may be a practical, cost-effective way to enable animals to consume tannins without suffering adverse effects (Rogosic et al., 2011; Silanikove et al., 1997; Villalba et al., 2002). Supplementation can help supply the protein and energy needed to fuel detoxification pathways and provide enzyme substrates for effectively converting tannins to inert compounds for excretion (Foley et al., 1995; Illius and Jessop, 1995).

The purpose of this study was to assess whether targeted sheep grazing could suppress sulfur cinquefoil. Specifically, we examined whether prescriptively grazed sheep would readily consume sulfur cinquefoil during flowering or seedset, the phenotypic stages when this invasive plant is most vulnerable to defoliation (Frost and Mosley, 2012). Furthermore, we examined whether protein-energy supplementation would increase sheep consumption of sulfur cinquefoil and whether sheep would satisfy their nutritional requirements with or without supplementation. We also investigated whether targeted sheep grazing would suppress viable seed production, yield, and plant community composition of sulfur cinquefoil without inhibiting perennial graminoids. We hypothesized that 1) sheep would readily consume sulfur cinquefoil when sulfur cinquefoil was in either the flowering or seedset phenotypic stage; 2) supplemented sheep would consume more sulfur cinquefoil than nonsupplemented sheep; 3) supplementation would be necessary to satisfy sheep nutritional requirements; and 4) sheep would consume sufficient sulfur cinquefoil to suppress its viable seed production, yield, and plant community composition.

Methods

Study Area

This 2-yr field study was located in northwestern Montana, on a rangeland terrace adjacent to the Flathead River (47°40′N, 114°17′W). Our study site was located within the bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve)/Sandberg bluegrass (*Poa secunda* J. Presl.) habitat type in the needleandthread (*Hesperostipa comata* [Trin. & Rupr.] Barkworth) phase (Mueggler and Stewart, 1980). The soil type was classified as Jocko gravelly loam (USDA-NRCS, 2016), and the ecological site was Shallow to Gravel within the Northern Rocky Mountains Major Land Resource Area (USDA-NRCS, 2016). Elevation was 830 m, and the 30-yr average annual precipitation was 385 mm, with 60% received from April through September (WRCC, 2016).

The entire study site was in degraded condition due largely to excessive grazing pressure by domestic sheep in the first half of the 20th century and by season-long cattle use in recent years. The study occurred within a heavy infestation of sulfur cinquefoil in which sulfur cinquefoil averaged 49% of the vegetative composition by weight, as quantified in ungrazed control paddocks in 2010 and 2011 (see "Treatments" and methods of "Field Data Collection and Laboratory Analyses" later). Other forbs, perennial graminoids, and annual grasses comprised 11%, 36%, and 4% of the plant community, respectively. Other major forbs included white prairie aster (*Symphyotrichum falcatum* [Lindl.] G. L. Nesom) and western yarrow (*Achillea millefolium* L.). Needleandthread, bluebunch wheatgrass, threadleaf sedge (*Carex filifolia* Nutt.), and Fendler threeawn (*Aristida purpurea* var. *longiseta* [Steud.] Vasey) were the dominant perennial graminoids, while cheatgrass (*Bromus tectorum* L.) and sixweeks fescue (*Vulpia octoflora* [Walter] Rydb.) were the dominant annual grasses.

Treatments

Thirty 0.5-ha paddocks were constructed. Three paddocks were ungrazed (control) in 2009, and three more paddocks were ungrazed in 2010. Twelve paddocks were grazed by sheep in 2009, and 12 paddocks were grazed by sheep in 2010. Each year, six paddocks were grazed when sulfur cinquefoil was in the early flowering phenotypic stage (late June) and six paddocks were grazed when sulfur cinquefoil was in the late flowering-early seedset phenotypic stage (mid-July). As stated earlier, our previous clipping study determined that defoliation during these two phenotypic stages was optimal for decreasing yield and seed production of sulfur cinquefoil (Frost and Mosley, 2012). Targeted sheep grazing occurred each year when sulfur cinquefoil remained green, but desirable grasses and forbs were largely dormant, thus encouraging sheep to consume sulfur cinquefoil and limiting potential adverse impacts to desirable vegetation. Targeted sheep grazing also occurred each year before sulfur cinquefoil had produced viable seeds.

Seven yearling Rambouillet ewes grazed within each paddock (total = 42 ewes $month^{-1}$ yr^{-1}). The same yearling ewes were used in June and July of a given year, but a different group of sheep was used in 2009 versus 2010. We equated sheep use across paddocks and years by keeping sheep in the paddocks until a targeted level of use was achieved. Sheep remained in the paddocks until perennial graminoids reached an 8 − 10-cm stubble height or until sheep grazing removed ≥ 90% of the buds, flowers, and seed heads from sulfur cinquefoil plants, whichever occurred first. Paddocks in 2009 were grazed for 7 d at a stocking rate of 0.5 animal unit month ha^{-1}. In 2010, paddocks were grazed for 17 d at a stocking rate of 1.2 animal unit month ha^{-1}. Longer grazing periods were needed in 2010 due to greater forage production from increased precipitation in 2010 versus 2009. Our targeted grazing prescription was intended to remove as many sulfur cinquefoil buds, flowers, and seed heads as possible without harming perennial graminoids. The 8- to 10-cm stubble height was intended to average about 50 − 55% utilization (Taylor and Lacey, 1999) and thereby remain within sustainable grazing use levels (40 − 60%) recommended for preferred forage plants on Montana rangelands (Lee-Campbell, 1999).

Grazing variables (i.e., paddock size, sheep stock density, stubble height, and stocking rates) were selected to balance research requirements with the need to mimic rangeland grazing conditions. Paddock size needed to be small enough to minimize interpaddock variation in the topography, soils, and plant community, yet paddock size and sheep numbers needed to be large enough for sheep to exhibit realistic grazing behavior. Previously we have used similar-sized or smaller paddocks to investigate targeted sheep grazing of spotted knapweed (Henderson et al., 2012; Mosley et al., 2016), and grazing responses were similar between our small experimental paddocks and larger pastures when we applied targeted sheep grazing at a landscape-scale (Surber et al., 2011; Thrift et al., 2008).

In each mo × yr combination, sheep in three paddocks were fed supplemental protein and energy. A barley-based commercial sheep pellet (17.6% crude protein [CP], 77% total digestible nutrients [TDN], 39% neutral detergent fiber [NDF], and 14% acid detergent fiber [ADF]) was hand-fed daily during late morning at a rate of 0.21 kg ewe^{-1} (37 g CP sheep^{-1} d^{-1} plus 0.17 kg TDN sheep^{-1} d^{-1}). Previous research demonstrated that this type and amount of supplementation did not depress forage intake by ewes grazing rangeland in Montana (Thomas and Kott, 1995). Water and trace-mineralized salt with 90 ppm added selenium were available ad libitum in all sheep-grazed paddocks.

Yearling ewes averaged 68 kg animal^{-1} in both 2009 and 2010. In June each year, all ewes were randomly assigned to the treatment paddocks following 7-d acclimation grazing periods. During the acclimation periods, sheep in the supplemented treatment group and sheep in the no-supplement treatment group grazed within two separate 4-ha paddocks on an adjacent sulfur cinquefoil infestation. Sheep in the supplemented treatment group received their supplement during the acclimation periods. Acclimation grazing periods enabled the sheep to become familiar with the forage on the study site before entering treatment paddocks. Sheep assigned to the supplemented group during the June grazing period were also assigned to the supplemented group during the July grazing period. The yearling sheep used in our study each year had no previous experience with protein-energy supplementation nor previous experience eating sulfur cinquefoil before arrival at our study site.

Field Data Collection and Laboratory Analyses

We sampled current year's plant standing crop immediately before and after sheep grazing. Vegetation in each sheep-grazed paddock was clipped to ground level within ten 50 × 50 cm quadrats. Quadrats were spaced at 5-m intervals along a permanently marked 60-m transect located near the center of each paddock. Quadrats were spaced to ensure that the same quadrat locations were not clipped more than once during the study, and all clipped quadrats were separated from each other by at least 1.5 m. Clipped samples were separated into four categories (sulfur cinquefoil, other forbs, perennial graminoids, annual grasses), oven-dried at 55°C for 48 h, and weighed.

Forage dry matter intake (DMI), botanical composition of sheep diets, and forage utilization were estimated from differences in current year's plant standing crop between the pregrazing and postgrazing clipped samples (Holechek et al., 1982; Macoon et al., 2003; Smith et al., 1963). Total pregrazing and postgrazing difference in current year's standing crop provided total forage disappearance. Total forage DMI was 0.769 of total forage disappearance (0.231 of forage disappearance attributed to trampling), as calculated from Quinn and Hervey (1970) and Sims et al. (1976). Daily forage DMI per sheep was calculated from total forage DMI, based on seven sheep per paddock that grazed each paddock for 7 d in 2009 and 17 d per paddock in 2010. The botanical composition of sheep diets was calculated for each vegetation class (sulfur cinquefoil, other forbs, perennial graminoids, annual grasses) by dividing the pregrazing and postgrazing difference in weight of each vegetation class by the total pregrazing and postgrazing difference in current year's plant standing crop. This method for estimating forage DMI and diet composition is suitable for situations like ours, where grazing periods were brief, forage use was relatively uniform within smaller paddocks, forage use was primarily by one species of herbivore, we accounted for trampling, and we observed no plant regrowth during the grazing periods (Holechek et al., 1982; Macoon et al., 2003; Smith et al., 1963). Sulfur cinquefoil DMI was estimated by multiplying total forage DMI by the percent composition of sulfur cinquefoil in sheep diets.

We used preference indices to evaluate diet selection by supplemented and nonsupplemented sheep (Heady and Van Dyne, 1965). Preference indices were calculated by dividing the mean percentage of the vegetation class in sheep diets by its mean percentage composition in the paddocks.

Pregrazing vegetation samples were ground through a 1-mm screen in a Wiley mill and then analyzed for CP (CP = %N × 6.25; AOAC, 2003), NDF (Van Soest et al., 1991), and ADF (Van Soest et al., 1991). The calculation of TDN followed (NRC, 2001). Identical procedures were used to analyze nutritive quality of the supplement. Dietary CP (g CP sheep^{-1} d^{-1}) and dietary TDN (kg TDN sheep^{-1} d^{-1}) were calculated by multiplying the daily forage DMI of each vegetation class (sulfur cinquefoil, other forbs, perennial graminoids, annual grasses) by its concentration of CP or TDN and summing the products (Urness and McCulloch, 1973). Dietary NDF (%) and dietary ADF (%) were calculated by multiplying the percentage diet composition of each vegetation class by its concentration of NDF or ADF and summing the products (Urness and McCulloch, 1973). Additional nutrients were provided by the supplement to supplemented sheep because, as noted previously, the amount of supplement fed (0.3% ewe body weight) was insufficient to cause the supplement to substitute for forage (Thomas and Kott, 1995).

Immediately before and after sheep grazing, we counted sulfur cinquefoil buds, flowers, and seed heads within ten 50 × 50-cm quadrats spaced at 5-m intervals along a 60-m transect located near the center of each grazed paddock. In late July we collected seeds from sulfur cinquefoil plants in sheep-grazed and ungrazed paddocks when seeds were developed to their fullest possible extent but while seed heads remained closed before seed dispersal. All buds, flowers, and seed heads were collected from sulfur cinquefoil plants growing within ten 50 × 50 cm quadrats per paddock. These quadrats were spaced at 5-m intervals along a permanently marked 60-m transect located near the center of each paddock. In the laboratory, seeds were extracted from buds, flowers, and seed heads using a rub board, counted, and tested for viability using the tetrazolium test (Grabe, 1970), as described by Frost and Mosley (2012).

Plant yield was sampled at peak standing crop (mid-July) of the yr (2010 or 2011) immediately following when grazing treatments were applied (2009 or 2010). Clipping and weighing procedures for plant yield matched the methods we used to estimate available forage immediately before sheep grazing periods, except control paddocks were also clipped when sampling plant yield. Plant community composition was calculated by dividing the oven-dried weight of each vegetation class (sulfur cinquefoil, other forbs, perennial graminoids, annual grasses) by the combined oven-dried weight of all four vegetation classes.

Statistical Analyses

The experiment was a completely randomized design, and the treatment arrangement was a 3 × 2 × 2 factorial, with three grazing treatments (supplemented sheep grazing, nonsupplemented sheep grazing, ungrazed control), two timings of grazing (late June, mid-July), and 2 yr (2009, 2010). The 0.5-ha paddocks ($n = 30$) were the experimental units. Data were analyzed with analysis of variance using the Generalized Linear Model of SAS software (Version 9.4, SAS Institute, Cary, NC). We examined the main effects of supplementation, timing of grazing, year, and their interactions on sheep diets and vegetation response. Interactions and differences were considered significant at $P \leq 0.10$. Data were evaluated for deviations from normality using the Shapiro-Wilk test ($P \leq 0.10$), and data were transformed as recommended by Steel et al. (1997). Forage DMI, TDN intake, and CP intake were transformed by $\log_{10}(Y)$; forage yield was transformed by $\log_{10}(Y + 1)$; viable seed density data were transformed by the square root of Y + ½; and percentage data were transformed by arcsine of the square root. Means and standard errors presented in the text and tables are from untransformed data.

Forage preference indices were evaluated for significance with 90% confidence intervals. When confidence intervals did not include 1.0, a preference index > 1.0 indicated preference, whereas a preference index < 1.0 indicated avoidance (Hobbs and Bowden, 1982).

Results

All year effects and interactions that included year effects were nonsignificant ($P > 0.10$) for all response variables. Therefore, combined results are reported from the 2 treatment yr of 2009 and 2010 (Steel et al., 1997).

Forage Nutritive Quality

Forage nutritive quality generally exhibited seasonal trends (Fig. 1). Forage quality of sulfur cinquefoil declined from June to July for CP ($P = 0.002$), TDN ($P = 0.010$), NDF ($P = 0.034$), and ADF ($P = 0.031$). Perennial graminoids' CP declined from June to July ($P < 0.001$), and forage quality of annual grasses declined from June to July for CP ($P = 0.010$), TDN ($P = 0.017$), and ADF ($P = 0.036$). Forage quality of other forbs did not decline from June to July ($P > 0.10$).

Botanical Composition of Sheep Diets

Sulfur cinquefoil comprised the largest proportion of sheep diets, averaging 46% across June and July ($P = 0.277$; Table 1). Supplemented sheep diets and nonsupplemented sheep diets contained similar proportions of sulfur cinquefoil ($P = 0.695$). The proportion of other forbs in sheep diets was also unaffected by month ($P = 0.568$) or supplementation ($P = 0.450$). Supplemented sheep diets contained a smaller proportion of perennial graminoids than nonsupplemented sheep (17% vs. 31%, respectively; $P = 0.079$; see Table 1), largely due to supplemented sheep in June consuming annual grasses instead. Supplemented sheep diets were 38% annual grasses in June but < 2% in July ($P < 0.001$).

Table 1
Botanical composition of sheep diets (±SE) for supplemented and nonsupplemented yearling ewes grazing in late June or mid-July 2009 or 2010 ($n = 3$ paddock replicates treatment^{-1} mo^{-1} yr^{-1}) on sulfur cinquefoil—infested rangeland in northwestern Montana

Forage class	Treatment	Month: June	July	Mean
		(%[1,2])		
Sulfur cinquefoil	Supplemented	38.5 (3.8) aA	56.8 (4.4) bA	47.6 (3.9) A
	No supplement	45.4 (12.6) aA	44.0 (7.1) aA	44.7 (6.5) A
	Mean	42.0 (5.8) a	50.4 (4.4) a	
Other forbs	Supplemented	15.4 (4.8) aA	14.9 (5.9) aA	15.2 (3.6) A
	No supplement	15.8 (6.0) aA	19.5 (2.9) aA	17.6 (3.0) A
	Mean	15.6 (3.6) a	17.2 (3.2) a	
Perennial graminoids	Supplemented	8.1 (6.8) aA	26.8 (8.2) bA	17.4 (5.8) A
	No supplement	34.2 (9.9) aB	27.7 (8.3) aA	31.0 (6.2) B
	Mean	21.2 (6.9) a	27.2 (5.6) a	
Annual grasses	Supplemented	37.9 (5.6) aA	1.5 (1.0) bA	19.7 (6.1)[3]
	No supplement	4.6 (2.4) aB	8.7 (6.2) aA	6.6 (3.4)
	Mean	21.2 (6.1)[3]	5.1 (3.2)	

[1] Means within rows with the same lowercase letter are not different ($P > 0.10$).
[2] Means within columns, within the same forage class, with the same uppercase letter are not different ($P > 0.10$).
[3] Month × treatment interaction ($P = 0.0007$).

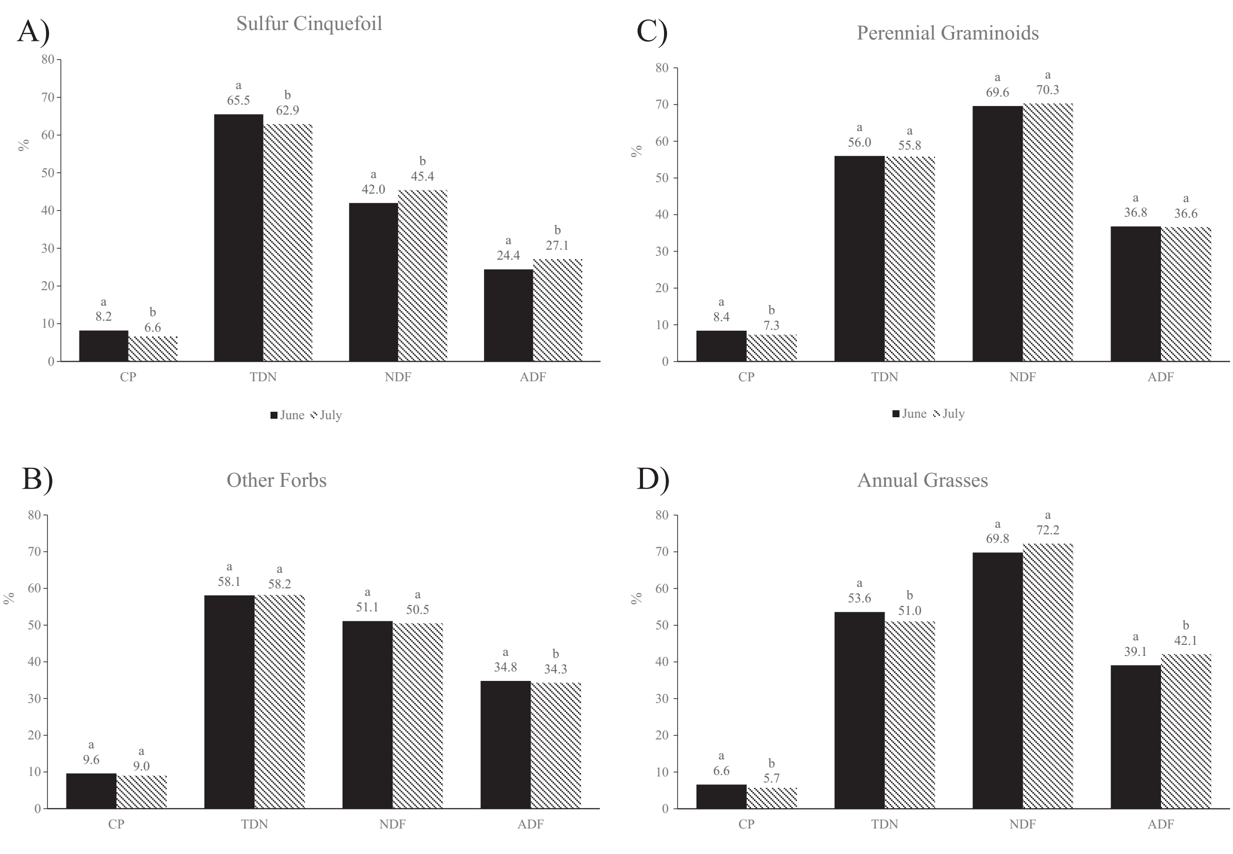

Figure 1. Forage nutritive quality of (**A**) sulfur cinquefoil, (**B**) other forbs, (**C**) perennial graminoids, and (**D**) annual grasses during late June and mid-July 2009 or 2010 ($n = 3$ paddock replicates treatment^{-1} month^{-1} yr^{-1}) on sulfur cinquefoil—infested rangeland in northwestern Montana. Within the same nutritive variable, means with the same lowercase letter are not different ($P > 0.10$).

Forage Preferences and Avoidances

Supplementation altered sheep diet selection for sulfur cinquefoil, perennial graminoids, and annual grasses (Table 2). During June, supplemented sheep preferred sulfur cinquefoil and annual grasses while avoiding perennial graminoids. During July, supplemented sheep avoided annual grasses. Nonsupplemented sheep avoided perennial graminoids during July.

Sulfur Cinquefoil DMI

Supplemented and nonsupplemented sheep diets averaged 0.8 kg DM sulfur cinquefoil $sheep^{-1}$ d^{-1} ($P = 0.885$; Table 3). Sheep consumed more sulfur cinquefoil during July than June ($P = 0.020$), and the influence of month was stronger for supplemented sheep ($P = 0.067$) than nonsupplemented sheep ($P = 0.152$). Field observations confirmed that sheep readily consumed sulfur cinquefoil stems, leaves, flowers, and developing seed heads.

Nutritive Quality of Sheep Diets

Dietary NDF ($P = 0.606$), ADF ($P = 0.709$), and CP intake ($P = 0.227$) did not differ between June and July (Table 4). In contrast, forage DMI and TDN intake were greater in July than June ($P = 0.091$ and $P = 0.094$, respectively). Overall, supplemented and nonsupplemented sheep diets did not differ in nutritive quality (forage DMI, $P = 0.383$; CP intake, $P = 0.782$; TDN intake, $P = 0.396$; dietary NDF, $P = 0.238$; and dietary ADF, $P = 0.354$).

Forage Utilization

Sulfur cinquefoil utilization trended heavier during July than June (72% vs. 63%, respectively; $P = 0.112$), averaging 67% across months and 67% between supplemented and nonsupplemented sheep ($P = 0.198$; Table 5). Perennial graminoid use remained ≤ 50% in every month × supplement combination. Perennial graminoid use was less during June than July (22% vs. 38%, respectively; $P = 0.034$) and less by supplemented sheep (18% vs. 41%, respectively; $P = 0.025$). Utilization of other forbs averaged 54% across months ($P = 0.878$) and supplementation treatments ($P = 0.222$). Annual grass use was greater during June than July (49% vs. 26%, respectively; $P = 0.014$), but annual grass use was unaffected by supplementation ($P = 0.161$), averaging 37%.

Sulfur Cinquefoil Viable Seed Production

Targeted sheep grazing removed 96% of sulfur cinquefoil buds, flowers, and seed heads (Table 6). Percentage removal was unaffected by supplementation ($P = 0.179$) or whether targeted grazing occurred in June versus July ($P = 0.493$). Compared with ungrazed paddocks, sulfur cinquefoil produced 97% fewer viable seeds in paddocks grazed during June ($P = 0.003$) and 95% fewer viable seeds in paddocks grazed during July ($P = 0.053$; Table 7). Viable seed production by sulfur cinquefoil did not differ between paddocks grazed by supplemented versus nonsupplemented sheep in either June or July.

Table 2
Forage preference indices (FPI) with 90% confidence intervals (CI) for supplemented and nonsupplemented yearling ewes grazing in late June or mid-July 2009 or 2010 ($n = 3$ paddock replicates $treatment^{-1}$ mo^{-1} yr^{-1}) on sulfur cinquefoil—infested rangeland in northwestern Montana

		Month			
		June		July	
Forage class	Treatment	FPI	90% CI	FPI	90% CI
Sulfur cinquefoil	Supplemented	1.8	1.1-2.4[1]	1.4	0.9-2.0
	No supplement	1.4	0.5-2.3	1.2	0.7-1.7
Other forbs	Supplemented	1.5	0.5-2.4	1.1	0.1-2.2
	No supplement	1.3	0.2-2.5	1.2	0.7-1.6
Perennial graminoids	Supplemented	0.2	0-0.4[1]	0.6	0.2-1.1
	No supplement	0.7	0.4-1.1	0.8	0.8-0.9[1]
Annual grasses	Supplemented	2.0	1.2-2.7[1]	0.3	0-0.8[1]
	No supplement	0.5	0-1.1	0.7	0-1.8

[1] When confidence intervals do not include 1.0, FPI > 1.0 indicates preference, whereas FPI < 1.0 indicates avoidance.

Table 3
Sulfur cinquefoil dry matter (DM) intake (± SE) by supplemented and nonsupplemented yearling ewes grazing in late June or mid-July 2009 or 2010 ($n = 3$ paddock replicates $treatment^{-1}$ mo^{-1} yr^{-1}) on sulfur cinquefoil—infested rangeland in northwestern Montana

Treatment	Month		
	June	July	Mean
	(kg DM $sheep^{-1}$ d^{-1})[1,2]		
Supplemented	0.56 (0.1) aA	1.01 (0.2) bA	0.78 (0.1) A
No supplement	0.62 (0.2) aA	1.01 (0.2) bA	0.82 (0.1) A
Mean	0.59 (0.1) a	1.01 (0.1) b	

[1] Means within rows with the same lowercase letter are not different ($P > 0.10$).
[2] Means within columns with the same uppercase letter are not different ($P > 0.10$).

Plant Yield and Plant Community Composition

Targeted sheep grazing during July reduced sulfur cinquefoil yield the next summer by 47% ($P = 0.038$; Table 8). Similarly, sulfur cinquefoil yield the following summer trended 41% less in June-grazed paddocks compared with ungrazed paddocks ($P = 0.148$). Sulfur cinquefoil yield the next summer was unaffected by whether sheep were supplemented. The percentage composition of sulfur cinquefoil in the year following treatment was markedly decreased by targeted sheep grazing in either June ($P = 0.042$) or July ($P = 0.002$). One yr after treatment, sulfur cinquefoil comprised 49% of the plant community in ungrazed paddocks versus 32% in sheep-grazed paddocks.

Yield of perennial graminoids or annual grasses was unaffected by timing of grazing or supplementation (see Table 8). However, in July-grazed paddocks the percentage composition of perennial graminoids increased from 36% to 48% ($P = 0.075$) and the percentage composition of annual grasses increased from 4% to 12% ($P = 0.024$).

Yield and plant community composition of other forbs varied among month × supplement combinations (see Table 8). Yield of other forbs the next summer increased 96% in paddocks grazed by nonsupplemented sheep during the previous July ($P = 0.070$), and the percentage composition of other forbs increased correspondingly from 11% to 25% ($P = 0.003$). Similarly, yield of other forbs trended 107% greater in paddocks grazed by supplemented sheep during the previous June ($P = 0.164$), with a corresponding increase in percentage composition of other forbs from 11% to 22% ($P = 0.092$).

Discussion

Forage Nutritive Quality

Nutritive quality of sulfur cinquefoil in our study was similar to slightly higher than sulfur cinquefoil from a more mesic environment in northern Idaho (Frost et al., 2008). During the flowering phenotypic stage, sulfur cinquefoil plants in northern Idaho averaged 6.6% CP and 48% NDF. Sulfur cinquefoil in our study averaged 8.2% CP and 42% NDF in late June (early flowering phenotypic stage) and 6.6% CP and 45% NDF in mid-July (late flowering—early seedset phenotypic stage). Nutritive value of sulfur cinquefoil in our study also was similar to other nonindigenous, invasive perennial forbs in the northwestern United States such as Dalmatian toadflax (*Linaria dalmatica* [L.] Mill.) and meadow hawkweed (*Hieracium caespitosum* Dumort.) (Frost et al., 2008). However, sulfur cinquefoil in our study was of lower nutritive quality than tansy ragwort

Table 4
Nutritive quality of sheep diets (± SE) for supplemented and nonsupplemented yearling ewes grazing in late June or mid-July 2009 or 2010 ($n = 3$ paddock replicates treatment^{-1} mo^{-1} yr^{-1}) on sulfur cinquefoil — infested rangeland in northwestern Montana

Nutritive variable	Treatment	Month		Mean
		June	July	
Forage dry matter intake (kg sheep^{-1} d^{-1})[1,2]	Supplemented	1.66 (0.5) aA	1.78 (0.3) aA	1.72 (0.3) A
	No supplement	1.46 (0.2) aA	2.37 (0.2) bA	1.96 (0.2) A
	Mean	1.57 (0.3) a	2.07 (0.2) b	
Crude protein intake (g sheep^{-1} d^{-1})	Supplemented	165.3 (39.8) aA	158.3 (19.9) aA	161.8 (21.2) A
	No supplement	126.0 (19.4) aA	177.2 (17.8) bA	153.9 (14.8) A
	Mean	147.4 (23.2) a	167.8 (13.0) a	
Total digestible nutrients intake (kg sheep^{-1} d^{-1})	Supplemented	0.97 (0.3) aA	1.06 (0.2) aA	1.02 (0.2) A
	No supplement	0.87 (0.1) aA	1.42 (0.1) bA	1.17 (0.1) A
	Mean	0.92 (0.2) a	1.24 (0.1) b	
Neutral detergent fiber (%)	Supplemented	52.8 (1.3) aA	51.7 (2.4) aA	52.3 (1.3) A
	No supplement	55.7 (2.4) aA	54.4 (2.8) aA	55.0 (1.8) A
	Mean	54.1 (1.3) a	53.1 (1.8) a	
Acid detergent fiber (%)	Supplemented	29.8 (0.9) aA	30.6 (1.1) aA	30.2 (0.8) A
	No supplement	31.4 (1.8) aA	31.8 (1.6) aA	31.6 (1.1) A
	Mean	30.5 (0.9) a	31.2 (1.0) a	

[1] Means within rows with the same lowercase letter are not different ($P > 0.10$).
[2] Means within columns, within the same nutritive variable, with the same uppercase letter are not different ($P > 0.10$).

(*Senecio jacobaea* L.) (Frost et al., 2008; Sharrow and Mosher, 1982), whitetop (*Cardaria draba* [L.] Desv.) (Frost et al., 2008; McInnis et al., 1993), leafy spurge (Fox et al., 1991), and spotted knapweed (Kelsey and Mihalovich, 1987; Olson and Wallander, 2001).

Botanical Composition of Sheep Diets

Potentilla species are generally considered poor to fair forage for sheep (Lommasson et al., 1937), but sheep diets in our study were dominated by sulfur cinquefoil. Our findings conflicted with Rice (1999), who stated that sulfur cinquefoil was consumed only minimally by livestock. Our results compared favorably with Parks et al. (2008), who reported that cattle in early summer consumed sufficient amounts of sulfur cinquefoil to notably reduce its plant height and density of seed heads. On native forb — dominated rangeland that was not infested with sulfur cinquefoil in southwestern Montana, Buchanan et al. (1972) documented that sheep diets in early summer averaged 24% slender cinquefoil, a native congener of sulfur cinquefoil throughout much of the northwestern United States and southwestern Canada. In comparison, early-summer sheep diets in our study averaged 46% sulfur cinquefoil. The proportion of sulfur cinquefoil in our sheep diets compared favorably with proportions of other invasive forbs consumed by targeted grazing sheep in Montana. Leafy spurge comprised 40 — 50% of sheep diets in late July and August (Bartz et al., 1985; Landgraf et al., 1984), and spotted knapweed averaged 45% of targeted sheep grazing diets in mid-June and mid-July (Thrift et al., 2008).

Forage Preferences and Avoidances

Although sulfur cinquefoil comprised the greatest proportion of sheep diets in our study, supplemented sheep preferred sulfur cinquefoil in June only, whereas nonsupplemented sheep did not prefer sulfur cinquefoil in either June or July. Thrift et al. (2008) similarly reported that when nonsupplemented, targeted sheep grazing was used to suppress a moderate infestation of spotted knapweed, sheep diets in June and July were dominated by spotted knapweed, but sheep did not prefer it. Henderson et al. (2012) also documented that nonsupplemented sheep did not prefer spotted knapweed during June, but sheep in their study strongly preferred spotted knapweed during July when graminoids were more phenologically advanced, less green, and less palatable than spotted knapweed. Targeted grazing sheep in our study generally avoided perennial graminoids during both June and July, as did targeted grazing sheep in Henderson et al. (2012).

Sulfur Cinquefoil DMI

Protein-energy supplementation in our study (37 g CP sheep^{-1} d^{-1} and 0.17 kg TDN sheep^{-1} d^{-1}) did not increase DMI of sulfur cinquefoil.

Table 5
Forage utilization (± SE) by supplemented and nonsupplemented yearling ewes grazing in late June or mid-July 2009 or 2010 ($n = 3$ paddock replicates treatment^{-1} mo^{-1} yr^{-1}) on sulfur cinquefoil — infested rangeland in northwestern Montana

Forage class	Treatment	Month		Mean
		June	July	
		(%[1,2])		
Sulfur cinquefoil	Supplemented	71.8 (7.4) aA	70.9 (5.6) aA	71.4 (4.5) A
	No supplement	53.4 (6.8) aA	73.4 (3.6) bA	63.4 (4.7) A
	Mean	62.6 (5.6) a	72.2 (3.0) a	
Other forbs	Supplemented	52.8 (18.8) aA	36.1 (16.0) aA	44.4 (12.2) A
	No supplement	54.9 (15.4) aA	71.6 (9.2) aB	63.2 (8.5) A
	Mean	53.8 (11.4) a	53.8 (9.8) a	
Perennial graminoids	Supplemented	11.5 (10.6) aA	25.0 (6.9) aA	18.2 (6.7) A
	No supplement	31.5 (8.7) aA	50.4 (8.2) aB	41.0 (6.4) B
	Mean	21.5 (7.3) a	37.7 (6.8) b	
Annual grasses	Supplemented	64.1 (9.4) aA	0 bA	32.0 (12.3) A
	No supplement	34.4 (12.7) aB	51.0 (13.9) aB	42.7 (9.4) A
	Mean	49.2 (8.9) a	25.5 (11.6) b	

[1] Means within rows with the same lowercase letter are not different ($P > 0.10$).
[2] Means within columns, within the same forage class, with the same uppercase letter are not different ($P > 0.10$).

Table 6
Removal of sulfur cinquefoil buds, flowers, and seed heads combined (± SE) by supplemented and nonsupplemented yearling ewes grazing in late June or mid-July 2009 or 2010 ($n = 3$ paddock replicates treatment^{-1} mo^{-1} yr^{-1}) on sulfur cinquefoil—infested rangeland in northwestern Montana

Treatment	Month		Mean
	June	July	
	(%[1,2])		
Supplemented	99.5 (0.5) aA	97.9 (1.6) aA	98.7 (0.8) A
No supplement	93.9 (3.7) aA	91.3 (5.2) aA	92.6 (3.2) A
Mean	96.7 (2.0) a	94.6 (3.2) a	

[1] Means within rows with the same lowercase letter are not different ($P > 0.10$).
[2] Means within columns with the same uppercase letter are not different ($P > 0.10$).

One possible explanation is that our supplementation rate was too low. Villalba et al. (2002) increased sheep intake of a high-tannin diet by supplementing 80 g CP sheep^{-1} d^{-1}. It is also possible that protein-energy supplementation in our study did not increase DMI of sulfur cinquefoil because sulfur cinquefoil may not have contained high concentrations of tannins. It is well established that high concentrations of tannins in sheep forage (75—100 g kg^{-1} DM) can reduce forage digestibility and intake (Barry and Manley, 1984; Barry et al., 1986). It is equally well established, however, that moderate concentrations of tannins in sheep forage (30—50 g kg^{-1} DM) do not limit intake and instead provide nutritional benefits by increasing bypass protein and increasing absorption of essential amino acids in the small intestine (Barry and McNabb, 1999; Frutos et al., 2004). Moderate concentrations of tannins also reduce gastrointestinal parasite loads and enhance immunity to gastrointestinal parasites (Butter et al., 2000; Niezen et al., 2002). Although Tomczyk et al. (2011) quantified high concentrations of tannins in European sulfur cinquefoil foliage (100 g kg^{-1} DM), tannin concentrations of North American sulfur cinquefoil foliage remain undocumented. In Spain, aboveground portions of erect cinquefoil (*Potentilla erecta* [L.] Raeusch.), a close relative of sulfur cinquefoil, contained only moderate tannin concentrations (46 g kg^{-1} DM; Gonzalez-Hernandez et al., 2003).

Nutritive Quality of Sheep Diets

Nutritional requirements for maintenance of 68-kg yearling range ewes (NRC, 2007) were exceeded during June and July. For example, maintenance requirements were exceeded in June for forage DMI (1.57 vs. 1.18 kg DMI sheep^{-1} d^{-1}), CP intake (147 vs. 88 g CP sheep^{-1} d^{-1}), and TDN intake (0.92 vs. 0.63 kg TDN sheep^{-1} d^{-1}). However, when considering nutritional requirements for maintenance plus growth of 68-kg yearling range ewes, requirements were not satisfied during June. Fortunately, requirements for maintenance plus growth were satisfied during July (2.07 vs. 1.86 kg DMI sheep^{-1} d^{-1}; 168 vs. 152 g CP sheep^{-1} d^{-1}; 1.24 vs. 1.24 kg TDN sheep^{-1} d^{-1}). Greater forage DMI by sheep during July enabled sheep to meet or exceed nutritional requirements for maintenance plus growth, and greater forage intake during July apparently reflected seasonal changes in plant succulence. We observed that forage plants had greater moisture content earlier in the growing season, which may have caused forage intake in June to be restricted by the physical capacity of the rumen. Buchanan et al. (1972) also reported increased forage intake by sheep as the summer grazing season progressed, and these authors similarly attributed the increased intake to less plant moisture content and greater rumen capacity later in the grazing season.

Dietary CP, dietary NDF, and dietary ADF averaged 9%, 54%, and 31%, respectively, across June and July in our study. These nutritive values reflected lower dietary nutritive quality than other reports of summer sheep diets in western Montana. Buchanan et al. (1972) reported sheep dietary CP averaged 13.5% and dietary ADF averaged 24% in early summer on native forb-dominated rangeland where slender cinquefoil, a close relative of sulfur cinquefoil, comprised 24% of sheep diets. Thrift et al. (2008) reported sheep dietary CP averaged 11.8%, dietary NDF averaged 41%, and dietary ADF averaged 24% across June and July on spotted knapweed-infested rangeland.

Table 7
Viable sulfur cinquefoil seeds produced (± SE) when treated with or without targeted grazing by supplemented or nonsupplemented yearling ewes in late June or mid-July 2009 or 2010 ($n = 3$ paddock replicates treatment^{-1} mo^{-1} yr^{-1}) on sulfur cinquefoil—infested rangeland in northwestern Montana

Treatment	Month	
	June	July
	(No. m^{-2})[1,2]	
Ungrazed control	8556.7 (3259.2) A	
Supplemented	47.2 (47.2) aB	232.5 (222.5) aB
No supplement	474.2 (474.2) aB	626.7 (334.7) aB

[1] Means within columns with the same uppercase letter are not different ($P > 0.10$).
[2] Means within rows with the same lowercase letter are not different ($P > 0.10$).

Forage Utilization

Perennial graminoid utilization by targeted sheep grazing in our study was light to moderate (18—41%), while sulfur cinquefoil use was heavy (67%). Sulfur cinquefoil use by targeted sheep grazing corresponded closely with levels applied in a clipping experiment in southwestern Montana (62% and 72% use of sulfur cinquefoil; Frost and Mosley, 2012). Utilization of sulfur cinquefoil in our study was greater than usually achieved by targeted sheep grazing of other invasive forbs in the northern Rocky Mountain region. Walker et al. (1994) reported 51% utilization of leafy spurge in southeastern Idaho, and Thrift et al. (2008) reported 35—54% utilization of spotted knapweed in western Montana. We speculate that study site differences in elevation may explain why sheep in our study achieved greater use of sulfur cinquefoil. We suspect that grasses and other forbs were more phenologically advanced and less palatable at our low-elevation study site (830 m) compared with the higher elevation study sites of Walker et al. (1994) and Thrift et al. (2008) (1850 m and 1400 m, respectively). Advanced phenology at our study site made grasses and other forbs more fibrous and relatively less palatable than the target weed. For example, in our study NDF averaged 44% in sulfur cinquefoil compared with 51% NDF in other forbs and 70% NDF in perennial graminoids (Fig. 1).

Sulfur Cinquefoil Viable Seed Production

Targeted sheep grazing in our study reduced viable seed production of sulfur cinquefoil by 97% in June-grazed paddocks and 95% in July-grazed paddocks. Our results compared favorably with Frost and Mosley (2012), who clipped sulfur cinquefoil at intensities and phenotypic stages similar to our targeted sheep-grazing treatments. In their study, viable seed production of sulfur cinquefoil was reduced 99—100%. Similar clipping treatments in western Montana reduced viable seed production of spotted knapweed by 99% (Benzel et al., 2009), whereas combined herbivory by targeted sheep grazing and biological control insects in northwestern Montana reduced viable seed production of spotted knapweed by 96—99% (Mosley et al., 2016).

Plant Yield and Plant Community Composition

Targeted sheep grazing in our study did not affect perennial graminoid yield the next summer, although the percentage composition of perennial graminoids increased from 36% to 48% in paddocks where supplemented sheep had grazed during the previous July. Targeted sheep grazing in our study reduced sulfur cinquefoil yield the following summer by 41% in June-grazed paddocks and 47% in July-grazed

Table 8
Plant yield (± SE) and plant community composition (± SE) in mid-July the year after treatment with or without targeted grazing by supplemented or nonsupplemented yearling ewes in late June or mid-July 2009 or 2010 ($n = 3$ paddock replicates treatment^{-1} mo^{-1} yr^{-1}) on sulfur cinquefoil — infested rangeland in northwestern Montana

Forage class	Treatment	Response variable			
		Plant yield		Plant community composition	
		June	July	June	July
		(kg ha^{-1})[1,2]		(%)	
Sulfur cinquefoil	Ungrazed control	768.4 (115.5) A		49.0 (3.0) A	
	Supplemented	460.3 (112.7) aA	387.3 (58.6) aB	28.6 (7.1) aB	32.0 (0.7) aB
	No supplement	449.4 (110.6) aA	426.4 (110.8) aB	34.3 (4.9) aAB	31.1 (4.5) aB
Other forbs	Ungrazed control	174.3 (49.4) A		11.1 (2.1) A	
	Supplemented	360.9 (96.2) aA	142.9 (80.9) bA	22.4 (5.6) aB	11.8 (3.9) bA
	No supplement	208.6 (45.4) aA	342.4 (45.4) bB	15.9 (3.0) aAB	25.0 (2.2) bB
Perennial graminoids	Ungrazed control	563.4 (81.9) A		35.9 (3.9) A	
	Supplemented	664.5 (84.0) aA	581.1 (31.0) aA	41.4 (1.3) aA	48.2 (5.7) bB
	No supplement	483.9 (84.1) aA	440.3 (106.4) aA	37.0 (8.0) aA	32.2 (5.5) aA
Annual grasses	Ungrazed control	62.9 (21.6) A		4.0 (1.1) A	
	Supplemented	122.0 (32.1) aA	97.4 (48.0) a A	7.6 (1.7) aA	8.0 (2.8) aAB
	No supplement	167.3 (79.9) aA	160.2 (29.0) aA	12.8 (5.9) aA	11.7 (2.5) aB

1 Means within columns, within the same forage class, with the same uppercase letter are not different ($P > 0.10$).
2 Means within rows, within the same response variable, with the same lowercase letter are not different ($P > 0.10$).

paddocks. A clipping study by Mueggler (1967) reported similar effects on slender cinquefoil, a native congener of sulfur cinquefoil in northwestern United States and southwestern Canada. Mueggler (1967) reported that clipping once during late flowering (mid-July) lowered yield of slender cinquefoil the next summer by 39%. After 2 consecutive yr of clipping during late flowering, slender cinquefoil yield was 50% less than unclipped controls and slender cinquefoil yield was 60% less than unclipped controls after 3 consecutive yr of clipping during the late flowering phenotypic stage.

Implications

Targeted sheep grazing can be used to suppress sulfur cinquefoil. Supplemented and nonsupplemented targeted sheep grazing, applied in either late June or mid-July, effectively suppressed sulfur cinquefoil in our study. Our results confirm that targeted sheep grazing should suppress sulfur cinquefoil when weed management can significantly defoliate sulfur cinquefoil plants without excessive defoliation of desirable plants. In the long term, sulfur cinquefoil yield and plant community composition also should be reduced wherever weed management can significantly limit sulfur cinquefoil recruitment. Given that most sulfur cinquefoil plants (> 85%) in untreated populations are ≤ 5 yr old and < 15% are 6 − 10 yr old (Perkins et al., 2006), sulfur cinquefoil plant density should decrease exponentially wherever sulfur cinquefoil recruitment can be limited significantly for ≥ 5 consecutive yr. Although our study did not directly quantify the effects of targeted sheep grazing on sulfur cinquefoil plant recruitment, we documented that 1 yr of targeted sheep grazing reduced annual production of viable sulfur cinquefoil seeds by ≥ 95%. With only 18% of sulfur cinquefoil seeds in the seed bank surviving from 1 yr to the next (Kiemnec and McInnis, 2009), targeted sheep grazing that dramatically reduces sulfur cinquefoil viable seed production for ≥ 5 consecutive yr should significantly inhibit sulfur cinquefoil recruitment.

Targeted sheep grazing diets in our study were dominated by sulfur cinquefoil during both late June and mid-July, but more sulfur cinquefoil DM was consumed by sheep during mid-July. Sheep readily consumed sulfur cinquefoil stems, leaves, flowers, and developing seed heads, with or without low amounts of supplemental protein and energy (37 g CP sheep^{-1} d^{-1} and 0.17 kg TDN sheep^{-1} d^{-1}). Sheep nutrition and sulfur cinquefoil DMI will be optimized when targeted sheep grazing is applied during mid-July. Sheep do not need to be confined to a corral before moving to a new area if targeted grazing occurs during the early flowering phenotypic stage (late June) when sulfur cinquefoil plants have not yet produced viable seeds. However, some viable seeds may be present in the seed heads of sulfur cinquefoil when an infestation is characterized on whole to be in the late flowering — early seedset stage. Sheep that graze sulfur cinquefoil infestations during the late flowering — early seedset stage should be quarantined in a corral for at least 3 d to prevent transporting viable sulfur cinquefoil seeds to other areas (Frost et al., 2013).

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