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Sulfur Cinquefoil (*Potentilla recta*) Response to Defoliation on Foothill Rangeland

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Sulfur cinquefoil is an invasive, perennial forb on rangelands of western Canada and the United States. Sulfur cinquefoil reproduces solely by seed and it is a prolific seed producer. Our 2-yr study (2006, 2007) investigated the optimal timing and intensity of defoliation to decrease aboveground productivity and seed production of sulfur cinquefoil plants on foothill rangeland in southwestern Montana. Each year, 150 sulfur cinquefoil plants within a 430-m^2 enclosure were tagged for identification and randomly assigned to one of 15 clipping treatments with 10 plants per treatment. Clipping treatments were conducted at three timings: (preflower [early June], flowering [late June], and seedset [mid-July]) and all possible combinations of timings for a total of seven timing treatments clipped to two stubble heights (7.5 cm or 15 cm), comprising 14 unique treatments. The final (15th) treatment consisted of an unclipped control. Response variables collected at senescence (late July) included aboveground biomass; number of buds, flowers and fruits on each plant; and number and viability of seeds produced. Results indicated that defoliation of sulfur cinquefoil can effectively reduce its yield and seed production. All clipping treatments reduced aboveground biomass of sulfur cinquefoil compared with control plants ($P \leq 0.05$), except clipping to 15 cm during preflowering in the wetter year of 2006. Clipping to either 7.5 cm or 15 cm at all times or combinations of timings reduced the number of buds, flowers, fruits, and seeds produced by sulfur cinquefoil ($P \leq 0.05$). Viable seed production was reduced 99 to 100% when plants were clipped once to either 7.5 or 15 cm during flowering or seedset. Results suggest that targeted livestock grazing or mowing applied one time per season during flowering or seedset could effectively suppress the biomass production and viable seed production of sulfur cinquefoil.

Nomenclature: Sulfur cinquefoil, *Potentilla recta* L. PTLRC.

Key words: Defoliation, yield, seed bank, viable seeds, clipping, rangeland.

Sulfur cinquefoil (*Potentilla recta* L.) is an exotic, invasive perennial forb on western rangelands of the United States and Canada. Large infestations of sulfur cinquefoil currently exist in the northern Rocky Mountain West and Pacific Northwest (Duncan et al. 2004, Rice 1999), as well as Kansas and Nebraska (USDA, NRCS 2010). Unfortunately, the plant has likely gone unnoticed in many areas because it is similar in appearance to native, co-occurring congeners, particularly Northwest cinquefoil (*Potentilla gracilis* Dougl. ex Hook.) (Duncan et al. 2004; Dwire et al. 2006; Rice 1999). In the central and eastern United States, sulfur cinquefoil is a minor agricultural weed (Werner and Soule 1976), but on western rangelands of the United States and Canada, sulfur cinquefoil has shown broad ecological amplitude. Conifer, grassland, shrubland, and seasonal wetland ecosystems are susceptible to invasion (Rice 1999). In Montana alone, sulfur cinquefoil has been found in 14 different plant community types (Rice 1993). Sulfur cinquefoil outcompetes other aggressive invasive plants such as spotted knapweed (*Centaurea stoebe* L.), yellow starthistle (*Centaurea solstitialis* L.), and leafy spurge (*Euphorbia esula* L.) (Rice 1999). Other characteristics that make the plant a concern on rangelands are sulfur cinquefoil's prolific seed production ($\approx$ 6,000 seeds/plant; Dwire et al. 2006) and the plant's ability to invade relatively undisturbed native plant communities (Lesica and Martin 2003; Naylor et al. 2005).

Control options for suppressing sulfur cinquefoil plant biomass and seed production are limited. Sulfur cinquefoil is closely related to domestic strawberries and native cinquefoil plants, making it a poor candidate for biological

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Management Implications

Sulfur cinquefoil is a nonnative, perennial, invasive weed that currently infests thousands of acres of rangeland and abandoned cropland in the western United States and Canada. This plant is a concern because it produces thousands of seeds and is capable of invading undisturbed rangeland. There are no approved biological controls, and herbicide treatment is expensive; therefore, we evaluated the potential for defoliation to reduce yield and seed production of sulfur cinquefoil. Hand-clipping treatments were applied at 14 different timing and intensity combinations to determine those most appropriate to suppress sulfur cinquefoil. Overall, clipped plants produced ~ 80% less aboveground forage and > 90% fewer viable seeds than control plants. Clipping applied when sulfur cinquefoil plants were flowering or in early seedset had the greatest impact on forage and seed production. Plants clipped one time to either a 15- or 7.5-cm stubble height at flower or later were unable to produce any viable seed during the current growing season. Multiple defoliations were not necessary to decrease seed production if the first defoliation occurred at the flower stage or later. The intensity of the defoliation did not matter so long as the fruits were removed from the plant. Because of the longevity and abundant seed production of the plant, areas infested with sulfur cinquefoil likely have a large soil seed bank, and multiple years of uniform defoliation will be necessary before any noticeable change in the existing population can be determined. However, defoliation holds potential to reduce the competitive ability of sulfur cinquefoil as well as the ability of the plant to add to the seed bank. Targeted livestock grazing or mowing are two potential ways to defoliate sulfur cinquefoil at the appropriate timing and intensity to suppress the plant on rangeland or pasture.

control (Duncan et al. 2004). Prescribed fire is ineffective (Lesica and Martin 2003), and herbicides have provided mixed results (Duncan et al. 2004; Endress et al. 2008; Lesica and Martin 2003; Powell 1996; Rice 1999; Sheley and Denny 2006). Herbicides can be an expensive management option and retreatment often is necessary after 3 to 5 yr (Duncan et al. 2004; Lesica and Martin 2003).

Recent recommendations have stressed that future management of sulfur cinquefoil should focus on controlling seed production to contain existing populations and prevent new invasions (Dwire et al. 2006; Perkins et al. 2006). Repeated defoliation has greatly decreased the accumulated soil seed bank of other perennial noxious weeds, such as leafy spurge and spotted knapweed. Bowes and Thomas (1978) demonstrated that 8 yr of repeated sheep grazing reduced the soil seed bank of leafy spurge more than 99% compared with ungrazed areas. Similarly, the number of viable spotted knapweed seeds in the seed bank was reduced 54% after three summers of sheep grazing in southwestern Montana, whereas viable seed numbers of spotted knapweed in ungrazed areas increased 88% (Olson et al. 1997).

Lesica and Ellis (2010) contend that management of seed production alone will not contain a sulfur cinquefoil population because of the long life span (> 10 yr) of individual plants (Perkins et al. 2006). Life history modeling indicates that reducing survival of adult plants is a more efficient way to suppress the population than reducing recruitment (Lesica and Ellis 2010). Defoliation is one method for decreasing the fitness of the population and the individual plant's ability to compete for resources and persist. For example, West and Farah (1989) demonstrated that repeated clipping of dyer's woad (*Isatis tinctoria* L.) caused mortality of adult plants. Similarly, repeated defoliations of leafy spurge decreased density of the perennial weed (Kirby et el. 1997). Rinella and others (2001) recommend a single annual mowing of spotted knapweed at the flower- or seed-producing stage to reduce cover and density of adult plants as well as seedling recruitment.

Plant defoliation via targeted (or prescribed) livestock grazing or mowing can effectively suppress biomass and seed production of numerous invasive plant species (Mosley and Roselle 2006; Olson and Launchbaugh 2006; Rinella et al. 2001; Schreiber 1967; Watson and Renney 1974). It is known that sheep (B. E. Olson, unpublished data), goats (R. A. Frost, personal observation), and cattle (Parks et al. 2008), will graze sulfur cinquefoil plants. However, information is scant about how sulfur cinquefoil responds to defoliation. Before initiating larger-scale studies of mowing or targeted livestock grazing for suppressing noxious weeds, it is prudent to first conduct an experiment to identify which timings, frequencies, and intensities of defoliation are most likely to suppress the target plant (Rinella and Hileman 2009). The purpose of this research was to determine the optimal timing(s) or combination(s) of timings and intensity of defoliation to decrease aboveground biomass and seed production of sulfur cinquefoil.

Materials and Methods

Study Area. This 2-yr study was located on foothill rangeland near Bozeman, Montana (45°39′N, 111°02′W). The ecological site is Silty, in the 381- to 483-mm (15 to 19 in) precipitation zone (USDA, NRCS 2007). The elevation of the site is approximately 1,597 m (5,240 ft) and it is classified as a big sagebrush [*Artemisia tridentata* Nutt. subsp. *vaseyana* (Rydb.) Beetle] / Idaho fescue (*Festuca idahoensis* Elmer) habitat type (Mueggler and Stewart 1980). The 30-yr average annual precipitation is 470 mm, with 55% occurring as rain between May and September (WRCC 2007). The 30-yr average minimum and maximum temperatures are 9.2 and 25.4 C (49 and 78 F) for the months of June, July, and August. At the study site, sulfur cinquefoil is the dominant forb with 7% canopy cover; other major forb species on the site include lupine (*Lupinus* L. spp.), western yarrow (*Achillea millefolium* L.),

Table 1. Clipping treatments applied to individual sulfur cinquefoil plants in 2006 and 2007. Plants were clipped to 7.5 or 15 cm at preflower, flower, or seedset phenological stages and all possible combinations of the phenological stages on foothill rangeland in southwestern Montana.

	2006		2007	
Timing of clipping	7.5 cm	15 cm	7.5 cm	15 cm
	Date clipped			
Unclipped control[a]	Not clipped		Not clipped	
Preflower	June 1	June 1	June 8	June 8
Preflower & Flower	June 1 & June 27	June 1 & June 27	June 8 & June 27	June 8 & June 27
Preflower & Flower & Seedset	June 1 & June 27 & July 17	June 1 & June 27 & July 17	June 8 & June 27 & July 17	June 8 & June 27 & July 17
Preflower & Seedset	June 1 & July 17	June 1 & July 17	June 8 & July 17	June 8 & July 17
Flower	June 27	June 27	June 27	June 27
Flower & Seedset	June 27 & July 17	June 27 & July 17	June 27 & July 17	June 27 & July 17
Seedset	July 17	July 17	July 17	July 17

[a] A total of 10 unclipped plants served as controls each year.

arrowleaf balsamroot [*Balsamorhiza sagittata* (Pursh) Nutt.], and yellow salsify (*Tragopogon dubius* Scop). Idaho fescue, bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Á. Löve], and oatgrass (*Danthonia* spp.) are the predominant grass species. Mountain big sagebrush is the dominant shrub on the site.

Treatments. One hundred fifty sulfur cinquefoil plants between 10 and 33 cm in height were selected each year (2006, 2007) on a site moderately infested (7% canopy cover) with sulfur cinquefoil. The 150 plants were fenced in an area approximately 430 m^2 (4,628 ft^2) with 1.8-m-tall welded-wire panels to exclude ungulate grazing. The 2007 exclosure was located about 25 m from the 2006 exclosure to ensure that results from the 2 yr were independent. Study plants were tagged for identification and located a minimum of 1 m apart. The percentage canopy cover of sulfur cinquefoil was estimated inside a 1-m diameter (0.79 m^2) circular plot surrounding each plant to account for potential competition from neighboring vegetation. Fifteen hand-clipped treatments were applied to the individual sulfur cinquefoil plants, with 10 plants randomly assigned to each of the 15 treatments (n = 150 plants yr^{-1}, Table 1).

Treatments included: (1) clipping to 7-cm stubble height during preflowering (bolting) in early June (mean relative utilization = 59%); (2) clipping to 15-cm stubble height during preflowering in mid-June (mean relative utilization = 27%); (3) clipping to 7-cm stubble height during flowering in late June (mean relative utilization = 81%); (4) clipping to 15-cm stubble height during flowering in late June (mean relative utilization = 62%); (5) clipping to 7-cm stubble height during seedset in mid-July (mean relative utilization = 85%); (6) clipping to 15-cm stubble height during seedset in early July (mean relative utilization = 72%); (7) Treatment 1 + Treatment 3 (7 cm, preflowering + flowering); (8) Treatment 1 + Treatment 5 (7 cm, preflowering + seedset); (9) Treatment 3 + Treatment 5 (7 cm, flowering + seedset); (10) Treatment 1 + Treatment 3 + Treatment 5 (7 cm, preflowering + flowering + seedset); (11) Treatment 2 + Treatment 4 (15 cm, preflowering + flowering); (12) Treatment 2 + Treatment 6 (15 cm, preflowering + seedset); (13) Treatment 4 + Treatment 6 (15 cm, flowering + seedset); (14) Treatment 2 + Treatment 4 + Treatment 6 (15 cm, preflowering + flowering + seedset); and (15) unclipped control. Treatments were applied when the majority of the plants in the treatment group were in the appropriate physiological state. Although phenology was used to determine treatment timing, dates were similar between years (Table 1). The experimental design was completely randomized. Treatments were arranged in an 8 by 2 by 2 factorial arrangement, with eight timings or combinations of timings of defoliation, two defoliation intensities, and 2 yr. Individual plants were the experimental units.

Response Variables. Response variables for each plant included: (1) aboveground biomass (2) number of buds, flowers, and fruits; (3) number of immature, intermediate, and mature seeds; (4) total number of seeds; (5) percent viability of immature, intermediate, and mature seeds; (6) number of viable immature, intermediate, and mature seeds; and (7) total number of viable seeds. Sulfur cinquefoil plant response was evaluated when plants in each treatment reached senescence (late July), when seeds were developed to their fullest possible extent but while seedhead bracts remained closed and before seed dispersal.

Aboveground Biomass. Each plant's standing crop of the current year's aboveground biomass was hand-clipped to ground level, collected, and dried for 24 h at 100 C (212 F). The fruits of plants were collected separately and dried for 48 h at 40 C to prevent the drying process from negatively impacting the subsequent viability testing of the seeds (Wallander et al. 1995). Dry weights of the plants and corresponding fruits were combined to calculate total aboveground biomass for each treatment plant.

Number of Flower Buds, Flowers, and Fruits. The total number of flower buds, flowers, and fruits present were counted prior to being collected. Immature flower buds, distinguished from newly forming leaves by visible bracts, were included in the final count.

Number of Seeds. The number of immature, intermediate, and mature seeds per plant and total number of seeds per plant were counted in the laboratory. Seeds were extracted from fruits using a rub board and were divided into three developmental stages: (1) immature—tiny, seedcoat light brown; (2) intermediate—medium-sized, seedcoat dark brown, netting not visible to the naked eye; and (3) mature—large, seedcoat nearly black with visible cream-colored netting. Seeds then were counted by stage. Total number of seeds per plant was calculated by totaling the number of seeds in each of the three developmental stages.

Viability of Seeds. Seeds were tested for viability using the tetrazolium test (Grabe 1970). Three subsamples from each of the immature, intermediate, and mature developmental stages of seeds from each treatment plant were used. Seeds within a given developmental stage were randomly assigned to one of three subsamples. Each subsample contained 20 seeds or one-third of the total number of seeds in that developmental stage if the total was less than 60 seeds. Percentage viability was calculated by averaging the proportion of viable seeds in each of the three subsamples.

Number of Viable Seeds. The number of viable immature, intermediate, and mature seeds was calculated by multiplying the number of seeds in each developmental stage by the percent viability of seeds in each respective developmental stage. Total number of viable seeds per plant was calculated by summing the number of viable seeds in the three developmental stages.

Statistical Analysis. Data were analyzed using the GLM procedure of SAS (SAS 2004). Percentage data, count data, and continuous data that were not normally distributed were arcsine, square-root and log10-transformed to stabilize variances and better approximate normal distribution of residuals (Kuehl 2000; Steel and Torrie 1980). Means and standard errors presented in the text and tables are from untransformed data. Analysis of covariance was used to compare responses among treatments. Percentage canopy cover of sulfur cinquefoil surrounding each treatment plant and the initial number of stems on the treatment plants were used as covariables in the analyses. Treatment means were compared using Tukey's Studentized Range Test (Steele and Torrie 1980). Interactions and differences were considered significant at $P \leq 0.05$.

Results and Discussion

The year-by-timing interaction was significant for all response variables; therefore, results are reported separately for 2006 and 2007. Rangeland plant growth and reproduction in our study area depend largely on the amount of precipitation received beginning September 1 and ending June 30 of the following year (Sneva and Bitton 1983; Sneva and Hyder 1962). Precipitation at our study site during the 2006 crop year (September 2005 to June 2006) was 25 mm greater than precipitation during the 2007 crop year (September 2006 to June 2007) (WRCC 2007) and might have influenced the significant interaction in our study. Aboveground biomass and seed production of unclipped sulfur cinquefoil plants was greater in 2006 than 2007, and sulfur cinquefoil plants clipped during preflowering were less impacted in 2006 than 2007.

Clipping to 7.5 cm at any timing or combination of timings reduced aboveground biomass of sulfur cinquefoil plants in both years (Table 2). The same was true for plants clipped to 15 cm, with the exception of clipping during preflowering in 2006. However, in the relatively drier year of 2007, clipping to 15 cm during preflowering reduced the amount of aboveground biomass present at senescence by 71%. A greater reduction in yield was observed when sulfur cinquefoil plants were clipped later in the year and in general when clipped to 7.5 cm vs. 15 cm. For instance, clipping sulfur cinquefoil to 7.5 cm during flowering reduced aboveground plant biomass 78% in 2006 and 89% in 2007, whereas clipping to 7.5 cm during seedset reduced aboveground plant biomass 84% and 81% in 2006 and 2007, respectively. Clipping sulfur cinquefoil to 15 cm during flowering reduced aboveground biomass 48 to 80%, whereas clipping to 15 cm during seedset reduced aboveground biomass 68 to 73%. Likewise, plant yield of both northwest cinquefoil and leafy spurge was more impacted by late-season clipping than clipping during preflowering (Kirby et al. 1997; Mueggler 1967).

Unclipped control plants averaged 38 flower buds + flowers + fruits and 3,236 seeds plant^{-1} in 2006 and 43 flower buds + flowers + fruits and 2,751 seeds plant^{-1} in 2007 (Tables 3 and 4). Mature seeds of unclipped control plants were 89 to 97% viable at senescence (Table 5).

Table 2. Aboveground biomass of sulfur cinquefoil plants at senescence (± SE) after clipping to 7.5 or 15 cm at different timings and combinations of timings on foothill rangeland in southwestern Montana. Analysis of covariance was used to compare responses among treatments and means were compared using Tukey's Studentized Range Test.

	2006		2007	
Timing of clipping	7.5 cm	15 cm	7.5 cm	15 cm
	g plant^{-1} [a,b]		g plant^{-1} [a,b]	
Unclipped control	3.74 ± 0.5 a,A		3.37 ± 0.5 a,A	
Preflower	1.68 ± 0.5 a,B	3.77 ± 0.8 b,A	0.54 ± 0.1 a,BC	0.99 ± 0.2 b,BC
Preflower & Flower	0.88 ± 0.1 a,C	1.32 ± 0.2 a,B	0.60 ± 0.1 a,B	1.42 ± 0.4 a,B
Preflower & Flower & Seedset	0.90 ± 0.2 a,C	1.18 ± 0.2 b,B	0.50 ± 0.1 a,BC	1.03 ± 0.1 b,BC
Preflower & Seedset	0.46 ± 0.1 a,D	1.29 ± 0.1 b,B	0.58 ± 0.1 a,B	0.91 ± 0.1 a,BC
Flower	0.84 ± 0.1 a,C	1.96 ± 0.4 b,C	0.38 ± 0.03 a,C	0.67 ± 0.04 b,C
Flower & Seedset	0.59 ± 0.1 a,D	0.73 ± 0.1 b,D	0.40 ± 0.1 a,C	0.90 ± 0.1 b,BC
Seedset	0.58 ± 0.1 a,D	1.01 ± 0.1 b,B	0.64 ± 0.1 a,B	1.08 ± 0.1 b,BC

[a] Means in the same row within year followed by the same lowercase letter are not significantly different ($P > 0.05$).

[b] Means in the same column followed by the same uppercase letter are not different ($P > 0.05$).

Kiemenic and McInnis (2009) also documented greater seed production by sulfur cinquefoil in wetter years in northeastern Oregon; similar patterns of seed production relative to precipitation were noted for spotted knapweed in western Montana (Benzel et al. 2009) and leafy spurge in southeastern Idaho (Al-Rowaily et al. 1996). However, greater overall seed production was reported by Dwire and colleagues (2006), who determined that sulfur cinquefoil plants averaged about 3,500 seeds plant^{-1} when growing in relatively undisturbed forest openings in northeastern Oregon, but up to 15,150 seeds plant^{-1} when growing on a formerly cultivated cropland field. Similarly, Lesica and Ellis (2010) found that large sulfur cinquefoil plants produced $> 10{,}000$ seeds plant^{-1} in grasslands of northwestern Montana.

Clipping to 7.5 cm at any timing or combination of timings reduced production of buds, flowers, and fruits (Table 3), total seed production (Table 4), and total viable seed production (Table 6) compared with controls. The same was true for plants clipped to 15 cm, with the exception that total seed production was not reduced by clipping during preflowering in 2006. Clipping treatments

Table 3. Total number of sulfur cinquefoil buds, flowers, and fruits at senescence (± SE) after clipping to 7.5 or 15 cm at different timings and combinations of timings on foothill rangeland in southwestern Montana. Analysis of covariance was used to compare responses among treatments and means were compared using Tukey's Studentized Range Test.

	2006		2007	
Timing of clipping	7.5 cm	15 cm	7.5 cm	15 cm
	No. plant^{-1} [a,b]		No. plant^{-1} [a,b]	
Unclipped control	38 ± 4.9 a,A		43 ± 8.1 a,A	
Preflower	11.1 ± 4.3 a,B	31.3 ± 0.8 b,B	0.2 ± 0.2 a,B	5.3 ± 1.5 b,BC
Preflower & Flower	1.7 ± 0.6 a,C	6.3 ± 2.2 a,C	0.9 ± 0.5 a,B	9.5 ± 3.0 b,B
Preflower & Flower & Seedset	0.6 ± 0.6 a,C	1.8 ± 0.9 a,D	0.1 ± 0.1 a,B	2.0 ± 0.5 b,CD
Preflower & Seedset	0 ± 0.0 a,C	0.8 ± 0.3 b,D	0.2 ± 0.2 a,B	1.8 ± 0.4 b,CD
Flower	0 ± 0.0 a,C	0.3 ± 0.3 a,D	0 ± 0.0 a,B	0 ± 0.0 a,D
Flower & Seedset	0 ± 0.0 a,C	0 ± 0.0 a,D	0 ± 0.0 a,B	0 ± 0.0 a,D
Seedset	0 ± 0.0 a,C	0 ± 0.0 a,D	0 ± 0.0 a,B	0 ± 0.0 a,D

[a] Means in the same row within year followed by the same lowercase letter are not different ($P > 0.05$).

[b] Means in the same column followed by the same uppercase letter are not different ($P > 0.05$).

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Table 4. Number of immature, intermediate, and mature sulfur cinquefoil seeds at senescence (± SE) after clipping to 7.5 or 15 cm at different timings and combinations of timings on foothill rangeland in southwestern Montana. Analysis of covariance was used to compare responses among treatments and means were compared using Tukey's Studentized Range Test.

		2006		2007	
Seed stage	Timing of clipping	7.5 cm	15 cm	7.5 cm	15 cm
		No. plant$^{-1a,b}$		No. plant$^{-1a,b}$	
Immature	Unclipped control	652.1 ± 113.6 a,A		485.9 ± 64.9 a,A	
	Preflower	196.0 ± 93.9 a,B	482.6 ± 111.7 b,A	1.9 ± 1.9 a,B	44.6 ± 17.8 b,BC
	Preflower & Flower	18.1 ± 6.8 a,C	90.4 ± 30.0 b,B	3.8 ± 3.3 a,B	105.2 ± 37.0 b,B
	Preflower & Flower & Seedset	8.2 ± 8.2 a,C	17.5 ± 10.1 a,C	0 ± 0.0 a,B	3.4 ± 2.1 a,CD
	Preflower & Seedset	0 ± 0.0 a,C	10.1 ± 5.8 a,C	0.1 ± 0.1 a,B	6.6 ± 3.6 a,CD
	Flower	0 ± 0.0 a,C	14.3 ± 14.3 a,C	0 ± 0.0 a,B	0 ± 0.0 a,D
	Flower & Seedset	0 ± 0.0 a,C	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,D
	Seedset	0 ± 0.0 a,C	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,D
Intermediate	Unclipped control	1,120.0 ± 127.7 a,A		1,101.0 ± 271.2 a,A	
	Preflower	386.3 ± 174.9 a,B	953.7 ± 160.8 b,A	1.9 ± 1.9 a,B	38.7 ± 14.9 b,BC
	Preflower & Flower	24.6 ± 14.3 a,C	176.3 ± 68.1 b,B	4.0 ± 2.9 a,B	171.0 ± 61.6 b,B
	Preflower & Flower & Seedset	22.2 ± 22.2 a,C	45.4 ± 30.0 a,C	0 ± 0.0 a,B	4.1 ± 3.0 a,C
	Preflower & Seedset	0 ± 0.0 a,C	14.3 ± 7.8 a,C	0 ± 0.0 a,B	12.0 ± 5.7 a,C
	Flower	0 ± 0.0 a,C	5.3 ± 5.3 a,C	0 ± 0.0 a,B	0 ± 0.0 a,C
	Flower & Seedset	0 ± 0.0 a,C	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,C
	Seedset	0 ± 0.0 a,C	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,C
Mature	Unclipped control	1,463.8 ± 319.4 a,A		1,163.8 ± 258.6 a,A	
	Preflower	81.3 ± 48.8 a,B	344.9 ± 160.0 b,B	1.4 ± 1.4 a,B	17.4 ± 8.2 b,B
	Preflower & Flower	4.0 ± 1.8 a,B	59.6 ± 19.8 b,C	0.3 ± 0.3 a,B	52.4 ± 23.0 b,B
	Preflower & Flower & Seedset	1.2 ± 1.2 a,B	19.0 ± 10.2 a,C	0 ± 0.0 a,B	0.5 ± 0.2 a,B
	Preflower & Seedset	0 ± 0.0 a,B	5.3 ± 3.0 a,C	0 ± 0.0 a,B	3.5 ± 1.4 b,B
	Flower	0 ± 0.0 a,B	1.2 ± 1.2 a,C	0 ± 0.0 a,B	0 ± 0.0 a,B
	Flower & Seedset	0 ± 0.0 a,B	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,B
	Seedset	0 ± 0.0 a,B	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,B
Total seeds	Unclipped control	3,235.9 ± 502.6 a,A		2,750.7 ± 554.0 a,A	
	Preflower	663.6 ± 308.2 a,B	1,781.1 ± 380.6 b,A	5.2 ± 5.2 a,B	100.7 ± 40.0 b,BC
	Preflower & Flower	46.7 ± 20.9 a,C	326.25 ± 113.1 b,B	8.1 ± 6.2 a,B	328.6 ± 117.3 b,B
	Preflower & Flower & Seedset	31.6 ± 31.6 a,C	81.9 ± 49.5 a,B	0 ± 0.0 a,B	8.0 ± 4.7 a,C
	Preflower & Seedset	0 ± 0.0 a,C	29.8 ± 14.9 a,B	0 ± 0.0 a,B	22.1 ± 9.2 a,C
	Flower	0 ± 0.0 a,C	20.8 ± 20.8 a,B	0 ± 0.0 a,B	0 ± 0.0 a,C
	Flower & Seedset	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,B	0 ± 0.0 a,C
	Seedset	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,B	0 ± 0.0 a,C

[a] Means in the same row within the same year followed by the same lowercase letter are not different ($P > 0.05$).

[b] Means in the same column within seed stage followed by the same uppercase letter are not different ($P > 0.05$).

generally reduced seed viability, except that clipping during preflowering in 2006 and clipping to 15 cm at any time earlier than flower or seedset in 2007 did not reduce seed viability (Table 5). The greatest impacts to sulfur cinquefoil reproduction occurred when plants were clipped one time during the flowering or seedset stages. Clipping one time to 7.5 cm during either flowering or seedset completely eliminated all floral production (Table 3), seed production (Table 4), and viable seed production (Table 6). Clipping one time to 15 cm at flowering or seedset decreased floral production 99 to 100% (Table 3), total seed production 99 to 100% (Table 4), and viable seed production 99 to 100% (Table 6). Benzel and colleagues (2009) similarly determined that clipping during flowering or seedset nearly eliminated viable seed production by spotted knapweed. Defoliation during preflowering in our study did harm sulfur cinquefoil in one way, by decreasing the viability of sulfur cinquefoil seeds that were

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Table 5. Viability (%) of immature, intermediate, and mature sulfur cinquefoil seeds at senescence (± SE) after clipping to 7.5 or 15 cm at different timings and combinations of timings on foothill rangeland in southwestern Montana. Analysis of covariance was used to compare responses among treatments and means were compared using Tukey's Studentized Range Test.

Seed stage	Timing of clipping	2006 7.5 cm	2006 15 cm	2007 7.5 cm	2007 15 cm
		%[a,b]		%[a,b]	
Immature	Unclipped control	5.8 ± 4.4 a,AB		1.0 ± 0.3 a,A	
	Preflower	5.8 ± 2.6 a,A	3.8 ± 1.3 a,A	0 ± 0.0 a,B	1.8 ± 1.1 a,A
	Preflower & Flower	2.6 ± 1.4 a,AB	0.0 ± 0.0 b,A	0 ± 0.0 a,B	3.1 ± 2.7 a,A
	Preflower & Flower & Seedset	0.8 ± 0.8 a,AB	0.6 ± 0.6 a,A	0 ± 0.0 a,B	1.0 ± 1.1 a,A
	Preflower & Seedset	0 ± 0.0 a,B	0.7 ± 0.7 a,A	0 ± 0.0 a,B	1.7 ± 1.2 b,A
	Flower	0 ± 0.0 a,B	1.6 ± 1.6 a,A	0 ± 0.0 a,B	0 ± 0.0 a,A
	Flower & Seedset	0 ± 0.0 a,B	0 ± 0.0 a,A	0 ± 0.0 a,B	0 ± 0.0 a,A
	Seedset	0 ± 0.0 a,B	0 ± 0.0 a,A	0 ± 0.0 a,B	0 ± 0.0 a,A
Intermediate	Unclipped control	86.8 ± 9.6 a,A		93.7 ± 2.0 a,A	
	Preflower	67.5 ± 14.8 a,AB	87.0 ± 9.6 a,A	9.4 ± 9.4 a,B	55.9 ± 15.2 a,AB
	Preflower & Flower	35.6 ± 14.7 a,BC	19.1 ± 12.8 a,B	7.3 ± 4.9 a,B	69.2 ± 12.6 b,A
	Preflower & Flower & Seedset	10.0 ± 10.0 a,C	28.4 ± 14.5 a,B	0 ± 0.0 a,B	18.1 ± 12.2 a,BC
	Preflower & Seedset	0 ± 0.0 a,C	13.0 ± 10.0 a,B	0 ± 0.0 a,B	43.3 ± 15.1 b,AB
	Flower	0 ± 0.0 a,C	9.8 ± 9.8 a,B	0 ± 0.0 a,B	0 ± 0.0 a,C
	Flower & Seedset	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,B	0 ± 0.0 a,C
	Seedset	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,B	0 ± 0.0 a,C
Mature	Unclipped control	88.8 ± 9.8 a,A		96.6 ± 1.0 a,A	
	Preflower	58.4 ± 15.9 a,AB	88.0 ± 9.8 a,A	10.0 ± 10.0 a,B	58.1 ± 15.8 a,AB
	Preflower & Flower	30.0 ± 15.3 a,BC	20.0 ± 13.3 a,B	3.3 ± 3.3 a,B	56.1 ± 15.4 b,AB
	Preflower & Flower & Seedset	10.0 ± 10.0 a,CD	29.8 ± 15.2 a,B	0 ± 0.0 a,B	20.0 ± 13.3 a,BC
	Preflower & Seedset	0 ± 0.0 a,C	19.5 ± 13.0 a,B	0 ± 0.0 a,B	49.2 ± 16.4 b,AB
	Flower	0 ± 0.0 a,C	10.0 ± 10.0 a,B	0 ± 0.0 a,B	0 ± 0.0 a,C
	Flower & Seedset	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,B	0 ± 0.0 a,C
	Seedset	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,B	0 ± 0.0 a,C

[a] Means in the same row within the same year followed by the same lowercase letter are not different ($P > 0.05$).

[b] Means in the same column within seed stage followed by the same uppercase letter are not different ($P > 0.05$).

produced after the plants were clipped. This was especially true in 2007 when plants were clipped during preflowering to 7.5 cm, whereby viability of mature seeds was reduced from 96% in unclipped plants to 10%, a 90% reduction in viability. This result compares favorably with that of Benzel and colleagues (2009), who determined that clipping spotted knapweed during preflowering reduced the viability of mature seeds from 89% in unclipped plants to 35%, a 61% reduction in viability. Contrary to our results, Crawley and Nachapong (1985) reported that seed viability of tansy ragwort (*Senecio jacobaea* L.) was unaffected by clipping. However, these authors did find that seeds from clipped tansy ragwort plants produced less competitive seedlings; thus, clipping effectively reduced recruitment of tansy ragwort into the plant community.

Axillary buds did not produce new stems after clipping occurred during flowering or seedset. However, regrowth from axillary buds explains why seed production of sulfur cinquefoil was not decreased by clipping during preflowering, nor by combinations of clipping that began during preflowering. After defoliation during preflowering, axillary buds in the clipped stubble produced new shoots that eventually formed flowers and viable seeds. Also, the internodes of these new shoots did not elongate appreciably, keeping most flowers and fruits below the height of subsequent clippings applied later in the growing season. A similar response from axillary buds occurred when wild carrot (*Daucus carota* L.) was clipped during preflowering (Harrison and Dale 1966).

Dwire and colleagues (2006) and Lesica and Ellis (2010) recommended that methods to suppress sulfur cinquefoil should target both established plants and the soil seed bank. Our results demonstrate that a single defoliation satisfied this criterion by reducing sulfur cinquefoil aboveground

Table 6. Number of viable sulfur cinquefoil seeds at senescence (± SE) after clipping to 7.5 or 15 cm at different timings and combinations of timings on foothill rangeland in southwestern Montana. Analysis of covariance was used to compare responses among treatments and means were compared using Tukey's Studentized Range Test.

	2006		2007	
Timing of clipping	7.5 cm	15 cm	7.5 cm	15 cm
	No. plant$^{-1a,b}$		No. plant$^{-1a,b}$	
Unclipped control	2,299.6 ± 467.0 a,A		2,169.7 ± 490.6 a,A	
Preflower	400.9 ± 220.6 a,B	1,145.1 ± 280.9 b,B	3.2 ± 3.2 a,B	53.4 ± 21.4 a,BC
Preflower & Flower	25.4 ± 15.6 a,BC	96.6 ± 80.7 a,C	1.6 ± 1.2 a,B	207.5 ± 79.8 b,B
Preflower & Flower & Seedset	24.1 ± 24.1 a,BC	55.9 ± 39.4 a,C	0 ± 0.0 a,B	3.9 ± 2.6 a,C
Preflower & Seedset	0 ± 0.0 a,C	9.9 ± 7.2 a,C	0 ± 0.0 a,B	15.1 ± 6.2 b,BC
Flower	0 ± 0.0 a,C	8.7 ± 8.7 a,C	0 ± 0.0 a,B	0 ± 0.0 a,C
Flower & Seedset	0 ± 0.0 a,C	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,C
Seedset	0 ± 0.0 a,C	0 ± 0.0 a,C	0 ± 0.0 a,B	0 ± 0.0 a,C

[a] Means in the same row within year followed by the same lowercase letter are not different (P > 0.05).

[b] Means in the same column followed by the same uppercase letter are not different (P > 0.05).

biomass and seed production. It is known that sheep and goats will readily graze sulfur cinquefoil plants (B. E. Olson, unpublished data; R. A. Frost, personal observations). Parks and others (2008) found that cattle grazing reduced sulfur cinquefoil seedheads by 78% compared to an ungrazed area, providing evidence that grazing can suppress the reproductive ability of sulfur cinquefoil. However, the extent to which animals select for sulfur cinquefoil and the subsequent control grazing can provide will depend on what other plant species occur on the site and their relative palatability. Sulfur cinquefoil does contain tannins that might limit consumption of the plant by herbivores (Werner and Soule 1976). Supplementation with protein (Roeder et al. 2005, 2007; Villalba et al. 2002a) or polyethylene glycol (Villalba et al. 2002b) might be necessary to enhance consumption of the plant on rangelands at the desired timing. Our results indicate that defoliation via mowing or targeted grazing warrants investigation for suppressing sulfur cinquefoil.

Implications

Our results document the timings, frequencies, and intensities of defoliation necessary to suppress sulfur cinquefoil. Information derived from this study will greatly enhance the efficacy of mowing or targeted livestock grazing, two prospective treatments for managing sulfur cinquefoil on rangelands. Our results suggest that targeted livestock grazing or mowing applied once annually during flowering or seedset could effectively suppress the biomass production and viable seed production of sulfur cinquefoil. Defoliation treatments will need to be reapplied for several successive years to deplete the soil seed bank, given that some sulfur cinquefoil seeds can remain viable in the soil for several years (Dwire et al. 2006; Kiemenec and McInnis 2009; Rice 1991). Nevertheless, targeted grazing and mowing could provide low-cost, ecologically based methods for managing sulfur cinquefoil in areas where herbicides are not suitable.

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