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Grass and Canada Goldenrod (*Solidago canadensis*) Competition and Implications for Management in the Northern Tallgrass Prairie

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ABSTRACT Canada goldenrod (*Solidago canadensis* L.) is a native perennial forb that can form dense clonal patches and become weedy in pastures of the Northern Tallgrass Prairie Ecoregion. Our objectives were to determine 1) the competitive effects between Canada goldenrod and grass, 2) the relationship between Canada goldenrod stem density and grass biomass, and 3) the distribution of Canada goldenrod stem density at the pasture scale. We used regression analysis to develop a relationship between Canada goldenrod stem density and grass biomass. Additionally, we estimated the frequency distribution of Canada goldenrod stem density categories using three evenly distributed 100 × 100-m sampling grids across the pasture at each site. Canada goldenrod biomass increased as a result of grass removal by clipping whereas grass biomass did not change. Our results indicate that Canada goldenrod was released from competition but perhaps the grass was still being influenced by the root/rhizome system of Canada goldenrod. Approximately 70% of plots ($n = 600$) had <10 stems m^{-2} and dense stands (>100 stems m^{-2}) occurred in <0.3% of sampled plots. Our findings give producers and managers a tool to make better estimates of the impact of Canada goldenrod on grass productivity in pastures in the Northern Tallgrass Prairie Ecoregion.

KEY WORDS biomass, clipping, competition, forbs, frequency, goldenrod, grasses

Canada goldenrod (*Solidago canadensis* L.) is a native C_3 perennial, rhizomatous forb that is widely distributed across North America (Werner et al. 1980, Johnson and Larson 1999). In Europe and China it has become invasive, threatening native plant diversity (Weber and Schmid 1998, Rebele 2000, Dong et al. 2006b). In Canada and the USA, Canada goldenrod inhabits old farm fields, pastures, prairie remnants, and undeveloped areas (Werner et al. 1980). It could be considered an early successional species, because it characteristically dominates abandoned cropland for many years (Werner et al. 1980). In well managed prairies and pastures it typically consists of <5% canopy cover (Gibson 1989, Gibson et al. 1993, Guretzky et al. 2005).

In eastern Canada and north central USA grasslands, Canada goldenrod exhibits patchy, clonal growth (Werner et al. 1980, Hartnett and Bazzaz 1983, 1985, Hartnett 1990, Dong et al. 2006a). Genetic analysis of Canada goldenrod clones and neighboring plants suggest that colonization of areas by new Canada goldenrod populations occurs mainly through sexual reproduction while patch expansion occurs vegetatively (Dong et al. 2006b). Clonal patches can reach up to 2.5 m in diameter (Werner 1976). Weaver (1958) described its root system as having rhizomes, root offshoots, numerous main roots of equal size, and indefinite lateral spread. It is one of the more deeply rooted forbs of the tallgrass prairie, reaching depths up to 3.5 m (Weaver 1958).

Canada goldenrod can become abundant, especially in overgrazed pastures in the northern tallgrass prairie of eastern South Dakota, and is often viewed as a weed by livestock producers (D. Deneke, South Dakota State University,

personal communication). It is commonly treated with herbicides (D. Deneke, personal communication) even though studies documenting the competitive effects of goldenrod on grass production are non-existent. Defining a yield threshold, if one exists, could give managers a more strategic way to manage goldenrod, ultimately reducing the use of herbicides which has been shown to negatively affect floristic quality in the northern tallgrass prairie (Smart et al. 2011). Our objectives were to determine 1) the competitive effects between Canada goldenrod and grass, 2) the relationship between Canada goldenrod stem density and grass biomass, and 3) the distribution of Canada goldenrod stem density at the pasture scale. We hypothesized 1) that the competitive effects between Canada goldenrod and grass were low because they have functionally different root systems, 2) that there existed a threshold at which Canada goldenrod stem density would cause a decrease in grass biomass, but 3) the high stem density occurrence on the landscape was low.

STUDY AREA

We conducted our study on native tallgrass prairie located near Clear Lake, South Dakota at The Nature Conservancy's 7-Mile Fen (44.75° N, 96.54° W) and at Crystal Springs Game Production Area (44.81° N, 96.66° W), owned and managed by the South Dakota Department of Game, Fish and Parks. Soils at both sites are the complex Barnes-Svea-Buse loams (Fine-loamy, mixed, frigid Udic Haploborolls) with 2–9% slope, and both sites were classified as a loamy ecological site (Soil Survey Staff 2012). The long-term (1908–2011)

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historical climate record for Clear Lake, SD indicated an average annual temperature of 6.3° C and average annual precipitation of 646 mm of which 75% occurs April–September (High Plains Regional Climate Center 2012). Vegetation consisted of warm-season C₄ perennial grasses such as sideoats grama (*Bouteloua curtipendula* [Michx.] Torr.), little bluestem (*Schizachyrium scoparium* [Michx.] Nash), big bluestem (*Andropogon gerardii* Vitman), switchgrass (*Panicum virgatum* L.), indiangrass (*Sorghastrum nutans* [L.] Nash), and prairie dropseed (*Sporobolus heterolepis* [A. Gray] A. Gray), and cool-season C₃ perennial grasses such as green needlegrass (*Nassella viridula* [Trin.] Barkworth), porcupine grass (*Hesperostipa spartea* [Trin.] Barkworth), and Scribner dichanthelium (*Dichanthelium oligosanthes* [Schult.] Gould subsp. *scribnerianum* [Nash] Freckmann and Lelong). Common forbs included Canada goldenrod, Missouri goldenrod (*S. missouriensis* Nutt.), heath aster (*Symphotrichum ericoides* [L.] G. L. Nesom), gayfeathers (*Liatris* spp.), purple coneflower (*Echinacea angustifolia* DC.), prairie coneflower (*Ratibida columnifera* [Nutt.] Wootton and Standl.), and wild bergamot (*Monarda fistulosa* L.). Common shrubs included leadplant (*Amorpha canescens* Pursh), prairie rose (*Rosa arkansana* Porter), and western snowberry (*Symphoricarpos occidentalis* Hook.). Introduced cool-season C₃ perennial grasses included Kentucky bluegrass (*Poa pratensis* L.) and smooth brome grass (*Bromus inermis* Leyss. subsp. *inermis*). Introduced forbs included Canada thistle (*Cirsium arvense* [L.] Scop.) and dandelion (*Taraxacum officinale* F. H. Wigg.).

Study sites have been managed with fire and with grazing at a moderate stocking rate. Seven-Mile Fen was in a patch-burn rotation at a moderate stocking rate from 2006 through 2008. The property was idled from 2009 to 2010, and a portion of the property was managed with prescribed fire only in 2011. Crystal Springs was in an intensive early spring grazing system over the previous three years, and prior to that it was in a patch-burn rotation for three years.

METHODS

In late May 2010, at each study site, we established permanent 2-m × 2-m plots in dense patches of Canada goldenrod, 10 at 7-Mile Fen and 6 at Crystal Springs. Within each plot, four 1-m² plots were randomly allocated to one of four treatments; clipping Canada goldenrod only, clipping grass only, clipping all vegetation, and no clipping. On 27 May 2010 and 18 May 2011, Canada goldenrod stem counts were made for each treatment. In 2010 and 2011, the grass only and Canada goldenrod only clipping treatments occurred on 1 June and were re-clipped on 24 June. The clipping all vegetation treatment occurred on 1 June to simulate a mowing treatment. We clipped vegetation close to the soil surface using hand shears at each clipping date. In 2011, the same clipping treatments were applied to the same plots as in the previous year. On 16 August 2010 and 22 August 2011 (near peak

standing biomass for this region), we destructively harvested all plots by clipping the vegetation to ground level and sorted into grasses, Canada goldenrod, and other forbs and shrubs; samples were dried at 60° C for 72 hrs in a forced air oven and weighed to determine biomass production.

To develop a relationship between Canada goldenrod stem density and grass biomass, we used the August destructive harvest data from the no clipping treatment from both sites and years ($n = 32$). In 2010, we did not count the number of goldenrod tillers at the August harvest, so the May 2010 stem counts were used as a surrogate. In 2011, we counted stems during the August harvest. We analyzed the recruitment of Canada goldenrod stems from the difference between the May and August stem counts in 2011 from the grass only clipping treatment and the no clipping treatment. The difference between August and May stem counts was only 6 stems and was equal between both treatments. Therefore, the May 2010 stem count was a satisfactory surrogate in the 2010 data set.

In 2011, we evenly spaced three 100-m × 100-m grids across each of the study sites (72.8 and 64.8 ha for Crystal Springs and 7-Mile Fen, respectively). We measured Canada goldenrod stem density by counting the number of stems in a 1-m² quadrat every 10 m in each grid ($n = 100$). We classified the samples into 12 categories by Canada goldenrod stem density as follows: 0, 1–9, 10–19, 20–29, 30–39, 40–49, 50–59, 60–69, 70–79, 80–89, 90–99, >100 stems m⁻².

Daily weather data was available during the study period at Lake Cochrane, SD approximately 5 and 10 km southeast of 7-Mile Fen and Crystal Springs, respectively (South Dakota Climate and Weather 2012). The 30-year average weather data (1971–2000) was available from Clear Lake, SD approximately 11 km west of 7-Mile Fen and 5 km south of Crystal Springs (South Dakota Climate and Weather 2012).

Statistical Analysis

We analyzed the effect of clipping treatment as a randomized complete block using analysis of variance in PROC MIXED (SAS Institute 2009) to determine the competition between Canada goldenrod and grass. The model included independent variables: site, treatment, site by treatment, year, site by year, treatment by year, and site by treatment by year as fixed effects and stem density as a covariate. Random effects included plot within site and plot within site by treatment. We considered ‘year’ a repeated measure and analyzed using the split-plot in time method as described by Steel and Torrie (1980) which adequately accounted for the error correlation among years. Dependent variables included August biomass of grasses, Canada goldenrod, and other forbs and shrubs. When the dependent variable, Canada goldenrod stem count from May was analyzed, we used the same model except we removed the covariate. When the dependent variable, weight per stem of Canada goldenrod from the August harvest was

analyzed, we used the original model but only compared the grass only clipping treatment and no clipping treatment. We considered all effects significant at $\alpha = 0.05$.

We used regression analysis to develop a relationship between Canada goldenrod stem density and grass biomass and to determine if a threshold exists for Canada goldenrod stem density to have an impact on grass biomass. We used PROC REG (SAS Institute 2009) to analyze data from the August harvest in the no clipping plots from both sites.

RESULTS

April was drier and warmer than the 30-year average for both study years (Table 1). In 2010, June precipitation was 62% above average with May and July slightly above average and August slightly below average (Table 1). In 2011, May and July precipitation was 59% and 73% above average, respectively, with June and August precipitation 15% and 81% below average, respectively (Table 1). Mean monthly average temperature in 2011 was identical to the 30-year average from May through July, while August averaged 1° C above the 30-year average (Table 1). In 2010, May averaged 2° C below 30-year average and July averaged 2° C above the 30-year average (Table 1).

There was a significant year by site by treatment interaction ($F_{3,56} = 4.80, P = 0.005$) for Canada goldenrod stem densities. In 2010, we found initial Canada goldenrod stem densities to be similar ($F_{3,42} = 0.04, P = 0.988$) between clipping treatments although they were nearly two times greater at Crystal Springs than at 7-Mile Fen (Table 2). Repeated application of clipping treatments and the destructive harvest on the same plots resulted in changes in initial 2011 stem counts (Table 2). Canada goldenrod stem densities were lower for all clipping treatments at 7-Mile Fen, whereas only the all vegetation and Canada goldenrod clipping treatments were

lower than the grass and no clipping treatments at Crystal Springs (Table 2).

There was no significant year by site by treatment interaction for mean August biomass of Canada goldenrod ($F_{3,55} = 1.85, P = 0.148$). Also, there was no significant year by site interaction for mean August biomass of Canada goldenrod ($F_{1,55} = 1.01, P = 0.320$). However, there was a significant site by treatment interaction for mean August biomass of Canada goldenrod ($F_{3,42} = 3.91, P = 0.015$). The grass only clipping treatment resulted in an increase of approximately 33% in mean Canada goldenrod biomass compared with the no clipping treatment at either site (Table 3). The interaction between the sites was a result of the all vegetation treatment having 59% and 46% of the Canada goldenrod biomass of the no clipping treatment at 7-Mile Fen and Crystal Springs sites, respectively (Table 3). Also, Canada goldenrod biomass from the Canada goldenrod only clipping treatment was 46% and 21% of the no clipping treatment at 7-Mile and Crystal Springs sites, respectively (Table 3). There was a significant year by treatment interaction for mean August biomass of Canada goldenrod ($F_{3,55} = 13.53, P < 0.001$). Canada goldenrod biomass from the grass-only clipping treatment was 19% and 62% greater than the no clipping treatment in 2010 and 2011, respectively (Table 4). Also, Canada goldenrod biomass from the all vegetation clipping treatment was 46% and 82% of the no clipping treatment in 2010 and 2011, respectively (Table 4). In addition, Canada goldenrod biomass in the Canada goldenrod only clipping treatment was 9% and 86% of the no clipping treatment in 2010 and 2011, respectively (Table 4).

There was no significant year by site by treatment interaction for mean August biomass of grass ($F_{3,55} = 0.70, P = 0.559$). Also, there were no significant 2-way interactions, year by treatment ($F_{3,55} = 2.62, P = 0.060$), year by site ($F_{1,55} = 0.95, P = 0.333$), or site by treatment ($F_{1,55} = 2.79, P =$

Table 1. Monthly total precipitation, monthly average temperature, and the 30-year average¹ from Lake Cochrane, South Dakota in 2010 and 2011 (Source: South Dakota Climate and Weather 2012).

Month	Precipitation (mm)			Temperature (° C)		
	2010	2011	30-yr average	2010	2011	30-yr average
Apr	28	17	57	9	11	6
May	73	126	79	12	14	14
Jun	175	92	108	19	19	19
Jul	94	152	88	24	22	22
Aug	60	15	79	21	22	21
Growing season ²	431	403	412	17	17	16

¹30-year average data is from Clear Lake, South Dakota approximately 15 km west of Lake Cochrane, South Dakota from 1971–2000; ²Apr–Aug.

Table 2. Canada goldenrod stem density and standard error in parentheses on 28 May 2010 and 18 May 2011 at 7-Mile Fen and Crystal Springs prairies near Clear Lake in eastern South Dakota. Clipping treatments were: all vegetation, clipped in early June; grass only, clipped early and late June; Canada goldenrod only, clipped early and late June; and no clipping.

Year	Site	Clipping treatment	Canada goldenrod stem density (No. m ⁻²) ¹
2010	7-Mile Fen	All vegetation	66 (9.1) ^b
		Grass only	62 (9.1) ^b
		Canada goldenrod only	64 (9.1) ^b
		No clipping	63 (9.1) ^b
	Crystal Springs	All vegetation	121 (11.7) ^a
		Grass only	120 (11.7) ^a
		Canada goldenrod only	120 (11.7) ^a
		No clipping	121 (11.7) ^a
2011	7-Mile Fen	All vegetation	22 (9.1) ^{c, d}
		Grass only	38 (9.1) ^{c, d}
		Canada goldenrod only	14 (9.1) ^d
		No clipping	18 (9.1) ^{c, d}
	Crystal Springs	All vegetation	84 (11.7) ^b
		Grass only	139 (11.7) ^a
		Canada goldenrod only	47 (11.7) ^{b, c}
		No clipping	117 (11.7) ^a

¹Means within a column followed by different letters are significantly different ($P < 0.05$).

Table 3. Mean biomass (g m⁻²) and (SE) of Canada goldenrod sampled at 7-Mile Fen and Crystal Springs prairies near Clear Lake, South Dakota in late August averaged over 2010 and 2011. Clipping treatments were: all vegetation, clipped in early June; grass only, clipped early and late June; Canada goldenrod only, clipped early and late June; and no clipping.

Site	Clipping treatment	Canada goldenrod ¹
7-Mile Fen	All vegetation	65 (13.1) ^d
	Grass only	143 (12.6) ^b
	Canada goldenrod only	51 (13.7) ^d
	No clipping	109 (12.8) ^c
Crystal Springs	All vegetation	75 (16.4) ^{c, d}
	Grass only	215 (18.7) ^a
	Canada goldenrod only	35 (16.2) ^d
	No clipping	161 (19.4) ^b

¹Means within a column followed by different letters are significantly different ($P < 0.05$).

Table 4. Mean biomass (g m^{-2}) and standard error in parentheses of Canada goldenrod sampled in late August 2010 and 2011 averaged over sites (7-Mile Fen and Crystal Springs prairies) near Clear Lake, South Dakota. Clipping treatments were: all vegetation clipped in early June, grass clipped early and late June, Canada goldenrod clipped early and late June, and no clipping.

Year	Clipping treatment	Canada goldenrod ¹
2010	All vegetation	88 (13.6) ^d
	Grass only	230 (13.5) ^a
	Canada goldenrod only	17 (13.5) ^e
	No clipping	192 (13.5) ^b
2011	All vegetation	52 (13.8) ^e
	Grass only	128 (14.1) ^e
	Canada goldenrod only	68 (16.2) ^{d,e}
	No clipping	79 (14.0) ^{d,e}

¹Means within a column followed by different letters are significantly different ($P < 0.05$).

0.054), for mean August grass biomass. There was, however, a significant treatment main effect ($F_{3,42} = 31.10$, $P < 0.001$). Goldenrod clipping only and no-clipping treatments had similar mean August grass biomass and were greater than the all vegetation and grass only clipping treatments (Fig. 1). The grass only clipping treatment had the least amount of mean August grass biomass (Fig. 1). Mean August grass biomass was greater ($F_{1,55} = 37.67$, $P < 0.001$) in 2011 (203.9 g m^{-2}) than 2010 (131.7 g m^{-2}). Mean August biomass was greater

($F_{1,14} = 11.02$, $P < 0.001$) for 7-Mile Fen (219.8 g m^{-2}) than at Crystal Springs (115.9 g m^{-2}).

There was no significant year by site by treatment interaction for mean August biomass of forbs and shrubs ($F_{3,55} = 0.58$, $P = 0.629$). Also, there were no significant 2-way interactions, year by treatment ($F_{3,55} = 0.18$, $P = 0.911$), year by site ($F_{1,55} = 2.04$, $P = 0.159$), or site by treatment ($F_{1,55} = 0.82$, $P = 0.492$), for mean August biomass of forbs and shrubs. There was no significant treatment main effect ($F_{3,42} = 2.79$, P

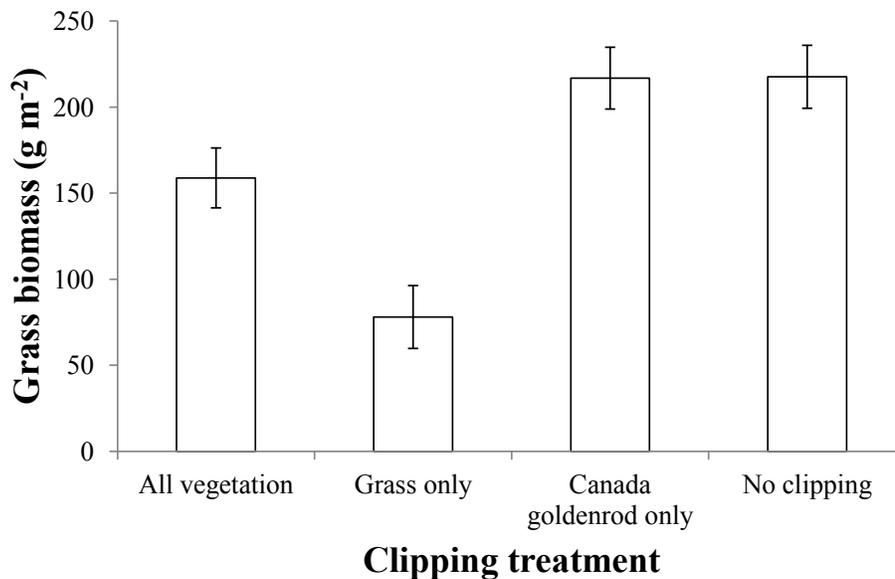


Figure 1. Mean grass biomass and standard errors from the August harvest averaged across sites and years for clipping treatments: all vegetation, clipped in early June; grass only, clipped early and late June; Canada goldenrod only, clipped early and late June; and no clipping in eastern South Dakota, 2010–2011.

= 0.052) or site main effect ($F_{1,14} = 2.80, P = 0.117$) for mean August biomass of forbs and shrubs. Mean August forbs and shrubs biomass was greater ($F_{1,55} = 15.18, P < 0.001$) in 2011 (67.1 g m^{-2}) than 2010 (46.6 g m^{-2}).

There was no significant year by site by treatment interaction for mean weight per stem of Canada goldenrod at the August harvest ($F_{1,28} = 0.70, P = 0.409$). Also, there were no significant 2-way interactions, year by treatment ($F_{1,28} = 0.06, P = 0.8135$), year by site ($F_{1,28} = 1.03, P = 0.319$), or site by treatment ($F_{1,14} = 0.05, P = 0.823$), for mean weight per stem of Canada goldenrod at the August harvest. Grass only clipping treatment resulted in significantly ($F_{1,14} = 10.17, P = 0.007$) greater weight per stem of Canada goldenrod (2.1 g) than the no clipping treatment (1.7 g). Also, weight per stem of Canada goldenrod was significantly ($F_{1,28} = 97.88, P < 0.001$) greater in 2010 (2.6 g) than in 2011 (1.2 g).

The regression analysis from the August harvest in the no clipping plots revealed a linear decrease in grass biomass as Canada goldenrod stem density increased (Fig. 2). The distribution of Canada goldenrod stem density categories across the landscape at these two sites showed that 67–71% of sampled quadrats ($n = 300$ for each site) had stem densities $< 10 \text{ m}^{-2}$ (Fig. 3). Using the frequency distribution of stem density (Fig. 3), the mean number of stems in each category (data not shown), and the linear equation (Fig. 2), we calculated a weighted average of the standing crop grass biomass compared to a hypothetical situation with no Canada goldenrod in the pasture. Using this method, 2011 grass biomass at 7-Mile Fen and Crystal Springs prairies was reduced 150 and 100

kg ha⁻¹, respectively, by the presence of Canada goldenrod compared to a pasture without Canada goldenrod.

DISCUSSION

The initial differences in stem densities between the sites in the first year (Table 2) are likely due to historical use, localized differences in soil nutrient availability, and clonal age. Hartnett and Bazzaz (1985) showed that clones with high ramet density produced shorter rhizomes than those of less density. They hypothesized that rhizomes from less dense clones were elongating to find higher soil fertility/water availability compared with shorter rhizome length of more dense clones that may have been growing in a localized nutrient rich microsite (Hartnett and Bazzaz 1985). As clones age, they begin to expand by producing longer rhizomes in order to exploit more resources (Hartnett and Bazzaz 1985). The differences in initial stem densities between sites in the second year (Table 2) may have been a function of initial clone density. The carbohydrate reserves and number of lateral roots (Weaver 1958, Werner et al., 1980) would be expected to be much greater from the high density clones at Crystal Springs compared to the lower density clones at 7-Mile Fen. Perhaps at lower stem densities, an intense clipping in late August of the first year more significantly reduced carbohydrate reserves and lateral roots going into the fall compared to clones with higher stem densities. Bradbury (1981) documented that new shoots in younger Canada goldenrod populations did not survive clipping to the extent that those in older populations did

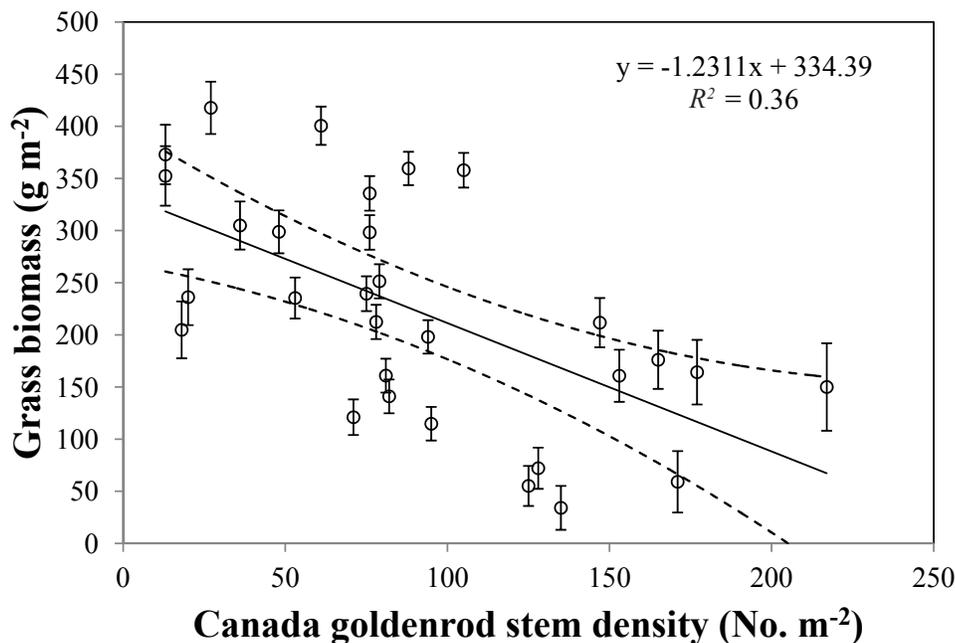


Figure 2. Relationship of Canada goldenrod stem density (No. m⁻²) and late August grass biomass (g m⁻²) from two eastern South Dakota native grasslands in 2010 and 2011. Dotted lines are the upper and lower 95% confidence intervals.

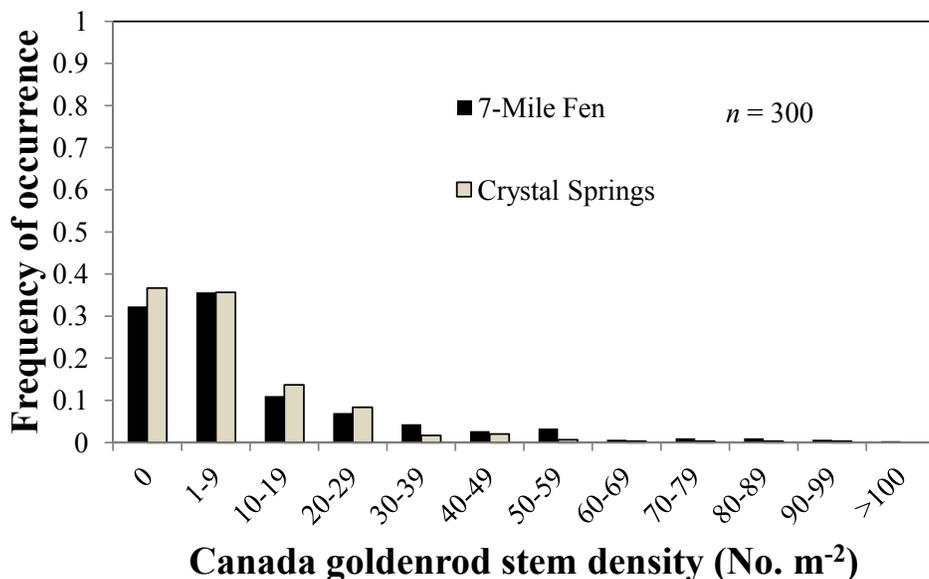


Figure 3. Frequency of occurrence of Canada goldenrod stem densities (No. m⁻²) sampled in late August 2011 from three 100 m × 100 m grids from 7-Mile Fen and Crystal Springs prairies ($n = 300$ for each site) in eastern South Dakota located near Clear Lake, South Dakota.

and this might be evidence to support our assertion.

The difference in Canada goldenrod biomass among treatments between sites was due to the inconsistent response by the all vegetation clipping and Canada goldenrod clipping treatments in relation to the no clipping treatment (Table 3). The Canada goldenrod response to the Canada goldenrod only clipping treatment or the all vegetation clipping treatment was an assessment of resource allocation by the genet(s) and could have been confounded by the close proximity of the other treatments because some clones have been shown to be as large as 2.5 m in diameter (Werner 1976). We recognize that physiological integration among ramets within clones (resource sharing) and edge effect undoubtedly strongly influenced how the vegetation responded to the treatments (Hartnett and Bazzaz 1983, 1985). The Canada goldenrod response in the grass only clipped plots may have demonstrated increased growth in response to the clipping treatment, but may also have been in response to increased photosynthesis because daughter ramets in goldenrod clipping treatments would demand more resources (source-sink relationship; resource sharing) as demonstrated by Hartnett and Bazzaz (1985). The difference in Canada goldenrod biomass among treatments between years (Table 4) was likely due to previously mentioned reasons in addition to differences in precipitation and temperature patterns between 2010 and 2011 (Table 1). Briggs and Knapp (2001) showed that interannual variability in biomass of C₄ grasses was highly related to water availability, but not so with C₃ forbs. Perhaps Canada goldenrod, as a C₃ forb, was more responsive to June precipitation than July and the destructive harvest in late

August was more detrimental to it than for the grasses as was shown for *Solidago altissima* (Stoll et al. 1998).

The removal of grass increased Canada goldenrod biomass, but the removal of Canada goldenrod did not increase grass biomass. We present two hypotheses regarding this phenomenon: 1) there could be lag in response from the grasses being released from competition, or 2) the two groups are exploiting different resources. Regarding the first hypothesis, grasses commonly increase in yield following a reduction in forbs through herbicide application (DiTamoso 2000). Reece and Wilson (1983) demonstrated that grass yield continued to increase 110%, 314%, and 212% over untreated plots in each of three consecutive years of Canada thistle control. Using simulated clipping, Kirby et al. (1997) defoliated leafy spurge (*Euphorbia esula* L.) at different developmental stages and at different frequencies annually for five consecutive years. In the first year there was no difference in grass biomass among the clipping treatments; but after five years of clipping leafy spurge two times per season, grass biomass doubled compared to the undefoliated control (Kirby et al. 1997). In our study, Canada goldenrod was likely still having an influence on the grass in the goldenrod clipping treatment because there was still some regrowth of goldenrod in the August harvest (Table 2, 3). If we had used an herbicide on the Canada goldenrod, it would have likely stopped all metabolic functions of the target and we may have seen a more typical response by grasses.

Alternatively, the two groups may be exploiting different resources. A common assumption regarding species interactions in communities is the reciprocal effect; e.g., if species

A is removed from the presence of species B, then removal of B from A would produce the same effect (Fowler 1981). This is based on the assumption that the same niche is being exploited by species A and B. However, in some cases a non-reciprocal effect occurs, e.g., if species A is removed from the presence of species B it doesn't produce the same effect if B is removed from A. In this case species A and B are not exploiting the same resources. Dwyer (1958) showed that the biomass of big bluestem significantly decreased in the presence of rhizomatous forbs, but not in the presence of taprooted forbs. Even though Canada goldenrod has been described as a rhizomatous forb, it has very deep roots (Weaver 1958). Canada goldenrod may be balancing the water use by grasses through hydraulic lift (Liste and White 2008). This process is normally associated with trees and shrubs, but it is now thought to occur in nonwoody plants as well (Liste and White 2008). Skinner et al. (2004) showed that grass plots with deep rooted forbs had higher water content than plots without deep rooted forbs suggesting that hydraulic lift probably occurred.

Canada goldenrod has effective distribution of its leaves for photosynthesis (Werner et al. 1980, Potvin and Werner 1983, Fay et al. 2003) and likely responded to increased light and water availability. Rebele (2000) showed evidence that the dense canopy of *Calamagrostis epigeos* (L.) Roth out-competed Canada goldenrod for light. Removal of grass in our clipping experiment would have allowed increased penetration of light lower in the canopy. Werner (1976) showed that when soil moisture increases, Canada goldenrod increases allocation of biomass toward vegetative propagation. Perhaps removing grass allowed more available water to be used for growth of existing stems rather than for production of new tillers.

The linear regression equation did not support our hypothesis that a stem density threshold existed. Grekul and Bork (2004) also found that Canada thistle had no stem density threshold effect and that the number of Canada thistle stems was linearly related to a decrease in grass biomass. Thus, while sporadic clonal patches of Canada goldenrod may be visually perceived as having a significant impact on reducing grass production, in reality the reduction is minor. Even though herbicides are effective in reducing broadleaf plants (DiTomaso 2000), herbicide use doesn't always translate to increases in beef production at the ranch scale (Fuhlendorf et al. 2009). Fuhlendorf et al. (2009) argued the reason for this is that typically ranchers don't make annual adjustments to stocking rate because year-to-year variation in precipitation, which is extremely hard to predict (Smart et al. 2007, Holechek et al. 2011), is more important than any other factor in determining forage production.

MANAGEMENT IMPLICATIONS

Our results suggest that Canada goldenrod is an "increaser" species under heavy grazing pressure (simulated by

our clipping grass only treatment). The frequency and distribution of Canada goldenrod stem density categories at the pasture scale were useful to calculate a weighted average reduction of grass biomass. At our observed levels of Canada goldenrod stem density, we estimated an average reduction of 125 kg ha⁻¹ in grass biomass at our study sites. This weighted average can be useful for making management decisions. For example, if a relatively inexpensive herbicide application (e.g., \$10 acre⁻¹) was used to control Canada goldenrod, it would translate to saved grass biomass costing \$180 ton⁻¹. We propose that producers and managers make relatively simple inventories of Canada goldenrod stem densities, and use our equation to help make more wise economic decisions regarding the use of herbicides.

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