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Canada Thistle (*Cirsium arvense*) Suppression by Sudangrass Interference and Defoliation

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Canada thistle is difficult to manage in organic farming systems and others with reduced reliance on herbicides. Previous field studies found that defoliation or sudangrass interference suppressed Canada thistle. Our objective was to understand the factors causing suppression of Canada thistle observed in the field. Three greenhouse studies were conducted utilizing frequency of defoliation, sudangrass interference and defoliation, and interspecific phytotoxicity to discern mechanisms of Canada thistle suppression. Increased defoliation frequency (up to four defoliations) decreased Canada thistle shoot height, shoot and root mass, and root-to-shoot ratio. Plants with larger root mass had greater shoot mass and number ($r = 0.87$ and 0.73, respectively), indicating a probable interdependence of root size (carbohydrate reserves), bud density, and subsequent shoot growth. In the sudangrass interference and defoliation study, Canada thistle shoot dry mass was 38.7, 2.76, and 0.39 g pot^{-1} in the defoliation only, sudangrass interference only, and defoliation + interference + surface mulch treatments, respectively. Sudangrass interference by itself was effective in suppressing thistle growth; combining interference with defoliation did not further reduce growth (2.76 and 2.83 g pot^{-1}, respectively). In the experiment minimizing interspecific competition, we found no evidence of sudangrass having a phytotoxic effect on Canada thistle. Overall results indicate that sudangrass competition or frequent shoot removal suppresses growth of Canada thistle.
Nomenclature: Canada thistle, *Cirsium arvense* (L.) Scop.; sudangrass, *Sorghum bicolor* (L.) Moench spp. *drummondii* (Nees ex Steud.) de Wet and Harlan.
Key words: Competition, cover crop, mowing, mulch, perennial weed.

Competitive cultivars, intensive tillage, and multiple defoliations are common methods to manage Canada thistle in cropping systems that minimize reliance on herbicides (Derksen et al. 1994; Edwards et al. 2000; Hatcher and Melander 2003; Moore 1975). These practices reduce production of Canada thistle photosynthates and decrease root carbohydrate reserves important for its perennation and regrowth. In previous field research, we found that a sudangrass cover crop reduced Canada thistle shoot mass and density for two growing seasons (Bicksler and Masiunas 2009). Combining sudangrass with defoliation did not reduce thistle growth more than the cover crop alone. Moreover, two defoliations during the growing season only reduced mass and number of shoots in the dense Canada thistle stand (30 plants m^{-2}). These results differed from other research that found defoliation alone or combined with competitive cultivars reduced Canada thistle spread and growth more than either practice alone (Bohm and Vershwele 2004; Cormack 2002; Graglia et al. 2006; Patriquin et al. 1986). More research is needed to explore the relative importance of defoliation and competitive crops and determine whether the two provide greater control alone or in unison.

Frequent defoliation by mowing is used in pastures and noncrop areas to reduce Canada thistle spread and growth. Shoot regrowth after mowing depletes root carbohydrate reserves and frequent mowing prevents young shoots from replenishing root carbohydrate reserves (Gragalia et al. 2006; Hatcher and Melander 2003). A critical time for Canada thistle defoliation is before flower buds open in May to July because the roots have their lowest carbohydrate reserves and are least able to regenerate (Sagar and Rawson 1964; Tworkoski 1992). Studies have found that combining mowing with perennial grasses, white clover (*Trifolium repens* L.), and rye (*Secale cereale* L.), or white clover and alfalfa (*Medicago sativa* L.) in mixed pastures reduced Canada thistle growth more than repeated mowing alone (Bohm and Vershwele 2004; Cormack 2002; Graglia et al. 2006; Patriquin et al. 1986).

Sudangrass differs from rye or pasture species used in previous studies. Sudangrass has optimal growth at warmer temperatures (25 to 30 C) and grows more rapidly and taller than rye or legumes and grasses commonly used in pastures (Ketterings et al. 2007). Sudangrass rapidly closes canopy, reaches heights of 3 m, and produces up to 8 Mg ha^{-1} shoot mass (Ngouajio et al. 2003). Sudangrass also tolerates repeated defoliations, regrowing from terminal buds and basal and axillary tillers (Clapp and Chamblee 1970). Previously, we found that mowing sudangrass caused regrowth and adventitious tillering and produced surface mulch (Bicksler and Masiunas 2009). But mowing sudangrass did not reduce Canada thistle growth more than interference from uncut sudangrass. Ngouajio et al. (2003) found that sudangrass cover crop mulches inhibited annual weed growth through preventing light from reaching shallow seeds, diminishing germination cues by reducing soil temperature and moisture fluctuations, and possible phytotoxicity. Further research is needed to determine if sudangrass regrowth and surface mulch plays a role in suppressing Canada thistle.

Mechanisms for reducing Canada thistle in a cover cropped sudangrass stand can consist of competition for resources and phytotoxicity. Sorghum [*Sorghum bicolor* (L.) Moench spp. *bicolor*] root hairs release sorgoleone [2-hydroxy-5-methoxy-3-[(8′Z,11′Z)-8′,11′,14′-pentadecatriene]-*p*-benzoquinone], its hydroquinone, and minor analogues, which inhibit photosystem II in susceptible plants (Czarnota et al. 2003; Weston and Duke 2003). These are exuded as hydrophobic droplets from the root hairs (Netzly and Butler 1986). It is unknown whether these compounds are generally present in the rhizosphere, or whether there is a localized effectiveness of the compounds (Czarnota et al. 2001; Weidenhamer 2005).

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In addition to root exudates, sorghum leaves damaged during defoliation caused degradation of the tyrosine-derived cyanogenic glucoside dhurrin (β-D-glucopyranosyloxy-(*S*)-*p*-hydroxymandelonitrile), leading to production of hydrogen cyanide and *p*-hydroxybenzaldehyde (Cicek and Esen 1998; Nielsen et al. 2008; Weston and Duke 2003), which also might act as phytotoxic plant inhibitors. It is unknown if sorghum is phytotoxic to perennial Canada thistle.

The unanswered questions from our previous work, described above, formed the rationale for the present study. We had two primary aims. First, we wanted to better understand the mechanisms underlying Canada thistle suppression by defoliation alone, cover crops alone, defoliation with cover crops, and potential phytotoxicity effects. Second, the use of sudangrass as a cover crop in the midwestern United States is a new addition to weed control, and its contribution to suppression of Canada thistle has not been investigated. Our research investigated the relative importance of mechanisms contributing to sudangrass and defoliation suppression of Canada thistle. Greenhouse studies were conducted to determine if (1) increased defoliation alone will decrease Canada thistle mass; (2) sudangrass interference is more effective than defoliation to reduce thistle growth; (3) sudangrass mulch suppresses Canada thistle growth; and (4) living sudangrass roots in the rhizosphere suppress Canada thistle growth.

Materials and Methods

Preparation of the Studies. On October 20, 2006, October 16, 2007, and May 13, 2008, Canada thistle roots were harvested from an extant field of Canada thistle at the University of Illinois, Urbana–Champaign Vegetable Crops Research Farm. The May harvest was necessary because of the poor quality of roots stored from October and the roots were only used for the repeat (June) of the phytotoxicity experiment. The soil was dug to 46 cm depth and Canada thistle roots were removed, cleaned by shaking, placed in breathable olefin bags (Hubco Inc., Hutchinson, KS), which were filled with moist vermiculite, and stored at 4.5 C (McAllister and Haderlie 1985). Before planting, thistle roots were removed from the cooler and washed; and healthy, living tissue was selected and cut into 6-cm pieces (Sagar and Rawson 1964). The selected roots were approximately 1.3 cm diam and uniform. All experiments utilized four thistle root pieces (Sagar and Rawson 1964) per pot. Subsequent research found the greatest Canada thistle emergence occurs with 11 cm long and 0.43-cm-diam root fragments buried at a depth of 10 cm (Sciegienka et al. 2011).

Studies were conducted in the University of Illinois, Plant Care Facility at Urbana, IL. In all experiments but the phytotoxicity study, the plants were watered daily to induce emergence (Sciegienka et al. 2011), fertilized once weekly with 300 mL solution pot^{-1} to deliver 90 mg total nitrogen, 90 mg available phosphorus, 90 mg water-soluble potassium, and trace elements (Soluble fertilizer, Plant Marvel Laboratories, Inc., Chicago Heights, IL). The plants additionally received 13,000 lumens m^{-2} of metal halide-produced supplemental lighting for 14.5 hr day^{-1}. The set point temperatures were 27 and 21 C day/night. Approximately 6 wk after planting, 85 g of a slow-release fertilizer (Osmocote, The Scotts Miracle-Gro Company, Marysville, OH) (280 g m^{-3} total nitrogen, 168 g m^{-3} available phosphorus, and 224 g m^{-3} water-soluble potassium) was applied to the soil surface in each pot. The high rate of slow-release fertilizer was used to avoid nutrient deficiencies in the organic, high-porosity soil. All experiments were randomized complete blocks with three or four replications and repeated.

Defoliation Frequency Study. On February 22, 2007 and February 18, 2008, 7.6 L pots (22.9 cm diam by 38 cm deep) were filled with general-purpose greenhouse medium (1 : 1 : 1 loam soil : peat : perlite + 2.9 kg m^{-3} dolomitic limestone + 2.5 kg m^{-3} phosphoric acid + 1.7 kg m^{-3} gypsum + 0.12 kg m^{-3} $MgSO_4$). Canada thistle root pieces were planted 5 cm deep in the medium in a ring 9 cm in diameter. In our study, all Canada thistle root pieces generated shoots.

The treatments were defoliation frequencies (none, one, two, three, or four cuttings) to mimic intensive defoliation over the course of a growing season. Canada thistle was first defoliated at flower bud formation (approximately 15 cm tall), when root carbohydrates reserves were reported to be the lowest (Tworkoski 1992). Subsequent defoliations occurred approximately every 20 d to simulate mowings in the field. At 53 or 51 d after planting (DAP) (2007 and 2008, respectively), treatments receiving the first defoliation were cut at a height of 10 cm, similar to the mowing height in the field studies. The subsequent defoliations were at 75 or 78 DAP, 96 or 99 DAP, and 116 or 118 DAP. Harvested shoots were dried at 70 C for at least 48 hr and weighed.

On July 6 and 8, 2007 and 2008 (134 and 139 DAP), the experiments were terminated. Plant height was measured from the soil surface to the upper-most outstretched emerged leaf for the tallest five plants in each pot. Shoots were counted and then cut at the soil surface. Roots were washed from the soil mixture and rinsed until clean. Roots and shoots were dried at 70 C and mass was measured. Shoot dry mass from each defoliation was added to shoot dry mass measured at the end of the experiment to calculate total shoot mass.

Sudangrass Interference and Defoliation Study. The experiment was a factorial combination of defoliation (none or three times), sudangrass (none or with sudangrass cover crop), and cover crop mulch (none or with sudangrass shoots as a mulch). The specific treatments were: (1) Canada thistle without sudangrass or defoliation (control); (2) Canada thistle with defoliation (defoliation); (3) Canada thistle with sudangrass but no defoliation (interference); (4) Canada thistle with sudangrass and defoliation (interference + defoliation); and (5) Canada thistle with sudangrass, defoliation, and cut shoots as mulch (interference+ defoliation + mulch). The purpose of this specific study was to segregate and quantify the effects of defoliation alone, sudangrass interference alone, sudangrass mulch, and their combinations.

On February 22, and June 25, 2007, 38 L pots (38.5 cm in diameter by 38 cm deep) were filled with a high-porosity greenhouse mixture (SB500 High Porosity Mix, Sun Gro Horticulture Canada, Ltd., Abbotsford, BC V2S 7T9, Canada) containing bark, sphagnum peat moss, perlite, vermiculite, Dolomitic limestone, gypsum, and wetting agent. The high-porosity mixture allowed removal of Canada thistle root systems. Canada thistle root pieces were planted 5 cm deep in the greenhouse medium in a concentric circle 20 cm in diameter. Sudangrass (Sweetleaf II sudangrass, NC+

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Hybrids, Lincoln, NE) was seeded 2.5 cm deep at 24 seeds pot^{-1} (207 seeds m^{-2}), a density similar to sudangrass emergence in the field studies (Bicksler and Masiunas 2009). The seeds were evenly spaced in concentric rings (8, 16, 24, and 32 cm diam, 2.5 cm above the thistle root pieces. Sudangrass seeds were placed in the concentric rings at a density of 3, 5, 7, and 9 seeds for the 8-, 16-, 24-, and 32-cm rings, respectively). At 21 DAP, sudangrass was thinned to 20 seedlings pot^{-1}.

When Canada thistle in the Control treatment began to form flower buds (at 36 and 45 DAP), the sudangrass and thistle shoots were cut at 10 cm. Canada thistle and sudangrass shoots were dried at 70 C for at least 48 hr and mass was determined. Shoots from plants in the interference + defoliation + mulch treatment were handled differently so surface mulch could be returned to the pots. The sudangrass and thistle shoots were cut, separated, and weighed wet. The sudangrass and thistle shoots were recombined, cut into 5-cm pieces, and placed onto the soil surface. Dry mass was estimated from fresh mass in the interference + defoliation + mulch treatment compared to fresh and dry mass in the interference + defoliation treatment. Further defoliations were timed with formation of flower buds on previously mowed thistle plants. The subsequent defoliations occurred at 60 or 74 DAP and 73 or 100 DAP. The delayed defoliation times in the June repeat were likely due to differences in temperatures, natural photoperiod, and light intensity that occurred despite the use of metal halide high-intensity discharge (HID) lights (Cathey and Campbell 1975).

On May 17 and November 7, 2007 (84 and 135 DAP), experiments were terminated, and sudangrass shoot heights were measured from the soil surface to the tallest free-standing emerged leaf for the highest three plants in each pot. Thistle and sudangrass shoots were cut at the soil surface, counted, and mulch (interference + defoliation + mulch treatment) removed from pots. The shoots and mulch were dried at 70 C and mass was measured. In the February repeat, sudangrass shoot dry mass was not determined in the first and third defoliations because of time constraints. In the June repeat, we determined shoot mass in each defoliation and thistle root fresh mass.

Phytotoxicity Study. We quantified Canada thistle phytotoxicity in response to sudangrass using root exclusion tubes (Nilsson 1994). This study was conducted before analysis for plant-active compounds because we wanted to determine if there was any evidence of phytotoxicity to Canada thistle from sudangrass. The treatments were: (1) Canada thistle in 38 L pots without sudangrass (thistle alone); (2) sudangrass in root exclusion tubes without Canada thistle in the 38-L pots (isolated sudangrass); (3) Canada thistle in the 38-L pots with sudangrass in root exclusion tubes (thistle + isolated sudangrass); and (4) Canada thistle and sudangrass in the same 38-L pot, sharing root zone space (thistle with sudangrass). The individual population densities of thistle and sudangrass remained constant; i.e., an additive experimental design was used.

We created root exclusion tubes by removing the solid bottoms of plastic pots (39.4 cm long and 14.6 cm by 14.6 cm at the top tapering to 10.2 cm by 10.2 cm at the bottom). Root exclusion tubes were sealed (GE Silicon II Window and Door Caulk, General Electric, Inc., Huntersville, NC) to the bottoms of 38-L pots directly over a drainage hole (Figure 1). All pots and root exclusion tubes were filled with a steam-pasteurized custom soil mix of 10 parts coarse quartz sand to three parts field soil (Drummer silty clay loam [fine Montmorillonitic, mesic Aquic Agridoll]). On February 19, and June 27, 2008, Canada thistle root pieces were planted as described for the defoliation experiment outside of the sudangrass seeding area. Sudangrass was seeded (14 sudangrass seeds pot^{-1}) in the isolation tubes or in an area the size of the isolation tubes (213 cm^2).

Figure 1. (A) The pots used for the phytotoxicity study. The root exclusion tube extended to the bottom of the large black pots. (B) The containers after emergence of Canada thistle and sudangrass. In the foreground is the thistle alone treatment, and in the background is the isolated sudangrass treatment. The sudangrass leaves are held upright by staking and tying with string.

Fertilizer applications were designed to minimize nutrient competition between sudangrass and Canada thistle. On February 20, and July 2, 2008, 85 g total of a slow-release fertilizer (Osmocote) was applied based on surface area of the isolation tube (25%) and remainder of the pot (75%) to supply 280 g m^{-3} total nitrogen, 168 g m^{-3} available phosphorus, and 224 g m^{-3} water-soluble potassium. Also, the plants were fertilized twice weekly with a water-soluble fertilizer[2] (2.7 mg m^{-3} total nitrogen, 1 mg m^{-3} available phosphorus, 1 mg m^{-3} water-soluble potassium at each fertilization). Throughout the studies, both thistle and sudangrass had dark green leaves and no evidence of nitrogen deficiency.

Competition for light was minimized through thinning and staking the sudangrass. Sudangrass seedlings were thinned to eight per isolation tube (376 plants m^{-2}) between 8 and 10 DAP. The density was similar to sudangrass emergence in the field studies (Bicksler and Masiunas 2009). Sudangrass plants were tied upright to bamboo stakes leached of soluble secondary metabolites. This concentrated sudangrass shoots in the center of the pot with thistle shoots with along the perimeter of the container.

At 41 DAP, sudangrass and Canada thistle shoot density and mass were measured as described above. Sudangrass and thistle roots were removed from the soil, washed, and separated. Roots and shoots were dried to constant mass and measured.

Statistical Analysis. Data for the interference and the phytotoxicity experiments were analyzed as linear mixed models using the PROC MIXED (SAS statistical software,

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Table 1. Regression equations and coefficients of regression for effect of defoliation frequency on Canada thistle growth parameters.

Dependent	2007		2008	
Variable (Y)	Regression equation[a]	R^2	Regression equation	R^2
Root mass[b]	Y = 27.2 − 2.9x	0.28*	Y = 74.7 − 17.0x	0.85***
Shoot mass[b]	Y = 55.6 − 6.7x	0.55***	Y = 168.2 − 37.1x	0.88***
Total shoot mass[c]	Y = 47.0 + 14.2x − 2.8x^2	0.38*	Y = 162.9 − 23.2x	0.70**
Shoot number[b]	NS[d]		Y = 87.4 − 12.6x	0.51**

[a] The independent variable (x) is number of defoliations and the dependent variable (Y) is mass (g) or number per pot.
[b] Measured at the end of the experiment.
[c] Total shoot mass includes the mass of each defoliation and the shoot mass at the end of the experiment.
[d] Abbreviation: NS, not significant
*, **, ***, significant at $\alpha = 0.05$, 0.01, and 0.001, respectively.

SAS Institute, Inc., Cary, NC). Both repeats and block were random factors, whereas treatment was a fixed factor. For all dependent variables, degrees of freedom were adjusted using the Satterthwaite correction (Littell et al. 2002), and normality of the raw data and residuals was evaluated using the UNIVARIATE procedure of SAS. When data sets were nonnormal, using a logarithm base 10 transformation attained normality. When factors were significant, means were separated with Fisher's Protected LSD Test at an alpha = 0.05 using the PDMIX800 macro (Saxton 1998).

The frequency of defoliation was regressed with Canada thistle root mass, shoot mass, number of shoots, shoot height, and root-to-shoot ratio using the linear or quadratic function of the PROC REG. Homogeneity of variances was evaluated by visual inspection of residuals and using the PROC UNIVARIATE; when homogeneity of variances was rejected, repeats were analyzed separately.

Results and Discussion

Defoliation Frequency Study. Defoliation reduced Canada thistle root and shoot mass at the end of the experiment (Table 1). The magnitude of mass reduction varied between repeats because of differences in thistle growth. In 2007, mass was reduced approximately 2.9 and 6.7 g (root and shoot, respectively) from each defoliation, whereas in 2008, there was more thistle growth and greater loss of mass from each defoliation (17 and 37 g defoliation^{-1} for roots and shoots, respectively). Controlling root systems is critical to manage Canada thistle. Correlation analysis and the root-to-shoot ratio help us to understand the effectiveness of defoliation in suppressing the root system. Canada thistle root and shoot masses were highly correlated ($r = 0.87$), suggesting that shoot defoliation can effectively suppress thistle root systems. Also the root-to-shoot ratio was reduced from 1 : 2 (no defoliation) to approximately 1 : 6 (four defoliations) [ratio = 0.51 − 0.085 (number of defoliations), ($R^2 = 0.64$)], indicating defoliation and the subsequent regrowth affected the roots more than shoots.

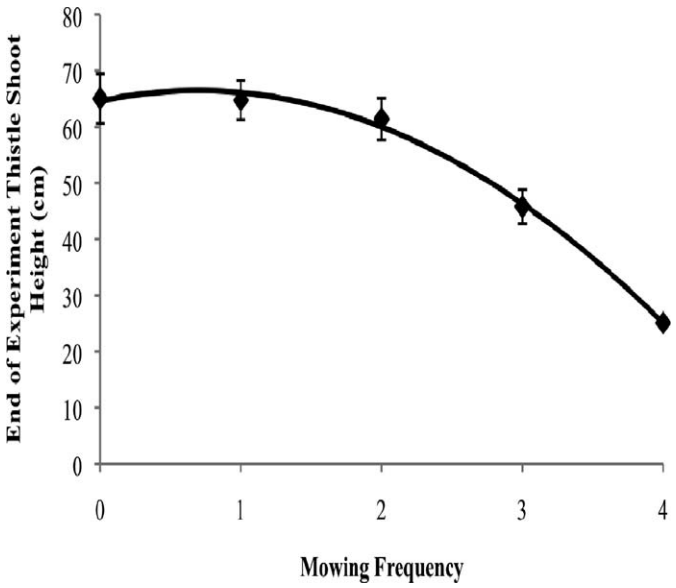

Figure 2. Effect of defoliation frequency on Canada thistle shoot height at the end of the Canada thistle defoliation frequency study. Results are averaged over repeats of the experiment. The regression equation is: Y = 64.63 + 5.26x − 3.79x^2, and $R^2 = 0.76$.

Defoliation can reduce shoot mass through a combination of fewer shoots or smaller plants. In 2007, thistles maintained similar number of shoots (data not shown), even after four defoliations caused a 40% reduction in root system mass compared to the control. Either defoliation did not kill shoots, or adequate buds existed on the smaller root systems for regeneration. In 2008, defoliation reduced the number of shoots from 87 pot^{-1} (no defoliation) to 37 pot^{-1} (four defoliations) (Table 1), while causing a 97% reduction in root mass. Number of shoots was positively correlated ($r = 0.73$) with root mass. In addition to reducing shoot number, defoliation reduced shoot size; for example, mass decreased from 1.92 g shoot^{-1} (no defoliation) to 0.53 g shoot^{-1} (four defoliations). Shoots after three or four defoliations were shorter with fewer leaves and branches than the control (Figure 2). Shoots defoliated three or four times were regrowing when the experiment was terminated, whereas shoots defoliated once or twice had similar heights as the shoots not defoliated. Our results suggest that Canada thistle management requires at least four defoliations and should concentrate on minimizing shoot size.

Similar to our study, other research found defoliation suppressed Canada thistle (Ang et al. 1994; Bicksler and Masiunas 2009; Graglia et al. 2006; Moore 1975) and mowing has been recommended for thistle control in organic or pasture systems (Bohm and Verschwele 2004; Cormack 2002). Defoliation likely caused lower assimilate production and translocation, and regrowth resulted in utilization of root carbohydrate reserves (Graglia et al. 2006; Gustavsson 1997; McAllister and Haderlie 1985). Low carbohydrate reserves also explain why Canada thistle is best controlled with defoliation at the flower bud stage (Tworkoski 1992). Depletion of root carbohydrate reserves is critical to manage Canada thistle and reduce overwintering (Bohm and

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Table 2. Effect of defoliation, sudangrass interference, and sudangrass surface mulch treatments on Canada thistle shoot dry mass, root fresh mass, and number of shoots, averaged across repeats of the sudangrass interference and defoliation study. The number of shoots and root fresh mass were measured at the end of the experiment. Canada thistle root fresh mass was only determined in the repeat. All data was log 10-transformed to normalize data to meet requirements of ANOVA. The untransformed means are shown.

	Canada thistle shoot dry mass						
	Defoliation number						
Treatment	1	2	3	End of experiment	Total	Root fresh mass	Number of shoots
	g pot^{-1}						No. pot^{-1}
Control	—[a]	—	—	145.91 a	145.91 a	839.56 a	83.67 a
Defoliation	1.96 a[b]	12.47 a	10.17 a	38.68 b	63.28 b	241.72 b	43.22 a
Interference	—	—	—	2.76 c	2.76 c	0.69 c	2.56 bc
Interference + defoliation	0.22 b[a]	0.86 b	0.11 b	1.55 c	2.74 c	1.11 c	3.85 b
Interference + defoliation + mulch	—[a]	—	—	0.39 d	0.39 d	0.00 d	0.30 c

[a] The control and interference treatments were not defoliated. In the interference + defoliation + mulch treatment, Canada thistle mass was a minimal portion of the mulch mass.

[b] Mean separation within columns by Fisher's LSD Test at alpha = 0.05 level.

Verschwele 2004; Graglia et al. 2006). However, a dense competitive crop combined with mowing might reduce Canada thistle survival more than repeated defoliation alone (Ang et al. 1994; Bohm and Vershwele 2004; Patriquin et al. 1986).

Sudangrass Interference and Defoliation Study. Sudangrass interference reduced Canada thistle shoot and root mass and number of shoots more than defoliation alone (Table 2). For example, thistle shoot mass at each defoliation ranged from 0.11 to 0.86 g pot^{-1} and from 1.96 to 12.47 g pot^{-1} for the interference + defoliation and defoliation only treatments, respectively. Thistles lose shoot tissue immediately during defoliation, but there is no residual activity; however, shoot size loss in interference is continuous throughout the growing season. Root mass was 839.56 (control), 241.72 (defoliation), and 0.69 g pot^{-1} (interference only), indicating that interference likely is more effective in reducing photosynthesis and replenishment of carbohydrate reserves than defoliation alone. Similar to our field study, combining sudangrass interference and defoliation did not suppress Canada thistle more than interference alone (Bicksler and Masiunas 2009). The addition of sudangrass mulch to sudangrass interference with defoliation further reduced shoot and root mass more than defoliation alone, interference alone, or interference + defoliation (Table 2). Combining interference and competition for resources by sudangrass, defoliation of Canada thistle, and a surface mulch that modifies the soil microenvironment appears to be most suppressive of Canada thistle and data suggest that mechanisms of suppression in this system are additive.

Defoliation reduced sudangrass mass and height, reducing its ability to capture photosynthetically active radiation (Table 3). At the end of the experiment, sudangrass shoot mass was 1,474 g pot^{-1} without defoliation and 192 g pot^{-1} after defoliation (Table 3), but reduction in total sudangrass mass from defoliation did not reduce Canada thistle suppression (Table 2). Sudangrass mass and height (interference-only treatment) were less important for Canada thistle suppression than the combination of the presence of sudangrass interference and defoliation. Mown sudangrass shoots readily regrow and tiller (Clapp and Chamblee 1970), but in our study the number of tillers was not different with inclusion of defoliation or mulch. Returning the shoot clippings to the pots did not impact sudangrass mass at the end of the experiment but could have advantages, such as changing the soil microenvironment where Canada thistle roots are concentrated or immobilizing nitrogen. The surface mulch was > 250 g pot^{-1} comparable to 7,190 kg ha^{-1}. In the field, we found sudangrass surface mulch mass ranging from 3,700 kg ha^{-1} to 4,900 kg ha^{-1} (Bicksler and Masiunas 2009). Weston et al. (1989) reported 328 g pot^{-1} in 38-L pots of weed-suppressing mulch over three defoliations, similar to our results.

Increased Canada thistle fresh root mass was correlated with increased thistle dry shoot mass (Table 2), further supporting a relationship between increased thistle root mass and shoot mass for Canada thistle seen in the mowing frequency study. Increased total dry sudangrass shoot mass was correlated with decreased total thistle shoot mass ($Y = 81.6 - 0.0577x$, $r = 0.69$) and thistle numbers ($Y = 64.94 - 0.0514x$, $r = 0.65$), further indicating the importance of interference provided by sudangrass for the management of this weed.

Table 3. Effect of defoliation, interference, and surface mulch on sudangrass shoot dry mass, number of tillers, and end of experiment height, averaged across repeats of the sudangrass interference and defoliation study. The number of tillers and height were measured at the end of the experiment. Sudangrass dry mass for defoliation 1 and 3 was only determined in the repeat. Data for end of experiment mass, total mass, and end of experiment height was log 10-transformed to normalize data to meet requirements of ANOVA. The untransformed means are shown.

	Sudangrass shoot dry mass						
	Defoliation number			End of experiment	Total	No. of tillers	Height at end of experiment
Treatment	1	2	3				
	g pot^{-1}					No. plant^{-1}	cm
Interference	—	—	—	1,474.49 a	1,474.49 a	5.16 a	340.41 a
Interference + defoliation	102.42 a[a]	107.53 a	80.69 a	192.42 b	483.06 b	9.65 a	96.74 b
Interference + defoliation + mulch	90.16 a	92.02 a	70.65 a	215.24 b	468.07 b	7.27 a	99.69 b

[a] Mean separation within columns by Fisher's LSD Test at alpha = 0.05 level.

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Table 4. The effect of intraspecific interference, interspecific interference, and sudangrass grown in root exclusion tubes on shoot, root, and plant mass, root-to-shoot ratio, and number of shoots of Canada thistle and sudangrass. Results are averaged over repeats of the phytotoxicity study.

Treatment	Dry mass			Root-to-shoot-ratio	No.of shoots
	Shoot	Root	Plant		
	g pot^{-1}				No. pot^{-1}
Canada thistle					
Thistle alone	4.08 a[a]	1.33 a	5.41 a	0.33 a	3.38 b
Thistle + isolated sudangrass	3.84 a	1.04 a	4.88 a	0.27 a	3.63 b
Thistle with sudangrass	3.57 a	1.34 a	4.91 a	0.38 a	4.88 a
Sudangrass					
Isolated sudangrass	19.86 b	10.46 a	30.32 a	0.53 a	—[b]
Thistle + isolated sudangrass	21.17 b	10.80 a	31.97 a	0.51 a	—
Thistle with sudangrass	27.62 a	4.99 b	32.61 a	0.18 b	—

[a] Mean separation within plant species and columns by Fisher's LSD Test at alpha = 0.05 level.
[b] Sudangrass was thinned to eight plants pot^{-1}.

In this study, dense, competitive sudangrass was more important than defoliation in reducing Canada thistle mass and number of shoots. Patriquin et al. (1986) found a competitive crop, such as alfalfa, was more effective in suppressing Canada thistle than mowing. A grass/white clover pasture combined with six mowings reduced Canada thistle mass more than pasture without mowing (Graglia et al. 2006). The differences between our results and those of Patriquin et al. (1986) likely are due to the taller sudangrass increasing competition for light and reducing net photosynthetic capacity compared to pasture species. Sudangrass has an erect morphology, rapid growth in summer (Snapp et al. 2005), competitiveness (Ngouajio et al. 2003), and phytotoxicity (Weston and Duke 2003; Weston et al. 1989), compared to white clover or grass used in pastures.

The greatest suppression of Canada thistle occurred when mulch was coupled with sudangrass interference and defoliation, possibly from the mulch shading the thistle regrowth, modifying the soil environment, and/or releasing phytotoxic compounds (Herrero et al. 2001). In all treatments, the reduced Canada thistle mass and shoot number likely was partly due to reductions in its photosynthetic capacity. Although it appears that the mechanisms of sudangrass interference, defoliation, and a weed-suppressing mulch work in unison, the role of sudangrass root phytotoxicity in the reduction of Canada thistle mass and population density is unclear.

Phytotoxicity Study. Canada thistle plant, shoot and root mass were similar whether grown alone, with isolated sudangrass, or with sudangrass (Table 4). Most mass was partitioned into shoots (the root-to-shoot ratio ranged from 0.27 to 0.38). Our experiment minimized sudangrass competition for photosynthetically active radiation (PAR), water, and nutrients with Canada thistle. Because Canada thistle mass was similar when grown alone or with sudangrass in isolation tubes, this suggests that the effects of interspecific and intraspecific competition were similar. This further suggests that phytotoxicity from actively growing sudangrass is not contributing to suppression of Canada thistle. However, contrary to expectation, more Canada thistle shoots occurred when the plants were grown with sudangrass. Belowground interference with sudangrass in our additive design might have shifted resources from Canada thistle root system growth to adventitious root bud formation and subsequent increased shoot number.

Unlike Canada thistle, treatment effects on sudangrass plant, shoot, and root mass and the root-to-shoot ratio were not always similar (Table 4). Sudangrass shoot mass increased and root mass decreased in the Canada thistle with sudangrass treatment compared to the isolated sudangrass treatment or Canada thistle with isolated sudangrass treatment. There were no treatment effects on total sudangrass mass. In the Canada thistle with sudangrass treatment, the root-to-shoot ratio for sudangrass was only 0.18 compared to an average of 0.52 in the other treatments. The root mass was only 4.99 g compared to an average of 10.63 g for other treatments. The close proximity of the interfering sudangrass and thistle plants might have favored aboveground growth over root growth. Although staking, daily watering, and the nutrient regime minimized competition, competition still might have occurred, leading to increased sudangrass shoot mass at the expense of root mass. Additionally, Canada thistle phytotoxicity might have inhibited sudangrass root growth, as seen in other species (Stachon and Zimdahl 1980).

In this research, phytotoxicity likely did not reduce thistle fitness. Other researchers have observed sorghum phytotoxicity. Most studies of sorghum phytotoxicity occur in laboratories using radicles of sorghum (Einhellig et al. 1993; Einhellig and Souza 1992; Netzly and Butler 1986; Weston et al. 1989) and seeds of indicator species (Einhellig and Souza 1992; Netzly and Butler 1986; Weston et al. 1989). This study used thistle root pieces as the receiver species and sudangrass plants as the donor species in greenhouse pot culture. Phytotoxic effects might not have occurred on Canada thistle because sorghum root phytochemicals tend to be hydrophobic and have localized effectiveness in the rhizosphere. Moreover, separating phytotoxic effects from environmental modifications is difficult because the allelopathic activity varies, depending on environmental factors (Bhowmik and Inderjit 2003; Einhellig 1999). It also is possible that the Canada thistle received or the sudangrass donated a quantity of phytochemicals below a threshold dose for inhibition.

Conclusions. Results from the three studies suggest that Canada thistle root mass, shoot mass, and number were reduced with greater defoliation frequency but the reduction was more consistent when combined with sudangrass interference. Sudangrass rapidly accumulates mass, readily over-tops competitors, produces numerous tillers, and when cut, can produce surface mulch. The inclusion of sudangrass defoliation was not essential to suppression of Canada thistle and it did not affect sudangrass' competitive ability, but it produced surface mulch. Canada thistles were not suppressed by sudangrass phytotoxicity in our experiments, but thistles might have exhibited allelopathic influence on sudangrass root mass. Overall, it appears that mechanisms of sudangrass interference coupled with defoliation work in unison to suppress Canada thistle. These results support the work of Ang et al. (1994) and Patriquin et al. (1986) in different systems and with different crops, and are consistent with our results in the field.

Future research should target better techniques for isolating hydrophobic allelopathic interactions that utilize living donor

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and receiver species. Little is known about phytotoxicity on roots of perennial plants. Additionally, future research should target sudangrass mulch's phytotoxic potential on Canada thistle, impacts on soil modification, and reduction of photosynthetic capacity of defoliated Canada thistle.

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