Weed Technology 2012 26:102–109

WSSA WEED SCIENCE SOCIETY OF AMERICA

Evaluation of Tef as a Smother Crop during Transition to Organic Management

Stephanie Wedryk and John Cardina*

Management of weeds is often a barrier to conversion from conventional to organic agriculture. Tef is a C_4 annual cereal that is valued for its small seeds, rapid establishment, and wide adaptation. The objective of this study was to evaluate tef as a smother crop for management of weeds during transition to organic production. Greenhouse and field trials were conducted in 2008 and 2009 to evaluate the growth of eight tef varieties and their effect on Canada thistle and annual weeds. In greenhouse studies, tef decreased the biomass of Canada thistle shoots and roots 44 to 74%, depending on variety. Emergence of Canada thistle shoots was affected by the planting depth of their roots. Tef variety Corvalis suppressed Canada thistle biomass and accumulated more biomass than most other tef varieties. In field studies, tef varieties suppressed annual weed biomass by 35 to 54% with varieties Corvalis, Dessie, and VA-T1 being least suppressive in 2008, but there were no differences between varieties in 2009. Canada thistle growth was suppressed an average of 73% by tef in 2008 and 37% in 2009, a year of cooler temperatures and unseasonal rainfall. Differences between varieties in suppressing Canada thistle and annual weeds were mostly inconsistent between years. However, tef variety Tiffany did consistently suppress biomass, height, and percentage cover of Canada thistle and other weeds in the field study in 2008 and 2009.

Nomenclature: Tef, *Eragrostis tef* (Zucc.) Trotter; Canada thistle, *Cirsium arvense* (L.) Scop.
Key words: Alternative weed management, cultural weed control.

El manejo de malezas es frecuentemente una barrera para la conversión de la agricultura convencional a la orgánica. Tef [*Eragrostis tef* (Zucc.) Trotter] es un cereal anual C_4 que es apreciado por sus semillas pequeñas, rápido establecimiento y amplia adaptación. El objetivo de este estudio fue evaluar el tef como un cultivo de cobertura para el manejo de malezas durante la transición a la producción orgánica. Estudios de invernadero y de campo se condujeron en 2008 y 2009 para evaluar el crecimiento de ocho variedades de tef y su efecto en *Cirsium arvense* y malezas anuales. En los estudios de invernadero, tef disminuyó la biomasa de los brotes y raíces de *C. arvense* de 44 a 74%, dependiendo de la variedad. La emergencia de los brotes de *C. arvense* fue afectada por la profundidad de siembra de sus raíces. La variedad Corvalis de tef suprimió la biomasa de *C. arvense* y acumuló más biomasa que la mayoría de las otras variedades de tef. En estudios de campo, las variedades de este cereal suprimieron la biomasa de las malezas anuales de 35 a 54%, con las variedades Corvalis, Dessie y VA-T1, siendo menos la supresión en 2008, pero no hubo diferencia entre las variedades en 2009. Tef suprimió el crecimiento de *C. arvense* en un promedio de 73% en 2008 y 37% en 2009, un año de temperaturas más frescas y lluvias fuera de temporada. Las diferencias entre variedades en supresión de *C. arvense* y malezas anuales fueron mayormente inconsistentes entre años. Sin embargo, la variedad Tiffany de tef suprimió consistentemente en 2008 y 2009 la biomasa, la altura y el porcentaje de cobertura de *C. arvense* y otras malezas en el estudio de campo.

Organic producers use the required 3-yr transition from conventional to organic management to improve soil fertility while suppressing weeds and other pests in preparation for growing certified organic crops (Hanson et al. 2004). During transition, farmers must adopt organic certification rules, which prohibit the use of synthetic herbicides and stipulate the use of biological, cultural, and mechanical controls (Greene and Kremen 2003). Since premium organic prices cannot be realized during this transition period, growers face contradictory goals of minimizing inputs while reducing potential weed populations in subsequent crops.

Weed management during transition is especially important in fields infested with species that are very difficult to control, such as rapidly growing annuals and deeply rooted perennials. For example, Canada thistle is regarded by farmers as one of the most troublesome perennial weeds in organic agriculture (Beveridge and Naylor 1999; Turner et al. 2007; Verschwele and Häusler 2004). Canada thistle can reproduce by seeds or underground propagative roots (hereafter roots) that have been found up to 6.75 m below the soil surface (Donald 1994a; Evans 1984). Organic farmers rely mostly on mechanical management practices, which are often not effective against all Canada thistle roots. The action of machinery cuts the roots into segments from which Canada thistle can regenerate (Evans 1984). Growth of Canada thistle in early spring comes at the expense of carbohydrates stored in underground roots (Gustavsson 1997). Root reserves and root bud numbers are at their lowest between May 15 and July 15 when Canada thistle is flowering (McAllister and Haderlie 1985). Targeted management of Canada thistle when carbohydrate reserves are at seasonal lows may suppress vegetative reproduction and population growth (Bicksler and Masiunas 2009). Cover crops planted when weed carbohydrate root reserves are at their lowest and integrating mowing with competitive crops in early summer have been effective at reducing Canada thistle biomass (Bicksler and Masiunas 2009; Graglia et al. 2006).

Smother cropping is an alternative weed management technique that is well adapted to the 3-yr transition required for organic production (Bàrberi 2002). Smother cropping

DOI: 10.1614/WT-D-11-00042.1

* Graduate Research Associate and Professor, Department of Horticulture and Crop Science, The Ohio State University, Wooster, OH 44691. Corresponding author's E-mail: wedryk.1@osu.edu

involves the use of a living plant to reduce the growth, development, or reproduction of weeds predominantly through competition for resources (Teasdale 1998). Many successful horticultural weeds, including Canada thistle, are shade intolerant, producing less robust growth when shaded by neighboring plants (Donald 1994a). A smother crop that emerges and grows quickly may have high rates of early resource use that can reduce resource availability, such as light, to annual weeds before the logarithmic phase of growth when increases in height or leaf area may increase resource preemption by weeds (Jordan 1993). Furthermore, smother crop cover when perennial weeds are emerging and sensitive to light may lead to depletion of carbohydrate reserves of weeds as they grow in an attempt to capture as much light as possible. Previous research investigating cover crops for quick establishment showed that annual cereal cover crops planted in early spring suppressed cover of weeds after 2 mo of growth (Nelson et al. 1991). Smother crops have been used to suppress perennial weeds and prevent vegetative reproduction (Regnier and Janke 1990). In the tropics, Udensi et al. (1999) found that a smother crop of velvetbean [*Mucuna pruriens* (L.) DC. var. *utilis*] reduced speargrass [*Imperata cylindrica* (L.) Beauv.] shoot density. Leguminous smother crops have also reduced the number and weight of yellow nutsedge (*Cyperus esculentus* L.) tubers (Collins et al. 2007). Spring-planted grass smother crops such as rye (*Secale cereale* L.) and triticale (×*Tritosecale rimpaui* Wittm.) have reduced weed density without additional inputs (Barnes and Putnam 1983; Schoofs and Entz 2000). Sudangrass [*Sorghum sudanese* (Piper) Stapf] smother crops reduced Canada thistle shoot density and biomass (Bicksler and Masiunas 2009).

We evaluated tef, a C_4 annual cereal commonly grown in Ethiopia, as a potential smother crop for use during transition from conventional to organic production. Characteristics of tef that make it a viable candidate smother crop are rapid establishment, drought tolerance, and lack of significant disease (DeHaan et al. 1994; Ketema 1997). Germination rates of tef seeds are greater than 90% within 24 h of planting when daytime temperatures are 25 C or greater (Debelo 1992). For use in a cropping system where perennials like Canada thistle are present, we expected tef to grow rapidly during the time when Canada thistle roots are low in carbohydrate reserves during late spring and early summer in the midwestern United States. Tef is commonly planted at high seeding rates (up to 55 kg ha^{-1}) to provide densities of 30,000 seedlings m^{-2}, which are expected to compete effectively with annual weeds and eventually aid in shading of Canada thistle (Ketema 1997; Yu et al. 2007). Studies of quantitative traits have demonstrated significant genetic variation among germplasm accessions and potential for improvement as a grain crop; however, few varieties are recognized and none has been evaluated as a smother crop (Adnew et al. 2005). Because of genetic variation present in tef, we hypothesized that varieties would differ in suppression of Canada thistle and annual weeds. We further hypothesized that suppression of Canada thistle would be a function of smother crop species, tef or sorghum–sudangrass, and Canada thistle root planting depth in the greenhouse study. The objective of this study was to evaluate available varieties of tef as smother crops for annual weed and Canada thistle suppression in greenhouse and field experiments.

Materials and Methods

Greenhouse Experiment. A greenhouse experiment was conducted at The Ohio State University, Wooster, OH during the spring and fall of 2009 to determine the ability of smother crops to suppress Canada thistle shoot growth. Canada thistle roots were collected in April 2009 and October 2009 at the Schaffter Farm near Wooster, OH (40°78′N, 81°92′W) when temperatures would have limited root bud elongation and root carbohydrate reserve use. Roots were stored under moist conditions at 5 C until used in this experiment. Root pieces (7.6 to 10.2 cm) were weighed and the number of visible buds recorded before planting.

Treatments were arranged as a 2 by 10 factorial in a randomized complete block design with 2 Canada thistle root planting depths (7.6 and 15.2 cm) and 10 smother cropping treatments with 3 replications. Two planting depths were chosen to simulate different possible depths of Canada thistle roots in the field. Smother cropping treatments included eight tef varieties, one sorghum–sudangrass, and a nontreated control. The tef varieties used were available commercially in the United States for potential use by organic producers, and represent tef seed production from different regions in the United States (Table 1). Tef seeds were not treated with the exception of variety Tiffany, which was treated with seed coating to facilitate ease of planting (Table 1). Sorghum–sudangrass was included because it has recently been shown to be effective as a smother crop against Canada thistle (Bicksler and Masiunas 2009).

Plastic pots 38 cm deep and 23 cm in diameter were filled with a 1 : 1 mix of commercial potting media (Pro-Mix, Premier Tech Horticulture, Quakertown, PA) and Wooster silt loam soil. Three Canada thistle root pieces were planted at the respective planting depth and then covered with the soil mix and watered. Tef and sorghum–sudangrass were seeded on April 7, 2009 and October 13, 2009 at an equivalent to the recommended field seeding rate of 30 kg ha^{-1} (Assefa et al. 2001; Kefyalew et al. 2000; Ketema 1997). Seeding rates in the greenhouse experiment were calculated from field seeding rates on the basis of the surface area of the pots. A small amount of soil was mixed with 0.83 g of tef seeds and pressed into the top of the soil mix to ensure uniform seeding. The average number of tef seeds in 0.83 g was 2,530. Sorghum–sudangrass seeds (0.83 g = 37 seeds) were planted into the designated pots at a depth of 2.5 cm and then covered with a thin layer of soil. Media in nontreated pots were also covered with a thin layer of soil. The smother crops and Canada thistle roots were grown under greenhouse conditions for 4 wk with 14/10 h light/dark and 24/18 C day/night cycles. Pots were irrigated with water for 1 min twice daily and rerandomized within blocks weekly to prevent effects of differences in light and temperature among treatments. The experiment was repeated in October 2009 under the same conditions.

Emergence of Canada thistle shoots was measured daily until the completion of the experiment. Height of Canada

Table 1. Varieties, seed color, and seed sources of varieties used in greenhouse and field studies.

Species	Variety	Seed color	Seed source
Tef	Corvalis	Brown and white	King's Agriseeds, Ronks, PA
Tef	Dessie	Brown and red	The Teff Company, Nampa, ID
Tef	Emerald	White	The Teff Company, Nampa, ID
Tef	Excalibur	White	United Seed, DeGraff, MN
Tef	Ivory[a]	White	Byron Seeds, Marshall, IN
Tef	Pharaoh	Brown	United Seed, DeGraff, MN
Tef	Tiffany[b]	White	Target Seed Company, Parma, ID
Tef	VA-T1	Brown and white	James VanLeeuwen, Halsey, OR
Sorghum–sudangrass	Special Effort	Tan	Production Plus Quality Seed, Plainview, TX

[a] Certified organic.

[b] Seed coated with Pinnacle Nutrient Coating™.

thistle shoots and smother crop varieties was measured weekly. After 4 wk, aboveground biomass of smother crops and Canada thistle was weighed, dried at 55 C for 72 h, and reweighed. Belowground roots of Canada thistle were removed from soil, rinsed in water, weighed, and the number of buds counted. Roots were dried at 55 C for 72 h and reweighed.

Field Experiment. A field experiment was conducted at The Ohio State University Schaffter Farm near Wooster, OH (40°78′N, 81°92′W) in 2008 and 2009 to evaluate commercial varieties of tef as smother crops. The soil type at the site is a Wooster silt loam with pH of 6.5 and 2.9% organic matter content. The site was managed without pesticides or fertilizers as mandated for the transition period from conventional to organic production. Percentage cover of Canada thistle was visually assessed to ensure uniform populations among treatments before treatments were imposed on June 9, 2008 and June 5, 2009. The field was disked and prepared for planting June 10, 2008 and June 11, 2009. Treatments were arranged in a randomized complete block design with six replications. Treatments consisted of the eight tef varieties used in the greenhouse experiment and a nontreated control (Table 1). In 2009, plots were located in a different part of the same field as the previous year. Each plot was 1.5 by 1.5 m in both years. In 2008, plots with low Canada thistle density (less than 10% cover) were augmented with Canada thistle roots. The roots had been propagated in the greenhouse from shoots collected during April 2008. Three roots that were 10 to 15 cm in length (average weight 3.88 g), with at least one adventitious bud per root piece, were planted at a depth of 15 cm. Varieties of tef used were the same as in the greenhouse study. Tef seeds were broadcast seeded at a rate of 30 kg ha^{-1} (approximately 16,000 seeds m^{-2}) by hand on June 11, 2008 and June 15, 2009. After seeding, a roller was passed over each plot to help ensure seed–soil contact. Plots were not irrigated during the course of the experiment.

Canada thistle shoots were counted on June 26, 2008 and 2009. The height and visual estimates of percentage cover of tef and Canada thistle were measured weekly for 8 wk, starting 10 d after planting. Visual estimates of percentage cover of annual weeds were also recorded weekly for 8 wk beginning 10 d after planting. Total plant biomass (tef plus annual weeds and Canada thistle) was harvested from a randomly placed 0.3 by 0.3 m quadrat per plot on August 22, 2008 and between August 27 and October 6, 2009. Plots were harvested when tef seeds were visually estimated to be 80% filled to capture maximum biomass before senescence. In 2009, plots were harvested on different days because of differences in time to maturity for individual plots. Harvested materials were separated into tef, Canada thistle, and annual weeds, weighed and dried at 55 C for 72 h, and weighed again. The most common annual weeds present were common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), yellow foxtail (*Setaria pumila* (Poir.) Roemer & J.A. Schultes), and green foxtail (*Setaria viridis* (L.) Beauv.).

Data Analysis. Greenhouse trial data were combined for the two repetitions of the study as the trial-by-treatment interactions were not significant ($P > 0.05$). Data were first analyzed for effect of root planting depth on smother crop biomass and final height using ANOVA in SAS (SAS 9.2 Statistical Software, Statistical Analysis Systems, SAS Institute, Cary, NC) When the interaction of root planting depth and smother crop treatments was significant ($P \leq 0.05$), data from the two planting depths were analyzed separately. Data that did not meet the assumptions of normality were analyzed using Kruskal–Wallis ANOVA. Canada thistle biomass and final height in the greenhouse study were subjected to analysis of covariance (ANCOVA) with initial Canada thistle root weight as the covariate and analyzed separately by root planting depth when the interaction of planting depth and smother crop treatment was significant ($P \leq 0.05$). Cumulative Canada thistle shoot emergence was also subjected to ANCOVA with initial root bud number as the covariate. Means were separated by Fisher's Protected LSD test. Pearson correlation coefficients were calculated for Canada thistle and smother crop biomass and height. Significant correlations ($P \leq 0.05$) between variables with $r < 0.4$ were considered weak; $0.4 \leq r \leq 0.8$ were considered moderate; $r > 0.8$ were considered strong.

Field experiment data were analyzed separately by year since the interactions of year and treatment were significant ($P \leq 0.05$). Biomass data were subjected to ANOVA in SAS and means separated by Fisher's Protected LSD test. Data that did not meet the assumptions of ANOVA were log transformed. Transformed data that did not meet the assumptions of ANOVA were analyzed using Kruskal–Wallis ANOVA. Percentage cover and height data were subjected to

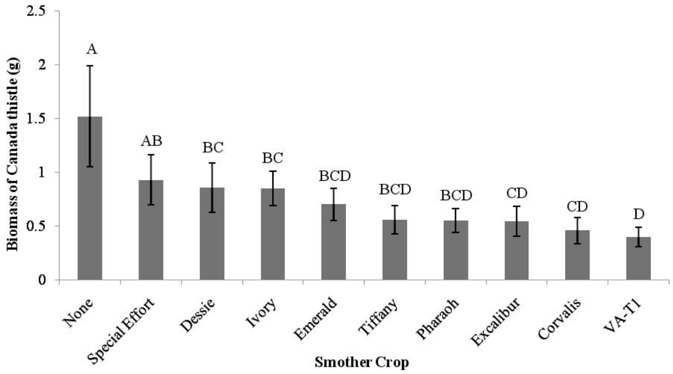

Figure 1. Dry biomass ± SE (g) of Canada thistle shoots and roots harvested from the greenhouse trial with eight varieties of tef, one variety of sorghum–sudangrass, and a no-smother-crop control. Bars with the same letter do not differ according to Fisher's Protected LSD test at $P \leq 0.05$.

repeated-measures analysis using PROC MIXED in SAS. Least-squares means of percentage cover and height generated in repeated-measures analysis were divided by the number of days between the initial and final sampling times to determine the rate of ground-cover spread and vertical growth. Differences between means were determined using the PDIFF option in PROC MIXED. Pearson correlation coefficients were calculated for Canada thistle, tef, and annual weed biomass and Canada thistle and tef height and percentage cover. Significant correlations ($P < 0.05$) between variables with $r < 0.4$ were considered weak; $0.4 \leq r \leq 0.8$ were considered moderate; $r > 0.8$ were considered strong.

Results and Discussion

Greenhouse Experiment. The interaction of planting depth and smother crop treatment was not significant ($P = 0.11$) for dry biomass of Canada thistle; therefore, data for root planting depths are combined. Total biomass of Canada thistle decreased 44 to 74% in pots where tef was grown compared with the nontreated control (Figure 1). Sorghum–sudangrass did not suppress Canada thistle growth. Tef varieties Corvalis (0.54 g), Excalibur (0.46 g), and VA-T1 (0.40 g) resulted in reduced Canada thistle biomass compared with sorghum–sudangrass (0.93 g). Tef seed weight is about 1.5% that of sorghum–sudangrass, and since the same weight of seeds was planted for both species, the number of individual plants in tef treatments was much greater than in the sorghum–sudangrass pots. The greater number of tef seedlings (~ 2,500) than sorghum–sudangrass seedlings (~ 37) may explain the greater effectiveness of tef in suppressing Canada thistle. The smother crops in the greenhouse study were seeded at comparable field rates with the surface area of the pots used. Increasing the density of sorghum–sudangrass plants under field conditions has been shown to have mixed results on weed suppression compared with lower planting densities (Iqbal et al. 2007; Wu et al. 2010). However, higher seeding rates of sorghum–sudangrass under limited nutrient conditions as may occur in the field without fertilizers or irrigation can result in density-dependent mortality (Rees 1986). In the greenhouse where nutrient conditions are not limiting to plant growth, increased sorghum–sudangrass plant number may result in greater weed suppression, but this response may not occur under field conditions.

The interaction of planting depth and smother crop variety was significant for smother crop biomass and results are separated by planting depth ($P = 0.002$). The tef varieties Corvalis, VA-T1, and Pharaoh had the greatest biomass (9.2 to 9.6 g), whereas sorghum–sudangrass produced the least amount of biomass (2.8 g) at the 7.6-cm planting depth (Table 2). Canada thistle biomass and smother crop biomass were weakly, inversely correlated ($r = -0.38$; $P = 0.0007$). Biomass of plants competing with weeds has been shown to be highly correlated with reduction of weed biomass and a proxy for competitive ability (Gaudet and Keddy 1988). There were no differences in biomass of smother crops at the 15-cm planting depth (Table 2). However, emergence of Canada thistle shoots was greater at the 7.6-cm depth (2.7 shoots)

Table 2. Final height of Canada thistle and smother crops and dry biomass of smother crops in greenhouse trial. Canada thistle root pieces were planted at depths of 7.6 and 15 cm. Data are means of six replications and two runs of the experiment.

	Height				Biomass	
	Canada thistle		Smother crop		Smother crop	
Treatment	7.6[a]	15[b]	7.6[a]	15[b]	7.6[a]	15[b]
	cm				$g\ pot^{-1}$	
Nontreated	6.28 c	8.63	N/A[c]	N/A	N/A	N/A
Corvalis	11.6 ab	3.80	22.9 bc	25.2	9.63 a	19.3
Dessie	15.9 a	9.80	20.9 c	25.3	7.59 c	19.3
Emerald	10.7 bc	8.11	20.7 c	27.3	6.51 c	16.2
Excalibur	11 bc	5.97	20.8 c	24.2	7.78 bc	19.0
Ivory	14 ab	10.7	19.6 c	25.9	9.06 ab	18.4
Pharaoh	13 ab	12.1	23.6 b	26.1	9.20 a	19.0
Special Effort	11.9 ab	6.62	33 a	45.8	2.78 d	12.6
Tiffany	11.5 ab	10.6	21.4 bc	25.2	6.68 c	16.6
VA-T1	9.71 bc	8.57	22.5 bc	26.5	9.50 a	22.2

[a] Least-squares means within a column followed by the same letter are not significantly different at $P \leq 0.05$.

[b] Least-squares means presented. Data in column are not significantly different according to Kruskal–Wallis Test at $P \leq 0.05$.

[c] Abbreviation: N/A, not applicable.

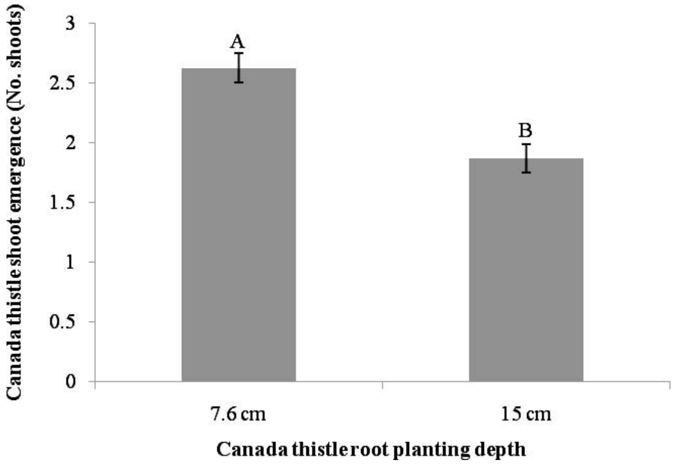

Figure 2. Cumulative Canada thistle shoot emergence (no. shoots) in the greenhouse trial at root planting depths of 7.6 cm and 15 cm. Bars with the same letter do not differ according to Student's t test at P $\leq$ 0.05.

than the 15-cm depth (1.9 shoots) (Figure 2). With fewer emerged Canada thistle shoots, aboveground competition between tef and Canada thistle was reduced at the 15-cm planting depth. Differences in weed suppression between varieties were more apparent at the 7.6-cm planting depth because of stronger competition from Canada thistle (Table 2). The difference between planting depths may be the result of the longer distance an elongating root bud must travel to reach the soil surface at the 15-cm planting depth. Smother crop populations may be able to establish before Canada thistle shoots produced from greater depths could exert competitive pressure. Additionally, elongation of Canada thistle root buds from greater depth depletes carbohydrate reserves and can result in weaker and less competitive shoots. If carbohydrate reserves are at their lowest when Canada thistle shoots emerge into established smother crop populations, the ability of Canada thistle to sequester photosynthate in roots for vegetative reproduction may be affected. Results suggest that establishment of smother crop populations in the field before emergence of Canada thistle shoots from underground roots is important for the success of smother crops to suppress Canada thistle. Tillage before smother crop seeding that buries Canada thistle roots deep in the soil may be more effective than shallow tillage operations.

Canada thistle shoots were taller in varieties Corvalis (11.6 cm), Dessie (15.9 cm), Ivory (14 cm), Pharaoh (13 cm), Special Effort (11.9 cm), and Tiffany (11.5 cm) than in the nontreated control (6.28 cm) at the 7.6-cm planting depth (Table 2). The Special Effort variety of sorghum–sudangrass had the highest final height (33.0 cm at 7.6-cm planting depth) (Table 2). Tef varieties Pharaoh and Ivory had the highest and lowest final height, respectively, a difference of 4 cm for treatments with roots planted 7.6-cm deep. The height of plant species or variety in competition with weeds can be an indicator of the competitive ability of the crop (Gaudet and Keddy 1988). Canada thistle and smother crop heights were weakly correlated (r = 0.28; P = 0.05). Canada thistle shoots grew taller in competitive smother crop treatments, presumably to reach light above the canopy of the smother crops. Canada thistle shoots in tef smother crops appeared to be lighter green in color with less pronounced thistles and weaker stems, suggesting competition for light and reduced photosynthetic levels (Moore 1975).

There were no differences in Canada thistle or smother crop height at the 15-cm planting depth (Table 2). Greater emergence of Canada thistle shoots at the 7.6-cm planting depth may have increased competition between Canada thistle and smother crops, resulting in differences in height of smother crops (Figure 2). Weed growth during early

Table 3. Monthly and 20-yr mean total precipitation and mean maximum and minimum temperatures during the growing season in 2008 and 2009.

Year	Monthly total precipitation					
	June	July	August	September	October	Total
	cm					
2008	14.7	11.3	3.24	7.26	3.89	40.4
2009	9.52	7.37	14.9	6.65	8.55	47.0
20-yr mean	9.13	8.98	8.52	7.32	6.75	40.7
	Monthly maximum temperature					
	Jun	Jul	Aug	Sep	Oct	Mean
	C					
2008	26.8	28.3	26.7	25.4	16.7	24.8
2009	25.9	25.6	26.7	22.9	14.9	23.2
20-yr mean	26.8	28.7	28.0	24.1	17.5	25.0
	Monthly minimum temperature					
	Jun	Jul	Aug	Sep	Oct	Mean
	C					
2008	15.0	15.8	13.6	11.5	3.70	11.9
2009	13.2	13.6	15.5	11.5	4.06	11.6
20-yr mean	13.9	16.0	15.2	10.9	5.06	12.2

https://doi.org/10.1614/WT-D-11-00042.1 Published online by Cambridge University Press

Table 4. Dry biomass of tef varieties, Canada thistle, and other weeds harvested in field trials in 2008 and 2009.

Treatment	Tef[a,b]		Canada thistle[a,c]		Other weeds[a,c]	
	2008	2009	2008	2009	2008	2009
	$g\ m^{-2}$					
Nontreated	N/A[d]	N/A	11 ab	149 a	1690 a	507 a
Corvalis	577	520	4 ab	79 bc	1180 ab	155 b
Dessie	833	432	6 ab	66 c	1030 abc	147 b
Emerald	955	492	2 b	136 ab	495 cd	132 b
Excalibur	1060	375	2 b	76 bc	256 d	129 b
Ivory	815	397	2 b	57 c	397 d	98 b
Pharaoh	1010	358	21 ab	72 bc	424 cd	105 b
Tiffany	974	420	2 b	69 c	563 bcd	150 b
VA-T1	789	446	26 a	104 abc	884 abc	128 b

[a] Data are means of six replications each year.

[b] Means presented. Data in column not significant according to ANOVA at $P \leq 0.05$.

[c] Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $P \leq 0.05$.

[d] Abbreviation: N/A, not applicable.

developmental stages can decrease the relative growth rate of crops (Wang et al. 2006). Height and biomass of smother crops at the 7.6-cm planting depth may have been affected by the smaller distance necessary for elongating root buds to reach the soil surface. Presumably, elongating shoots would reach the soil surface more quickly and compete with smother crops at an earlier stage of crop growth. The onset of later competition by Canada thistle at the 15-cm planting depth may have allowed less competitive smother crop varieties to grow similarly to more competitive varieties.

Field Experiment. Monthly maximum temperatures in July and August were about 11 and 5%, respectively, lower than the 20-yr mean in 2009 (Table 3). August maximum temperatures in 2008 were 5% lower than the 20-yr mean (Table 3). Monthly precipitation was 43% higher in June and July 2008 compared with the 20-yr mean, with a subsequent decrease in August rainfall of 62% (Table 3). In 2009, there was an 18% decrease in July precipitation and an increase in August precipitation of 75% (Table 3).

There were no differences in biomass among tef varieties in 2008 and 2009 (Table 4). Tef varieties did not suppress Canada thistle biomass compared with the nontreated control in 2008 (Table 4). However, Canada thistle biomass was 92% greater in the VA-T1 variety than the Emerald, Excalibur, Ivory, or Tiffany varieties. In 2009, all varieties of tef except Emerald and VA-T1 suppressed Canada thistle biomass 47 to 62% (Table 4). There was no significant correlation between tef biomass and Canada thistle biomass in 2008 ($r = -0.17$; $P = 0.33$) or 2009 ($r = -0.23$; $P = 0.10$). Some tef varieties suppressed the growth of annual weeds both years (Table 4). In 2008, varieties Excalibur and Ivory had annual weed biomass of 256 and 397 $g\ m^{-2}$, respectively, compared with 1,690 $g\ m^{-2}$ for the nontreated control. In 2009, annual weed biomass was 64 to 80% lower with all tef varieties than in the nontreated control (Table 4). Tef biomass and annual weed biomass were negatively correlated in 2008 ($r = -0.68$; $P < 0.0001$) and 2009 ($r = -0.77$; $P < 0.0001$). Tef biomass may be an indicator of competitive ability with annual weeds, but it does not indicate suppression of Canada thistle.

Tef varieties differed in rate of shoot growth over the course of the growing seasons in 2008 and 2009 (Table 5). Emerald (1.4 $cm\ d^{-1}$) and Pharaoh (1.5 $cm\ d^{-1}$) had the lowest rates of shoot growth in 2008. Rates of shoot growth in Pharaoh (1.29 $cm\ d^{-1}$), Excalibur (1.38 $cm\ d^{-1}$), Emerald (1.4 $cm\ d^{-1}$), Ivory (1.44 $cm\ d^{-1}$), and Tiffany (1.46 $cm\ d^{-1}$) were not different in 2009. Tef varieties also affected the growth of Canada thistle shoots (Table 5). Canada thistle shoots had lower shoot growth rates than the non-treated control in the Ivory (0.31 $cm\ d^{-1}$) and Tiffany (0.39 $cm\ d^{-1}$) varieties in 2008 (Table 5). In 2009, all tef varieties suppressed Canada thistle shoot growth (average 22%) (Table 5). Colder temperatures in 2009 may have favored growth of Canada thistle as its growth rate was 54% greater than in 2008 (Table 5). Pearson correlation coefficients calculated for relationships between shoot growth of tef and Canada thistle were neither significant nor meaningful in 2008 ($r = -0.12$; $P = 0.40$) or 2009 ($r = -0.05$; $P = 0.75$).

Ground cover of tef, Canada thistle, and annual weeds differed between tef varieties in 2008 and 2009 (Table 5). All tef varieties in 2008 and 2009 suppressed ground cover spread of annual weeds by 35 to 54% (Table 5). Excalibur and Tiffany reduced ground cover spread of annual weeds by an average of 54 and 49% in 2008 and 2009. In 2008, the Tiffany treatment had the lowest rate of Canada thistle spread (0.055% d^{-1}) and highest rate of tef ground cover (1.76% d^{-1}) (Table 5). In 2009, the Dessie treatment had the lowest rate of Canada thistle spread (0.70% d^{-1}) and highest rate of tef ground cover (1.91% d^{-1}) (Table 5). The inconsistency of variety performance between years may be due to cooler temperatures in 2009 and change in rainfall pattern (Table 3). The ability of smother crops to compete for space can decrease the space available for Canada thistle. Ground cover spread of tef and Canada thistle were inversely correlated in 2008 ($r = -0.43$; $P = 0.02$) and 2009 ($r = -0.41$; $P = 0.002$). Tef covered space at the expense of Canada thistle. Decreased above-ground Canada thistle spread implies that fewer shoots will be available for photosynthesis and thus restoration of Canada thistle root carbohydrate reserves in the summer months will be

Table 5. Rate of shoot growth (cm d^{-1}) and ground cover spread (% d^{-1}) of tef, Canada thistle, and annual weeds in field trial 2008 and 2009.

Treatment	Tef[a]		Canada thistle[a]		Tef[a]		Canada thistle[a]		Annual weeds[a]	
	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
	cm d^{-1}				% d^{-1}					
Nontreated	N/A[b]	N/A	0.96 a	2.06 a	N/A	N/A	0.746 ab	1.26 a	1.89 a	2.11 a
Corvalis	1.54 ab	1.58 a	0.78 ab	1.65 b	1.37 cd	1.8 ab	0.36 bcd	0.96 b	1.23 b	1.38 b
Dessie	1.62 a	1.58 a	0.99 a	1.56 bc	1.52 bcd	1.91 a	0.76 a	0.70 c	1.06 bc	1.18 bc
Emerald	1.4 c	1.4 abc	0.85 a	1.38 c	1.58 abc	1.71 ab	0.49 abc	0.94 bc	1.04 bc	1.16 bc
Excalibur	1.54 ab	1.38 bc	0.56 abc	1.66 b	1.51 bcd	1.47 cd	0.28 cd	1.2 a	0.875 c	0.98 c
Ivory	1.57 ab	1.44 abc	0.31 c	1.54 bc	1.49 bcd	1.7 ab	0.040 d	1.0 ab	1.21 b	1.35 b
Pharaoh	1.5 bc	1.29 c	0.75 ab	1.72 b	1.35 d	1.38 d	0.36 bcd	1.2 a	1.07 bc	1.2 bc
Tiffany	1.54 ab	1.46 abc	0.39 bc	1.64 b	1.76 a	1.67 bc	0.060 d	0.94 bc	0.961 c	1.08 c
VA-T1	1.56 ab	1.49 ab	0.60 abc	1.73 b	1.59 ab	1.7 ab	0.055d	0.87 bc	1.17 b	1.31 b

[a] Least-squares means within a column followed by the same letter are not significantly different at P ≤ 0.05.

[b] Abbreviation: N/A, not applicable.

suppressed (McAllister and Haderlie 1985). The expansion of Canada thistle patches occurs through underground roots that form adventitious root buds after elongation (Donald 1994b). Without replenishment of carbohydrate root reserves, Canada thistle underground roots may be unable to grow and spread extensively. Thus, the ability of a smother crop to occupy space may enhance suppression of Canada thistle especially if growth of emerged shoots is negatively affected by an established smother crop.

The relationship between weed and tef ground cover spread was not consistent between 2008 ($r = -0.18$; P = 0.19) and 2009 ($r = -0.77$; P = 0.0001). In suppression of annual weed populations that spread through seed production after accumulation of biomass during the logarithmic growth phase, crop biomass may be a more relevant indicator of suppressive ability as the correlations between annual weed and tef biomass were consistent in 2008 and 2009. However, crop ground cover may be a more relevant indicator of competitive ability when a creeping perennial such as Canada thistle is the target weed. Indeed, Canada thistle biomass was inversely correlated with tef ground cover spread in 2008 ($r = -0.35$; P = 0.04) and 2009 ($r = -0.41$; P = 0.002). Although these relationships are not strong, they nonetheless suggest that suppression of laterally spreading weeds such as Canada thistle may be more effective using smother crops that can more effectively and quickly occupy space than accumulate biomass.

In summary, tef was an effective smother crop for suppressing annual weeds, but was not as consistent in suppressing Canada thistle. In the greenhouse experiment, variety Corvalis suppressed Canada thistle biomass and produced more biomass than most other varieties. The planting depth of Canada thistle roots affected emergence of Canada thistle shoots and growth of smother crop varieties. Establishing smother crop populations before emergence of Canada thistle may enhance suppression of Canada thistle and depletion of carbohydrate root reserves. Canada thistle survival in established alfalfa (*Medicago sativa* L.) stands was reduced relative to 3 yr of continuous cropping of spring wheat (*Triticum aestivum* L.) (Hodgson 1958). In the field experiment, variety Tiffany consistently suppressed Canada thistle and annual weed biomass, height, and percentage cover in 2008 and 2009. Suppression of annual weeds and Canada thistle by Tiffany may also be due to the seed coating used to facilitate planting (Table 1). However, suppression of annual weeds among all varieties was more consistent than suppression of Canada thistle. There was evidence to show that smother crops capable of occupying available ground quickly either through higher planting densities or growth habit may be more effective at suppressing Canada thistle. However, further research using additional smother crops and weed species are needed to determine the generality of this crop trait in conferring greater suppressive ability.

Acknowledgments

Field assistance was provided by Lynn Ault and K. Gregory Smith. Critical knowledge of tef management was provided by James VanLeeuwen. Thank you to undergraduate students who assisted in data collection and fieldwork. Salaries and research support were provided by state and federal funds appropriated to the Ohio Agriculture Research and Development Center, The Ohio State University. Manuscript No. HCS-11-4.

Literature Cited

Adnew, T., S. Ketema, H. Tefera, and H. Sridhara. 2005. Genetic diversity in tef [*Eragrostis tef* (Zucc.) Trotter] germplasm. Genet. Resour. Crop Evol. 52:891–902.

Assefa, K., H. Tefera, A. Merker, T. Kefyalew, and F. Hundera. 2001. Quantitative trait diversity in tef [*Eragrostis tef* (Zucc.) Trotter] germplasm from Central and Northern Ethiopia. Genet. Resour. Crop Evol. 48:53–61.

Bàrberi, P. 2002. Weed management in organic agriculture: are we addressing the right issues? Weed Res. 41:177–193.

Barnes, J. P. and A. R. Putnam. 1983. Rye residues contribute weed suppression in no-tillage cropping systems. J. Chem. Ecol. 9:1045–1057.

Beveridge, L. E. and R.E.L. Naylor. 1999. Options for organic weed control—what farmers do. Pages 939–944. *in* The 1999 Brighton Crop Protection Conference—Weeds. Brighton, UK: British Crop Protection Council.

Bicksler, A. J. and J. B. Masiunas. 2009. Canada thistle (*Cirsium arvense*) suppression with buckwheat or sudangrass cover crops and mowing. Weed Technol. 23:556–563.

Collins, A. S., C. A. Chase, W. M. Stall, and C. M. Hutchinson. 2007. Competitiveness of three leguminous cover crops with yellow nutsedge (*Cyperus esculentus*) and smooth pigweed (*Amaranthus hybridus*). Weed Sci. 55:613–618.

Debelo, A. 1992. Germination, Yield and Yield Components of Tef (*Eragrostis tef*) as Affected by Environment, Tillage, and Weed Control Practices. Ph.D dissertation. Stillwater, OK: Oklahoma State University. 162 p.

DeHaan, R. L., D. L. Wyse, N. J. Ehlke, B. D. Maxwell, and D. H. Putnam. 1994. Simulation of spring-seeded smother plants for weed control in corn (*Zea mays*). Weed Sci. 42:35–43.

Donald, W. W. 1994a. The biology of Canada thistle (*Cirsium arvense*). Rev. Weed Sci. 6:77–101.

Donald, W. W. 1994b. Geostatistics for mapping weeds, with a Canada thistle (*Cirsium arvense*) patch as a case study. Weed Sci. 42:648–657.

Evans, J. E. 1984. Canada thistle (*Cirsium arvense*): a literature review of management practices. Nat. Areas J. 4:11–21.

Gaudet, C. L. and P. A. Keddy. 1988. A comparative approach to predicting competitive ability from plant traits. Nature 334:242–243.

Graglia, E., B. Melander, and R. K. Jensen. 2006. Mechanical and cultural strategies to control *Cirsium arvense* in organic arable cropping systems. Weed Res. 46:304–312.

Greene, C. and A. Kremen. 2003. U.S. Organic Farming in 2000–2001: Adoption of Certified Systems. Washington, DC: U.S. Department of Agriculture, Economic Research Service, Resource Economics Division, Agriculture Information Bulletin No. 780. 55 p.

Gustavsson, A.M.D. 1997. Growth and regenerative capacity of plants of *Cirsium arvense*. Weed Res. 37:229–236.

Hanson, J., R. Dismukes, W. Chambers, C. Greene, and A. Kremen. 2004. Risk and risk management in organic agriculture: views of organic farmers. Renew. Agr. Food Syst. 19:218–227.

Hodgson, J. M. 1958. Canada thistle (*Cirsium arvense* Scop.) control with cultivation, cropping, and chemical sprays. Weeds 6:1–11.

Iqbal, J., Z. A. Cheema, and M. An. 2007. Intercropping of field crops in cotton for the management of purple nutsedge (*Cyperus rotundus* L.). Plant Soil 300:163–171.

Jordan, N. 1993. Prospects for weed control through crop interference. Ecol. Appl. 3:84–91.

Kefyalew, T., H. Tefera, K. Assefa, and M. Ayele. 2000. Phenotypic diversity for qualitative and phonologic characters in germplasm collections of tef (*Eragrostis tef*). Genet. Resour. Crop Evol. 47:73–80.

Ketema, S. 1997. Tef (*Eragrostis tef* (Zucc.) Trotter). 50 p. *in* J. Heller, J. Engels and K. Hammer, eds. Promoting the Conservation and Use of Underutilized and Neglected Crops. 12. Rome: Institute of Plant Genetics and Crop Plant Research.

McAllister, R. S. and L. C. Haderlie. 1985. Seasonal variations in Canada thistle (*Cirsium arvense*) root bud growth and root carbohydrate reserves. Weed Sci. 33:44–49.

Moore, R. J. 1975. The biology of Canadian weeds 13. *Cirsium arvense* (L.) Scop. Can. J. Plant Sci. 55:1033–1048.

Nelson, W. A., B. A. Kahn, and B. W. Roberts. Screening cover crops for use in conservation tillage systems for vegetables following spring plowing. HortScience, 26:860–862.

Rees, D. J. 1986. Crop growth, development, and yield in semiarid conditions in Botswana I. The effects of population density and row spacing on *Sorghum bicolor*. Exp. Agr. 22:153–168.

Regnier, E. E. and R. R. Janke. 1990. Evolving strategies for managing weeds. Pages 174–202. *in* C. A. Edwards, R. Lal, P. Madden, R. H. Miller and G. House, eds. Sustainable Agricultural Systems. Boca Raton, FL: CRC Press.

Schoofs, A. and M. H. Entz. 2000. Influence of annual forages on weed dynamics in a cropping system. Can. J. Plant Sci. 80:187–198.

Teasdale, J. R. 1998. Cover crops, smother plants, and weed management. Pages 247–270. *in* J. L. Hatfield, D. D. Buhler and B. A. Stewart, eds. Integrated Weed and Soil Management. Chelsea, MI: Sleeping Bear Press.

Turner, R. J., G. Davies, H. Moore, A. C. Grundy, and A. Mead. 2007. Organic weed management: a review of the current UK farmer perspective. Crop Prot. 26:377–382.

Udensi, U. E., I. O. Akobundu, A. O. Ayeni, and D. Chikoye. 1999. Management of cogongrass (*Imperata cylindrica*) with velvetbean (*Mucuna pruriens* var. *utilis*) and herbicides. Weed Technol. 13:201–208.

Verschwele, A. and A. Häusler. 2004. Effect of crop rotation and tillage on infestation of *Cirsium arvense* in organic farming systems. Pages 187–194. *in* 6th EWRS Workshop on Physical and Cultural Weed Control. Lillehammer, Norway: European Weed Research Society.

Wang, G., M. E. McGiffen Jr., J. D. Ehlers, and E.C.S. Marchi. 2006. Competitive ability of cowpea genotypes with different growth habit. Weed Sci. 54:775–782.

Wu, H., S. R. Walker, V. A. Osten, and G. Robinson. 2010. Competition of sorghum cultivars and densities with Japanese millet (*Echinochloa esculenta*). Weed Biol. Manag. 10:185–193.

Yu, J. K., E. Graznak, F. Breseghello, H. Tefera, and M. E. Sorrells. 2007. QTL mapping of agronomic traits in tef (*Eragrostis tef* (Zucc) Trotter). BMC Plant Biol. 7:30.

Received April 4, 2011, and approved September 30, 2011.