Weed Science 2012 60:618–623

Smother Crop Mixtures for Canada Thistle (*Cirsium arvense*) Suppression in Organic Transition

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Canada thistle poses a particular threat to organic producers in temperate agriculture due to its ability to reproduce through an extensive system of underground roots. The Canada thistle life cycle, growth, and development are seasonally affected, and exploiting this biology may be useful for weed management. The objective of this study was to evaluate smother crop mixtures, seeded at different times, for Canada thistle control. Field trials were established in 2009 and 2010 to evaluate the ability of smother crop mixtures to suppress Canada thistle growth and development. Canada thistle aboveground biomass was suppressed 50% in 2009 and 87% in 2010 by the sorghum–sudangrass mixture, averaged over planting times. The oat mixture suppressed annual weed biomass more than 58% in 2009 and 67% in 2010 in all planting dates. Percent cover of Canada thistle was affected by crop mixture in 2009 and 2010, with sorghum–sudangrass being the most suppressive. The sorghum–sudangrass mixture was more suppressive of Canada thistle, probably because it included soybean and sunflower, all high-biomass, competitive crops. Planting date affected smother crop suppression of Canada thistle growth, but the effect was not consistent between 2009 and 2010 due to differences in weather conditions.

Nomenclature: Canada thistle, *Cirsium arvense* (L.) Scop.; oat, *Avena sativa* L.; sorghum-sudangrass, *Sorghum bicolor* (L.) Moench. × *Sorghum sudanese* (Piper) Stapf.; soybean, *Glycine max* (L.) Merr.; sunflower, *Helianthus annuus* L.

Key words: Organic weed management, smother crop.

Canada thistle is a noxious weed throughout temperate agricultural regions; it causes extensive yield losses, particularly in organic production where the use of herbicides is prohibited (Holm et al. 1977; Menalled et al. 2009; Rzewnicki 2000; Walz 1999). Canada thistle can infest new fields by seeds or vegetative reproduction through deep and extensive root systems that can be found up to 6.75 m below the soil surface (Donald 1994a; Evans 1984). From these propagative roots, Canada thistle produces new shoots that can occupy aboveground space in a field. Nonherbicidal approaches for Canada thistle management have relied on mechanical control methods (Riemens et al. 2010). However, cultivation and tillage machinery cut the roots into smaller pieces that can be spread more widely (Evans 1984). Mowing is not an effective means of suppressing Canada thistle, especially in field crop production (Graglia et al. 2006).

Canada thistle shoot emergence from underground buds begins in spring and peaks in June or July (Donald 1994a). Root carbohydrate reserves are depleted during the bud-to-bloom stage that starts during early summer (Donald 1994a; McAllister and Haderlie 1985). Carbohydrate reserves are replenished by photosynthesis during the fall months before cool temperatures limit growth (Donald 1994a). Strategies that take advantage of this seasonal cycle in Canada thistle biology have been used for management. In pastures, for example, appropriately timed mowing of established perennial species such as white clover (*Trifolium repens* L.) with grass or red clover (*Trifolium pretense* L.) over 3 years has been effective at reducing Canada thistle populations (Graglia et al. 2006). The perennial forage species present in early spring may compete with emerging Canada thistle shoots and decrease replenishment of root carbohydrate reserves in the fall. Summer crops of buckwheat (*Fagopyrum esculentum* Moench.) or a mixture of sudangrass [*Sorghum sudanese* (P.) Stapf.] and cowpea [*Vigna unguiculata* (L.) Walp.], in combination with mowing, have also been shown to reduce Canada thistle biomass and shoot density (Bicksler and Masiunas 2009). The use of crops that have high biomass production rates during summer when Canada thistle root reserves are low may be an effective strategy for suppression.

Smother crops are living plant species or mixes of species growing alone or in combination with a main crop to reduce the growth, development, and reproduction of undesirable plants through resource competition (Teasdale 1998). If smother crops could effectively suppress Canada thistle growth and reproduction, the need for mechanical or chemical inputs could be reduced. This is especially important during the transition from conventional to organic agriculture, when the use of herbicides is prohibited and growers need methods to reduce weeds in preparation for organic production. Annual smother crops with the potential for rapid biomass production may be especially effective in suppressing Canada thistle. Additionally, the use of several species in a smother crop mixture may be more effective at suppression than individual species due to occupation of different above- and belowground niches by the different species (Creamer and Baldwin 2000; Linares et al. 2008). Smother crop species that differ in their adaptation might compete most effectively at different stages in the life cycle of Canada thistle. However, previous research has not addressed the functionality of smother crop mixtures adapted to different stages of Canada thistle growth.

This research was conducted to compare smother crop mixtures for suppression of Canada thistle. We examined three cover crop mixtures seeded at different dates for their ability to suppress Canada thistle. We hypothesized that composition and yield of the smother crop mixture are influenced by planting date and that both mixture and planting date impact Canada thistle growth and development. We expected mixtures of smother crops with species adapted to both cool and warm temperatures targeting vulnerable periods in Canada thistle growth and development to provide the greatest thistle suppression. This study examined the impact of annual management conducted over two seasons in northeast Ohio.

DOI: 10.1614/WS-D-11-00140.1

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Table 1. Dates of harvest of smother crop mixtures in 2009 and 2010. Planting dates in 2009 were May 12, May 27, and June 9 for early, middle, and late treatments; planting dates in 2010 were May 6, May 27, and June 15.

	Harvest date					
	Early		Middle		Late	
Smother crop mixture	2009	2010	2009	2010	2009	2010
Nontreated	August 7	August 17	August 24	August 30	September 9	September 23
Oat–field pea–mustard	July 23	July 9	August 14	July 22	August 24	August 10
Sorghum–sudangrass–sunflower–soybean	August 26	August 30	September 9	September 23	September 22	September 23
Tef–burr medic–buckwheat	August 7	August 17	August 21	August 30	September 22	September 23

Materials and Methods

Experimental Design. Field experiments were conducted at The Ohio State University Schaffter Farm near Wooster, OH, in 2009 and 2010 to evaluate time of planting and species composition of smother crop mixtures for Canada thistle management. The soil type at the site was classified as a fine, mixed, Typic Fragiaqualf (Luvisols) of the Wooster series. The soil is a moderately well-drained silt loam with pH of 7.3, organic matter content 2.9%, and available P and K were 21.3 and 80.6 mg kg^{-1} soil, respectively. The site was a 3-yr-old conventionally managed red clover pasture before experiment initiation. The experiment was managed without the use of pesticides or fertilizers to represent the transition period from conventional to organic production. Treatments were arranged as a 3 × 4 factorial in a randomized complete block design with three planting dates and three smother crop mixtures and a nontreated control with four replications. Individual plots were 3 m × 6 m. Since Canada thistle occurs in patches, we attempted to account for irregularity in patch distribution and density by visually rating each patch individually for percent cover of Canada thistle shoots before assigning treatments to plots. Patches were rated on a 1-to-4 scale according to percent cover on May 4, 2009, and April 16, 2010. This approach ensured uniform Canada thistle populations within a replication. After plot randomization was applied, and before field preparation, the initial density of Canada thistle shoots in each plot was assessed by counting shoots in four 0.09-m^2 quadrats randomly placed throughout each plot. Measurements of Canada thistle percent cover and shoot density before field preparation and seeding of smother crop mixtures were used as covariates in data analysis to adjust for the effect of initial Canada thistle population.

Plots for the early planting date were prepared using a 1.5-m-wide, PTO-driven, rototiller followed by a cultipacker to produce a fine seedbed on May 12, 2009, and May 6, 2010; plots used for the middle and late planting dates were prepared in the same way on May 27, 2009, and 2010, and June 8, 2009, and June 15, 2010, respectively. Smother crop mixtures were seeded the day following field preparation as listed in Table 1. Hereafter, the three planting dates will be referred to as early, middle, and late. Planting dates were chosen to target competitive effects at different stages of Canada thistle growth and underground storage capacity of carbohydrate reserves (McAllister and Haderlie 1985). The early planting date was the first available time for planting the smother crop mixtures with decreasing concentrations of root carbohydrates at subsequent planting dates. The late planting date was chosen to represent the time when the lowest amount of root carbohydrates were available for Canada thistle growth.

The smother crop mixtures were oat (cv. Royal)–pea (*Pisum sativum* L. cv. Packer)–India mustard (*Brassica juncea* L. cv. Florida broadleaf), sorghum–sudangrass–soybean (cv. Stonewall)–sunflower (cv. 620CL), and tef [*Eragrostis tef* (Zucc.) Trotter cv. VA-T1]–burr medic (*Medicago polymorpha* L. cv. Santiago)–buckwheat (cv. Common). The mixtures will hereafter be referred to as oat, sorghum–sudangrass, and tef. The oat mixture was designed to represent an early season–adapted mix that would compete under cooler temperatures when Canada thistle shoots are emerging and beginning to form rosettes. The tef mixture contains densely seeded tef and species that are low growing and mature rapidly. We were interested in learning whether the quick-growing species in the tef mixture would be able to outcompete Canada thistle for resources and reduce light attenuation. Smother crop species in the sorghum–sudangrass mixture are capable of high-biomass production and are adapted to warmer temperatures when Canada thistle carbohydrate reserves are depleted. Smother crop mixture composition, seeding rate, and planting depth in 2009 and 2010 are listed in Table 2.

Table 2. Varieties, seeding rates, and depths of smother crop mixtures in 2009 and 2010.

Smother crop mixture	Variety	Seeding rate (kg ha^{-1})	Seeding depth (cm)
Oat			
Oat	Royal	54[a]	2.5
Field pea	Packer	54[a]	2.5
India mustard	Florida broadleaf	6	1.2
Sorghum–sudangrass			
Sorghum–sudangrass	Special Effort	25	1.2
Soybean	Stonewall	20	2.5
Sunflower	620CL	3	2.5
Tef			
Tef	VA-T1	27	Surface
Burr medic	Santiago	8	1.2
Buckwheat	Common	25	2.5

[a] Oat and field pea seeded as commercially available Sprint oat and pea mix.

https://doi.org/10.1614/WS-D-11-00140.1 Published online by Cambridge University Press

Table 3. ANOVA results for biomass of Canada thistle (CIRAR), annual weeds, and crops, final percent cover of crops, and ANCOVA results for final percent cover and final shoot density of Canada thistle in 2009 and 2010.

	Probability values											
	CIRAR						Smother crops				Annual weeds	
	Biomass		Percent cover		Shoot density		Biomass		Percent cover		Biomass	
Source	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
Smother crop mix (ScM)	0.0002	0.05	0.02	0.02	0.05	0.11	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Planting date (PD)	0.0001	0.0001	0.18	0.01	0.10	0.0005	0.03	0.18	0.07	0.004	0.46	0.001
ScM × PD	0.08	0.11	0.59	0.09	0.58	0.0001	0.09	0.08	0.72	0.33	0.0006	0.0001
Covariate, initial CIRAR population	—	—	0.009	0.18	0.0001	0.0001	—	—	—	—	—	—

Before seeding smother crop mixtures, soybean seeds were inoculated with *Rhizobium* bacteria at rate of 2.5 g TerraMax Dry (TerraMax, Inc. Bloomington, MN) per kilogram of seed immediately prior to planting. Burr medic and field pea seeds were pre-inoculated with *Rhizobium* and no additional application was needed. Treatments were seeded using a Great Plains no-till drill (Great Plains Mfg., Inc., Salina, KS). In the oat smother crop mixture, oat and pea were premixed and seeded from the main hopper, whereas mustard was seeded from the smaller forage hopper. In the tef mixture, buckwheat was seeded from the main hopper and burr medic was seeded from the forage hopper. Inoculated soybean and sunflower were premixed and seeded from the main hopper and sorghum–sudangrass from the forage hopper in the sorghum–sudangrass mix. In each mixture, seeds were drilled in 18-cm rows at a half-seeding rate in the first pass of the plots. On the second pass of each plot, seeds were drilled in between the previously seeded 18-cm rows at a half-seeding rate to give an effective row spacing of 9 cm in each plot and a full seeding rate as listed in Table 2 after two passes of the plot with the no-till drill. This approach was used in an effort to achieve dense, uniform stands, and because equipment for 9-cm spacing was not available to us. Tef was broadcast seeded on appropriate plots after drill-seeding and was followed by a cultipacker to ensure soil–seed contact. After seeding the smother crop mixtures, there was no additional mechanical management of plots.

Data Collection. Canada thistle shoot density was measured every week starting 1 wk after planting for 4 wk, and again at destructive harvests of aboveground biomass in four permanent 0.09-m^2 quadrats per plot. Percent cover of grass, legume, and forb smother crops, Canada thistle, and annual weeds was visually assessed on a 0 to 100% scale using two permanent 0.09-m^2 quadrats per plot every week starting 2 wk after planting and continuing until biomass harvest. Height of the grass crop within a smother crop mixture was measured every week starting 2 wk after planting and continuing until biomass harvest. For brevity, only final measurements of Canada thistle shoot density and Canada thistle and crop percent cover and height are presented or discussed. Aboveground biomass was harvested from two 0.09-m^2 quadrats per plot when all component crops of the smother crop mixture reached maturity. Harvest dates for each planting date and cropping treatment are listed in Table 1. Within a planting date, the nontreated control plots were harvested at a time point halfway between harvest of the first cropping treatment and third cropping treatment within one planting date. For example, at the early planting date in 2009, the oat mixture was harvested first on July 23. The tef mixture and nontreated control were harvested on August 7, and the final cropping treatment within the early 2009 planting date was harvested on August 26. We applied this strategy of harvesting nontreated control plots, where possible, in order to represent growth of Canada thistle and other weeds without a smother crop mixture for the entire period between harvest of the first smother crop mixture and the final mixture within a given planting date. Harvested biomass was separated into grass, legume, and forb smother crops, Canada thistle, and annual weeds, weighed, dried at 55 C for 72 h, and weighed again.

Statistical Analysis. Data were analyzed separately by year due to differences in planting and harvest dates as a result of

Table 4. Biomass and final percent cover of Canada thistle in 2009 and 2010 at the early, middle, and late planting dates and in cropping mixtures.

	Biomass[a]		Percent cover[b]	
	2009	2010	2009	2010
	$g\ m^{-2}$		%	
Smother crop mixture				
Nontreated	210 a	14 a	47 a	5.2 a
Oat–field pea–mustard	81 b	19 a	23 bc	6.2 a
Sorghum–sudangrass–sunflower–soybean	106 b	1.8 b	12 c	0.42 b
Tef–burr medic–buckwheat	102 b	18 a	33 ab	4.1 a
Planting date				
Early	199 a	28 a	27	7.8 a
Middle	96 b	11 b	24	3.8 b
Late	81 b	0.84 c	36	0.34 b

[a] Means within a column followed by the same letter do not differ according to Fisher's Protected LSD (P ≤ 0.05).
[b] Means within a column followed by the same letter do not differ according to Tukey-Kramer method (P ≤ 0.05).

https://doi.org/10.1614/WS-D-11-00140.1 Published online by Cambridge University Press

Table 5. Biomass of annual weeds in 2009 and 2010 in each cropping treatment at the early, middle, and late planting dates.

Planting date	Smother crop mixture	2009[a]	2010[a]
		g m^{-2}	
Early	Nontreated	276 ab	645 b
	Oat–field pea–mustard	85 e	189 efg
	Sorghum–sudangrass–sunflower–soybean	223 abc	452 c
	Tef–burr medic–buckwheat	185 bcd	279 def
Middle	Nontreated	285 ab	524 c
	Oat–field pea–mustard	121 de	171 fg
	Sorghum–sudangrass–sunflower–soybean	191 bcd	84 g
	Tef–burr medic–buckwheat	138 cde	330 d
Late	Nontreated	308 a	844 a
	Oat–field pea–mustard	14 f	110 g
	Sorghum–sudangrass–sunflower–soybean	251 ab	69 g
	Tef–burr medic–buckwheat	198 bcd	309 de

[a] Means within a column followed by the same letter do not differ according to Fisher's Protected LSD ($P \leq 0.05$).

changes in climatic conditions between 2009 and 2010. Data for biomass of smother crops, Canada thistle, and annual weeds and final percent cover of smother crops were subjected to ANOVA in SAS v9.2 (SAS Institute, Inc., Cary, NC) to test for the effects of planting date, smother crop mixture, and the interaction of planting date and smother crop mixture. Data that did not meet the assumptions of normality and/or homogeneity of variances in ANOVA were square root transformed prior to analysis, and means separated by Fisher's Protected LSD ($P < 0.05$).

Data for final percent cover and final shoot density of Canada thistle were subjected to analysis of covariance using PROC MIXED with visual estimates of initial percent cover before experiment initiation and Canada thistle shoot density before seeding used as covariates, respectively, to test for the effects of planting date, smother crop mixture, and interaction of smother crop mixture and planting date. Initial measures of Canada thistle population were used as a covariate in order to accurately assess the effect of planting date and/or smother crop mixture on Canada thistle suppression without bias from initial population. Means adjusted for the covariate were separated using the Tukey-Kramer method ($P < 0.05$). Pearson correlation coefficients were calculated for relationships between biomass measures, percent cover, crop emergence, Canada thistle shoot density, and Canada thistle and crop height.

Results and Discussion

Smother crop mixture affected aboveground biomass of Canada thistle and final percent cover of Canada thistle in 2009 and 2010 (Table 3). In 2009, all smother crop mixtures suppressed Canada thistle biomass by more than 50% compared to the nontreated control. In 2010, only the sorghum–sudangrass mixture suppressed Canada thistle aboveground biomass (1.8 g m^{-2}) in comparison to the nontreated control (14 g m^{-2}) (Table 4). Aboveground biomass suppression can help reduce root reserves by forcing plants to rely on stored carbohydrates for shoot growth (Donald 1994a; Bicksler and Masiunas 2009). The sorghum–sudangrass mixture suppressed the final percent cover of Canada thistle by 74% in 2009 and 92% in 2010. The oat mixture was effective at suppressing Canada thistle final percent cover by 51% in 2009 only (Table 4). Higher temperatures during July and August in 2010 accumulated 300 more growing degree days$_{10}$ in 2010 than in 2009, which may have contributed to the accelerated growth and greater effectiveness of warm-season–adapted crops in the sorghum–sudangrass mixture in suppressing Canada thistle. The oat mixture adapted to cooler temperatures may have been able to compete more effectively with Canada thistle in 2009.

Planting date affected the aboveground biomass of Canada thistle in 2009 and 2010 and the final percent cover of Canada thistle in 2010 (Table 3). Biomass of Canada thistle in the early planting date, averaged across mixtures, was more than 52 and 61% greater than the middle or late planting dates in 2009 and 2010, respectively. In the early planting date in 2010, percent cover of Canada thistle was more than 51% greater than the middle and late planting dates (Table 4). Canada thistle growth is strongly affected by seasonal fluctuations in root carbohydrate reserves (McAllister and Haderlie 1985). Field operations followed by subsequent planting of smother crops when carbohydrate reserves are low in early summer at the time of seeding of smother crop mixtures at the middle and late planting dates could have affected the ability of Canada thistle to compete with crops for resources.

The interaction between planting date and smother crop mixture was significant for annual weeds in 2009 and 2010 (Table 3). The most common annual weeds present in both years were scarlet pimpernel (*Anagallis arvensis* L.), hairy galinsoga (*Galinsoga quadriradiata* Cav.), Virginia copperleaf (*Acalypha virginica* L.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and yellow foxtail [*Setaria pumila* (Poir.) Roem. and Schult. ssp. *pumila*]. The oat mixture at each planting date in 2009 and 2010 effectively suppressed the biomass of annual weeds compared to the nontreated control (Table 5). The oat mixture was harvested earlier than other smother crop mixtures within each planting date and the amount of time between seeding and harvest could have affected biomass production by competing annual weeds (Table 1). In 2009, only the oat mixture suppressed annual weeds within each planting date. However, all smother crop mixtures effectively suppressed annual weed biomass in comparison to the nontreated control (Table 5). Cooler temperatures in 2009 may have favored the growth of smother crops in the oat mixture and suppressed growth of warm-season–adapted crops in the tef and sorghum–sudangrass mixtures, affecting the ability of smother crops to compete with annual weeds.

Crop aboveground biomass was affected by crop mixture in 2009 and 2010 (Table 3). The sorghum–sudangrass mixture produced 44 and 71% more biomass than the oat or tef

Table 6. Biomass of smother crop mixtures and percent composition ($\bar{x}$ ± SE) of each mixture in 2009 and 2010 at the early, middle, and late planting dates and in cropping mixtures.

	Biomass		Percent composition					
			2009			2010		
	2009[a]	2010[a]	Grass	Legume	Forb	Grass	Legume	Forb
	g m^{-2}		%					
Smother crop mixture								
Oat–field pea–mustard	349 b	109 c	46 ± 7	18 ± 4	11 ± 2	48 ± 4	30 ± 5	22 ± 5
Sorghum–sudangrass–sunflower–soybean	771 a	1,130 a	59 ± 4	21 ± 4	20 ± 4	42 ± 5	53 ± 5	5 ± 3
Tef–burr medic–buckwheat	433 b	325 b	96 ± 1	1 ± 0.4	3 ± 1.4	99 ± 0.4	1 ± 0.4	0
Planting date								
Early	512 b	434 a	64 ± 6	13 ± 4	22 ± 4	64 ± 6	18 ± 5	19 ± 5
Middle	639 a	544 a	79 ± 4	12 ± 3	8 ± 2	57 ± 7	40 ± 7	3 ± 1
Late	402 b	582 a	56 ± 8	15 ± 4	4 ± 1	68 ± 6	27 ± 6	6 ± 2

[a] Means within a column followed by the same letter do not differ according to Fisher's Protected LSD (P ≤ 0.05).

mixtures in 2009 and 2010 (Table 6). The difference in biomass between sorghum–sudangrass and tef and oat mixtures may be attributable to greater height in sorghum–sudangrass. Sorghum–sudangrass (155 cm) grew taller than crops in the oat (85 cm) or tef mixtures (61 cm) in 2009 and crop biomass was positively correlated with crop height in 2009 (r = 0.69; P < 0.001). In 2009, crop biomass was 20 and 37% greater in the middle planting date than the early or late planting dates, respectively (Table 6). In 2009, the proportion of grass smother crops in the mixtures was greatest at the middle planting date and may have contributed to greater biomass accumulation. In 2009 and 2010, percent cover of crops was affected by crop mixture (Table 3). Sorghum–sudangrass mixtures covered 24% or more ground in 2009 and 45% or more in 2010 than the oat or tef mixtures (Table 7). The growth habit and percent cover of component crops in the sorghum–sudangrass mixture impacted total percent cover of the smother crops mixture. Sorghum–sudangrass produces more tillers than oat or tef, which are more erect in growth habit, contributing to the ability to cover the ground more effectively. Poor growth of the legume and forb components of the tef mixture reduced percent cover of this treatment (Table 7). The sorghum–sudangrass mixture grew taller than the oat or tef mixtures, further contributing to effective ground cover.

The sorghum–sudangrass mixture was the most effective smother crop mixture for suppressing aboveground biomass and reducing final percent cover of Canada thistle in 2009 and 2010 (Table 4). The sorghum–sudangrass mixture produced more biomass, had greater final percent cover, and more equal contribution of component crops in the mixture than the oat or tef mixtures (Tables 6 and 7). Previous studies have shown that biomass of crops competing with weeds can function as a proxy for competitive ability (Gaudet and Keddy 1988). The sorghum–sudangrass crop mixture may be more effective at competing with Canada thistle for resources as evidenced by higher biomass output (Table 6). The ability of the sorghum–sudangrass mixture to effectively cover the ground can also impact Canada thistle populations. The quantity of ground cover from smother crops has been shown to be inversely proportional to ground cover by weeds (Liebman and Davis 2000). Canada thistle spreads through underground roots that can occupy unused space, although how Canada thistle roots can sense unoccupied space is not clear (Donald 1994b). Sorghum–sudangrass mixtures provided greater ground cover than the tef or oat mixtures and contributed to suppression of Canada thistle populations (Table 7).

The competitive ability of the sorghum–sudangrass mixture, indicated by biomass production and percent cover, contributed to Canada thistle suppression; the composition of the mixture likely contributed to effective suppression as well. Biomass composition and percent cover of the tef mixture were dominated by tef (Tables 6 and 7). The intended advantage of using smother crop mixtures as opposed to monocultures was to take advantage of more above- and belowground niches for resource acquisition and thereby compete more effectively with weeds (Creamer et al. 1997; Haynes 1980). The minimal input of burr medic and buckwheat in the tef mixture may have reduced potential

Table 7. Final percent cover ($\bar{x}$ ± SE) of smother crop mixtures and component grass, legume, and forb crops in 2009 and 2010 at the early, middle, and late planting dates and in cropping mixtures.

	2009				2010			
	Grass	Legume	Forb	Total[a]	Grass	Legume	Forb	Total[a]
	%							
Smother crop mixture								
Oat–field pea–mustard	18 ± 2	24 ± 4	10 ± 3	52 b	5 ± 1	5 ± 1	4 ± 1	14 c
Sorghum–sudangrass–sunflower–soybean	40 ± 3	19 ± 3	15 ± 3	72 a	27 ± 4	45 ± 7	5 ± 2	77 a
Tef–burr medic–buckwheat	29 ± 4	2 ± 1	14 ± 2	44 b	41 ± 5	1 ± 1	1 ± 1	42 b
Planting date								
Early	23 ± 3	13 ± 2	21 ± 2	57 a	18 ± 3	11 ± 5	3 ± 1	33 b
Middle	38 ± 4	14 ± 3	9 ± 2	61 a	24 ± 5	25 ± 7	1 ± 1	51 a
Late	25 ± 3	18 ± 5	9 ± 2	50 a	30 ± 5	14 ± 5	5 ± 2	50 a

[a] Means within a column followed by the same letter do not differ according to Fisher's Protected LSD (P ≤ 0.05).

competitiveness as indicated by low values for ground cover and biomass production. Altering seeding rates in this mixture could improve the representation of burr medic and buckwheat. Although the composition of smother crops in the oat mixture was more evenly distributed among grass, legume, and forb components, suppression of Canada thistle was weaker in comparison to the sorghum–sudangrass mixture (Table 4). The oat mixture consisted of crops adapted to cooler temperatures and was expected to be a more suppressive mixture for the early planting date. However, Canada thistle growth in spring draws on stored carbohydrate reserves rather than current photosynthesis, so even a spring-adapted smother crop mixture is at a competitive disadvantage with this perennial weed (McAllister and Haderlie 1985). When Canada thistle root reserves were at a seasonal low at later planting dates, temperatures would not have been favorable for growth of crops in the oat mixture. However, the oat mixture was effective at suppressing annual weeds (Table 5). The oat mixtures matured more quickly than the sorghum–sudangrass or tef mixtures and were harvested, on average, 73 d after planting in 2009, and 56 d after planting in 2010 (Table 1). Rapid growth of the oat mixture can outcompete weeds for resources, but Canada thistle can still compete for resources with available carbohydrate reserves that annual weeds do not possess. Since the oat mixture was not as effective in covering the ground as the sorghum–sudangrass mixture, Canada thistle would have been able to reproduce if only a few shoots could obtain light for photosynthesis.

In summary, single-year suppression of Canada thistle aboveground growth with smother crops depended on the planting date and crop mixture. The sorghum–sudangrass mixture suppressed Canada thistle more effectively than the oat and tef mixtures regardless of planting date, despite seasonal adaptation of these mixtures to planting conditions and temperatures. The oat mixture suppressed annual weeds more effectively than the other mixtures at each planting date. Canada thistle suppression tended to be more effective when smother crop mixtures were planted at a probable low point in Canada thistle root carbohydrate reserves later in the growing season. However, changes in annual climatic conditions can affect Canada thistle biology and planting date should reflect this for better suppression.

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 field work. 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-11-17

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Received August 19, 2011, and approved June 6, 2012.